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MECHANISMS OF BLAST–FIRE INTERACTION

T. C. Goodale
J. Backovsky
SRI International
333 Ravenswood Avenue
Menlo Park, CA 94025-3434

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Technical Report

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Prepared for
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The objective of this investigation was to obtain a more basic understanding of the physical mechanisms by which blast waves interact with fires. This information is needed to ensure that the correlation functions to be used in formulae for predicting the extinction or enhancement of fires by nuclear blast waves will include all the controlling variables. The study was limited to wood fires and fires over liquid hydrocarbon fuels.

Flames were displaced from burning wood surfaces by blast waves propagating parallel to the burning surface in all tests. At low blast strength, flame persisted in crevices in the char surfaces to reignite the fire. At high blast strength, glowing combustion of the char was stimulated.

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Fires burning over flat wicks containing a liquid hydrocarbon were displaced off the wick in all tests. Reignition of the wick by flames swept into the wake depended on whether the vapor pressure over the liquid fuel was reduced enough, by cooling the liquid, so that concentration of fuel vapor flowing into the wake was depressed below the flammability limit before the end of the positive phase of the flow.

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SUMMARY

The objective of this investigation was to obtain a more basic
understanding of the physical mechanisms by which blast waves interact
with fires. This information is needed to ensure that correlation func-
tions to be used in formulae for predicting the extinction or enhancement
of fires by nuclear blast waves will include all the controlling variables.
The study was limited to wood fires and fires over liquid hydrocarbon
fuels.

Interaction of blast waves with fires was studied in a blast wave
simulator. Experiments were also conducted in which the effects on fires
of the fast-rising air flow velocities that follow shock fronts were
observed separately from the effects of the shock front. This was accom-
plished by rapidly accelerating burning fuel systems into still air.

When the flow was parallel to the burning surface, fast-rising flows,
whether produced in blast waves or by rapid acceleration of fires into
still air, displaced flames from burning wood surfaces even at the lowest
peak velocities. In the case of wood fires accelerated into still air,
flame persisted in crevices in the char up to peak velocities of about
15 ft/s (4.6 m/s) to reignite the fire after flow over the surface had
stopped.

Glowing combustion of char following displacement of flames was
stimulated by high overpressure and particle velocity, independent of
the positive displacement of the flow.

Fires burning over flat ceramic fiber wicks containing liquid
n-hexane were invariably displaced off the wick by fast-rising flows
produced either by blast waves or by rapid acceleration of the firebed
into still air. Survival of these fires after passage of the blast wave
depended on their being reignited by flame that had been swept into the
wake. Evidence is presented to show that reignition depends on whether
the vapor pressure over the liquid fuel was reduced enough by cooling so

that the concentration of fuel vapor flowing into the wake was depressed below the flammability limit before the end of the positive phase of the flow.

Analytical modeling of the extinction of liquid-fueled fires by blast waves is thus considered to be a problem in the theory of inter-phase heat and mass transfer between the cooling liquid and the blast wave flow. Further work on the extinction of liquid-fueled fires by blast waves should be preceded by development of an analytical model of the reduction of fuel vapor concentration in the flow downstream of the fuel bed due to cooling of the liquid. The experimental work should then be designed to supply data to test the model.

The properties of open wood fuel systems to be incorporated in functions for correlation of blast strength with flame extinction thres-hold in that fuel system should be those that determine the amount of recirculation of flow behind the members of a randomly arranged crib or lattice structure.

A second phenomenon that will probably need to be accounted for in developing a correlation function for extinction of open wood fires by blast is reignition of flaming combustion at high blast overpressures due to stimulation of glowing combustion of char.

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ─────────────→ BY ─────────────→ TO GET
TO GET ←───────────── BY ←───────────── DIVIDE

angstrom	1.000 000 X E −10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E −28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E −2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	giga becquerel (GBq)*
degree (angle)	1.745 329 X E −2	radian (rad)
degree Fahrenheit	$\tau_K = (t°f+459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E −19	joule (J)
erg	1.000 000 X E −7	joule (J)
erg/second	1.000 000 X E −7	watt (W)
foot	3.048 000 X E −1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E −3	meter^3 (m^3)
inch	2.540 000 X E −2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)**
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E −6	meter (m)
mil	2.540 000 X E −5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E −2	kilogram (kg)
pound-force (lbf avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E −1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E −2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E −1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E −2	kilogram-meter^2 (kg·m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E −2	Gray (Gy)**
roentgen	2.579 760 X E −4	coulomb/kilogram (C/kg)
shake	1.000 000 X E −8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22 X E −1	kilo pascal (kPa)

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

The thermal pulse emitted along with the blast wave in nuclear explosions can cause ignition of fire in exposed kindling fuels over areas comparable in size to the area devastated by blast. With the advent of nuclear weapons, therefore, fire has assumed a new order of importance as a damage mechanism in warfare.

In damage assessment in nuclear attack scenarios, it was formerly customary to estimate damage due to fire separately from damage due to blast. In experiments conducted in 1953[1] and, under more realistic conditions, in 1970,[2] however, it was shown that fires started by the thermal pulse from a nuclear explosion can be blown out in some circumstances by the blast wave from the same explosion arriving later. Thus, the incidence of fire in target areas became dependent on the effectiveness of blast-fire interaction in extinguishing primary fires started under various conditions by the thermal pulse.

The early experimental programs in which the interaction of the blast wave with fires was discovered were very limited in scope, each being conducted in only a single experimental arrangement with limited variation of the parameters that were subject to control. The results were expressed in terms of threshold values of the particle velocity of the flow, or the overpressure of the incident blast wave, above which all fires were extinguished. Some persons familiar with the subject believed that the thresholds observed might be fortuitous values, possibly due to some unrecognized controlling variable having been held constant in the tests, and that more extensive testing might reveal that extinction of fire was dependent on additional variables in some circumstances. In short, it was held that a more basic understanding of the physical mechanism of blast-fire interaction was needed to ensure that the correlation equations for predicting fire extinction by blast would

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include all the controlling variables. The objective of the present project was to gain such an understanding.

The Federal Emergency Management Agency (FEMA), in pursuing its responsibilities in development of civil defense against nuclear attack, sponsored one of the two early experimental investigations in which the effectiveness of blast waves in extinguishing fires lit by the thermal pulse of nuclear explosions was first discovered.[2] FEMA has continued to support blast-fire interaction research, and, in accordance with the statement of work of our present contract, we have coordinated our work with that of FEMA to ensure that our efforts complement their research activities.

SECTION 2

APPROACH

An understanding of the mechanism of blast-fire interaction could not be expected to proceed directly from theoretical analysis, since neither the physics of fires nor the propagation of shocks in other than plane geometries are readily amenable to analysis. An experimental approach was therefore needed.

We expected that, in an early phase of the investigation, the most useful approach to identifying variables important in fire extinction by blast would be an heuristic one in which variables thought to be influential were eliminated from particular experiments or reduced to their limiting values. The importance of each variable could then be judged by comparison of results in the presence and in the absence of its effect.

In the later stages of the investigation, after identification of a full set of variables controlling fire extinction by blast in a given fuel system, it was expected that a correlating function composed of the controlling variables could be formulated against which fire extinction data for that fuel system would be plotted. These correlation curves would then be used to predict the conditions required for fire extinction by blast in the fuel system to which they applied. A fuel system, in this context, is defined by the mechanism by which fires ignited in it interact with blast waves. Thus, the same fuel in a different arrangement would constitute a different fuel system if the different arrangement resulted in a different set of variables controlling extinction of fires by blast waves.

Fuel systems in which it was supposed a priori that fires might respond to blast waves by differing mechanisms are included in Table 1, together with the principal properties by which the response of fires in each of the fuel systems would be distinguished. The present investigation was limited to fuel systems 1 and 2 in Table 1.

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Table 1. Fuel systems in which fires may respond to blast waves by differing mechanisms.

1. Fire in open wood structures, debris piles, and cribs

Reduction of flow velocity and recirculation of flow over burning surfaces within the structure may determine resistance to extinction by blast waves.

2. Fire in rooms enclosed except for windows and doors

Flashover* of the fire is expected to exert an important influence on blast extinction threshold.

3. Fires over pools of flammable liquids

Fire swept off the pool surface by blast burns in its wake supported by fuel vapor evaporated from the pool. As blast flow diminishes, fire in the wake may reignite the pool.

4. Fires in noncharring plastics

These fires may show similarity to pool fires, except that the fire is usually fed by depolymerization instead of evaporation of the fuel.

5. Smouldering fire remaining after extinction of flaming combustion in fuels such as cotton batting, mattresses, forest litter.

Fires in certain smouldering fuels sustain glowing combustion within the body of the fuel after extinction of flaming combustion by blast. Glowing combustion reignites back to flame after an induction period.

6. Fire in fuel fragments of low mass and relatively high surface areas such as paper, curtains, leaves, and other combustibles capable of being transported by blast.

Fuel items of low mass and large surface area, ignited by the thermal pulse, are quickly accelerated in the blast wave to the particle velocity of the flow. Their exposure to high flow velocity over their surface is thus limited to the short time required for their acceleration, which is a very small fraction of blast flow duration. Owing to their short exposure to the flow, fire may survive the blast in such fuel items in spite of their otherwise low resistance to being blown out. Light masses of smouldering fuels may present a special proclivity toward such behavior.

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*Flashover is the sudden transformation of one or more separate fires in a room to inflammation of the entire room and its contents.

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SECTION 3

EXPERIMENTAL METHODS

The interaction of blast waves with fires was observed in a blast wave simulator developed and operated by SRI International at Camp Parks, California. This system was designed specifically to investigate the interaction of fires with blast waves of various overpressures and of durations up to three seconds. Thus it was possible to achieve a range of positive phase durations and overpressures including those characteristic of the blast waves produced by nuclear weapons.

Experiments were also conducted in which the effects on fires of the fast-rising* air flow velocities that follow shock fronts were observed separately from the effects of the shock front. Air shock fronts are strongly diffracted in passing through fires because of the numerous random temperature and composition gradients, resulting in strong turbulence in the flow immediately following them.

Change in ambient pressure affects the relation between convective, inertial, and gravity forces operating in fires chiefly through its effect on the densities of the participating gases. This has made possible the modeling of fires at reduced scale by placing them under increased pressure[3-5]. The abrupt pressure and density increase occurring at shock fronts may be expected to exert a similar influence on fires in proportion to the pressure rise above ambient. To observe the effect of fast-rising flows on fires unobstructed by effects due to the shock front, we performed experiments in which fully developed fires were impulsively accelerated into still air.

The blastwave simulator used in the present investigation, shown schematically in Figure 1, is 29 inches (.74 m) in diameter at the test

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*In this report, the term "fast-rising" is used to denote flows that accelerate from rest to peak velocity in milli-seconds or less.
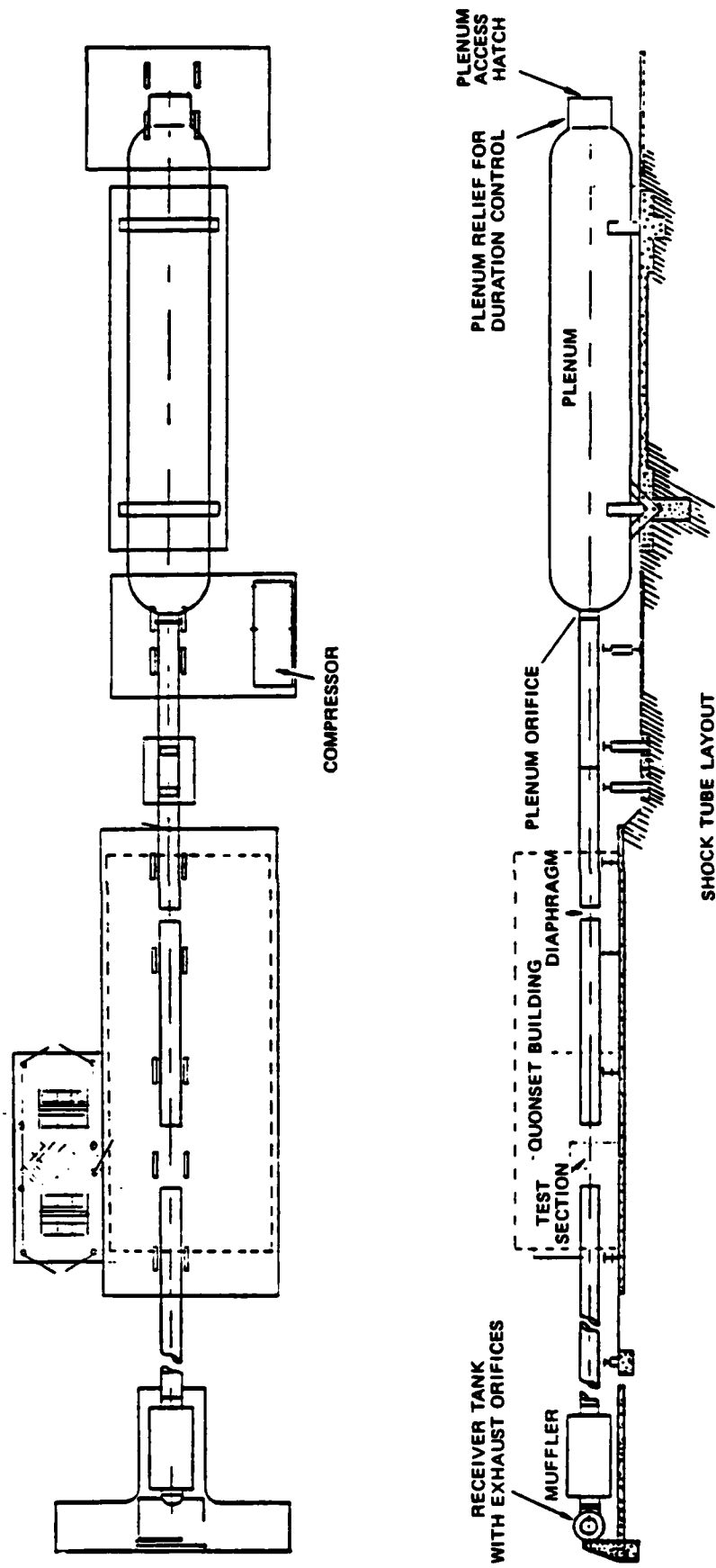
Figure 1. Blast/fire shocktube facility.

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section with an overall length of 310 feet (94.5 m). Having been described
in detail previously,[6] its operation will be summarized only briefly.

After the section to the right of the diaphragm in Figure 1, inclu-
ding the plenum, is pumped to an appropriate pressure, the diaphragm
is ruptured to initiate a shock wave, which propagates to the left in
Figure 1. Simultaneously, a rarefaction wave proceeds in the opposite
direction and arrives at the plenum where it lowers the pressure in the
plenum orifice. Blowdown of the plenum through the orifice supports
the pressure in the tail of the shock wave, which would otherwise be
reduced quickly by the reflected rarefaction wave if the tube were closed
at the plenum.

Operation of the test section is illustrated in Figure 2. The
sliding cover remains open during initiation and development of the fire,
which is supported on a test stand near the center of the shock tube.
At a preselected time, the cover is driven shut pneumatically, and its
latching initiates the blast wave automatically.

After passing the test section, the shock front proceeds to the
muffler where it is degraded sufficiently to prevent its being reflected
from the receiver tank as a shock. Orifices in the receiver tank control
the flow to the atmosphere and prevent the penetration of rarefaction
waves.

Achieving a continuous pressure profile in the test section,
characteristic of a long-duration blast wave, depends on selecting ori-
fices at the plenum and in the receiver tank of sizes appropriate to the
particle velocity of the wave. The size of the plenum orifice is chosen
to provide passage of a flow equal to the shock particle flow when driven
by a pressure drop across the orifice equal to the difference between
the shock driving pressure and the shock pressure. The orifices in the
receiver tank are sized to provide the same flow rate by a pressure drop
from the shock pressure to atmospheric.

The duration of the blast wave, which extends to slightly more than
three seconds with the entire contents of the plenum contributing, can

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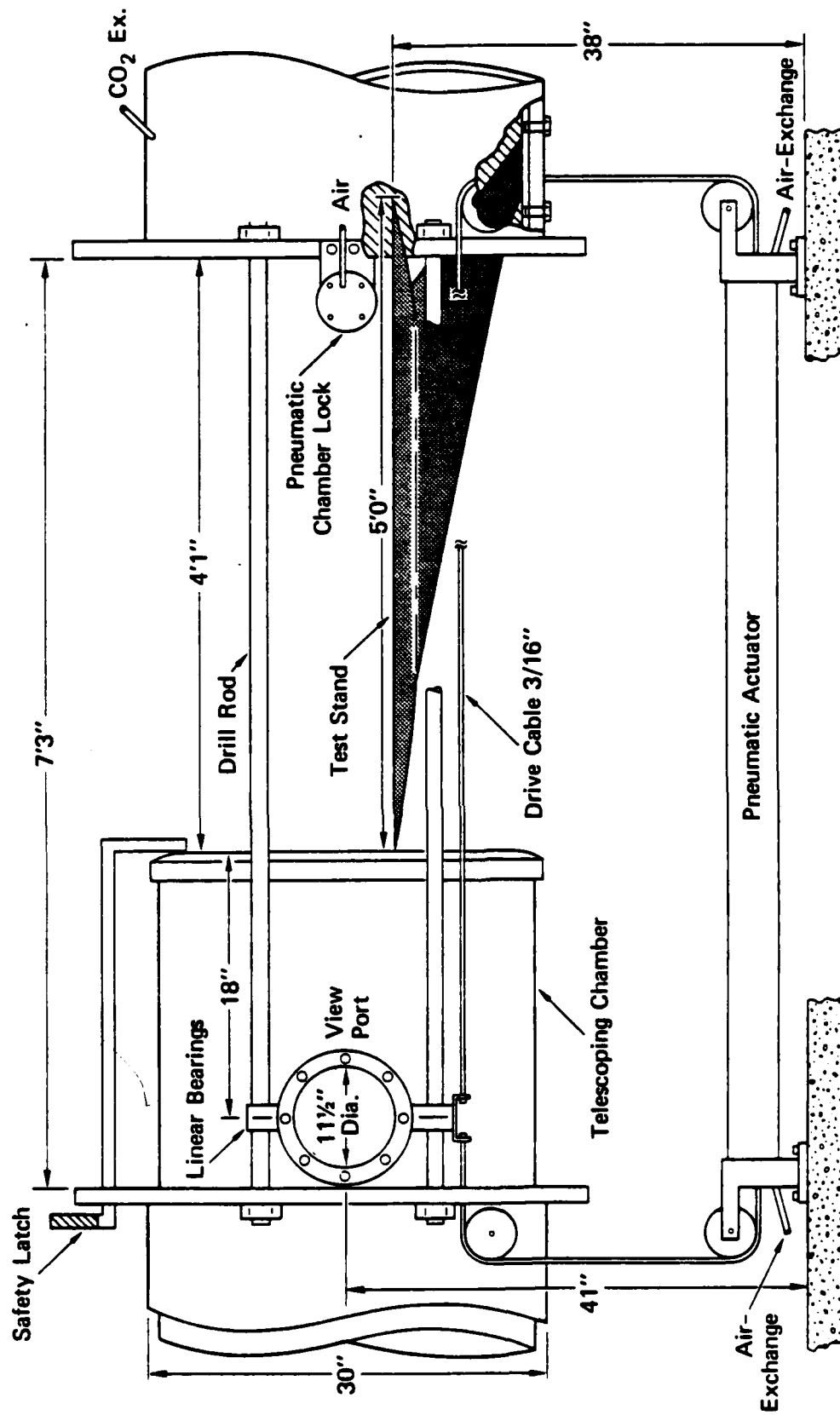
Figure 2. Shocktube Test Section.

be reduced by discharging part of the air pressure in the plenum directly to the atmosphere. This is done via a diaphragm in the rear of the plenum that is opened at the same time as the shock tube diaphragm. A continuous range of durations is thus available down to 300 milliseconds. With its connection to the plenum sealed, the shock tube is operated in the conventional manner with a positive duration of about 60 milliseconds.

SECTION 4

DEVELOPMENT OF THE IMPULSIVE
ACCELERATION FACILITY

THE CONCEPT

The apparatus for impulsive acceleration of experimental firebeds was designed and built during the present project to provide a means for observing the effect on experimental fires of fast-rising flows, similar to those occurring in blast waves. In this system, the fire bed is accelerated impulsively into still air so that there is no pressure jump such as occurs at shock fronts, and the effect of the fast-rising flow can be observed without the complications due to interaction of a shock front with the fire.

A principal novel effect that fast-rising flows have on fires is due to the absence of any significant boundary layer at the surface of a flat firebed across which the flow passes. Thus, flames are swept off the firebed down to its surface, the region of low velocity at the surface being thinner than is necessary for proper flame attachment.

In simulating the fast-rising flow that occurs behind shock fronts, therefore, it is important that the thickness of the fluid-velocity boundary layer built up during acceleration of the firebed be comparable to the fluid-velocity boundary layer thickness developed behind a shock front during the same time interval. The boundary layers to be compared are the laminar flow boundary layers because they form first and become turbulent later after start of the flow.

In the case of the impulsively accelerated firebed, we assumed a set of coordinates fixed in the surrounding still air. The firebed began to accelerate at a uniform rate at time $t = 0$ and continued to accelerate until $t = t_*$, when acceleration stopped. The equations describing flow in the boundary layer[7] and appropriate initial and boundary conditions are

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$$\frac{\partial u}{\partial t} = \nu \frac{\partial^2 u}{\partial y^2} \tag{1}$$

$$u = 0 \text{ for all } y, \ t \le 0$$

$$u = \frac{t}{t_*} U_o \text{ for } y = 0, \ t_* > t > 0$$

$$\lim_{y \to \infty} u(y,t) = 0$$

where u is flow velocity at a distance y from the surface at any time, t, between zero and t_*; ν is the kinematic viscosity of air; and U_o is the final (or maximum) velocity of the accelerated system.

The solution is

$$u(y,t) = \frac{2U_o t}{t_*} \left[(\tfrac{1}{2} + \eta^2) \ \text{erfc} \ \eta - \frac{\eta}{\sqrt{\pi}} \ \exp(-\eta^2) \right] \tag{2}$$

in which $\eta \equiv y/2\sqrt{\nu t}$.

We want to know the value of η for which $u = 0.01 \ U_o$ when $t = t_*$. Thus

$$0.005 = (\tfrac{1}{2} + \eta^2) \ \text{erfc} \ \eta - \frac{\eta}{\sqrt{\pi}} \exp(-\eta^2) \tag{3}$$

and

$$\eta \approx 1.484 \equiv y_*/2\sqrt{\nu t_*} \tag{4}$$

Thus

$$y_* = 2.968\sqrt{\nu t_*} = \text{boundary layer thickness} \tag{5}$$

The laminar boundary layer thickness behind a plane shock is given by Bradley[8] as $y_s \approx 3.84\sqrt{\nu t_s}$

---

*The acceleration of our firebeds, although not perfectly uniform, was nearly so because the ratio of initial to final pressure in the cylinder driving the firebed was not large.

Therefore,

$$y_* / y_s = 0.77\sqrt{\frac{t_*}{t_s}} \quad .$$ (6)

indicating that the boundary layer thickness over the firebed at peak velocity (at the end of its acceleration) is comparable to that formed behind a plane shock front in an equal interval of time after its passage.

The minimum value of t_s for which this comparison is meaningful is the time required for the shock front to pass across the firebed, since at shorter times the firebed is not fully engulfed in the flow. This suggests that $0.77\sqrt{t_*}$ should approximate the square root of the shock passage time across the firebed for optimum similarity of boundary layers, and this criterion was followed in design of the firebed acceleration system. This means, for a bed a foot or two in length, that the time of acceleration should not exceed about 3 ms.

THE FIREBED ACCELERATION SYSTEM

The firebed is accelerated by an explosive-driven ram shown in cross-sectional diagram in Figure 3. Firing of the explosive charge drives the piston, which is in contact with the rear of the firebed. At the end of its stroke, the piston is decelerated by crushing a thin, corrugated aluminum sheet wrapped around its stem that is retained by a heavy washer attached to the end of the tube. The firebed continues in motion at the maximum velocity reached by the piston.

The explosive used to drive the ram is composed of pentaerythritol tetranitrate (PETN) powder coated on foamed polystyrene spheres of uniform diameter (about 0.030 inch, 0.076 cm). This explosive has been standardized by SRI International for research use as a low-density detonating explosive. The use of a detonating explosive to drive the piston instead of a deflagrating propellant, such as gunpowder, simplified the timing of photography because it eliminated the need to establish reproducible ignition and burn times.
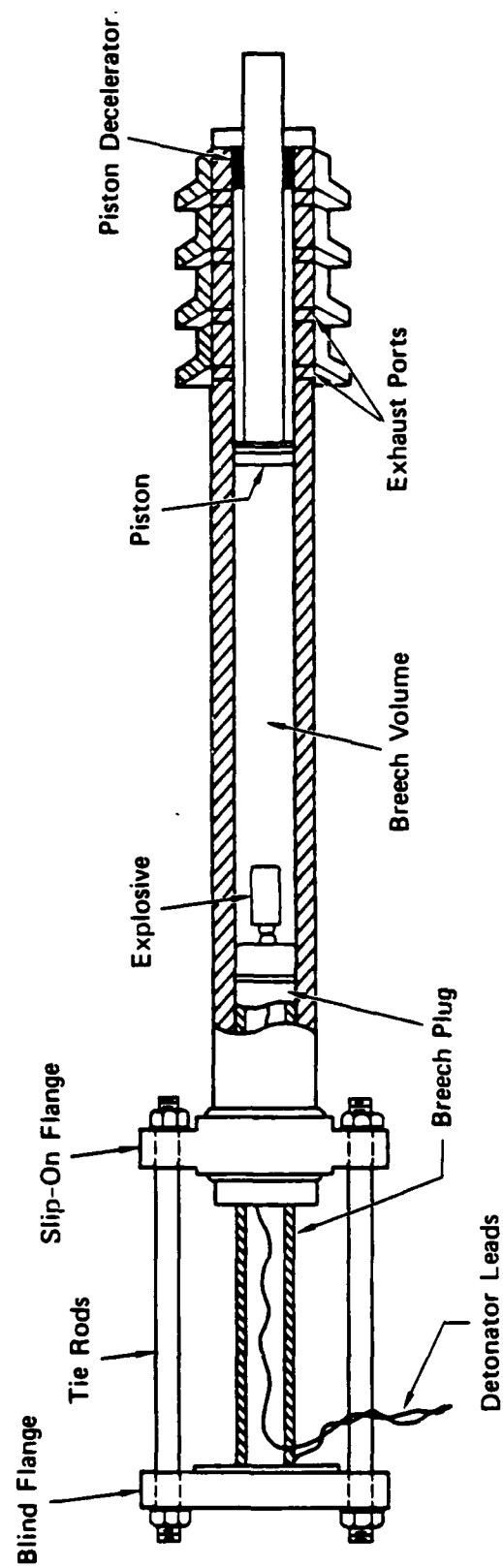
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Figure 3. Explosive-driven ram for rapid acceleration of firebeds.

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The composition used in our experiments produces a pressure in the detonation wave of only 2 kilobars (29,000 psi, 2×10^8 Pa). The detonation products expand throughout the breech volume of the ram and reach equilibrium before significant motion of the piston has occurred. Friction losses in the system are relatively small, and because of the promptness of the process, very little of the heat in the explosion products is lost to the walls during the expansion. Thus, for design purposes, the process can be treated as a free expansion of the detonation products into the breech volume, followed by their isentropic expansion in driving the piston. The properties of the explosion products at various stages of the process were calculated using the TIGER* code.

The peak velocity that the piston and firebed assembly will reach, driven by a given amount of explosive, was estimated by equating the kinetic energy of the assembly to the work done in isentropic expansion of the explosion products behind the piston at the end of the piston stroke. TIGER code calculations showed that the average molecular weight of the explosion products and their adiabatic exponent remained nearly constant during the expansion, so it was possible to calculate the work of isentropic expansion analytically.

The analytical expression for the velocity of the piston/firebed assembly thus obtained was used to estimate the acceleration time of the firebed by numerically integrating its reciprocal over the length of the piston stroke. Shorter acceleration times for the same peak firebed velocity were obtainable by shortening the piston stroke and increasing the driving pressure appropriately.

The experimental firebeds are supported on a pair of rails on which they slide smoothly. The rails are of 1-inch-diameter (2.54 cm) precision-ground steel shafting 20 feet long, (6.1 m). The rails are mounted in a steel frame, and each is placed under about 10,000 pounds (44484 N.) of

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*The TIGER Code is a general digital computer code for calculating thermochemical equilibria of mixtures described by an arbitrary equation of state, including the calculation of detonation parameters.

tension by tightening nuts on their threaded ends using a torque wrench. The tension ensures that the rails are straight and virtually eliminates any transverse vibration during passage of the firebed. In acceleration of the firebeds, thrust is applied on a line passing near their center of mass so that no large rotational moment is applied that could induce vibration in the rails.

EXPERIMENTAL FIREBEDS

The design of experimental firebeds to undergo impulsive acceleration must achieve a strength-to-mass ratio large enough that the firebeds can support the inertial stress induced by accelerating them within a few milliseconds to peak velocities corresponding to the particle velocity of shocks in the 0-5 psi (0-34.47 kPa) overpressure range. A firebed design that has been entirely satisfactory is shown in Figure 4.

The firebed was built of aluminum hexcel in the form of a series of sandwich beams with their load-bearing axis oriented in the direction of piston thrust. This design is adaptable to any fuel system that can be supported on a flat horizontal surface.

In our experiments, the firebed supported a flat wick to supply liquid hydrocarbon fires. The wick consisted of a 9.5 by 12 inch (24.1 by 30.5 cm) sheet of ceramic fiber insulation board,[*] 0.35-inch thick (0.89 cm), glued into a recess in the top of the firebed so that its surface was flush with the surrounding deck of the firebed. The surface of the wick is smooth with a texture similar to that of blotter paper. The ceramic fiberboard composing the wick has a bulk density of 0.27 g/cm^3, indicating that it consists mainly of air space. Thus, when saturated with hexane, most of its volume consists of the fuel. In our experiments we used the minimum amount of hexane (about 100 cm^3) necessary to maintain the fire in a near steady-state condition for the duration of the experiment. This amount of hexane was only enough to

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[*]Fiberflex Duraboard manufactured by Carborundum Corporation.
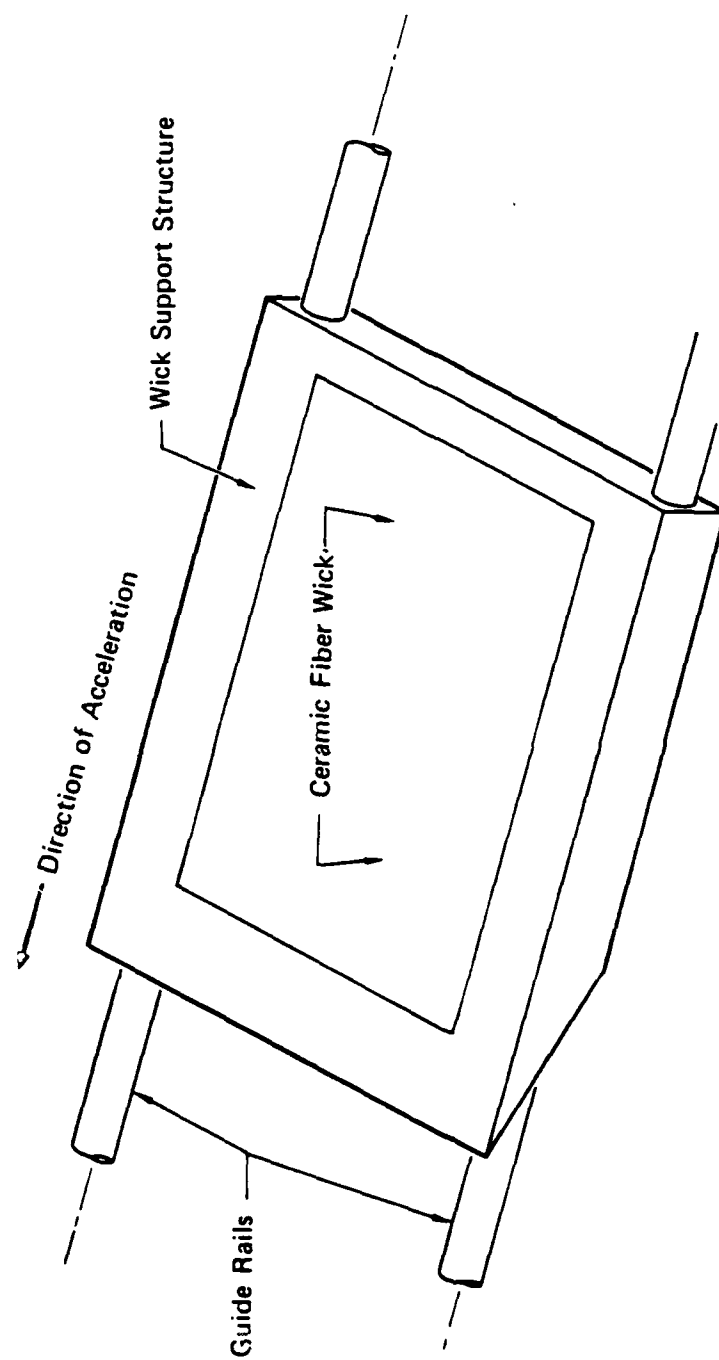
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Figure 4. Firebed for impulsive acceleration of liquid-fueled fire burning on flat wick.

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coat the fibers composing the wick in a thin layer of liquid, which was held by viscosity and surface tension against the inertial forces arising from the initial acceleration of the fire bed.

A special firebed arrangement is diagrammed in Figure 5. Vertical wood panels 2 inches (5 cm) apart were arranged parallel to one another and to the direction of flow. It was necessary for the space between the panels to be open at the bottom to allow unimpeded air draft upward during development of the fire. Therefore, it was not practical to mount the panels above the horizontal structure illustrated in Figure 4. The special structure took advantage of the stiffness and strength of the wood panels themselves in withstanding inertial stresses.

DECELERATION OF THE FIREBED

In all our experiments, the firebeds were stopped by shock absorbing mats attached to the track on which the firebeds moved. These mats were made of plastic film bubble sheets of the kind used for packing sensitive equipment for shipment, backed by three layers of low-density foamed poly-styrene, each 4 inches (10.2 cm) thick. This stopped the firebeds without damage in all our experiements. The mats suffered no significant damage except in tests at the higher firebed velocities and hence were reusable in most cases.

Stopping of the firebeds by this means resulted in their moving at nearly constant velocity over most of the track before being suddenly brought to rest at the mat. Their velocity profile thus resembled that obtained in our experiments in the blast simulator, most of which were done in the short duration mode in which the entrance from the shocktube to the plenum was closed. In this mode, the shocktube produces rela-tively short waves (about 60-ms duration) that are flattopped in pressure and particle velocity. In view of this similarity, the development of a drogue system capable of more versatile performance than the mats in de-celerating the firebed was not pursued beyond the preliminary stage.
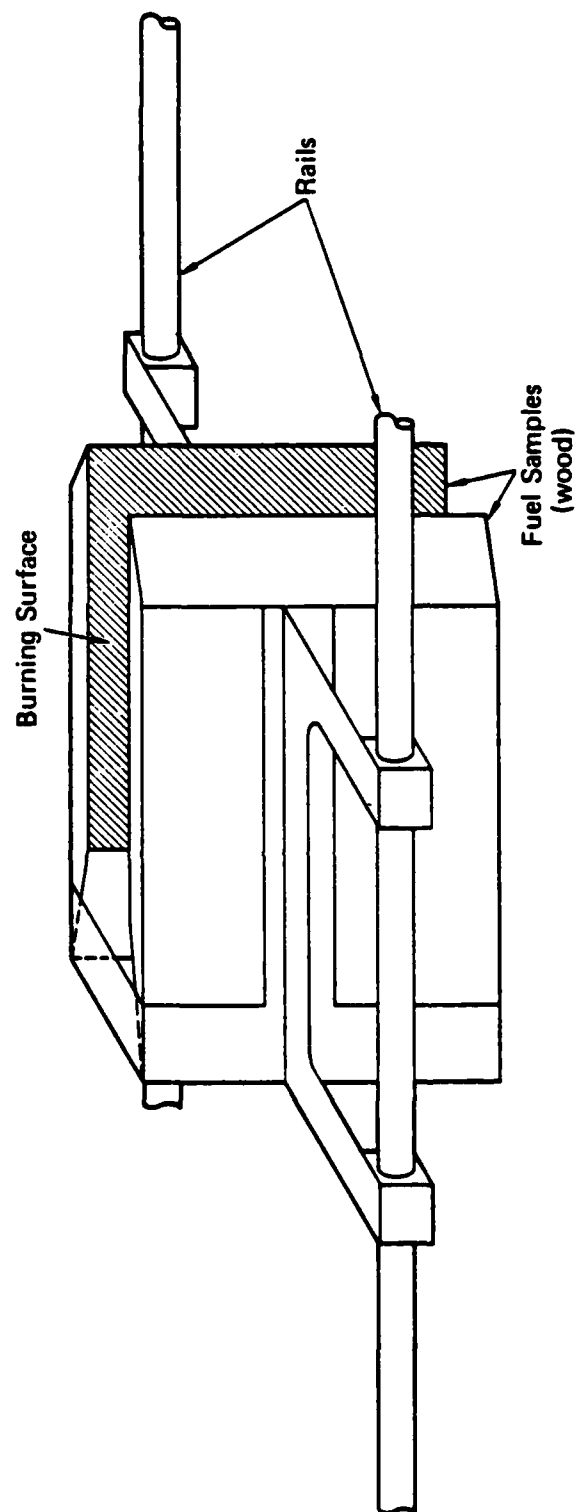
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Figure 5. Arrangement for impulsive acceleration of two parallel vertical burning wood surfaces.

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SECTION 5

EXPERIMENTAL PROGRAM

The experiments performed are described below. Much of the infor-
mation and insight gained from the experimental program was obtained from
motion pictures taken of the experiments and from comparison of the
various test series. This is brought together in Section 6, Experimental
Results. In Section 7 we discuss the recommended direction for developing
correlation equations for predicting fire extinction by blast, based on
the results of this program.

Experimental tests were divided into series A through G. Within
each series, tests were numbered in sequence.

TEST SERIES A

Three tests were conducted to confirm the integrity of the system
for impulsive acceleration of firebeds under the inertial stresses imposed.
The firebed illustrated in Figure 4 was accelerated to peak velocities as
follows:

Test No.	Peak Velocity (ft/s)	(m/s)
A-1	35	10.7
A-2	101	30.8
A-3	195[*]	59.4

[*]195 ft/s corresponds approximately to the particle
velocity of an air shock of 5-psi (34.5 kPa) over-
pressure.

These tests had no discernable effect on the structure of the firebed
or other parts of the impulsive acceleration system. Further testing could
therefore proceed to the effect of fast-rising air flows on fires.

TEST SERIES B

Seven tests were performed with the firebed illustrated in Figure 4. A flat ceramic wick was glued into a recess in the top surface of the firebed with its surface coplanar with the firebed surface, as described in Section 4. An amount of liquid n-hexane (about 100 cm^3) sufficient to mantain the fire in a nearly steady-state condition for the duration of the experiment was applied evenly to the wick. Experimental fires were allowed 15 seconds to become fully developed after ignition and were then impulsively accelerated to various peak velocities as follows:

Test No.	Peak Velocity (ft/s)	(m/s)	Condition of the Fire after Test
B-1	Fire failed to ignite		--
B-2	93.2	28.4	Out
B-3	46.0	14.0	Out
B-4	38.2	11.6	Out
B-5	30.2	9.20	Out
B-6	Misfire of driving charge; test failed		--
B-7	25.2	7.68	Burning

High speed motion picures (about 1000 frames/s) of these tests are discussed in Section 6. These were the first tests showing smooth displacement of the fire from the wick with no visible attachment of the flame at the wick surface. The films showed the vortices produced by separation of flow behind the square stern of the firebed functioning as a flame holder for burning vapor displaced from the wick.

TEST SERIES C

Eight tests were conducted with the firebed used in Test Series B mounted in the blast wave simulator, which was operated in the short duration mode in which the connection between the shocktube and plenum was closed off. The positive duration of the blast waves was therefore 60 to 70 ms.

Overpressures and calculated particle velocities and displacements in these tests were as follows:

Test No.	Peak Overpressures (psi)	(kPa)	Peak Particle Velocity (ft/s)	(m/s)	Total Particle Displacement (ft)	(m)	Condition of the Fire after Test
C-1	1.68	11.6	89	27.1	5.6	1.71	Burning
C-2	3.25	22.4	165	50.3	10.5	3.20	Burning
C-3	3.50	24.1	177	53.9	11.1	3.38	Burning
C-4	6.40	44.1	303	92.4	22.5	6.86	Out
C-5	5.10	35.2	246	75.0	17.4	5.30	Out
C-6	4.19	28.9	203	61.9	12.8	3.90	Out
C-7	4.20	29.0	203	61.9	12.8	3.90	Burning
C-8	4.25	29.3	204	62.2	13.1	3.99	Out

The high speed motion pictures showed that flames were displaced completely from the firebed in every test. In those tests in which the firebed remained burning, the motion pictures showed that the fire, initially displaced, returned to relight the wick as particle velocity slowed.

TEST SERIES D

Ten tests were conducted in which fires established between two wood surfaces 11.25 inches high by 12 inches long spaced 2 inches apart (28.6 by 30.5 by 5.1 cm) were impulsively accelerated parallel to the plane of the burning surfaces. The arrangement is indicated schematically in Figure 5.

In the burning of wood, the heat conducted from the fire into the fuel, as well as the considerable amount of heat radiated by the char surface, affect the energy balance of the fire to the extent that a flat wood surface (for example) will not support continuous combustion, whereas wood arranged so that the ignited surfaces radiate one to another can burn stably. Our objectives in selecting the present arrangement

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was to provide a geometry of wood surfaces that would burn stably, but be free of flame-holding protuberances in the direction of blast flow. It was also important that the events in the burning region during inter-action of a shock or fast-rising flow be observed photographically without obstruction by fuel elements.

Flame holding, which occurs in wakes and vortices where flow recir-culates or is slower than elsewhere, is thought to have a major effect on the resistance of wood fires to extinguishment by blast. Our objec-tive in these experiments was to eliminate flame holding within the wood fuel structure and thus reveal the relative effectiveness of other mechanisms whose operation would be obscured in the presence of an arbi-trary and unquantified flame-holding capability.

Fires were initiated by uniformly preheating the wood surfaces to their ignition temperature by inserting a planar Nichrome element between them; the element was withdrawn after the fire started. Preburn times (times between ignition and the start of acceleration of the firebed) were from 60 to 360 seconds.

Weight loss of the panels as a function of preburn time varies according to the prevalence of drafts and temperature gradients affecting the convective flow between the panels. Weight loss was about 15% during the first 100 seconds and 10% per 100 seconds thereafter.

These experiments indicated that fire was displaced by fast-rising flows parallel to the burning surface even at the lowest peak velocities. At the lowest velocities, fire appeared to remain in crevices in the char, where it was sheltered from the flow, to reignite the char surface after flow stopped.

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| Test No. | Preburn time (sec) | Peak Velocity | | Condition of the m/s |
		(ft/s)	(m/s)	Fire after the Test
D-1	300	16.4	5.0	Excessive preburn time;
D-2	300	16.2	4.93	char extended nearly through panels.
D-3	180	13.9	4.24	Burning
D-4	210	10.5	3.20	Burning
D-5	160	9.9	3.02	Burning
D-6	100	10.8	3.29	Burning
D-7	60	9.3	2.83	Burning
D-8	200	69.7	21.2	Fire Out
D-9*	160	106.8	32.6	Fire Out
D-10*	100	115.0	35.1	Fire Out

*Firebed structure was deformed by inertial forces.

TEST SERIES E

Five tests were conducted with the firebed used in Test Series D mounted in the blast wave simulator, which was operated in the short duration mode in which the connection between the shocktube and the plenum was closed off. The positive duration of the blast waves was therefore 60 to 70 ms. The conditions in these tests were as follows:

| Test No. | Preburn Time (sec) | Peak Overpressure | | Condition of the Fire |
		(psi)	(kPa)	after the Test
1-E	100	2.5	17.2	Out
2-E	200	0.5	3.4	Out
3-E	200	0.3	2.1	Out
4-E	200	8.5	58.6	Out
5-E	200	0.45	3.1	Out

The outcome of this test series was that the fire was extinguished at the lowest shock strength that we could obtain in the blast simulator.

TEST SERIES F

The firebed used in Test Series B was modified by adding a structure to the rectangular rear of the firebed to streamline it and thereby prevent separation of the flow passing over its stern. The modified firebed was used in experiments in which n-hexane fires, burning on the flat wick flush with the firebed surface, were impulsively accelerated into still air. The objective of these experiments was to observe the fire extinction mechanism in the absence of the flame-holding function. (Flame holding had been provided by the square stern of the firebed in the earlier experiments described in Test Series B.)

Seven experiments were performed under the following conditions:

Test No.	Peak Particle (ft/s)	Velocity (m/s)	Condition of the Fire after Test
F-1	23.0	7.01	Burning
F-2	24.0	7.31	Burning
F-3	22.2	6.77	Burning
F-4	19.9	6.07	Burning
F-5	42.0	12.8	Out
F-6	34.0	10.4	Burning
F-7	44.0	13.4	Out

The fire was swept off the firebed in every test, but continued to burn at some distances behind the tail fairing of the firebed, where the velocity of the fuel was reduced by addition of entrained air.

TEST SERIES G

In Test E-4, it was noticed that glowing of the char persisted after the test, which did not occur in the fires extinguished at the lower overpressures. The question arose as to whether the increased glowing of the

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char in this test was due to greater positive displacement of the flow, higher particle velocity, or some effect of pressure, per se. The question is important because strong glowing of char in some fuel geometries can lead to reignition of flaming combustion. In Test Series G, tests were conducted at both high and low overpressures at durations of about 3 seconds, and also at durations of about 0.065 second. The tests are summarized as follows:

	Test G-1	Test G-2	Test G-3	Test G-4	Test G-5
Peak overpressure (psi)	0.4	0.5		5.8	5.7
(kPa)	2.76	3.45		40.0	39.3
Peak particle velocity (ft/s)	21.8	27.3		277	273
(m/s)	6.64	8.32		84.4	83.2
Approximate time duration (s)	0.06	3		3	0.06
Approximate particle displacement (ft)	1.3	81.5		416	16.4
(m)	0.40	24.8		127	5.0
Prevalence of glowing char	None	Minor glowing		Leading edge of sample glowing	Widespread glowing

(Test G-3 column: Fire incompletely ignited)

As in Test Series E, flaming combustion was extinguished in all cases. Glowing combustion prevailed at the higher overpressures, irrespective of flow duration. Thus, high particle velocity and/or higher pressure was more conducive to development of glowing combustion than was the volume of air flowing over the firebed.

SECTION 6

EXPERIMENTAL RESULTS

WOOD FIRES

Within the scale at which our experiments were performed, the results indicate that flames burning over wood surfaces are displaced by fast-rising flows, parallel to the burning surface, having peak particle velocities lower than those developed in blast waves of practical interest (e.g., blast waves of less than 0.2-psi overpressure). The displaced flames do not continue to burn in the wake of the firebed, as they do in the case of liquid hydrocarbon-fueled fires (discussed below). The persistence of flame in the wake cannot, therefore, reignite the wood fire at the end of the positive phase of the blast wave.

The wood firebed used in these experiments, shown in Figure 5, was designed to be free of flame-holding protrusions. Flame holding, which occurs in wakes and vortices where flow recirculates or is slower than elsewhere, is thought to have a major effect on the resistance of wood fires to extinguishment by blast. Our objective in these experiments was to eliminate flame holding within the wood fuel structure and thus reveal the relative effectiveness of other mechanisms whose operation would be obscured in the presence of an arbitrary and unquantified flame-holding capability.

At peak velocities below about 14 ft/s (4.3 m/s), burning wood panels that were accelerated parallel to the panel surfaces continued to burn in crevices in their char surface, although no flame was visible over their surface. This was indicated in the high-speed motion pictures, which showed the flames being displaced, followed by smoke trailing downstream from the surfaces. As the progress of the firebeds slowed, fire spread again over the char surfaces.

At a peak velocity of 70 ft/s (25.3 m/s) and higher, the flames were displaced and no trace of smoke followed the firebed. In these cases, the fire remained extinguished.

In the blast wave simulator, fires burning on the surfaces of wood panels aligned parallel to the blast flow were extinguished in every test. The lowest peak overpressure in any of these tests was 0.3 psi (2.07 kPa) corresponding to a particle velocity of 16.5 ft/s (5.03 m/s). At this low overpressure level, pressure disturbances associated with breaking the diaphragm to initiate the blast wave were comparable in amplitude though much shorter in duration than the overpressure produced. The pressure disturbances are superimposed on the leading edge of the blast wave, so that the effective overpressure and particle velocity are not precisely defined.

The results of these experiments indicate that, in the absence of any structural fire-holding protrusions in wood fuel assemblies, the crevices formed in charring of the surface serve this function to a limited extent. In fast-rising transient flows having peak velocities less than about 15 ft/s (4.6 m/s), fire appears to be retained in the crevices after fire has been displaced off the remainder of the charred surface. Even at these low peak velocities, therefore, survival of flaming combustion does not depend primarily on flame speed or combustion kinetics in relation to flow velocity, but rather on the presence of flame-holding crevices in the char surface in which the fire is sheltered against being displaced by the flow.

This result suggests that in wood fuel systems such as cribs or debris piles, which have many structural fire-holding protrusions, the threshold peak particle velocity for extinction of flaming combustion would be one for which the peak flow velocity over the most sheltered part of the structure exceeded about 15 ft/s (4.6 m/s). Such an approximate approach will be complicated in some cases by the presence of flows in which hot burning gaseous pyrolysis products emanating from the wood recirculate in vortices over some of the burning wood surfaces, instead of being displaced

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uniaxially as in our experiments. Heat flow into the surface and continued evolution and burning of gaseous pyrolysis products will tend to be conserved in such regions. Finally, there is also the effect of glowing combustion to be considered. Glowing combustion of char is largely inhibited during strong flaming combustion of wood because the atmosphere at the char surface is generally a chemically reducing one due to the presence of pyrolysis products emanating from the wood. A higher temperature at the char surface is produced in glowing combustion than in flaming combustion, however, which causes greater heat flow into the wood where it can accelerate production of pyrolysis products, leading to reestablishment of the flaming regime. Thus, extinction of flaming combustion by a blast wave could be followed, in some circumstances, by spontaneous reignition of glowing char to flame.

Our experiments indicate that glowing combustion of char, following extinction of flaming combustion by blast waves, is promoted by higher overpressure and concommitant higher peak particle velocity and not by high positive displacement or time duration of the flow. Thus, areas of burning wood surface that are most sheltered from the blast wave flow by structural protrusions are in the best position for survival of flaming combustion and in the least favorable position for enhancement of glowing combustion. In unsheltered areas, the inverse would be true.

In open wood fuel systems with large internal surface areas,[*] therefore, fires might survive blast waves of high overpressure due to reignition of glowing combustion to flame after initial extinction of flaming combustion. At lower overpressures, the glowing combustion might lack enough intensity to cause reignition of flame, and at still lower overpressures, areas sheltered from the blast flow would not experience enough flow velocity to cause extinction of flaming combustion. Thus, in

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[*] The word "open" is used to describe wood fuel systems such as cribs and debris piles that have reentrant passages in which the fire burns and through which flow is driven by a blast wave. "Internal surface areas" refers to wood fuel surface areas from which most of the 2π solid angle is subtended by other adjacent wood fuel surface areas.

the same fuel system, fires might survive very high and moderate over-pressure levels while being extinguished at intermediate levels. Such a phenomenon has been observed in the FEMA research program,[9,10] although no evidence was presented to show that it was due to the mechanism described above.

LIQUID POOL FIRES

In our experiments, we simulated liquid pool fires with fires over flat ceramic fiber wicks in which the liquid fuel was held within the fiber matrix. The wick, which is described in Section 4, stabilized the liquid against dispersal by inertial or aerodynamic forces.

The results of our experiments indicate that, at the scale in which they were performed, liquid-fueled fires burning over flat wicks are invariably displaced off the wick by fast-rising flows having peak particle velocities that are lower than those developed in blast waves of practical interest. Survival of the fire then depends on reignition of the wick by the flaming wake extending downstream from the firebed. The proper study of the extinguishment of such fires by blast, therefore, is the study of the parameters affecting the flame in the wake, especially the flame's survival through the duration of the blast flow until it can propagate against the flow and reignite the firebed.

The effect of fast-rising flows on n-hexane fires for two different firebed configurations are illustrated in Figures 6 and 7, in which sequential frames from high-speed motion pictures are reproduced. In both cases, the fires were displaced by fast-rising flows produced by impulsive acceleration of the firebed into still air.

In Figure 6, the rear of the firebed ends abruptly in a rectangular cross section. Flow separation behind the firebed produces a region of reduced flow velocity and recirculation in which the fire propagates in the mixture of n-hexane vapor and air swept off the wick. Although fire has been displaced off the wick, it remains in the region behind the firebed because the average velocity there relative to the firebed is low, and the fire is carried with the firebed as long as a combustible supply of n-hexane vapor continues to flow from the wick. Discontinuities in the firebed surface, either holes or protrusions, will function as flame-holding structures in a manner analogous to that shown in Figure 6.
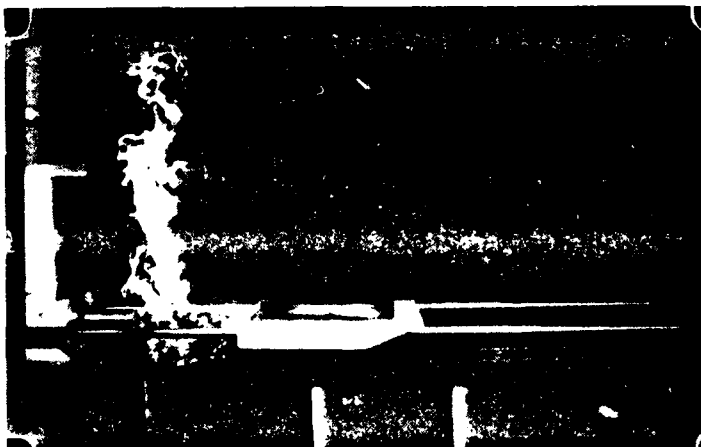
29

(a) t = 0
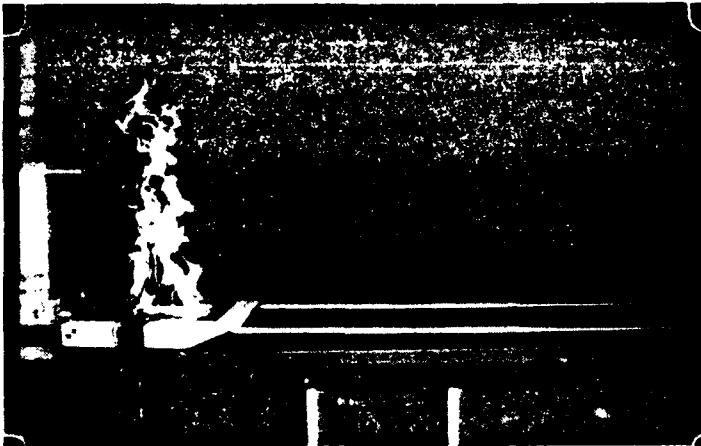
Time of firing
of charge behind
the ram to drive
fire bed to peak
velocity.
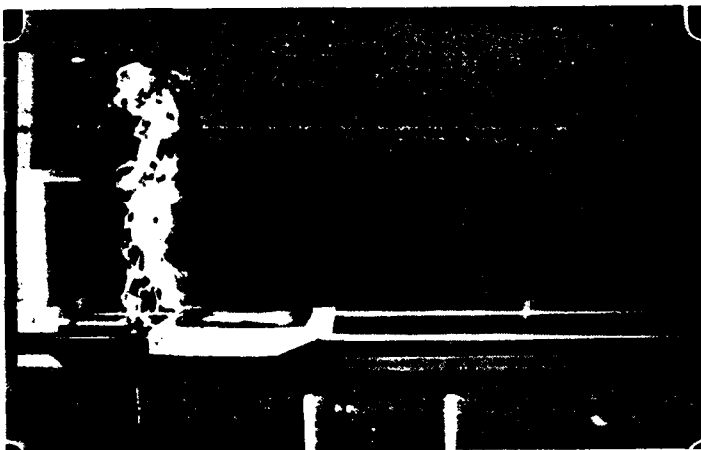
(b) t = 33 ms

Fire is swept off
the fire bed.

(c) t = 56 ms

Fire follows in the
wake of the fire
bed, the rear of
which functions
as a flame holder.

FIGURE 6   HEXANE FIRE ON AN IMPULSIVELY ACCELERATED FIREBED

Peak velocity of 25.2 ft/s was reached approximately
2.5 ms after firing the charge driving the ram.

In Figure 7, a streamlined fairing has been attached to the rear of
the firebed, and the horizontal deck surrounding the flat ceramic fiber
wick has been extended laterally and forward to eliminate separation of
the flow passing the rear of the firebed.* The flow approximates that
occurring when a fast-rising flow passes over a pool fire burning on a
planar surface of large lateral extent. In Figure 7, a thin boundary
layer has formed over the firebed surface. Relative to the ambient air,
velocity within the boundary layer is less than the firebed velocity, but
in the same direction. The boundary layer, therefore, flows off the rear
of the firebed where it merges with a similar boundary layer, formed by
flow under the firebed, to form a jet in the direction of motion of the
firebed. The jet contains most of the stream of fuel vapor evaporated
from the wick. Although the tip of the jet is attached to the firebed,
its velocity downstream is steadily reduced by turbulent entrainment of
ambient air. Fire initially displaced off the firebed propagates in the
slower portions of the jet as long as a sufficient supply of fuel vapor
continues to flow from the wick. Thus, a mechanism exists by which fire
can persist in the wake of a liquid hydrocarbon fire in the absence of
any fire-holding protrusions in the vicinity of the firebed.

With the firebed incorporating the flat ceramic fiber wick installed
in the blast simulator, the viewport of the test section was only large
enough to allow observation of the wick and the surrounding surface of
the firebed. Events downstream of the firebed were therefore not directly
observable as they were in the experiments illustrated in Figures 6 and 7.
It was observed, however, that the fire was displaced from the wick, even
at the lowest overpressures in the test series, to disappear downstream.
In those tests in which fire survived the blast, the high-speed motion
pictures showed that flame returned upstream to reignite the wick. Thus,
the mechanism of survival of liquid-fueled fires exposed to blast waves
was essentially the same as that observed for fires accelerated in still
air.

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* Some separation of flow occurred over each of the rails supporting the
firebed as the flow passing under the firebed flowed up and around them;
however, this was not sufficient to annul the purpose of the experiment.
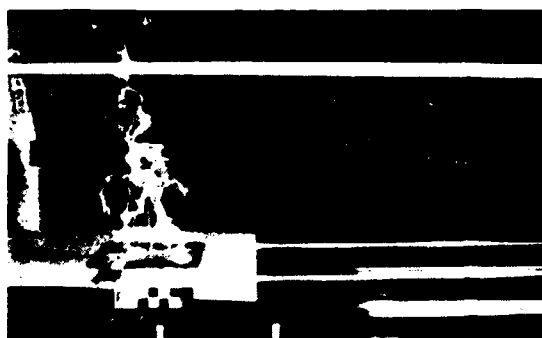
(a) t = 0
Time of firing
of charge behind
the ram to
accelerate firebed.

(b) t = 23 ms
Fire is swept off
the wick and
stands over the
streamlined tail
fairing of the
firebed.

(c) t = 74 ms
Turbulent wake
developed behind
streamlined tail
fairing.

(d) t = 106 ms
Flame fully
developed in wake
downstream
of streamlined
tail fairing.

FIGURE 7   HEXANE FIRE ON AN IMPULSIVELY ACCELERATED
STREAMLINED FIREBED

Peak velocity was 44 ft/s.

The particle velocity corresponding to the threshold shock over-
pressure necessary to extinguish fires over the liquid-fueled firebed
was 203 ft/s (61.9 m/s) compared with a peak velocity of about 25 ft/s
(7.6 m/s) required to just extinguish fires over the same firebed sup-
plied with the same fuel (n-hexane) when impulsively accelerated into still
air. The positive phase displacement of flow in the two experiments did
not differ greatly, however, being 12.8 ft (3.9 m) in the experiment con-
ducted in the blast simulator and 15.5 ft (4.7 m) for the impulsively
accelerated firebed.

Owing to the transient nature of blast waves, their particle velocity
is eventually reduced to the flame velocity of the fire in the wake, however
low it may be. Thus, if the concentration of the fuel vapor flowing off
the liquid fuel source remains above the lower flammability limit in the
wake, the flame there will eventually propagate upstream and reignite the
liquid fuel. If it is accepted that liquid-fueled fires are displaced
off their fuel source by blast waves of even minimal shock strength and
that their survival depends on reignition by fire initially swept into
the wake, then extinction of such fires must depend on reduction of fuel
vapor in the wake below the flammability limit while the flow velocity
over the liquid fuel still exceeds the flame velocity of the fire in the
wake.

The conditions under which liquid-fueled fires survive blast waves,
therefore, depends to some extent on the flame velocity of the fire
propagating in the wake. A flame of higher velocity will propagate
upstream earlier against the decreasing profile of particle velocity in
the tail of the blast wave and hence may achieve reignition of the fuel
source sooner, before the concentration of the fuel vapor emanating from
it descends below the flammability limit. Of more fundamental importance,
however, is the rate of cooling and consequent reduction of the vapor
pressure over the liquid fuel, for it determines whether a combustible
mixture will exist in the wake near the end of the positive phase of
the blast wave.

The fuel vapor concentration in the wake after displacement of the
fire from the firebed depends on the vapor pressure of fuel over the fuel

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bed, the rate of its transport into the blast flow passing over the bed, and its dilution by turbulence and diffusion in the wake. When flame is first swept off the firebed, the liquid fuel is near its boiling point, and its vapor pressure is approximately atmospheric. Later, the liquid fuel is cooled by transfer of heat to the air flow passing over it, and especially by evaporation of fuel vapor, so that the rate of evolution of vapor decreases as the flow continues. No steady state can be reached, however, because of the changing temperature of the fuel and because the temperature and velocity in the blast flow decreases steadily throughout its duration. If the temperature of the liquid drops enough, the vapor pressure can become low enough that its mixture with air flowing over the liquid is below the lean flammability limit. Flame will then no longer propagate in the wake, and the fire will become extinguished.

Estimation of the rate of heat and mass transfer from the liquid-fuel source to the blast wave flow is complicated by the transient nature of the blast and the absence of any established boundary layer at the beginning of the process. Thus, immediately after passage of the shock front when the vapor pressure of the fuel is nearly atmospheric and blast particle velocity is a maximum, there is virtually no boundary layer separating the flow from the firebed surface. Qualitatively, it appears that this situation would result in a phenomenally high mass transfer rate of fuel vapor into the blast flow and a corresponding high cooling rate of the remaining liquid. However, established procedures for predicting interphase heat and mass transfer at high rates of mass transfer appear to be confined to steady-state processes.[11]

SECTION 7

APPROACHES TO ANALYTICAL MODELING

The most important outcome of the present program in its implications for analytical modeling of blast-fire interaction is the realization that, at the scale of our experiments, fires fueled by either wood or liquid hydrocarbons, are displaced from the fuel surface by fast-rising flows of very low peak velocity. The minimum peak velocity parallel to the surface required to just sweep a fire off a burning wood or liquid fuel surface is so low that we have not yet observed the threshold in our experiments in the shocktube, and it must correspond to a weak shock of insignificant overpressure.

In particular circumstances, however, fires are known to survive the passage of blast waves of substantial strength. In the case of liquid hydrocarbon pool fires, the fire swept off the fuel surface persists at some point in the wake of the pool, in vapor swept downstream from the pool, and under appropriate conditions can propagate upstream, as the particle velocity of the blast wave diminishes, to reignite the pool. Wood fires burning in cribbed arrangements of sticks have survived the passage of blast waves of moderate-to-high overpressure.[9,10] Such fires are sheltered from the blast flow by the crib structure with considerable recirculation of hot gases behind and between individual parts of the structure. Flow velocity within the structure can therefore be much reduced from the free stream velocity, depending on the intricacy of the structure, and recirculation retains the hot gases that would be displaced by a uniaxial free-stream blast flow parallel to the surface. The situation in wood fires is further complicated by the alternate existence of flaming combustion, a gas-phase reaction fed by gaseous pyrolysis products emerging from the wood, or glowing combustion in which the char burns in a heterogeneous reaction. Glowing combustion of char is largely inhibited during strong flaming combustion of wood because

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the atmosphere at the char surface is generally a chemically reducing one due to the presence of pyrolysis products emanating from the wood. Glowing combustion of char produces a high temperature at the char surface, which causes heat to flow into the wood where it can accelerate production of pyrolysis products, leading to reestablishment of the flaming regime.

Our experiments indicate that, at high blast wave overpressures and correspondingly high particle velocities, flaming combustion exposed to the flow is extinguished, whereas glowing combustion is stimulated. Thus, the possibility exists that flaming combustion might be reignited after passage of strong blast waves by stimulated glowing combustion.

Modeling of Blast-Interaction with Liquid-Fueled Fires

Evidence was presented in Section 6 indicating that cooling of the liquid fuel and consequent reduction of its vapor pressure by blast flow following displacement of fire from the firebed was a principal process leading to extinguishment of liquid-fueled fires by blast waves. Analytical modeling of this process is a problem in the theory of heat and mass transfer and a difficult one because of the high rate of mass transfer and the transient nature of the process.

To assess the possibility that extinction of liquid-fueled fires by blast waves is due principally to exhausting of fuel vapor in their wake, we have developed a simplified theoretical model incorporating the concept, and we have applied it to data obtained recently in the FEMA fire research program. As part of the FEMA work, blast extinction thresholds were determined in the SRI blast simulator for five different liquid fuels, using the same firebed in all the tests. The firebed was similar to that shown in Figure 6, but the wick holding the liquid fuel was 36 inches long (0.91 m) in the direction of blast flow instead of 12 inches (0.30 m). The blast simulator was operated in the same mode in all the tests, the driving section being restricted to a 31-feet-long (9.45 m) straight section of the tube upstream from the diaphragm. The positive duration of flow varied from about 60 ms at low overpressures to about 70 ms at the highest overpressures.

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In our simplified theoretical model, it is assumed that all the heat required to evaporate fuel is supplied from the sensible heat of the remaining liquid, neglecting other forms of heat transfer. The model is based on the assumption that the rate of transfer of fuel vapor into the air flow passing over the liquid increases with the velocity of the flow.[*] It is also assumed that the rate of transfer is similar for different fuels, since the process starts, in every case, with the fuel vapor pressure near atmospheric and proceeds until the vapor pressure is reduced by cooling of the liquid to the vicinity of the lean flammability limit in air. The fuels differ from one another, however, in the volume of liquid that must be vaporized and transported into the airflow to achieve the required cooling of the remaining liquid. Thus, fuels that require evaporation of a greater proportion of liquid to reduce their vapor pressure to the flammable limit will do so only in blast waves of increased particle velocity, and therefore of greater particle displacement and overpressure, if the blast waves are of equal duration.

The simplified relation was derived as follows: If dn_v moles evaporate from n_{liq} moles of liquid fuel, the heat absorbed by the vapor is $H_v dn_v$, where H_v is the heat of vaporization. This amount of heat is equal to $-Cn_{liq}dT$, the loss of heat by the liquid. Thus:

$$H_v dn_v = - C \; n_{liq} dT \qquad (7)$$

where C is the liquid heat capacity and T is the temperature of the liquid. Because fuel entering the vapor is lost from the liquid, $dn_v = -dn_{liq}$, and

$$\frac{dn_{liq}}{n_{liq}} = \frac{(C)}{H_v} \; dT \qquad (8)$$

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[*]For blast waves of equal positive duration, increased flow velocity implies increased total positive displacement of the flow and higher overpressure.

or

$$\ln \frac{n_*}{n_o}_{liq} = \frac{C}{H_v} (T_* - T_o) \qquad (9)$$

where subscripts zero and asterisk denote initial and final conditions. The final temperature, T_*, is the temperature at which the fuel vapor pressure, measured in atmospheres, becomes equal to the volume percent fuel at the lean flammability limit.

Data for four fuels[*] for which the shock overpressure necessary for extinction was determined in the FEMA program are given in Table 2. We see that the calculated fraction, $(n_*/n_o)_{liq}$, of the liquid fuel that would remain when the vapor pressure over the liquid was reduced to the lower limit of flammability varies in order of decreasing threshold over-pressure and peak particle velocity of blast waves necessary for extinction of fires over the fuels as determined experimentally. This result suggests that the mechanism of blast extinction of these fires involves initial displacement of fire from the wick followed by cooling of the liquid to reduce the concentration of fuel vapor in air flowing into the wake until it is too lean to burn.

It appears desirable that further work on extinction of liquid fueled fires by blast waves be preceded by development of an analytical model of the reduction of fuel vapor pressure by evaporation of the liquid, and that the experimental work be designed to supply input data to test the model. Thus, for example, temperature measurements of the liquid near its interface with the blast flow should be useful if these could be made with a fast enough time response.

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[*] Data for a fifth fuel, kerosene, that was included in the tests are not presented. Kerosenes are mixtures having boiling points and other properties dependent on the source of crude petroleum and refining process by which they are obtained. In the present instance, these properties were not well-known.

Table 2. Estimated fraction, $(n_*/n_o)_{liq}$, of liquid remaining after reduction of vapor pressure to the flaming limit, compared with extinction threshold by blast waves.

	n-Hexane	n-Pentane	Acetone	Methanol
Heat of vaporization, H_v (cal/g)	89.03	87.1	125.0	236.0
Liquid heat capacity, C (cal/g/deg K)	0.6	0.53	0.53	0.6
Initial temperature, T_o (deg K)	341.0	309.2	329.9	337.9
Final temperature, T_* (deg K)	243.3	222.5	252.9	282.1
Fraction of liquid fuel $(n_*/n_o)_{liq}$	0.477	0.590	0.721	0.880
Extinction threshold overpressure (psi)	5.2	2.8–3.0	1.5–1.9	< 1
(kPa)	35.8	19.3–20.7	10.3–13.1	< 6.9
Peak particle velocity (ft/s)	252	129–144	79–105	54
(m/s)	76.8	39.3–43.9	24.1–32.0	16.4

Modeling of the Interaction of Blast Waves with Open Wood Fires

Our experiments indicate that flaming combustion of wood is extinguished by blast waves of even minimal strength when their flow is parallel to the burning surface. Survival of wood fires subjected to blast must therefore depend on sheltering of the burning surfaces from the free-stream particle velocity by the structure of the wood fuel system, and especially by recirculation of hot gases over the burning surfaces.

The recirculation of flow in the wake of isolated pieces of wood is expressed to some degree by their drag coefficient. It has been known for some time[12] that an improved correlation of the stability limits of flames in jet engines for different flame holder shapes is obtained by using the product of the characteristic dimension, D, and the flame holder drag coefficient, C_d, rather than D alone, in a correlating function of the form:

$$\phi(f) = \frac{U_{max}}{(DC_d)n} \qquad (10)$$

where U_{max} is maximum flow velocity, and n is an experimentally determined constant. The flame-holding capability in this case was due to recirculation of flow in the wake of the flame holder.

Where two pieces of wood are adjacent to one another, the drag coefficient of each piece is affected by the presence of the other. Taylor[13] contributed to the development of theory relating the flow velocity through an array of many adjacent pieces to the free stream velocity, and developed the relationship between the drag coefficients of the individual pieces and that of the assembly as a whole.

The selection of the properties of open wood fuel systems to be incorporated in functions for correlation of blast strength with flame extinction threshold in that fuel system should therefore be based on the theory of recirculation of flow behind the members of a randomly arranged crib or lattice structure. Our experiments suggest that the relation

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of flame speed or combustion kinetics to free stream flow velocity has little or no bearing on the question of survival of flaming combustion in wood fires exposed to blast.

A second phenomenon that will probably need to be accounted for in developing a correlation function for extinction of open wood fires by blast is reignition of flaming combustion at high blast overpressures due to stimulation of glowing combustion of char. Our experiments indicate that glowing combustion is stimulated by high overpressure and the consequent high particle velocity and not by long, positive displacement of flow. Further experimental work is needed to establish that flaming combustion can, indeed, be reignited from stimulation of glowing combustion at high blast strength and to determine the kinds of fuel configurations in which it occurs.

SECTION 8

CONCLUSIONS

Fast-rising flows, whether produced in blast waves or by rapid acceleration of fires into still air, displaced flames from burning wood surfaces even at the lowest peak velocities when the flow was parallel to the burning surface.

Glowing combustion of char following displacement of flames was stimulated by high overpressure and particle velocity, independent of the positive displacement of the flow.

The properties of open wood fuel systems to be incorporated in functions for correlation of blast strength with flame extinction threshold in that fuel system should be those that determine the amount of recirculation of flow behind the members of a randomly arranged crib or lattice structure.

A second phenomenon that will probably need to be accounted for in developing a correlation function for extinction of open wood fires by blast is reignition of flaming combustion at high blast overpressures due to stimulation of glowing combustion of char.

Fires burning over flat ceramic fiber wicks containing liquid n-hexane were invariably displaced off the wick by fast-rising flows produced either by blast waves or by rapid acceleration of the firebed into still air. Survival of these fires after passage of the blast wave depended on their being reignited by flame that had been swept into the wake. Evidence is presented to show that reignition depends on whether the vapor pressure over the liquid fuel was reduced enough by cooling that the concentration of fuel vapor flowing into the wake was depressed below the flammability limit before the end of the positive phase of the flow.

Analytical modeling of the extinction of liquid-fueled fires by blast waves is thus considered to be a problem in the theory of interphase heat and mass transfer between the cooling liquid and the blast wave flow.

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Further work on the extinction of liquid-fueled fires by blast waves
should be preceded by development of an analytical model of the reduction
of fuel vapor concentration in the flow downstream of the fuel bed to
cooling of the liquid. The experimental work should then be designed to
supply data to test the model.

SECTION 9

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