AN ANALYSIS OF THE GROWTH AND SPREAD OF OPEN FIRES

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PREFACE

The purpose of this study is to present a framework within which to analyze all open fires. It is not intended to present detailed analyses. The scope of this work is too broad to do more than point out what is or is not important and explain why. This study will then be a guide to the future research necessary on open fires.

The author wishes to express his gratitude to his major advisor, Dr. Kenneth J. Bell, for his guidance and assistance in conducting this research. Appreciation is also expressed to the U. S. Air Force which funded the research.

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LIST OF SYMBOLS

A	- Area
A_p	- Projected area of moving body
A_{si}	- Surface area of droplet in a given size increment
c	- Specific heat
C_d	- Drag coefficient
D	- Diameter of projectile in inches
du/dt	- Derivative of velocity component with respect to time
dm/dt	- Derivative of mass with respect to time
E	- Energy term
F_d	- Drag force
F_{ji}	- Any force, j, acting in a given direction, i
g_c	- Gravitational conversion constant
h	- Heat transfer coefficient
H_{rx}	- Heat of reaction
ΔH_{fi}	- Heat of formation of component i
H_v	- Heat of vaporization
k_2, K_1	- Constants that are determined for a given earth medium
l	- Thickness of solid fuel sample

m	- Mass
n_i	- Moles of component i
$(n/\Delta s)_i$	- Number of droplets in a given size increment
Q	- Radiant exposure (BTU/Ft^{2}deg.F)
r	- Radius of a droplet
T	- Temperature
T_o	- Room temperature
ΔT	- Temperature driving force - the temperature of the air minus the temperature of the droplet surface
t	- Time
u	- Resultant velocity
u_i	- Component of velocity
u_o	- Velocity of droplet with respect to carrying fluid
$\overline{u}$	- Time averaged velocity
Vol	- Volume
V_o	- Resultant initial velocity of the projectile
v_s	- Striking velocity in feet per second
W	- Weight of the projectile in pounds
x	- Position variable
Y	- Total penetration in inches
ΔZ	- Height of projectile above reference
α	- $k/\rho c$ - Thermal diffusivity
ρ	- Density

σ	- Surface tension
Γ	- Vortex strength

CHAPTER I

INTRODUCTION

The general term, "unconfined combustion," comprises phenomena such as large building fires, forest, brush, and range fires, and fires resulting from fuel spills. To see how these are related and to describe the term "unconfined combustion," consider the following examples.

When gasoline is burned in an internal combustion engine, the amount and composition of fuel are known, the amount of air consumed is known, and the reaction chamber dimensions and conditions are known. With unconfined combustion, however, the system is not as easily defined. In a forest fire, only a general knowledge of fuel composition is available; the amount of fuel is generally unknown; and atmospheric dynamics must be considered both on a very large scale and on a local basis. In fuel spills, the composition is closely known, but the detailed manner in which the fuel is dispersed and ignited is usually not known. Again, interaction with the atmosphere plays a vital role in the dispersal and subsequent burning.

It is clear that there are additional considerations in analyzing unconfined combustion that do not present problems in a combustion chamber. These are:

1. Are the fuel composition and quantity known?

2. What are the boundaries of the fire as a function of time and space?

3. How is the fuel dispersed?

4. How is the fuel ignited?

5. How do the atmosphere and the combustion process interact?

Depending upon the situation being considered, not all of the above considerations may be involved. However, it is desired to develop a general framework from which all types of unconfined combustion can be examined.

It is helpful to break down unconfined combustion into several basic steps for easier analysis and to note the similarities among the examples given. These steps are:

1. Impact - This is the step which initiates the dispersion of the fuel and/or the ignition source if not already in place where combustion occurs.

2. Dispersion and/or distribution of the fuel ("Dispersion" refers to the dynamic spreading of the fuel following impact. "Distribution" refers to the amount and arrangement of fuel statically in place.)

3. Ignition

4. Spread of the burning zone

5. Interaction of the combustion zone and the atmosphere.

Impact is important only as it leads to and sets the initial conditions for the other steps. For forest and brush fires, this step (involving the dispersion of the ignition source) may be of importance only at the beginning and have little to do with the nature of the fully developed fire. In a fuel spill or explosion, the initial event is important since it determines how the fuel is distributed and, hence, how it will ignite and burn. Since impact is applicable only to a few cases, it will be discussed in an appendix.

In fuel spills and explosions, the development of the distribution, or the dispersion, of the fuel is important. This includes an analysis of fuel droplet trajectories in air and droplet size distributions. This is dependent upon the "energy available for dispersion." An explosion will provide the greatest dispersion while a fuel spill will, in general, be more limited in its dispersion. The dispersion or distribution of fuel, then, is directly related to the "impact." For forest and brush fires, the fuel is in place, but the ignition source may be dynamically distributed or dispersed.

The next step, ignition, may occur either at impact or after the fuel is dispersed. Here, the principles of ignition are explored as well as basic combustion theory specification of the conditions necessary for combustion.

Once the fuel is dispersed and ignited, the fire consumes the dispersed fuel and the surrounding available fuel. The way the fire spreads and the maximum rate of burning is determined by the atmospheric dynamics as the immediately surrounding air is heated and convection currents are set up, supplying oxygen and removing heat and combustion products.

The purpose of this paper is to survey the literature to find the information available on the basic steps just stated. The result will show the current state of investigation of the basic steps and give a bibliography of articles which will provide a key to the available literature.

CHAPTER II

IGNITION

The purpose of this chapter is to give a summary of the current literature available on the subject of ignition. Detailed analyses will not be included. It should also be pointed out that the majority of the current literature on ignition deals with uniform liquid-vapor fuel systems. While the basic ideas and mathematics of ignition also apply to more complicated systems such as brush and timber, the application of these ideas is too cumbersome except for very simple systems. Reaction rate theory will not be discussed since the basic theory has been well developed and can be found in any kinetics textbook. Levenspiel (1) and Trotman-Dickenson (2) both have good contributions in this area. There are also too many specific reaction phenomena, few of these of general interest, to be reported here.

Definition of Terms

To begin a discussion on the subject of ignition, several definitions must first be established. First, what is meant by inflammable? A fuel is said to be inflammable if a mixture of the fuel and air is capable of liberating enough heat to sustain self-propagation of a flamefront through the unignited fuel. This leads to a discussion of flammability limits. Basically

> ....flammability limits are conditions defining the state of a fuel-oxidant mixture at which the application of a strong external ignition source is only just capable of producing flammability in a given test apparatus.(3)

There are four types of flammability limits defined for a given apparatus and fuel. They are as follows:(4)

1. Flammability limits as a function of fuel-oxidant ratio for a fixed temperature and pressure

2. Flammability limits as a function of pressure for a fixed temperature and fuel-oxidant ratio

3. Flammability limits as a function of temperature for fixed pressure and fuel-oxidant ratio

4. Saturated flammability limits of liquid or solid fuel as a function of pressure for fixed fuel-oxidant ratio

The U. S. Bureau of Mines has developed a standard apparatus for measuring flammability limits of fuel vapors. (5) It measures composition limits at fixed temperatures and pressures. The mixture is considered flammable if a flame propagates through the entire length of tube containing the vapor after a small flame or spark is applied. During the tests, oxidant is added to the fuel so that an upper and then a lower limit of oxidant necessary for ignition is determined.

There is no single physical parameter which defines flammability limits. The limits are, instead, a set of conditions. Included are factors such as apparatus and direction of flamefront propagation with respect to Earth's gravitational field (convection effects). Most authors agree that these limits are not a fundamental property of explosive systems but serve as "reasonable practical limits." (6)

Ignition Energy

The next topic of discussion is that of ignition energy. When discussing ignition energy, minimum ignition energy is the factor of prime importance. As with the definition of flammability limits, minimum ignition energy is not a fundamental value and requires a description of the physical situation for which a particular value is obtained. Minimum ignition energy depends upon such factors as: nature of ignition source and its geometric arrangement, apparatus, and fuel-oxidant mixture. A popular basic idea used in quantitative ignition theories is that the ignition source must supply enough thermal energy locally to a gas mixture for the steady propagation of a combustion wave. Minimum ignition energy may be defined as follows:

> ....by the condition that the rate of energy transport per unit area by thermal conduction, from the gases exposed to the ignition source, equals the rate of enthalpy change produced by thermal conduction from unit area in a steadily propagating flame.(7)

The energy available for ignition must be at least enough to sustain a steadily propagating flame assuming no other means of dissipation.

Attempts have been made to correlate experimental minimum ignition energy to other calculable energies. One such energy involves computing the sensible heat in a sphere of burned gas at the burned gas temperature in excess of the heat at the initial unburned temperature.(8) Correlation can only be done for a given ignition source. The main fact to remember about minimum ignition energy is that it depends upon many factors and to also note the dissipative factors influencing the ignition.

Mechanics of the Ignition Process

The most common ignition source discussed in the literature is spark ignition. The mechanism of spark ignition of a homogeneous hydrocarbon fuel-air mixture is as follows (9) (Figures 1 and 2). A spark causes a small gas volume to have, nearly instantaneously, a very high temperature. This temperature drops rapidly as this heat is transferred to the surrounding unburned gas. The immediately surrounding gas eventually reaches a temperature sufficient to form a combustion wave that then propagates uniformly to the surrounding gas. When the temperature at the origin has decreased to approximately the normal flame temperature, the flame should be large enough so that the temperature gradient between the burned gas in the core and the outer unburned gas has about the same slope as the temperature gradient in the steady state wave. If not, the rate of heat liberation in the core reaction zone does not make up

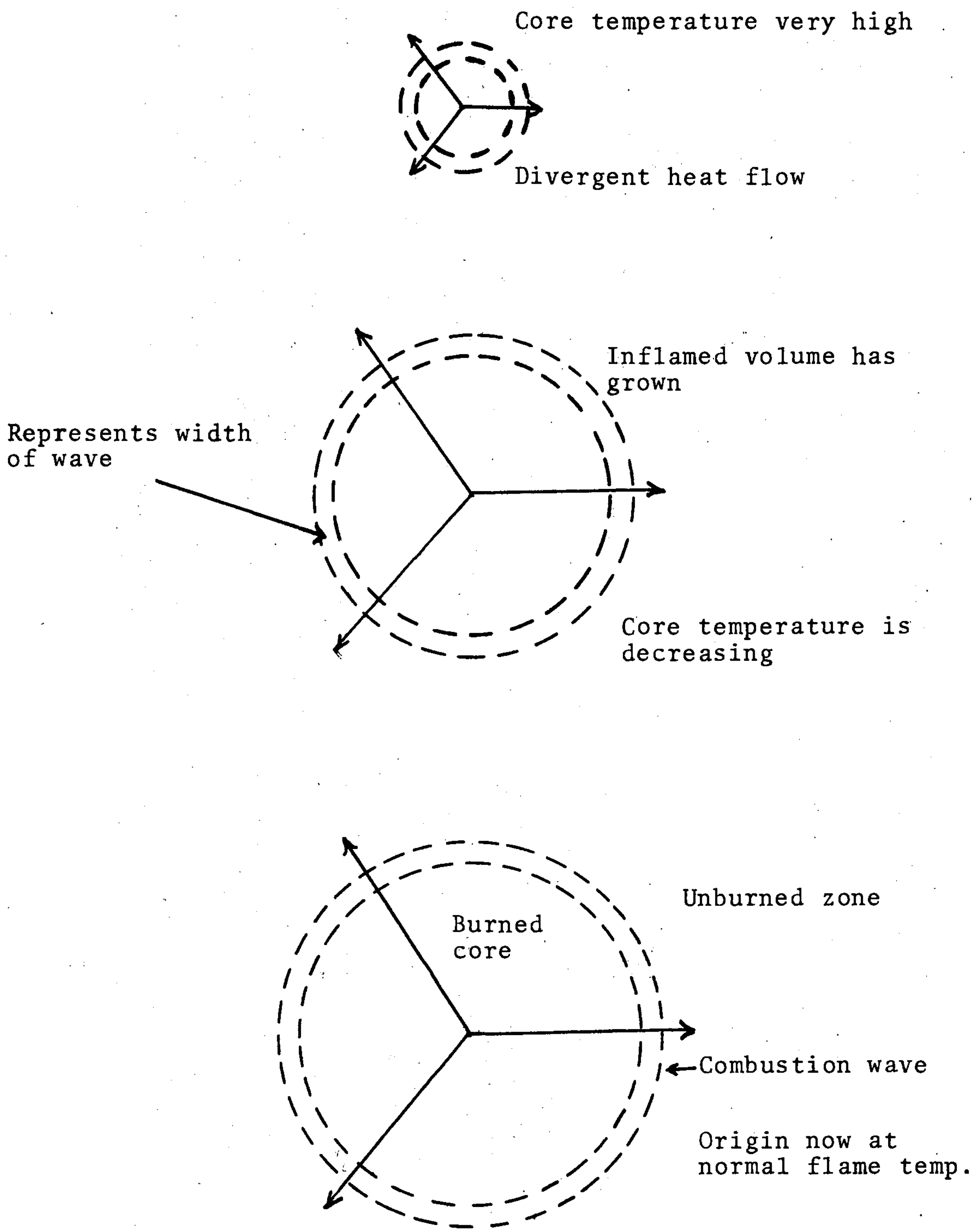


Figure 1. Spark Ignition Model

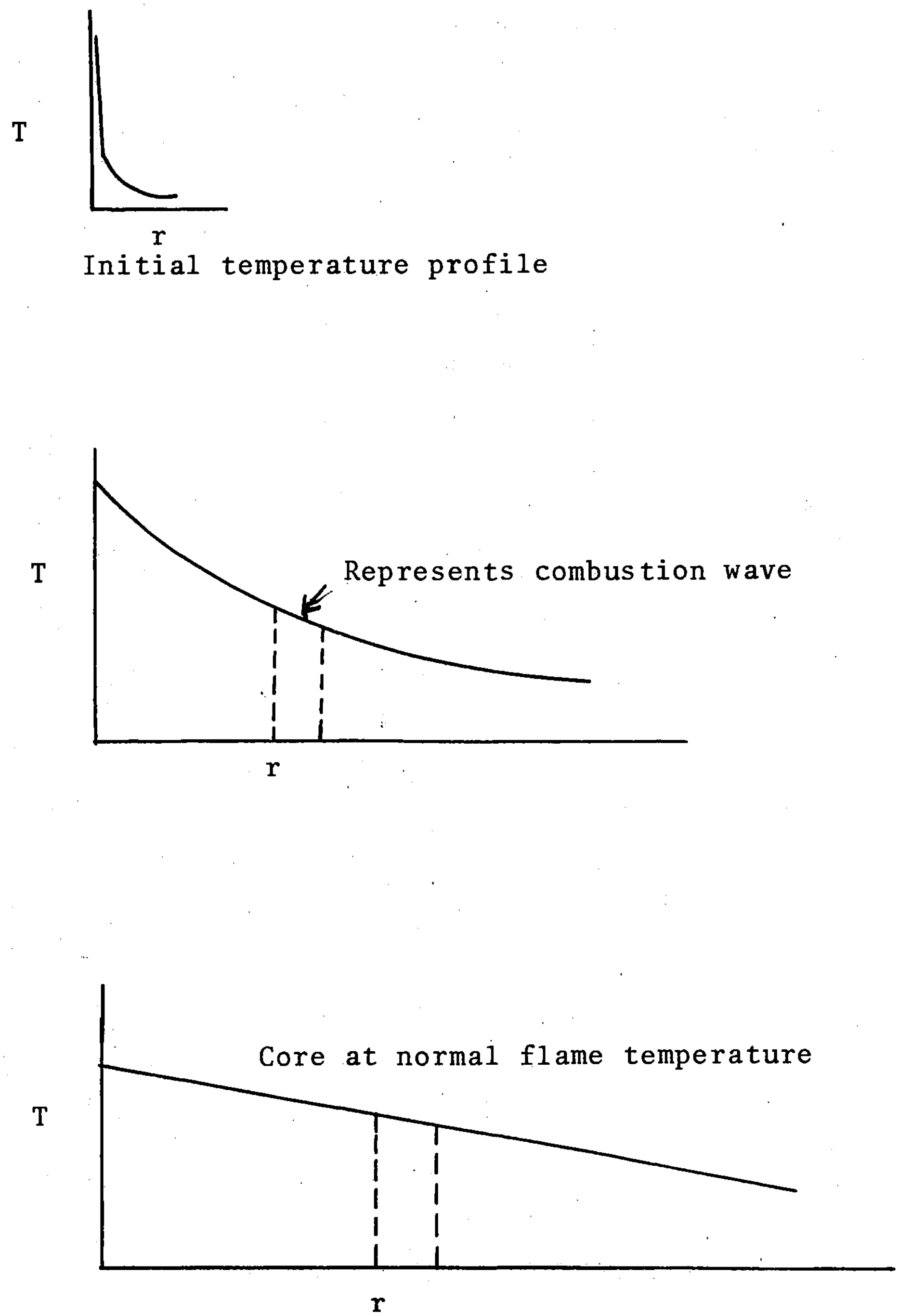


Figure 2. Temperature Profiles as Original Spark Volume Grows

for the heat loss to the outer zone of preheated unburned gas and the combustion wave dies as the temperature declines.

The other type of ignition to be discussed is spontaneous ignition. Spontaneous ignition is defined as a process in which a "...combustible undergoes chemical reaction accompanied by a rapid evolution of heat and the emission of light...without the assistance of a spark or flame..." (10) A spontaneous ignition temperature is also defined, above which this process occurs. Again, this temperature is not a fundamental value, but depends upon the apparatus and procedures used.

Once the conditions are suitable for ignition, the ignition is spread by means of detonation and combustion waves. The first step in discussing detonation and combustion waves is to distinguish between the two. A combustion wave is propagated by diffusion and heat transfer processes. "Detonation waves are shock waves which are sustained by the energy of the chemical reaction that is initiated by the shock compression."(11) Combustion waves are subsonic while detonation waves are supersonic. A combustion wave is the propagation of burning in which each succeeding layer of gas is ignited by the heat of the adjacent burning layer. In a spherical combustion wave, the transfer of heat to the unburned gas is divergent so that heat is always transferred to a larger area. This effect is called flame stretch and is most important when the combustion wave is at the point source of ignition. In this case the dimension of the wave width is on the same order as the diameter of the spherical flame. As this diameter becomes much greater than the wave width, the effect becomes unimportant. When this effect is important, it is possible that the wave may be quenched. Criteria for this effect have been investigated.(12)

Much experimental study has been done on detonation waves and much knowledge has been obtained on the nature of these waves. Also, much mathematical analysis has been applied to a steady, one-dimensional detonation wave under simplified conditions. For the case of fully-developed, stable detonation for fully-reacted gas, the detonation velocity has been calculated and it compares closely with experimental results.(13) The basis of stability involves the fact that a rarefaction wave directly follows the detonation wave and decelerates the burned gases when the reaction is complete. This theory also involves the concept that the detonation wave is a reaction zone of finite width. When the rarefaction wave is anywhere in the reaction zone, a stable zone exists between the shock front and the front of the detonation wave. Instability comprises alternate periods of acceleration and periods during which the rarefaction wave moves faster than the shock front. The wave slows down so more chemical reaction takes place. These alternate phases may merge to produce stable detonation.

For a given mixture and apparatus, method of ignition does not affect limits of detonability unless the ignition source is very strong. It has also been shown that as a mixture departs markedly from stoichiometric composition, no detonation wave can be supported.(14) While geometry is important in determining limits, it has little effect on propagation velocity. More recent work has uncovered the nature of three-dimensional detonation waves and spinning detonation.(15)

Ignition of vegetation has not yet been mentioned. In an article by Anderson (16) on the ignition of forest fuels, a correlation is given of radiant energy as a function of Fourier modulus. This results in three zones: nonignition, transient ignition, and persistent ignition. The radiant exposure quantity is $Q/\rho c l$ where Q is the radiant exposure; ρ is the sample density; c is the sample specific heat; and l is the sample thickness. The Fourier modulus is $\alpha t/l$, where α is the thermal diffusivity, and t is the exposure time.

Ignition of any solid involves adding enough heat to produce combustible vapors. If the fuel of interest is a uniform solid propellant, the heat needed is simply that to vaporize the fuel plus the minimum ignition energy. If the fuel is nonuniform cellulosic material, there are three energy factors involved. First, heat must be added to dry the fuel. Next, heat is needed to initiate pyrolysis and produce combustible vapors. Finally, minimum ignition energy is needed to ignite the vapors. This will be discussed more fully in Chapter IV.

Much research has been done to study the basic concepts of ignition as applied to uniform gas-oxidant mixtures. Mathematical analysis has been limited to the most basic of these cases. Lewis and von Elbe (17) comment:

> An elaboration of the outlined model of ignition threshold in terms of physical-mathematical theory is possible in principle, but is prohibitively complicated and unrewarding in view of the many unknowns of diffusion and reaction processes.

From the standpoint of this paper, the information needed is: under what conditions will a given fuel ignite; how much will ignite; and how quickly does the fuel ignite? Most research is done on a confined fuel where the system is completely specified. For fuel spills and forest and brush fires, the fuel is unconfined and the system is not neatly specified. The important factor is the physical state of the fuel at the time of ignition. This is determined either by its dispersion after impact or its natural distribution.

CHAPTER III

DISPERSION

Unlike the previous chapter on ignition, there is no basic discussion of dispersion collected. Information on dispersion will have to be collected by looking at topics the author thinks are important as contributions to the analysis of this step. Dispersion mainly applies to liquid fuels which are distributed over a given area either by explosions or fuel spills, but it is also a factor in forest fires. This factor involves spreading forest fuels and ignition sources during a fire by convection currents. This mechanism will be discussed later in the final chapter which covers fire spread and growth. The ultimate purpose of this discussion will be to provide an analysis that will lead to a distribution of fuel from the point of impact, whether burned or unburned. This discussion will include such topics as: droplet trajectories in air, droplet size distribution, effect of burning and evaporation on droplet trajectories, and spills. The end result of a thorough quantitative analysis should give a percentage of the fuel burned before coming to a final resting point, plus a distribution of the remaining fuel at the final point in its trajectory. Five areas of investigation are listed below:

1. Droplet trajectories
2. Effect of vaporization and burning
3. Droplet size distribution
4. Flow of fuel in a spill
5. Breakup of fuel mass

In this chapter it is necessary to relate the impact energy to the dispersion of the fuel. In a fuel spill this energy will simply be the potential energy of the mass of fuel. In an explosion it will be part of the chemical reaction energy. This chapter will begin with the "impact" having taken place, and with the fuel in motion to its final destination.

Calculation of droplet trajectories is important only as a means to find the final position of a droplet of dispersed fuel. If it were possible to calculate the droplet trajectory of every droplet of moving fuel, then a final distribution of fuel could be obtained by simply plotting the trajectory of each droplet.

Particle Motion

The basic equation for the motion of a particle in one direction is:(18)

$$\Sigma F_{ji} = \left(\frac{m}{g_c}\right)\left(\frac{du_i}{dt}\right) \tag{3.1}$$

By breaking down the various forces acting on a particle into three coordinate directions, a three-dimensional picture of the motion of the particle can be obtained. This equation may be numerically integrated to some time, t_1, and the position at the end of this interval may be calculated by assuming constant velocity over the time increment.(19) The change in position, Δx, is given by the product of the average velocity, $\bar{u}$, over the time increment, Δt. It is necessary to know ΣF_i as a function of time, and also m, if it varies with time. Average values of these two terms can then be taken over the time increment. This leads to evaluation of the changing mass when vaporization occurs. Ingebo (20) has written several papers in this area. He gives the basic equation for vaporization as:(21)

$$\frac{dm}{dt} = \frac{hA}{H_v}\Delta T \tag{3.2}$$

The main problem is to calculate the heat transfer coefficient, h. Ingebo correlates h as a function of a new number, which is simply the product of the Reynolds and Schmidt numbers, and the thermal conductivities of the air and droplet vapor. The term, dm/dt, can then be put into a form for varying diameter by noting that for constant density:

$$dm = \rho d(Vol) \tag{3.3}$$

$$Vol = (4/3)\pi r^3 \tag{3.4}$$

$$d(Vol) = 4\pi r^2 dr \tag{3.5}$$

$$\frac{dm}{dt} = 4\pi r^2 \rho \frac{dr}{dt} \tag{3.6}$$

Another problem remaining is to evaluate the various F_i to be included. These forces include: gravity, buoyancy, and drag forces. Gravity and buoyancy both act only in a vertical direction. Drag may act in any direction. The forces that present the greatest problem in analysis are the impact and drag forces. The equation for drag force is: (22)

$$F_d = \frac{C_d u_o^2 \rho A_p}{2g_c} \tag{3.7}$$

C_d may just be defined as the value that makes Equation (3.7) correct. The term, C_d, has been correlated as a function of Reynolds number for solid spherical particles falling at a constant velocity in a motionless fluid without being influenced by other particles or by the containing vessel.(23) For present purposes, none of these conditions is rigidly applicable. Papers are available in which the drag coefficient for spherical droplets has been correlated for the conditions of burning or evaporating droplets. Ingebo (24) obtained results for sprays where more than one droplet was present. In a paper by Eisenklam, Arunachalam, and Weston (25), drag coefficients for small, free-falling burning droplets were presented.

The development of some interaction parameter is also needed to allow for the movement of many droplets of all sizes through a fluid at the same time. This parameter would account for collisions between droplets. These collisions make the conditions different from those for which the drag coefficients were correlated, and, hence, reduces the accuracy of the drag coefficients and the calculated droplet trajectories. However, the interaction parameter would allow the usage of the drag coefficients for one droplet in an undisturbed infinite fluid. This parameter would represent the transfer of momentum from one droplet to another during dispersion. This might take a form similar to the kinetic theory of gases in which collisions between molecules are considered. While the kinetic theory deals with molecular quantities and dispersion involves macroscopic quantities, it may be possible to draw analogies between the two, and use the kinetic theory to develop a macroscopic version.

Finally, an initial size distribution must be known. After breakup of the mass of fuel there will probably be masses of fuel ranging from minute droplets up to "globs" of fuel of undefined geometry. For quantitative analysis, it will be assumed that the droplet distribution is made up of perfect spheres which may collide or evaporate, but which do not transmit mass to each other. This seems to be the best one may hope for now with such random events as breakup of the fuel mass and collision of fuel droplets during dispersion. From a theoretical approach, it is very difficult to obtain a size distribution. There are too many variables to make this practical. Size distribution is a function of viscosity and surface tension (as a factor in the formation of very small droplets) and is dependent upon the initial shape of the mass, its velocity at impact, and the energy of explosion. A more practical approach might be through dimensional analysis combined with experimental results to obtain an equation which would include the most important variables as characterizing parameters. For example, using dimensional analysis, a distribution might look like:

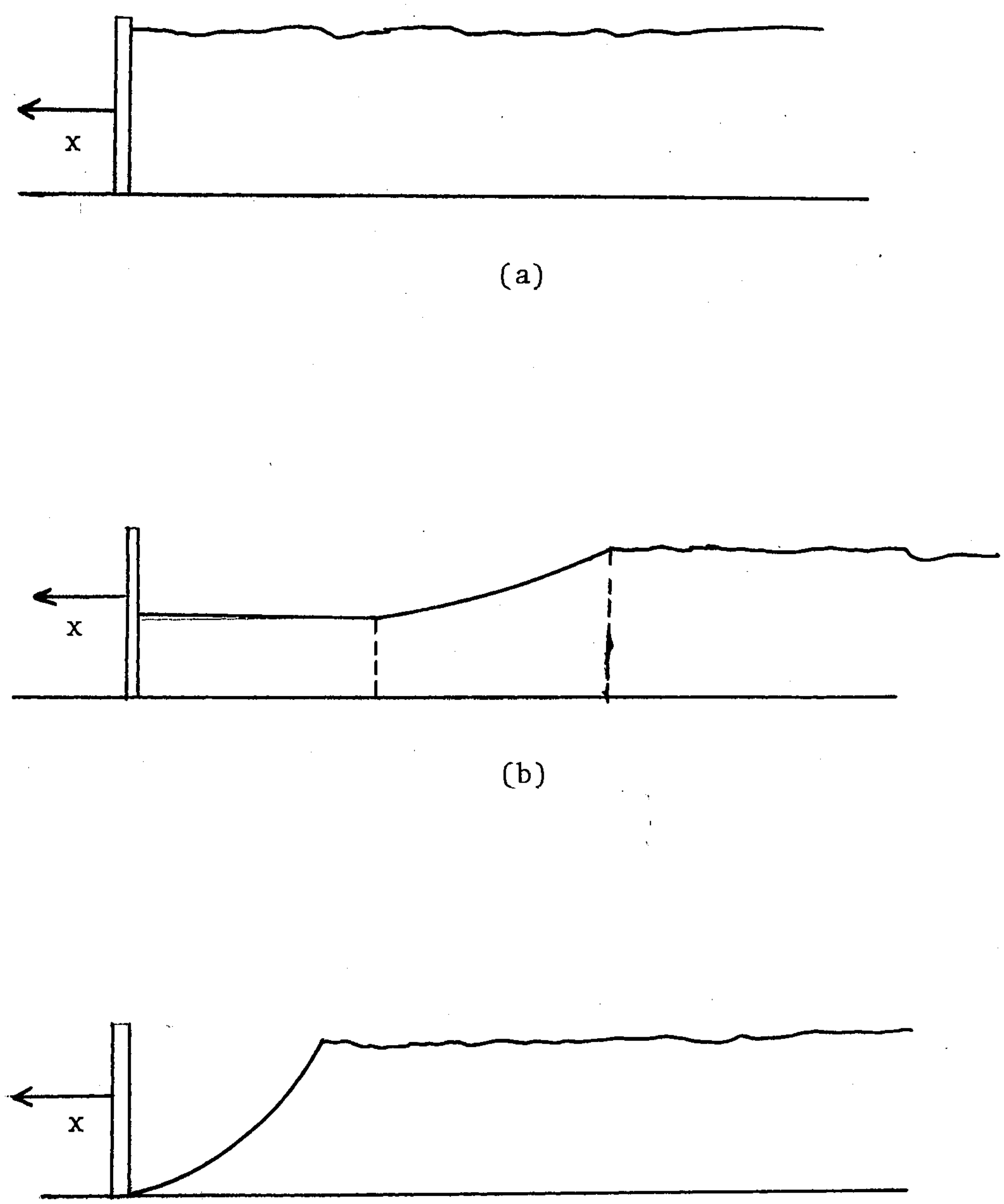
$$\left(\frac{n}{\Delta s}\right)_i = F\left(\frac{E}{A_{si}\sigma}\right) \quad (2.8)$$

The term, A_{si}, represents a characterizing area of the droplet size, i. The term, E, represents either the kinetic or explosive energy of the entire mass at impact. This correlation group may be viewed as a modified Weber number as used in a paper by Harmon (26) on mean drop size prediction. This particular form has not been tested, so it is unknown whether this group would prove useful. Experimental results are needed to determine the function, "F." Given a droplet size distribution, it would be possible to plot the trajectories of all the droplets in each initial size increment to obtain a final approximate distribution. A paper by Lapple and Shepherd (27) covers this topic of droplet trajectories.

Fuel Spills

The final area of investigation in this chapter is fuel spills. The important factors are how fast and how far the fuel will spread. The closest topic in fluid dynamics to the unconfined nature of flow in a spill is open channel flow. A textbook on this topic has been written by Henderson.(28) In the chapter on unsteady flow, Henderson discusses "the dam-break problem." This situation most nearly simulates a fuel spill. The analysis is made by assuming a plane barrier holds back a reservoir of fluid in a rectangular channel. The plane barrier may be moved at any finite speed so that the fluid is always in contact with the barrier. At any time, t, a profile may look like Figure 3b. In this part, three zones are observed. If the plate is moved fast enough, it will lose contact with the water and the water will be able to flow at a free rate. This profile is shown in Figure 3c.

Henderson solves the equations of motion for this system by the method of characteristics. His equations of motion involve partial differential equation in which velocity and height are both functions of position and time. By picking the correct reference (observer moves at some convenient velocity), one side of these partial differential equations becomes a total derivative. In the simplest cases, an explicit solution can be obtained. More complex cases require numerical methods for solution.



(c)

Figure 3. The Dam-Break Problem

For fuel spills, it is difficult to lump all events into one physical description. In some cases, the above example may be a close approximation to the actual event. In other cases, using cylindrical coordinates and assuming no angular dependence, will result in, still, only two independent variables, radial position and time. Many cases would require two position coordinates and would, hence, result in three independent variables. Also, in his analysis of the "dam-break problem," Henderson neglects shear and frictional forces. However, for low viscosity fluids, this would provide a good approximation and is probably the best that can be done for this system.

Fuel may also be spread by the mechanism of splashing. Numerical methods have been used to plot the motion of a droplet as it splashes into an undisturbed liquid surface. The Marker-and-Cell Method shows a cross-section of a splashing drop at a given velocity and time (from initial contact of liquid surface).(29) Numerical techniques have predicted splash behavior quite well.

CHAPTER IV

GROWTH AND SPREAD OF THE FIRE

The final discussion involves the growth and spread of the fire plus its interaction with the atmosphere. Since forest fires are the most extreme example of unconfined combustion, a general description of forest fire phenomena will first be given. From this, it will be obvious which aspects need to be investigated and which, under very special conditions, can be mathematically analyzed.

For a forest fire to be sustained, there must be an adequate bed of fuel. The fuel supply is, in general of two classifications.(30) First, there is the ground fuel composed of fallen leaves, grass, low shrubs, dead branches, and downed logs. Another classification is called aerial fuels. This includes living tree trunks, branches, leaves, and other organic matter not close to the ground.

Pyrolysis and Ignition of Forest Fuel

Forest fuel in its natural state is not combustible with oxygen.(31) Instead, the wood must be decomposed by heat through a process called pyrolysis. Products of this decomposition are: water vapor, carbon dioxide, combustible gases, charcoal, residuals of tarry products, and mineral ash. If heating is rapid enough, these products are produced at such a rate that they may be ignited and a continuous flame is produced. The following generalities have been found concerning temperatures and the process of pyrolysis. (32)

1. At temperatures below 400°F pyrolysis products (gaseous) are noncombustible. These gases consist mainly of water vapor.

2. At temperatures between 400°F and 536°F the product gases are still generally not combustible, but contain, in addition to water vapor, carbon dioxide, formic acid, acetic acid, glyoxal, and traces of carbon monoxide.

3. At temperatures greater than 536°F larger amounts of combustibles are produced and the reaction becomes exothermic. Gas products are carbon monoxide, methane, methanol, formaldehyde, and formic and acetic acids.

4. At temperatures greater than 900°F the products are mainly hydrogen and carbon monoxide.

To ignite forest fuel material enough heat must be added to decompose the organic material into combustible products, to evaporate moisture content, and to supply minmum ignition energy.

All naturally occurring vegetation contains a certain amount of moisture.(33) This content depends upon whether the material is living or dead and also the surrounding atmospheric conditions. This aspect is important since heat is required to vaporize this moisture and since the water vapor dilutes the decomposition gases. Moisture content in green wood may range up to 25 percent by weight, while wood under normal conditions may have a moisture content of 5 to 15 percent. In large fires, the available heat is much more than enough to vaporize the contained moisture. In this case, the moisture acts only as a time delay and does not prevent ignition.

As stated previously, a certain minimum ignition energy must be supplied to a combustible so that under specified conditions combustion can be sustained. A recent literature survey was performed by Ulrich and Sasine (34) at Brigham Young University. In this paper, the authors collect recent works in the area of experimental determination of ignition characteristics of wood and cellulosic solids. Information included about each work was: method of experimental analysis, ignition data and conditions, correlation parameters, experimental results, and authors' conclusions. Method of analysis refers to the exact data taken in a given experiment. Data obtained are dependent upon the material tested. In general, the surface temperature was the prime correlating parameter used in the experiments. One method of analysis used temperature as a function of time, while another used time to ignition at a given heating rate. These examples show that several different types of measurements may be useful in ignition analysis.

Once the data are obtained, some way is needed to turn these data into interpretable results. The literature survey categorizes the works investigated into four areas in each of which a different model was used to correlate the data. The models chosen were very much simplified so that analytical solution would be possible. The basic equation used in the four models was the one-dimensional heat conduction equation.

$$\alpha \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{4.1}$$

The differences between the models occur due to: geometry (infinite versus semi-infinite slab), heat losses at the surface either neglected or included, and burning in which the material is consumed.

With the method of analysis (experiment) known and a simplified model available, the data may be correlated to allow results to be obtained and conclusions to be made. The authors conclude that a more complicated model than the simple conduction model is needed to represent the heat transfer through the slab of fuel. The model used by Ulrich and Sasine neglects any chemical change and does not account for changing physical properties. Other factors influencing results are: orientation of ignition source with respect to the surface to be ignited, heating source (flame or radiant), effect of area of surface heated, errors in measurement.

The remaining heat that needs to be added to the fuel to initiate ignition is the heat to decompose the fuel into combustible gases. In the presence of air, pyrolysis products will oxidize at temperatures much below 500^{o}F.(35) This is the temperature at which pyrolysis becomes exothermic. The combination of pyrolysis and oxidation of products causes an overall exothermic reaction before pyrolysis alone becomes exothermic. However, heat must still initially be added to form the pyrolysis products.

The description of the experiments used in the previous discussion (Ulrich and Sasine survey), shows that the heat of decomposition plus the minimum ignition energy of the resulting gases, plus the heat of vaporizing the moisture is the actual quantity measured in the ignition of wood. However, it would be difficult, if not impossible, to heat the wood, collect the pyrolysis gases, separate the combustibles, and then measure the minimum ignition energy of the actual combustibles. Also, this procedure would add little useful information and would necessitate the precise description of the procedures used in doing this.

For a continuous flame to be produced, enough heat must be added to a fuel to provide a continuous supply of a combustible vapor. This supply of vapor may be from simply vaporizing a fuel or it may involve evaporating water vapor plus the process of pyrolysis.

Environmental Factors

The growth and spread of a forest fire involves complex interactions with the environment. Environmental factors include weather, fuel, and topography in a given area.(36) Hence, a forest fire may be discussed qualitatively in terms of these three factors. The two classifications of fuel, aerial and ground, have already been mentioned. Other factors to be considered are the concentration of the fuel and how finely the fuel is divided. In finely divided fuel, the flame will usually spread very rapidly depending upon moisture content. In areas of highly concentrated fuel, heat is transferred vertically to ignite the tree crowns. When flames are driven by winds, the flame travels horizontally in a sporadic manner. The flamefront travels through the finely divided fuel while the heavier fuels burn long after the flamefront has passed. In areas of mainly larger units of fuels (logs) the flame travels slower but it is a much more intense flame.

Another factor of prime importance in forest fires is the weather. Major factors are wind and air moisture content, which, in turn, affect the fuel moisture content. Great variations occur in these factors throughout a 24 hour period. Fire activity is greatest in the afternoon when air temperature reaches its maximum and air moisture content is at a low. During this time a well defined convection plume (Figure 4) is set up and fuel consumption reaches a maximum. At night, the fire diminishes in intensity and, hence, so does the rate of spread. By

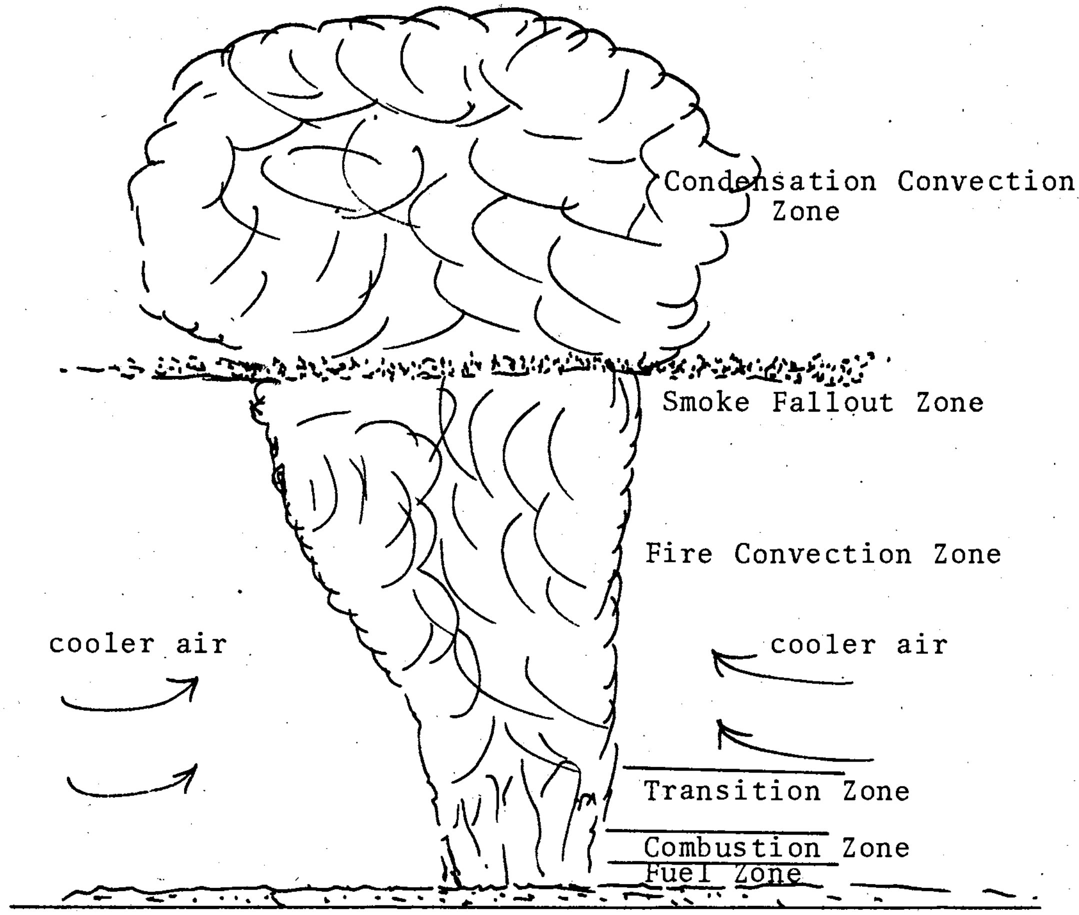


Figure 4. Countryman's Fire Model-Convection Column

morning the fire is at its lowest point and smoke has collected in low areas due to lack of a strong convection column.

The Convection Column

Under the condition of no wind, the greatest heat transfer occurs in a vertical direction. Cool air enters at the base of the column (There is evidence that this may occur well above the ground line.), is heated, and is carried upward along with smoke, combustion gases, and small fuel particles (Figure 4).(37) This does not imply that the wind pattern in and around a convection column is a simple upward movement of gases. Due to variation in atmospheric density, the convection column spreads out as it rises. The convection column may reach heights of five miles or more.(38) Normal surface winds have the effect of tilting the column so that maximum heat transfer is no longer in a perfectly vertical direction and the convection column does not extend as high as when there are no ambient winds. Under proper wind conditions, the convection column may become horizontal. However, there are still strong convection forces working to carry smoke upward. During peak intensity, there appears to be a single, well-developed convection column. However, Countryman (39) reports:

> From a distance, a convection column looks like a single rising stream of gases and smoke. Viewed close to the fire, however, it is seen

> to be made up of a number of smaller convection columns that develop over relatively small 'hot spots' of active fire and then merge some distance above the fire area.

A well-developed column may sometimes display characteristics of whirling motion and sometimes rhythmic, pulsing motion. Byram and Nelson (40) have attempted to model pulsating fires by developing scaling relationships to scale up laboratory results. Once the peak intensity has passed, the pulsing diminishes and several small columns are set up on the edge of the fire.

These mass fire characteristics are observations and are valid under the conditions for which they were observed. In general, the characteristics just discussed will be observed where there are heavy fuels that will support intense combustion.

Topographic factors include altitude, mountain and canyon contours, and slope angle.(41) These factors affect the fire by either blocking it or aiding in its spread. A wide canyon would tend to block the fire since there would be a void of accessible fuel. A steep slope aids in spreading the fire uphill since the heat is transferred upward. When the flame reaches a certain height, gradient winds predominate and spread the fire parallel to the slope.

A general description of forest fire behavior has been given since it most typifies the uncontrollable factors of unconfined combustion. Similarities can be found in this type of fire whether it is in a forest or over a fuel spill. The main difference is in the range of size and distribution of the fuel.

In a fire, heat must be supplied to the fuel at such a rate as to supply minimum ignition energy and overcome heat losses through conduction, convection, and radiation. Radiation and convection losses are the main considerations. The importance of radiation is shown in the case where a forest fire spreads across a barrier, such as a road, by radiation heating only.

Experimentation in the area of large, uncontrolled fires is in the early development stages. Most work so far has only revealed general qualitative results. Difficulties have been encountered in determining what variables need to be measured in addition to the procedures for making such measurements. Also, instrumentation needs to be developed to measure the physical characteristics of a fire. One problem with experimentation is that data taken from small laboratory type fires cannot be extrapolated to large fires. Different controlling factors seem to take over when a fire reaches a certain size or intensity.(42)

With forest fire development as background information, more detailed discussions will be presented on the various physical aspects of large-scale fires. Perhaps, the best way to present these more detailed discussions is by selecting a few articles from the current literature that typify present work being done and giving a brief summary of these articles. The following are just a few articles that show where the efforts of research are being directed currently.

Survey of Literature

In a paper by Countryman (43) qualitative results are given of observations of mass fires. Most of these results have been stated previously in the qualitative discussion. Countryman was interested in air flow and wind velocities around and associated with a large fire. In addition to measuring air flow, Countryman also measured temperatures at various points in the fire area.

Countryman tried to simulate an urban fire, noting that the main difference from a forest fire would be fuel bed characteristics. He performed this physical simulation by arranging naturally occurring fuel in a pile with the same general burning characteristics as a building. He spaced several of these so as to simulate residential subdivisions. Countryman then measured the air flow pattern at various stages of the fire development at various altitudes. Both vertical and horizontal components were measured.

From his observations of mass fires, Countryman developed a fire model with six zones of the convection column (Figure 4, page 30). They are:

1. Fuel bed which extends from the ground to the top of the fuel bed. The height of this zone ranges from less than an inch to several feet.

2. Combustion zone of active flaming. The height of this zone is less than 100 feet.

3. Transition or turbulence zone located between the combustion zone and the more organized convection column. The height of this zone ranges from 100 to 200 feet above the combustion zone.

4. Fire (thermal) convection zone extending from the top of the turbulent zone to the base of the convection column cap. This zone ranges in height from less than 1000 feet to more than 15,000 or 20,000 feet.

5. Smoke fallout zone. This layer is a thin zone at the base of the convection column in which smoke spreads out from the convection column.

6. The condensation convection zone. This zone extends from the fallout zone to the top of the convection column, where the column widens to form a cap. This zone has a light color due to condensed water vapor or, sometimes, ice crystals. This zone does not occur in all fires.

In a paper by Emmons and Ying (44), theoretical and experimental results of fire whirl data are compared. A fire whirl consists of rising gases rotating at a high velocity. A naturally occurring whirl depends upon two factors. One is the presence of ambient vorticity plus a concentrating mechanism to bring this vorticity to a vortex core. Basically, the hot gases rising from a fire provide a concentrating process for the vortex, thus producing a fire whirl. Emmons and Ying give a more detailed discussion of these mechanisms in their paper.

Sets of data were taken in a specially designed apparatus. The apparatus consisted of a pool of liquid on a circular table above which rose a cylinder of window screen. The screen was fixed so that it could rotate at several speeds. The whirl was set up by the rotating screen and the burning fuel. Temperature and velocity distributions were obtained. Results showed the effect of the strength of the fire whirl on the burning rate and on the visible flame height. The continuity, energy, and momentum equations were solved after all terms were eliminated except the largest term in each equation. Results were generally poor due to the unexpected variance of a turbulance mixing parameter with height. Results were recorded as vortex strength as a function of plume height and radius (Figure 5). This figure shows results recorded at 1.26 meters above the pool. These represent results typical of all intermediate elevations (greater than zero and less than three meters). The temperature is reported as the temperature at a given radial position minus the room temperature, T_o.

The authors conclude:

> The extension of simple plume theory to include the fire whirl is not yet adequate to make reliable predictions of the phenomena. In the

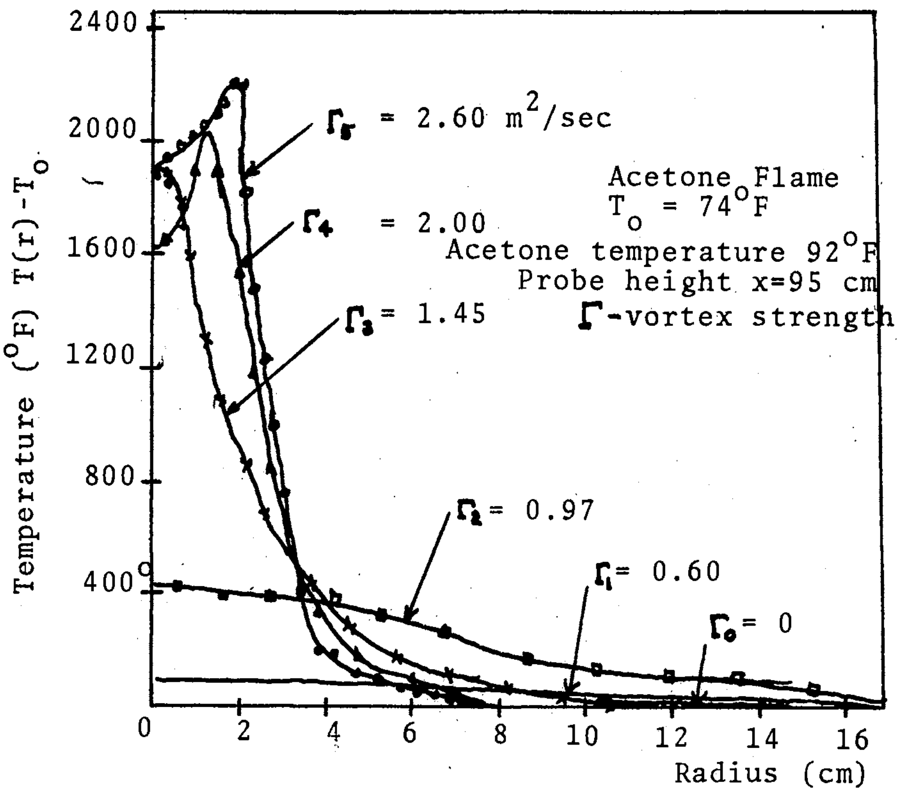


Figure 5. Mean Temperature vs. Radial Position and Vortex Strength in a Fire Whirl

> absence of an adequate theory of turbulence it seems necessary to make additional detailed measurements to determine the cause of the inadequacy.

In another paper, McAlevy and Magee (45) investigate the mechanism of flame spreading over the surface of igniting condensed-phase materials. Experimental procedures involved igniting a rectangular specimen along one of its edges. Results were recorded by cinecamera or stopwatch, depending upon the rate of spread. Experiments were done in a chamber designed to hold the pressure constant. The theory proposes that the exothermic reaction of importance in flame spreading takes place at a site in the gas phase. Ignition is initiated ahead of the flamefront at a given location due to the heat of the flame. The vapors diffuse away from the surface and react with an active component in the environment (oxygen for our purposes). Heat is released and increases the local temperature and heat feedback to the surface. As the flame moves closer to a given location, the process of vaporization accelerates, and, hence, the reaction rate increases in the vapor phase. This acceleration leads to a very rapidly increasing temperature to ignition. Ignition occurs as the flamefront reaches the given location. Experiments were done in a motionless environment but are believed to be valid in an environment in motion. Results were reproducible to within five percent and the authors conclude:

> ....when specimens are prepared with care and experimental conditions are well defined, a reproducible flame-spreading velocity can be

> measured that is an intrinsic combustion property of the particular system.

In his article on firespread in brush, Albini (46) proposes a physical model for this particular type of fire. In this article the author points out that significant parameter groups for correlating data on firespread through brush have been developed through dimensional analysis and semi-theoretical treatment. However, actual correlations are missing from his paper. Albini concentrates here on developing a physical model for firespread through brush, so that analytical models may be applied to each step of the physical model. He does this by establishing four regions of the fire spread (Figure 6).

1. Preheating and Outgassing Region - This region extends from the forward base of the flame into the unburned fuel. In this region the fuel is heated by radiation and water vapor is driven off. No ignition takes place in this region.

2. Intermittent Deflagration Region - This region extends from the forward base of the flame to some critical distance into Region 1. Here volatile hydrocarbon concentrations will occasionally be high enough to support a deflagration wave.

3. Flame Attachment Region - As the process of outgassing - deflagration - cooling continues, the surface temperature of the fuel increases, pyrolysis occurs, and the flame attaches to the fuel particle surface. When the fuel particle surface will sustain an attached flame, the

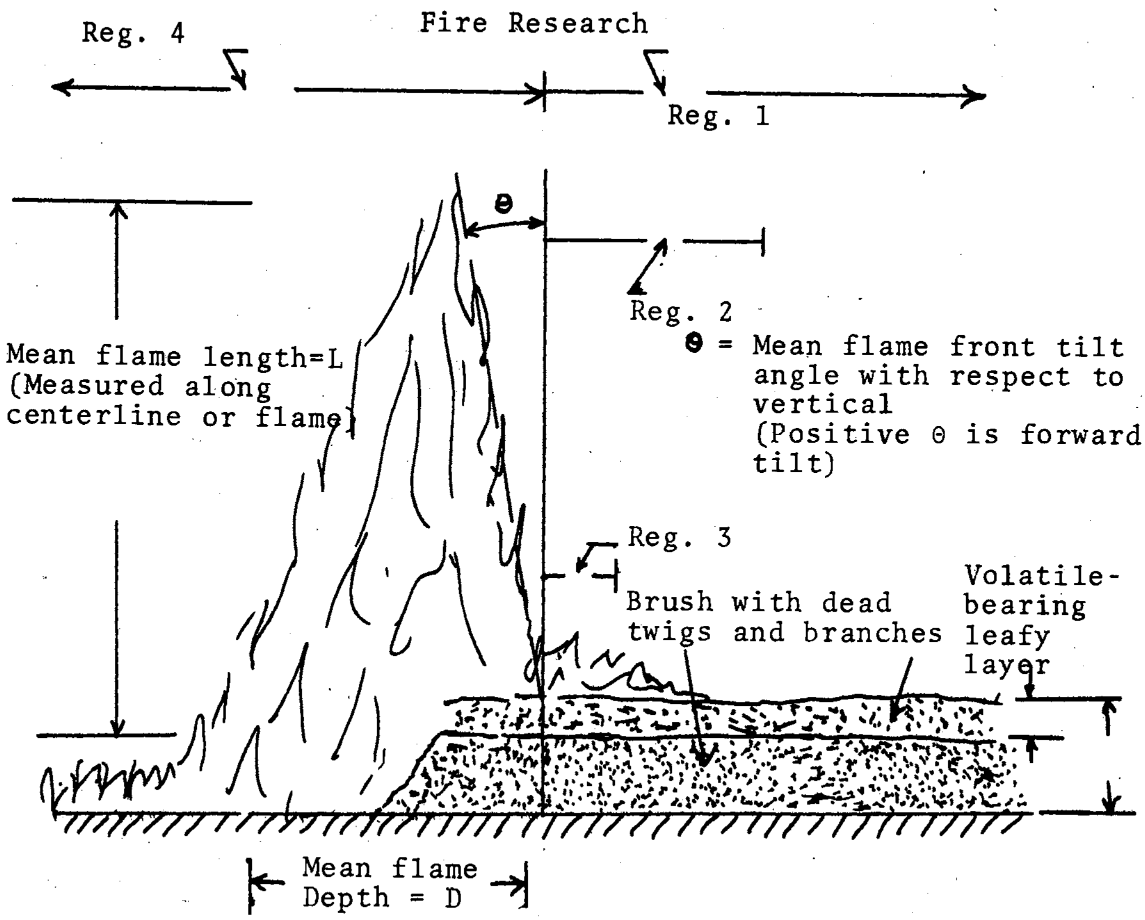


Figure 6. Albini's Physical Model of Firespread in Brush

flamefront will advance through this region to the next flamefront position. If this move is considered to be stepwise, the flame-attachment region is the area between the present flamefront and its next position.

4. Steady Burning Region - This region extends from the flamefront back to the area where the fuel has been reduced to the glowing stage. This region is one in which the fuel is consumed at a steady rate.

Simple analytic models were developed for each region, but no experimental data existed with which to compare the results.

In a paper about the effects of radiation on large fire plumes, Smith (47) gives a model for the flow in a turbulent fire plume at levels where strong buoyancy and radiation effects are still important. The simplified equations of energy, momentum, and continuity are solved for this situation. Radiation is given in terms of a lateral and vertical component. These equations are written with turbulent components added. That is, velocity components are a combination of an average point term plus a turbulent fluctuation from the point mean. If U is a velocity component, then $U=\overline{U}+U'$. The term, $\overline{U}$, is the point mean and the term, U', is the point deviation from the point mean due to turbulence.

The final two articles both involve liquid pool fires. The first article, by Welker and Sliepcevich (48), investigates burning rates and heat transfer with data taken from wind-blown liquid pool fires. They report that for large diameter fires the burning rate becomes constant. The burning rate is defined as the mass of material burned per unit area per unit time. The burning rate is dependent upon the rate of heat feedback, which is a function of conduction, convection, and radiation. For large diameter fires, radiation dominates and flux is constant. Hence, feedback is constant. Changing the view factor of the column changes the radiation rate. This occurs when wind causes the convection column to tilt. As the tilt increases, the view factor decreases, decreasing the rate of heat feedback.

The second article, by Huffman, Welker, and Sliepcevich (49), investigates the interaction of multiple pool fires. Burning rate data are correlated for various burner arrangements which simulate pool burning of several pools in close proximity.

These articles do not represent an exhaustive survey of articles in this area. They are given to show what type of research is being done and to provide additional sources, through their included references, for further search.

The main contributions being made at this time are development of experimental techniques combined with very simple theory to correlate the results. Much work is needed on procedures and instrumentation in taking data on mass fires. Also, simple models of fire spread and convection column characteristics must be developed so that data can be correlated to obtain results.

CHAPTER V

CONCLUSIONS

The purpose of this research was to, first, propose a framework within which to analyze "unconfined combustion" and then to determine the nature and extent of research performed within this framework. Conclusions, then, should report the success, or lack of it, in finding information to fit this framework. This will be the format used in stating conclusions.

Ignition

The main efforts of research on ignition have used uniform gas-liquid fuel mixtures. Relatively little has been done on nonuniform fuels such as wood and other vegetation. Minimum energy to ignition must be measured in some manner. First, however, the variables to be measured must be determined as well as standard procedures and techniques to obtain them. This will have to be done essentially by trial and error. A list of possible correlating variables can be obtained by using basic analysis of the system, studying previous experimental results, or by intelligent guessing. Then these variables are measured experimentally. Statistical methods can then be used to determine if and where a correlation exists. Finally, correlations must be developed to correlate the data obtained.

Impact

In impact, no collection of the necessary information was found. Research is needed on the breakup mechanism of a vessel or casing with the ultimate goal being to determine the energy dissipated during this event. Also, the energy absorbed by the impact material (usually rock or soil), either by compaction or shear, needs to be correlated. When these correlations are accomplished, the energy available to disperse the fuel can then be calculated.

Dispersion

Here the breakup and coalescence of the liquid masses must be investigated as they move to their final positions after impact. Drag coefficients for the moving liquid masses are needed as they interact with the atmosphere. Also, open flow in fuel spills needs to be correlated in terms of general flow parameters. This should give the time for the fluid to spread over a given area to a given height of fluid.

Growth and Spread of the Fire

Fire spread and growth is the area in which the greatest amount of research is needed. First, the parameters which best characterize open fires must be determined. This would be done as stated previously under ignition. Next, instrumentation to measure these parameters must be developed. Finally, correlations are needed for the data measured. These data include temperature and velocity distributions in and around the fire.

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APPENDIX

Impact

The first step in the process of unconfined combustion will be called impact. This is the initial event that leads to the combustion process. This step is important because it determines the energy available for the dispersion of the fuel. Because this step only plays an important role in bomb drops and the explosion of fuel vessels, it has been included as an appendix. For forest fires this step is not important because it does not lead to dispersal of fuel. For a fuel spill, the impact would simply be the event that allows the fuel to escape and the dispersion energy would just be the potential energy of the mass of fuel.

Impact Energy

In an explosion the impact is the explosion and the dispersion energy is the explosive energy of reaction. When a bomb is dropped from an airplane, the impact is the actual impact of the bomb with the ground. The dispersion energy is the kinetic energy of the bomb plus the reaction energy of the portion of the explosive which actually does explode.

The energy that may be available for dispersing the fuel comes from several sources. They are: potential energy, kinetic energy, and reaction energy. The potential energy of the mass of fuel is the energy calculated from the center of mass of the fuel to the surface over which the fuel is dispersed (Figure 7).

$$P.E. = \frac{mg(\Delta Z)}{g_c} \tag{A.1}$$

The kinetic energy is applicable in bomb drops in which a large velocity is given to the mass of fuel. This is calculated as:

$$K.E. = \frac{mV_o^2}{2g_c} \tag{A.2}$$

The reaction energy is calculated using the heats of formation of the reactants and products assuming total reaction.

$$H_{rx} = \sum_{prod} n_i \Delta H_{fi} - \sum_{reacts} n_i \Delta H_{fi} \tag{A.3}$$

Not all of the fuel will necessarily burn. Test data are needed to establish the percentage of fuel burned under given conditions.

The total reaction energy is not necessarily the most important quantity in determining the fuel dispersion. Reaction rate plays a vital role also. In an explosive reaction great amounts of gaseous products are produced at high temperature. The important factor is the amount of pressure buildup before the containing vessel yields. The higher the pressure can build before rupture of the vessel,

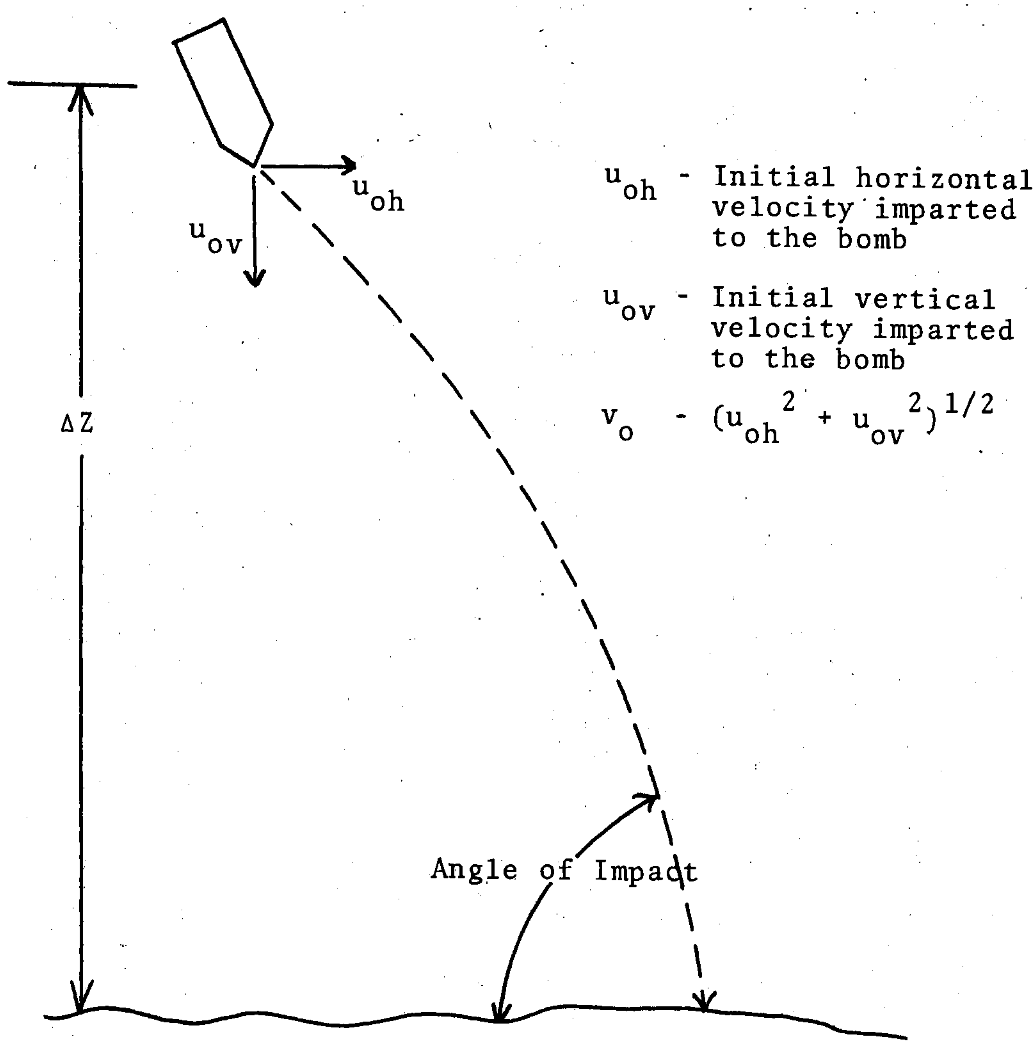

Figure 7. Bomb at Release

the more violent will be the explosion. Hence, there will be greater dispersion of the fuel.

Dissipation of the Impact Energy

If all of the above energy were used to disperse the fuel, the calculations would be greatly simplified. However, this energy is dissipated in various ways before dispersion.

First to be considered will be the energy dissipated as drag resistance in a bomb drop. This can be calculated by Equation A.4.(51)

$$\sum_j F_{ji} = \frac{m}{g_c}\frac{du_i}{dt} \qquad \text{(A.4)}$$

The forces acting on a projectile must be resolved into three directions and the motion equations must be written for each of the three directions. Some sign convention must be assumed and used consistently for each direction. The equations included here must be written for each direction. The equations included here must be written for each direction and then combined vectorially to obtain the three-dimensional result. The two main forces acting are drag and gravity. The gravity term reflects the potential energy of the bomb. As the bomb falls it loses its potential energy (height)(Equation A.1) and gains kinetic energy. The drag force is given by the following equation. (52)

$$F_d = \frac{C_d u^2 \rho A_p}{2g_c} \tag{A.5}$$

The term, C_d, must be correlated for a particular projectile geometry at various Reynolds numbers. If the bomb is released sufficiently close to the ground, this dissipative effect may be negligible.

The next dissipative source is due to the energy required to shatter or break the container in which the explosive material is contained. This may either be a storage tank or it may be a bomb casing. This requires an analysis of strength of materials. In the case of an exploding fuel vessel, information is needed concerning the strength of the material of the tank. If a stress-strain curve of the material is available, the are under the curve is the energy per unit volume the material absorbs as it deforms. A limit is reached at which the material can no longer deform without breaking. This is the upper limit used in finding the area under the curve.(53)

In the case of ductile material, deformation is the primary energy absorption mode of the vessel material. However, the material is usually brittle in bomb casings and vessels. In this case, the main dissipative effect is in fragmentation of the material.(54) Complete analysis of this pehnomenum is not practical. Many simplifying assumptions must be made and some mode of failure must be assumed.

The final dissipating action before the fuel is dispersed is the energy absorbed by the ground and surroundings. Since the nature of the impact area varies considerably, so does the amount of energy absorbed. Correlations have been developed to calculate penetration in various earth media. This takes the following form for penetration into hard rock.(55)

$$Y = \frac{K_1 W}{D^2} (v_s - k_2) \tag{A.6}$$

For soft rock, the equation has the following form.(56)

$$Y = \frac{4.6W}{D^{1.53}} (\frac{v_s}{1000}) \tag{A.7}$$

Results of experiments using identical targets and identical projectiles show a great deal of scattering. Prediction of results (Y) within a factor of two may be the best possible for any one penetration. Also, if a curve of projectile velocity versus penetration depth is plotted, a break is noted with a transition area (Figure 8).(57) Above the transition region is the region of hypervelocity. This break is due to the breakup of the projectile. At this point the curve changes to the following approximate form.

$$Y \alpha v_s^{2/3} \tag{A.8}$$

The hypervelocity region is simply defined by this experimentally observed breakpoint.

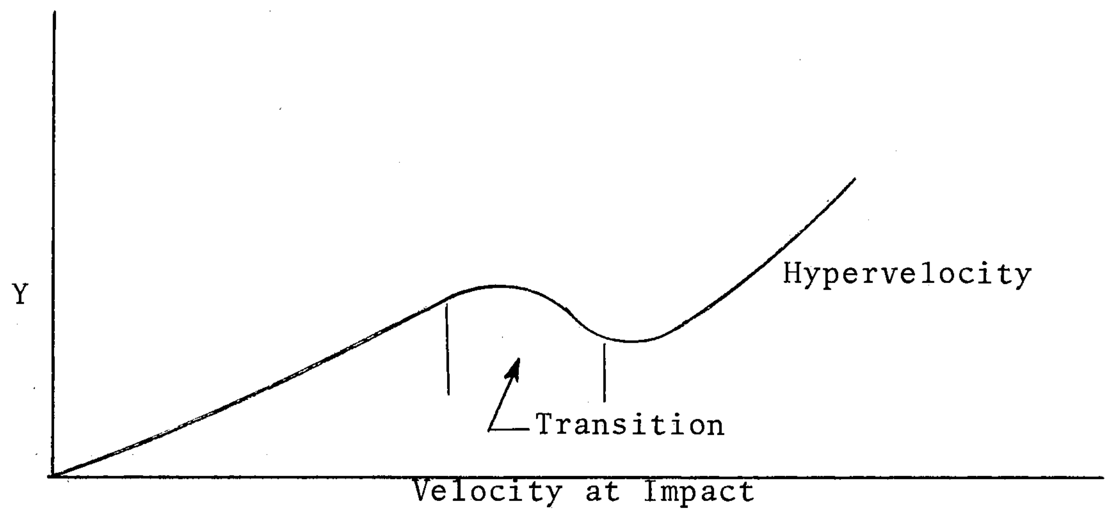

Figure 8. Penetration Depth vs. Velocity

The effect of angle of impact (Figure 8) probably involves several considerations. As the angle of impact decreases, the energy of impact is dissipated more as lateral shear of the earth medium and somewhat less as compaction. Data would be needed to determine the extent of this effect. The nature of the target material also, would influence this effect. Hard, brittle material would tend to shear rather than compact at any angle.

If all the energy of the projectile at the time of impact were absorbed by the earth, no matter would leave the crater formed and the dissipation of energy would end here. However, matter usually does leave the crater. If the amount of energy absorbed by the earth is known, the remaining energy is available for dispersion of the fuel and some projectile fragments.

The impact process is described as follows in rock.(58)

1. The projectile displaces material laterally and creates a cylindrical "burrow" for itself.

2. Bowl-shaped cleavage areas appear around the burrow caused by maximum shear planes developed during the displacement process.

3. Inertia of the material being moved laterally causes this material to be thrown violently from the crater.

4. Finally, the projectile bounces out ot the crater at some small percentage of its impact velocity (for high impact velocities).

Again, this is for impact on rock. As the impact material becomes softer, this may result in burial of the projectile with no cratering and no exiting of material from the crater. This may occur in such impact material as pumice rock. This action is due to the pumice's poor ability to transmit stress waves. If some property of the target material were known (elasticity or shear), this would be a good correlating parameter in calculating the energy absorbed. If an assumption of the crater geometry is made, with an equation for Y, the volume of material involved can be calculated and, hence, the energy absorbed. The energy absorbed would be the product of an elasticity or shear modulus and the volume of the material involved. The remaining energy is available for dispersing the fuel.

From the investigation of this step, the areas most in need of further investigation are the nature of the impact target and the mechanics of breakup. This should include a survey of the various rock and soil materials. The result should give a quantitative idea of the energy absorbed by a particular medium so that dispersion information could be obtained. Also needed is investigation of the mechanics of the breakup of the bomb casing or vessel and the mass of fuel contained within. This should lead to quantitative information on the energy dissipated during breakup.

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