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# BLAST EFFECTS ON FIRES

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December 1980

Annual Report

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Office of Mitigation and Research
Washington, D.C. 20472

Contract No. DCPA 01-79-C-0245
FEMA Work Unit 2564A

SRI Project PYU 8421



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By: Jana Backovsky
Stanley Martin
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Experiments on extinction of fires by airblast were conducted in the shocktube facility dedicated to blast/fire interaction studies. Three series of tests were conducted to gain practical understanding (quantitative and mechanistic) of blast effect on fires, using: (1) liquid-fuel fires of various sizes; (2) liquid-fuel fires, of various sizes, with flow-obstructing barriers upstream of the fuel source; and (3) wood-crib fire tests.

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Results affirm the concept of flame displacement as a mechanism of extinguishment for liquid-fuel fires on flat surfaces but suggest its limitation in describing blast/fire interactions when flow-perturbing obstacles are present upstream of the fuel bed. Even small barriers are seen to significantly increase the fire resistance to blowout by blast, by providing flame-retentive flow recirculation in their wake and effectively serving as flame-holders. For charring fuels such as wood cribs, after-shock flame displacement is seen to be augmented by sustained, blast-enhanced char involvement. The crib fire history before blast arrival and the extent of char-combustion enhancement (depending on blast strength) determine whether the crib fire is reestablished by rapid rekindling.



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## SUMMARY


**Objective and Scope:**

The overall objective of this experimental program is to determine and evaluate the physical variables that govern extinction of sustained burning, in representative fuels, caused by simulated airblast characteristic of nuclear explosions. The experiments are also to provide data for analytical models being developed concurrently at Notre Dame and TRW. This year's work included investigations of effects of flow-perturbing barriers on blowout resistance of class B fuels and of the resistance of complex, three-dimensional (class A) fuel arrays (wooden cribs) having gas and solid-phase combustion and charring, with significant heat stored in the char.

**Approach:**

The tests of extinction of fires by blast were performed in the SRI-developed shocktube facility. For most of the tests in FY80, the shocktube was used with positive-phase durations between 70 and 133 ms. n-Hexane fires of 1- to 3-foot fuel bed length, with and without flow-barriers, were subjected to blast overpressure extinction thresholds. The barriers were 1-3/4-inch high and were positioned 3-1/4 and 9-1/4 inches upstream of the upstream fuel bed edge, although other barrier heights and distances were tested for simple scaling rules. Methanol fires were tested for contrast with hexane results. With blast extinction of crib fires, the approach has been to design and use fully reproducible, self-sustained class A fires, even though lacking a suitable thermal source, to furnish an easy and sustained ignition simulation of, for example, flat wooden samples. The crib fires were initiated by an alcohol source-fire on a wick placed (for 60 s) under the crib and allowed to burn freely for a predetermined time (1-1/2 to 3 minutes total preburn time). The extent of crib-fire involvement was then correlated with the blast extinction response.

**Significant Results:**

Increased fire blowout resistance and an apparently different physical mechanism of fire retention (reestablishment) above the fuel bed were observed with flow barriers, as compared with the flush, basic flat-plate bed configuration. Even with the low (1-3/4-inch high) barrier used in most tests, the flow-perturbing effect is pronounced; at the 3-1/4 inches position upstream the overpressure threshold is effectively increased by 1 psi

at each bed length, compared with the case with no barrier. Photographs of particle-laden after-blast airflow (without fire) show the extent of flow deflection by the barrier and a region of reverse flow behind the barrier; film coverage (with fires) indicates that fuel reignition occurs in the large eddy behind the barrier, showing its function as a flame holder.

The role of char (glowing embers) in crib tests was found to be significant, especially at the higher overpressures and the accompanying high blast winds. Film coverage attests to the strong fanning by blast, causing intense glowing and growth of embers (as well as significant firebrand production). Surprisingly, two extinction overpressure thresholds were observed for the cribs tested: a lower threshold, below which the blast wind apparently does not completely blow off the primary flame, and a higher threshold, above which strong fanning of embers aids the return to flaming combustion. Finally, there appears to be a critical preburn time ($\sim$ 170 s for the cribs tested), after which permanent extinction by blast does not occur at any of the applied overpressures.

In summary, the resistance of initially self-sustained, freely burning fires to relatively short duration blast was found to be substantial, especially with flow disturbances. The effect of intermediate and long-duration pulses has yet to be fully studied, as well as introduction of thermal pulse simulation.

## FOREWORD

This is the second annual report of work accomplished for the Federal Emergency Management Agency (FEMA) under Work Unit 2564A, Contract No. DCPA 01-79-C-0245, Modification No. 2. The Statement of Work for this contract reads as follows:

> SRI International will continue to use the Camp Parks Blast/Fire Shocktube and provide its best efforts within the limitation of available time and funds to evaluate the resistance to shockwave blowout of established flaming and smoldering combustion in composite fuel arrays of representative, practical composition.
>
> Specific work and services will include:
>
> (1) Investigation of the influences of fuel bed configuration, orientation, and surface texture.
>
> (2) Investigation of scale effects, such as the minimum fuel-bed length necessary to prevent extinction, evaluation of effects of non-freefield shock interactions, such as those experienced by fuels inside enclosures. This will be accomplished by including in the test section nonfailing baffles and fixed apertures to represent perturbations due to walls and windows.
>
> Since the major emphasis in this project has been given to class B fuels, this continuation effort will be applied mainly to investigation of extinction in class A fuel arrays.

The scope of this effort was further delineated in a contract initiation conference between the COTR and project principal investigators. A detailed approach was documented in the approved Work Plan (Appendix A). Progress report dated July 30, 1980 indicated and documented the need for redirection of technical effort in some of the tasks of the approved work plan; these changes were essentially fine-tuning of the approach and scope of work as work progressed.

With the publication and distribution of this report, all contractual requirements of the subject contract are satisfied. The work will continue under a new FEMA contract to be awarded in 1981.

# INTRODUCTION

In the context of potential nuclear attack on the United States, the current uncertainties regarding the interactions of airblast with fires and the consequent uncertainties in the potential threat by fire to population survival and national recovery are major obstacles to defense planning and national security decisionmaking. These uncertainties substantially preclude any reliable quantitative estimates of the outcome of nuclear attack on the United States.

Perhaps the most serious deficiency is in estimates of threshold airblast conditions for the extinction of fires initiated by thermal radiation from the nuclear fireball. The research reported here covers the second year of an experimental program to provide a data base and an understanding of the physical mechanisms involved, from which reliable estimates of this combined effect can be developed.

## BACKGROUND

The historical and technical background of the current study was summarized in the report[1] of the first year's experimental activity. SRI has developed a shocktube facility specifically designed for investigating the interactions of blast with fire by direct observation of the phenomena and dependence of these phenomena on the basic characteristics of nuclear airblast waves.[2] The facility, shown schematically in Figure 1, provides repeatability of test conditions, convenience of operation, and allows many tests to be conducted in a relatively short experimental program at reasonable cost. It makes systematic investigation possible through independent variation of airblast characteristics over the practical range of values for civil defense concerns.

This facility was used during 1979 for experiments in airblast blowout, mostly of class B (in particular, hexane-fueled) fires. Only a modest experimental effort was possible because modification of the facility to accommodate these experiments absorbed a substantial part of the available funds.

The limited data resulting from the 1979 study, as yet unstructured by a theoretical model, allowed us to offer only the following tentative conclusions for the specific case of flat-plate geometry, zero angle of attack attitude, and for volatile class B fuels stabilized mechanically by inert substrates:

(1) Flame displacement is a mechanism of extinguishment.

(2) Airblast conditions representing the threshold for fire extinction scale with fuel bed length; more specifically, for 100- to 300-ms duration pressure pulses, the critical bed length is proportional to peak overpressure (in the range of 1 to 5 psi or more) and appears proportional to the distance the air is displaced during the positive phase of the pressure pulse. The critical length is, however, only about one-sixth of the estimated air displacement for the waveform used.

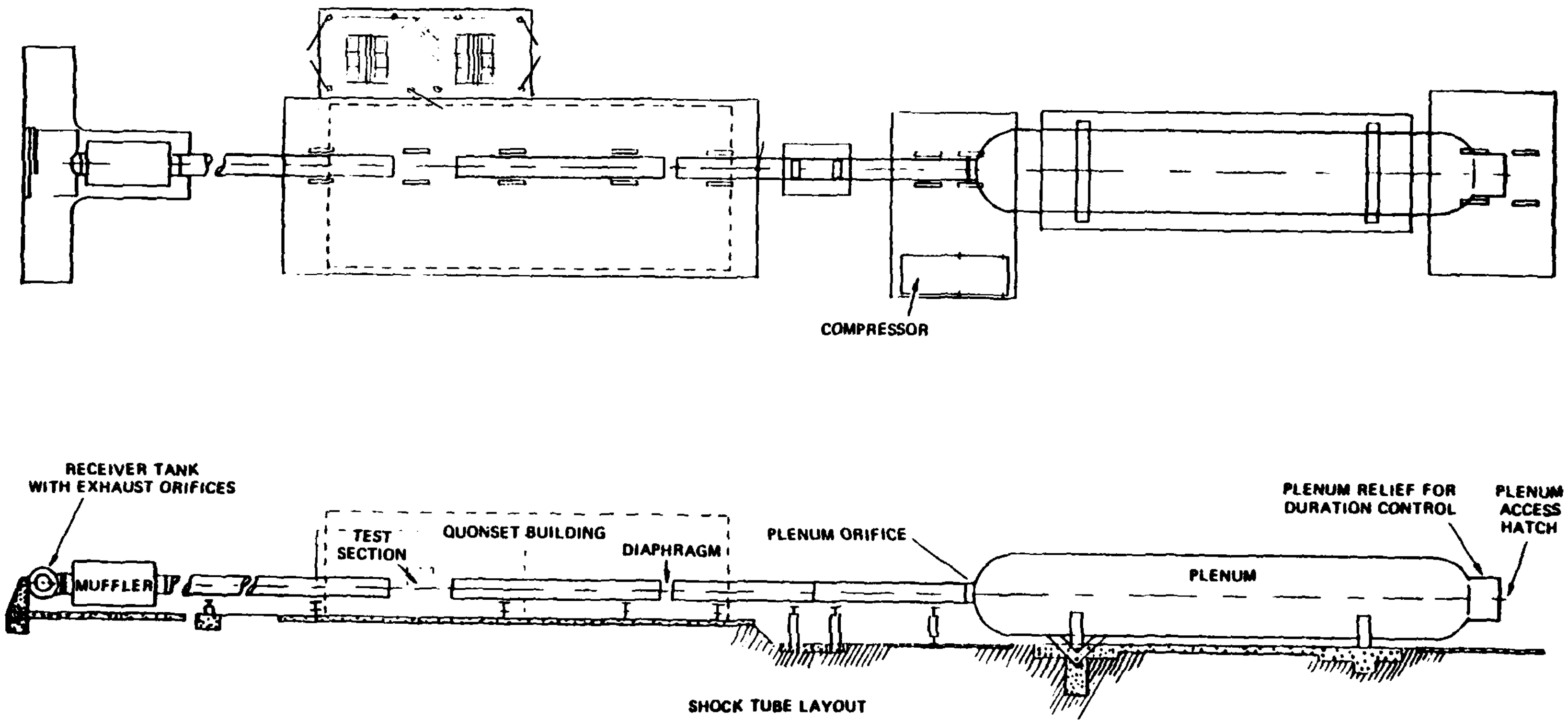


FIGURE 1 BLAST/FIRE SHOCKTUBE FACILITY

(3) Results do not seem to depend on the character of the solid substrate used to stabilize the liquid fuel.

(4) The effect of a barrier to airflow is pronounced and apparently very sensitive to the position of the barrier relative to the upstream edge of the fuel bed. Even a small obstruction introduced into the flow immediately in front of the fire may allow it to survive airblast conditions that would otherwise readily blow the fire out, but this "stabilizing wake" does not persist to appreciable downstream distances (i.e., less than ten barrier heights).

Only a single datum was available for fires involving a class A fuel, totally inadequate to permit comparisons with class B fuels. The displacement mechanism appeared to have some applicability to extinction of flames over class A fuels in flat-plate configurations oriented edge-on to the incident shock, but other geometries were not attempted. These results were summarized in an annual report.[1]

Disconcertingly, the fuels and fuel-bed configurations used in the 1979 study produced fires that were so easily blown out that, in order to allow some of the test fires to survive the airblast effects, we had to restrict the test conditions to low peak overpressures and the shortest available positive-phase durations. These results, if generally applicable, would seem to contradict field test experience and the longstanding conclusions based on the bomb surveys of Hiroshima and Nagasaki. A principal factor in the ease of extinction was thought to be the flat-plate experimental design, which did not include geometrical complexities that could have flow-stagnating and flame-holding effects. Limited tests with barriers tended to confirm this hypothesis.

To enhance the realism of these experiments, it was considered necessary to begin introducing geometrical complexity as a test variable. To gain an early assessment of the potential magnitude of this factor, we decided at that time to switch over immediately to the most difficult to extinguish (while still experimentally convenient) configuration we could imagine, i.e., a wood crib.

Many practical questions remained to be answered at the start of this year's effort:

(1) If one accepts the conclusion that flame displacement is a **mechanism** for airblast extinction of fire* and that in simple, flat-plate geometries in edge-on orientations, the size of the fuel bed supporting a fire that will just manage to survive the passage of an air blast can be scaled to the distance that air is displaced by the blast, how does this apply to practical situations? What are the scaling parameters and relationships?

(2) When air flow becomes significantly stagnated or diverted by the fuel or its surroundings, do totally different mechanisms of flame extinction operate? Dominate? Or do fires burning under such circumstances become essentially impossible to extinguish by airblast effects alone?

(3) How important is the time delay between fire initiation and airblast arrival (preburn time)?

(4) When flame displacement is not an important mechanism, what other airblast characteristics are important? Pressure? Rate of pressure change? Pressure jump? Impulse [i.e., $\int P(t)dt$]? Dynamic pressure?

It is essential to place these questions within the current perception of the nature and the critical factors of the fire-related effects of nuclear bursts and discuss the degree of physical simulation consistent with the state of the art. Several factors can be recognized at the outset to be potentially important to the ability to predict the outcome of these fires. Until these factors have been evaluated, any test program should attempt to include them all. In addition, there may be other factors not yet recognized. To foster the discovery of such factors, wide ranging exploratory experiments were conducted during the early stages of this study.

The explicit or otherwise evident factors germane to the ignition/extinction of fires after a nuclear burst may be summarized as follows:

(1) Fire-initiating mechanisms

- Ignition by exposure to thermal pulse
- Secondary ignition
- Multiburst complications

*In some cases, providing the necessary, but not always sufficient, means for the extinguishment.

(2) Fire growth environment and factors acting to sustain the fire

- Fuel descriptors and array variables
- Enhancing/retarding factors

(3) The delay between fire initiation and airblast arrival (preburn time)

(4) Airblast characteristics (free-field)

- Peak overpressure
- Positive pressure-phase duration
- Nonideal airblast (e.g., precursor effects)

(5) Geometrical influences (e.g., flow-stagnating orientations, enclosure effects).

Total simulation is impractical, not only because atmospheric nuclear tests are banned by treaty and the substituted high-explosive field tests, even with contrived thermal radiation sources, are deficient simulations, but simply because there are too many combinations of the recognizable factors to test them all. This naturally suggests the use of systematic experiments using shocktubes or other appropriate controllable sources of air-flow dynamics. Unfortunately, no such currently available facilities are adequate for full simulation; they cannot properly treat the transient elements, and the applicability of their results lacks credibility in greater or lesser degree, depending on the nearness of their approach to full dynamic simulation.

The SRI-operated facility at Camp Parks comes closest to this ideal, is being steadily improved, and will soon achieve total simulation capability with addition of a thermal-radiation-pulse accessory. Its design provides for independent variability of the factors listed above to allow systematic study of parametric dependence and the development of a generally applicable technology from which prediction modeling can derive. Moreover, it enjoys a credibility that no other simulation approach can match.

# EXPERIMENTAL APPROACH

## GENERAL METHOD AND GOALS

The experimental work reported here pursued two primary lines of investigation:

(1) Quantify the flow-perturbing barrier effects for extinction thresholds of flames over one or more class B fuels in terms of airblast characteristics for observable extinction criteria and the dependence of these thresholds on the height of the barrier and its upstream distance from the leading edge of the fuel supply. Details of these experiments and their results are described in the following section, "Class B Fuel Tests".

(2) Ascertain the airblast extinction thresholds for wood crib fires (i.e., hard-to-blow-out fires in class A fuels of complex geometry) in terms of overpressure levels and durations and their dependence on preburn times (i.e., ignition-to-blast-arrival delays). Lacking a suitable thermal radiation source, ignition was effected with an alcohol-soaked wick at the expense of realism in both intensity of the ignition source and the time scales of the ignition/preburn sequence. Details of these experiments and their results are described in the section on "Crib Fire Extinguishment by Blast".

Some preliminary experiments were also undertaken using a small makeshift wind tunnel to guide the selection of fuels representing interesting ranges in potentially pertinent properties. The concept was that distinct differences in flame blowout behavior observed for different fuels in steady (or quasi-steady) airflow should be reflected in observed behavior in the shocktube. Although it was readily acknowledged that unique dynamic-flow effects could accompany airblast exposures, effects that might either add to, modify, or even replace the steady-flow responses, it was hoped that such preliminary experiments might provide a simple, low-cost method of screening fuel properties for selecting candidates for shocktube study. Moreover, anomalous results in the comparison of steady and nonsteady flow were expected to point immediately to the unique aspects of transient-flow interactions.

Although this concept is basically sound when wind tunnel and shocktube experiments are conducted in comparable scale, geometry, etc. the differences between the small wind tunnel and the shocktube tests (due probably to scale) yield significantly different results, which would need to be reconciled analytically by theory or scaling rules.

The approved work plan for this year's experimental study is reproduced as Appendix A.

RATIONALE FOR FUEL SELECTION

As noted in the "Theoretical Background" section of Reference 1, superficially similar combustion/extinction problems (e.g., in steady air flow) have received considerable attention, sufficient to provide engineering concepts that self-consistently encompass the experimentally observed variability in and interdependencies of several parameters. One such concept, the Damköhler number, addresses the competition between chemical and aerodynamic processes. It compares the rates of mixing of the fuel and oxidant reactants with the rates at which they react once mixed. Its magnitude measures the tendency for flames to be interrupted by air (and/or fuel supply) flow in applicable combustion processes (e.g., counterflow diffusion flames). The concept holds that flame extinction results whenever the time available for essential chemical reactions to take place becomes short in comparison with the time required for these reactions to occur. Fuel properties that may be identified with the magnitude of the Damköhler number are: (1) a characteristic length dimension associated with the fuel supply, (2) kinetic constants associated with the combustion reaction(s), (3) the stoichiometry of the reaction (e.g., the fuel/air equivalence ratio), and (4) change-of-state and/or pyrolysis rate factors that govern fuel-supply rates. The mass transfer number (B) is a useful engineering parameter embodying some of the foregoing.

Another concept, relating to flame displacement, compares the competing rates of motion of the flame swept along by the displacing air flow relative to its upstream propagation against the flow. Thus, a relevant fuel property is flame speed. Effects of turbulence on flame speed are pertinent, as are effects of dilution, cooling, and loss of reactive species. Lean extinction limits are potentially pertinent here.

Other relevant properties can be identified, but these examples illustrate the application of theoretically based rationale in the identification of test-variable properties and conditions.

## WIND TUNNEL SCREENING OF FUELS

A few exploratory tests were conducted to identify fuels with properties that could help clarify blast/fire interactions. It has been variously suggested that the airflow following the shock front disturbs the flames and extinguishes the fire when the amount and duration of the airflow exceeds some threshold conditions, whereas the shock front itself generates only a minor perturbation in the flame zone. Therefore, it seemed appropriate to examine the fuel parameters and mechanisms that effect flame blowout in high speed airflow.

Extinguishment of liquid and gas fuels was explored in a small mock-up wind tunnel. Hexane, methanol, methane, and acetylene were burned on small porous spheres* with steady and unsteady burning and wind/air velocities and with various sphere sizes (flame curvatures). The results suggested qualitatively that, among the properties varied, the fuel properties (tentatively flame speed†) show the greatest effect on the onset of extinction, which was taken as that airflow value at which the first rupture of flame occurred on the upwind side of the sphere. The following observations were made:

- Steadiness of airflow made little difference; i.e., both steady and suddenly accelerated flow started extinction for each fuel at about the same air flowrate.

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*Liquid fuels were applied to spherical Marinite board wicks and gases were diffused through Kaowool balls.

†Flame speed is the speed at which a flame will propagate in a fuel-air mixture or, conversely, remain attached at a flame holder with the mixture moving at the flame speed. The region where a diffusion flame (such as used in shocktube) is attached to the fuel bed is often viewed as premixed, and the ability of the flame to withstand opposing flow and remain attached is viewed as related to the flame speed.

- As (liquid) fuel availability and flame intensity decreased, the flames, as expected, were easier to blow out. Gas flame extinguishment was relatively insensitive to the fuel flow rate, except at quite low flow rates where flames were easier to blow out.
- Flame curvature, thought to affect flame stretch response, had only a small effect on extinction. Gas flames on small spheres were easier to extinguish than flames on larger spheres at the same total fuel supply rate. (The fact that smaller spheres had a larger fuel supply rate per unit surface area is probably not important because of the above-mentioned insensitivity of extinction to gas supply rate.)
- Acetylene (with maximum flame speed three to four times as large as the remaining fuels) required an extinction blowing rate about 2.4 times the remaining fuels. This was the most significant effect observed in the wind tunnel.

From these very preliminary blowout observations, it is obvious that acetylene would be an interesting fuel for use in the shocktube extinguishment studies. The other three fuels gave essentially the same blowout results, suggesting that for liquid fuels the heat of vaporization (or the mass transfer number) is relatively unimportant in such small-scale blowoff experiments.

Experience dictated that even such qualitative results should be interpreted cautiously in view of the great difference in scale between these and the shocktube tests. In fact, the shocktube tests (described below) indicate great differences in extinction thresholds for hexane and methanol. Since physical properties--such as heat of vaporization (or the mass transfer number, which is a related dimensionless parameter) --play an important role in freeburning pool fires, their role in extinction cannot be ruled out and must be analytically and experimentally modeled over the range of scales of interest.

## SHOCKTUBE TEST VARIABLES AND DIAGNOSTICS

### Overpressures

Nearly all the tests were run in the short-duration pressure pulse mode, using only the 20-ft tube section between the plenum tank and the diaphragm as the compressed-air driver (refer to Figure 1). Figure 2

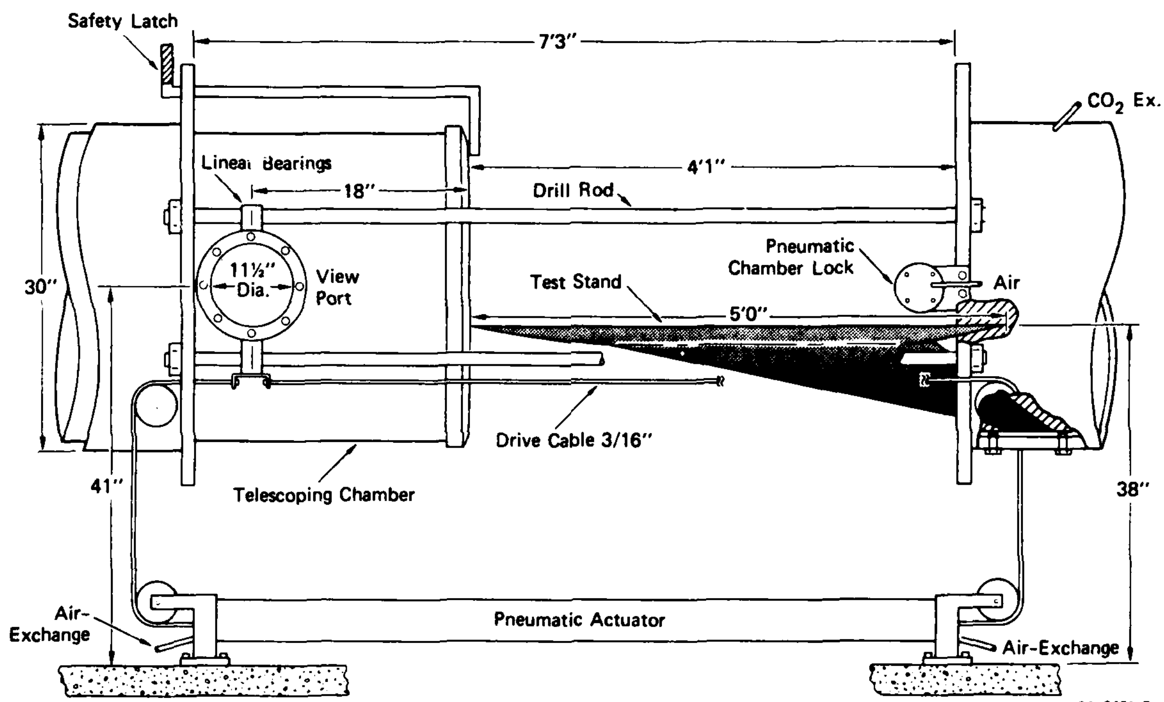


FIGURE 2 SHOCKTUBE TEST SECTION

shows the details of the shocktube test section. In a few tests of crib fires, conducted near the end of the year's activities, the plenum tank was included in the compressed-air driver to provide long durations of blowdown as the ultimate test of the difficulty of extinguishment of flames in deep-seated crib fires.

The shocktube was operated with peak overpressures in the range of 1.0 to 11.5 psi. The pressure gage that was used for the pulse evaluation at the test section was initially located 10 inches upstream of the test section flange and $90^{\circ}$ to the horizontal, mounted in the top of the tube. During the initial series of tests, the gage exhibited baseline drift as soon as the test section was closed. The drift was attributed to convective and/or radiative heating of the pressure gage sensing element. The location was changed to 12 inches upstream of the test section and $60^{\circ}$ below the horizontal, satisfactorily reducing the perturbing effects of the test bed flames.

The pressure gage used for the measurements was a solid state silicon device in a wheatstone bridge configuration. The natural frequency of the gage is 100 kHz (40-$\mu$s rise time), which is fast enough for our measurements. The remaining gages that were used have a much lower frequency response, but were used primarily for overall pulse positive phase evaluation, so a time response adequate to follow the initial rise time was not as important as in the test section gage.

Several representative short-duration pressure pulses are shown in Figure 3, as recorded at the test section. Time zero in the pressure histories corresponds to shock firing (diaphragm rupture). The first-arriving sharp spike at about 17 ms arises from the Detasheet detonation and is of relatively short duration ($\sim$ 5 ms). After the disturbances accompanying diaphragm rupture subside ($\sim$ 15-20 ms after shock arrival), the overpressure level stabilizes or only slightly decreases, yielding a pressure plateau for about 35 ms. The end of this plateau and the onset of pressure decay corresponds to the arrival of the returning rarefaction wave, reflected from the extreme upstream end of the cylindrical driver section. This rarefaction is immediately preceded

*The elements and operation of the test section are described in Refs. 1 and 2 and also briefly on page 24 and 47 of this report.

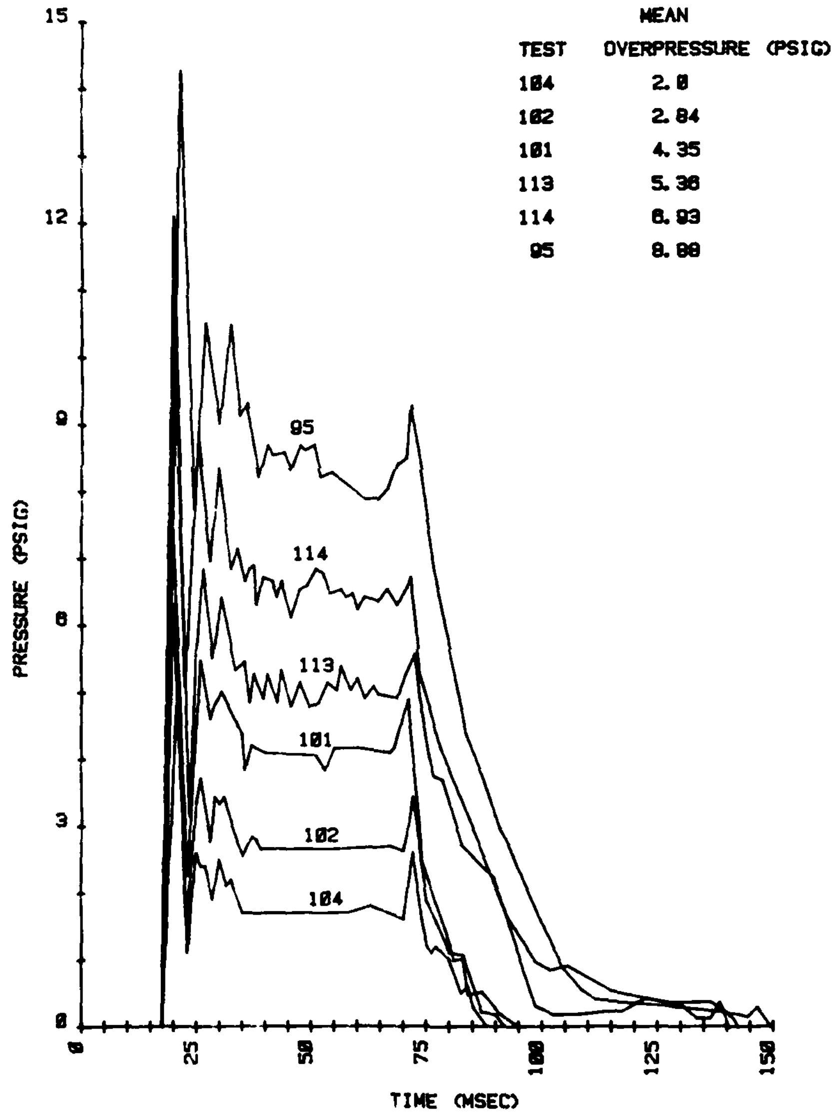


FIGURE 3 SHORT DURATION PRESSURE PULSES

by a pressure spike, reflected from the same end, originating from the Detasheet detonation.

In contrast to the steady overpressure period, whose duration is determined primarily by geometrical factors, the tail end varies in duration, from about 15-25 ms for the low overpressure pulses to 70-80 ms for the high overpressure pulses, and is due mainly to viscous impedance. The entire positive phase duration, consequently, can be seen to vary from 70 to 133 ms for the range of overpressures shown in Figure 3, whereas the plateau of high overpressure indicative of the shock strength and delivering most of the shock impulse is of constant duration independent of the overpressure (about 55 ms from first to last peak).

The similarity and difference between the short- and long-duration pressure pulses can be seen in Figure 4. The first 60-ms period after shock arrival is in both cases governed by the pressurized tube section (its pressure and geometry), resulting in nearly identical pressure histories during this period. The difference arises as the rarefaction wave (from the diaphram rupture) reaches the upstream tank, at which time it lowers the pressure in the orifice separating the tank and the tube, thereby initiating flow through the orifice. The effect of this flow, however, is not felt at the test section until the reflected rarefaction wave would arrive there (or $\sim$60 ms after shock arrival) had the orifice been closed. With the size of orifice used in these tests, the tank later supports an overpressure of about one-half the first pressure plateau for about 300 ms longer (see Figure 5). For the long duration pulses, Figure 5, the positive-phase duration is first interrupted about 400 ms after shock firing by a rarefaction wave propagating upstream from the muffler.

These pressure pulses do not represent the ultimate simulation capability of the facility. The good reproducibility of pressure pulse characteristics,[1] as shown here in the near-identical, first 60 ms of the short- and long-duration pulses, indicates the repeatability and control of test conditions. However, improvements in pressure pulse shapes can be made by removing extraneous spikes and troughs. Especially in the long-duration pulses, careful matching of orifice and receiver tank sizes should completely eliminate the perturbing rarefactions.

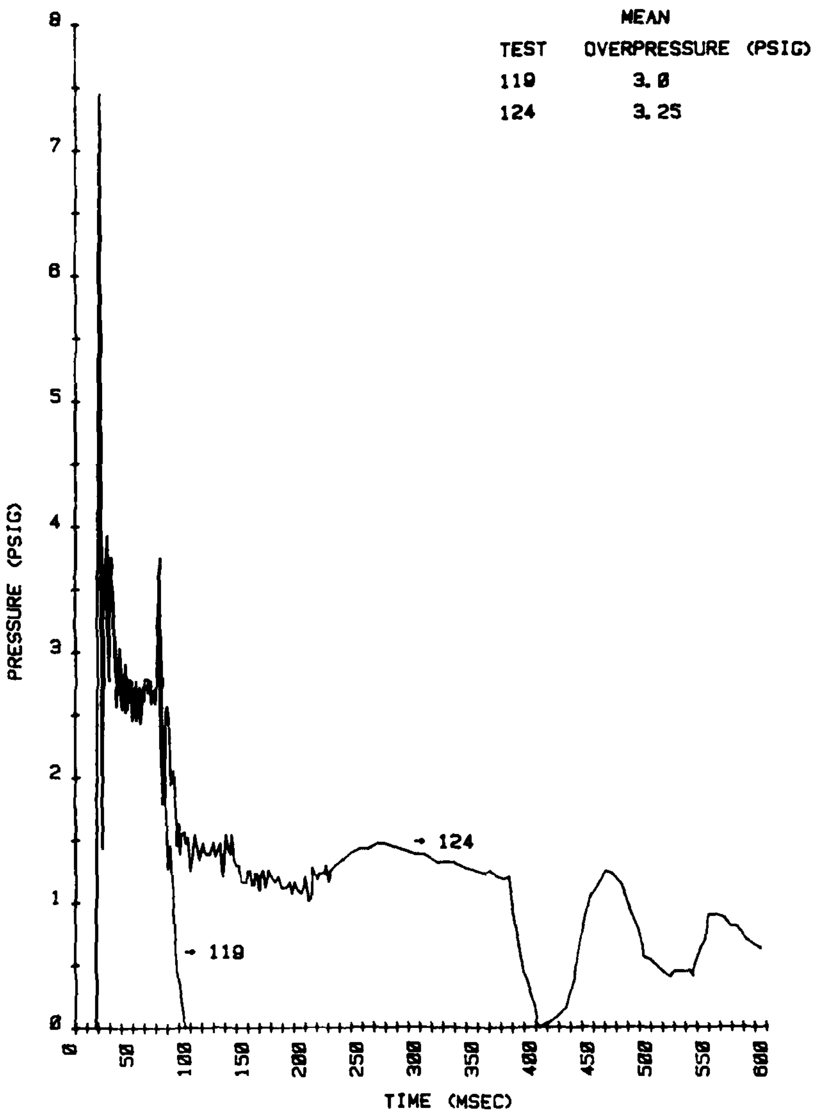


FIGURE 4 LONG AND SHORT DURATION PRESSURE PULSES

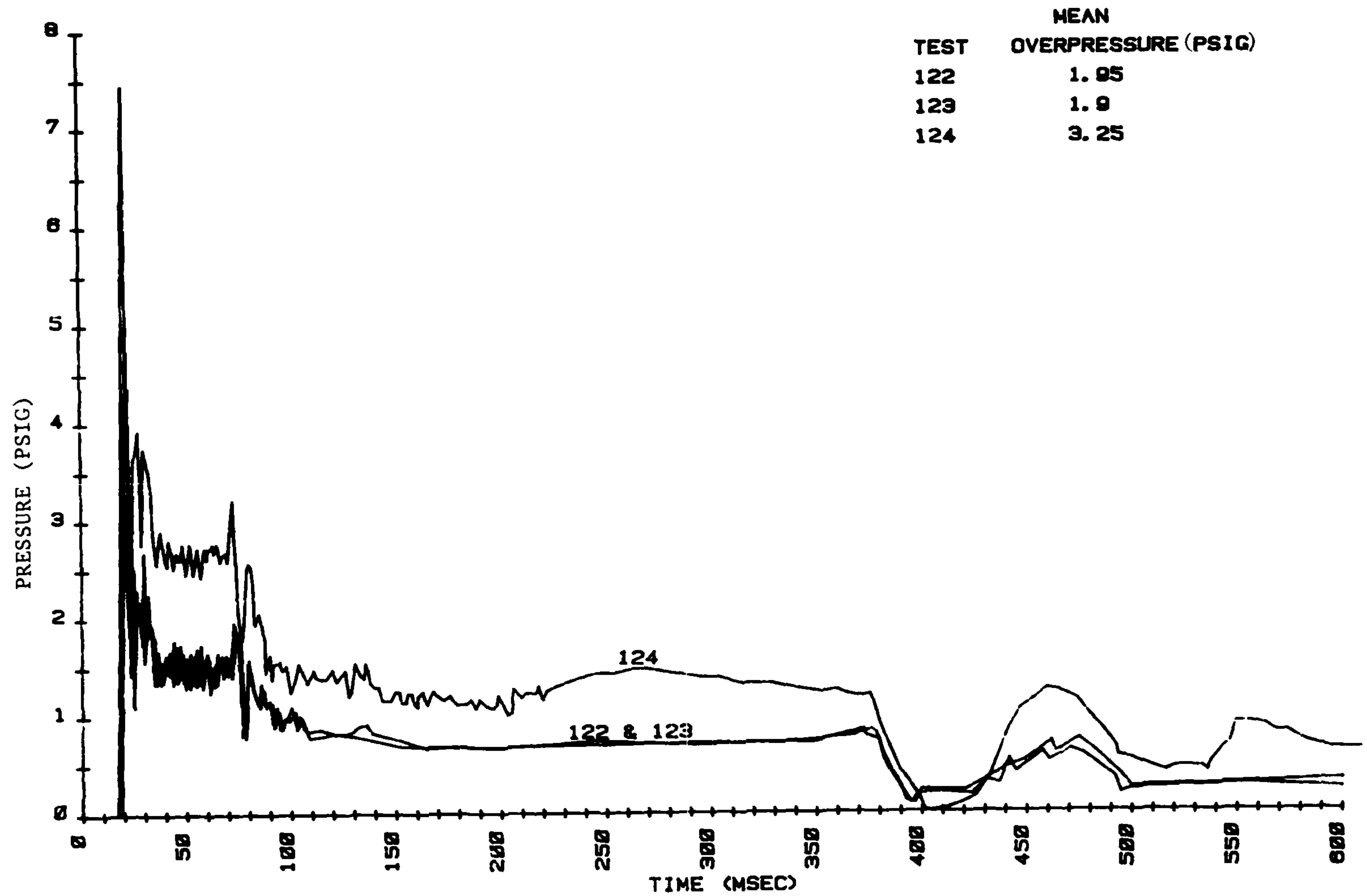


FIGURE 5 LONG DURATION PRESSURE PULSES

At the present level of understanding of blast extinction phenomena, it is unclear which aspect of the pressure history or which dynamic consequence will be found to be the determining factor in permanent fire extinguishment by blast, in the shocktube-simulation or in a hypothetical blast. In the present study, the mean (time-integrated) overpressure over the entire positive phase duration is used (provisionally) as the shock parameter for the short-duration pulses. Figure 3 lists the calculated mean overpressure values for the given pressure histories. Comparing these for each test shows that the observed pressure plateau is slightly below the mean overpressure value for the full positive-phase duration.*

For the long-duration pulses in Figures 4 and 5, only the estimated mean overpressure values over the first 60-65 ms after shock arrival are listed. The rationale was to compare two pulses with the same short-pulse mean overpressure equivalent (the same "beginning"), to see if the remainder of the long pulse had any effect on blast extinction.

The mean overpressure values are tabulated in Appendix B for all tests performed, together with the time interval used in pressure averaging and the total positive phase duration.

Flame Motion

Photooptical measurements of flame motion were added to supplement the high-speed film coverage and to permit following the complex recursive motion and behavior occurring outside the camera's field of view.

The photo transistor units were mounted in a fixture that permitted viewing the full cross section of the tube, but limited the upstream and downstream view to $\sim$ 2 inches. The units were not calibrated because they were used as flame indicators only. Initially, the flame detectors were mounted downstream of the test section. In the later test series, two stations were located upstream of the test section.

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*Only the first positive-phase period is used for the calculation. If there is a later period of small positive overpressure, that overpressure is not included in the calculation.

The camera used for the flame motion evaluation was located in front of the view port in the test section. The camera was run at a maximum framing rate of 2,000 frames/s.* Because of the fixed position of the viewing port in the test section, the camera's field of view was limited to the middle 12-inch section of the 3-foot test bed.

## Shock and Flow Visualization

Other diagnostics were used to aid in the investigation and description of shock diffraction and aiflow behind the shock. A shadowgraph technique permitted visualization of successive stages of the passage of the shock over the fuel-bed housing surface and around a barrier when no fire was present. Shock interactions and the associated steep air density gradients diffract the light and produce shadows for a very brief† period immediately following shock transit. As shown in Figure 6, reflected shocks are readily seen, and the formation and decay of a strong vortex downstream of the barrier in the wake of the passing shock front can be followed visually. The shock front appears reestablished at the support-plate and fuel-bed surface within two barrier height distances downstream of the barrier.

Miniature spheres of styrofoam were used in addition to the shadowgraph technique to render visible the airflow patterns that are not discernible by shadowgraph. This flow-visualization technique also extends the time scale of observable airblast effects well past the period of shadowgraphable events. Flow visualization demonstrated the extent of flow deflection by the barrier and the region of reverse flow behind the barrier. When the barrier was positioned in view as in Figure 6, the region of reverse flow extended downstream out of view of the camera, for a total length of about one foot (3.6-psi shock).

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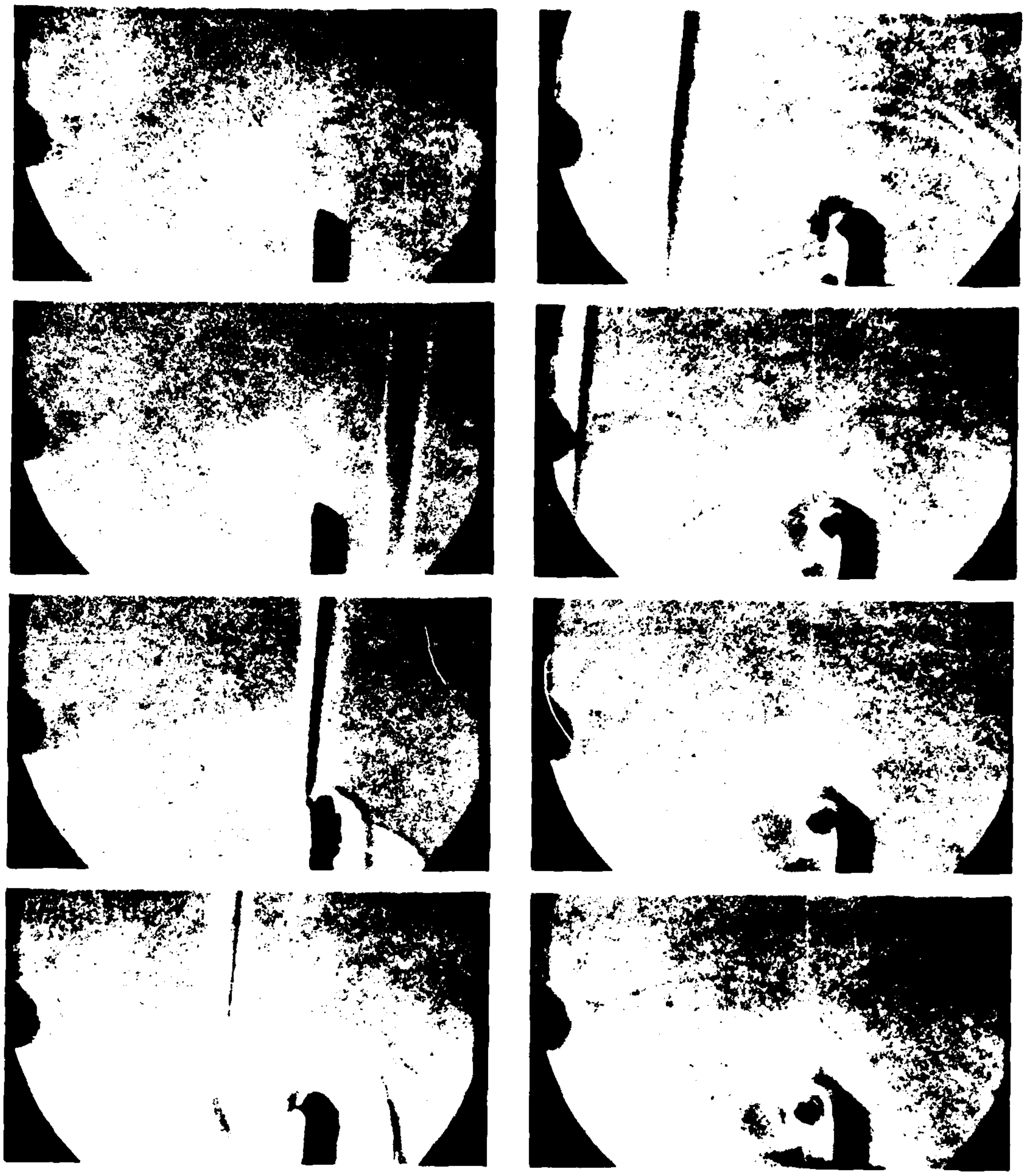
*The actual, accelerating camera speed just after shock arrival was between 850 and 1,000 frames/s, as indicated by the timer.

†For shock visualization, a Hycam camera was used with a nominal framing rate of 10,000 frames/s. In Figure 6 (Test 87) the time elapsed between frames is 98 μsec or ∿ 0.1 ms.



SP-8421-11

FIGURE 6 SHOCK-BARRIER INTERACTION

Shock (3.6 psi) is incident from the right on a 1-3/4-inch high barrier located 26-3/4 inches from the leading edge of the test stand. Time between frames is 0.1 ms. The eddy shed behind the barrier is transient, dying within 2 ms of shock arrival, but long-term rotating flow is set up behind the barrier.

## Shocktube Preparation

Pressure-Transducer Calibration. Before each series of tests, the pressure transducers and thermocouples at each station are calibrated. A dead weight tester, which generates a known pressure, is used to calibrate the pressure transducers. The thermocouples are calibrated by injecting a known millivolt signal. Before each day's testing, the test-section pressure transducer and the tank or plenum transducer are checked to ensure that the calibrations are still valid.

Diaphragm Preparation and Mounting. To date, only dead-soft aluminum has been used as the diaphragm material. Depending on the desired over-pressures, sheets of either 10-mil or 32-mil thickness have been used. Line charges of Detasheet are used to explosively shear the diaphragm, initiating the airblast. An asterform pattern* has been used on the 32-mil diaphragms. A simple cross pattern has been used with 10-mil diaphragms to reduce to a minimum the amount of Detasheet, thereby minimizing the pressure spike.

Before each test, after the airblast characteristics are selected, the diaphragm (with line-charge pattern in place) is installed between the plenum and test section (see Figure 1). When all other preparations for the test are complete, the Detasheet lead-in is connected to an electrically fired initiator, and the plenum is pressurized.

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*specifically, a six-point asterisk with capitals

## CLASS B FUEL TESTS

This extension of the work performed during 1979 was undertaken mainly to quantify the effects of barriers interposed in the shocktube, upstream of the fuel supply, which deflect the shock and perturb the ensuing airflow. It was also hoped that we could discover a basis for scaling these effects.

### TEST PARAMETER SELECTION AND CONTROLLABILITY

#### Fuel Type

The approved work plan and work plan modification included a task on effects of fuel properties (Task C), with suggestions for candidate class B fuels. As work progressed, however, a strong diversification into tests with many different fuels appeared less suitable within this year's scope of work. The strong and qualitatively different effect observed for extinguishment with flow barriers raised many important questions on the extent of applicability and generality of the basic problem of blast/fire interaction in isolated fuel beds flush with the shock approach path (i.e., no interference of after-shock flow with neighboring objects or terrain unevenness). The basic problem of simple, unobstructed, one-directional flame blowoff remains, but may be representative of only one class of extinction cases pertaining to one clear-cut extinction mechanism. Therefore, data generation was limited to the two fuels, hexane and methanol, each being a good representation of a class of fuels and together spanning a fair range of fuel properties and fire blast-extinction susceptibility.

The real behavior of fuels, in contrast to their idealized, expected behavior, was also noted and will have to be taken into account. Specifically, hexane and similar higher-molecular-weight fuels are, by nature, hard to contain in the pool configuration. The reason is physical and is unrelated to experimental care and technique. Because a fuel such as hexane gasifies vigorously, it supplies a great amount of fuel vapor for consumption in the flame. This dense fuel vapor penetrates laterally outward, away from fuel bed, and condenses on neighboring cooler surfaces. A tongue of the flame proper follows this spreading fuel pool, effectively increasing the fuel-bed area. This creeping flame fuels itself with more dense vapor leakage and condensation until the neighboring surface (in this case, the test stand housing the fuel bed) is too warm for vapor condensate to form. Such flame creep is known to occur even when pans or fuel containers with a considerable lip (even 1-inch high) are used. However, intervention to eliminate the fuel creep may lead to alteration of test conditions that could be more intrusive on the blast/fire extinction simulation than the fuel creep itself.

Other accumulated observations raise questions regarding fuel selection in the future: Are well-controllable, "well-behaved" fuels more appropriate for simulation efforts or are representative real fuels desirable? For example, in several tests with hexane, a significant number of droplets were generated, and a retreating flame or flashback was observed as a flame propagating through a droplet spray. The origin of the droplets is unclear. They may have been formed by blast wind shearing them off the fuel-bed surface, or they may have condensed from fuel vapor after shock passage. Whether such droplet production is a simulation deficiency or represents real behavior of liquid fuels under blast conditions may thus also be addressed in future fuel selection. Moreover, at present neither wind tunnel testing nor theory (similarity) provided any clear indication toward fuel selection. (Analytical efforts at Notre Dame and TRW were initiated in the second half of this contract period, but results are not yet available.)

Fuel Bed Scale and Position

The basic fuel bed was 35-1/2 inches long by 9-1/4 inches wide. With hexane (but not methanol), the effective fire base at shock firing (15 s preburn time) extended outward up to 5 inches on each side. However, the basic size is referred to as a 3-foot bed, and all such tests are classified in Appendix B as 3-foot bed lengths. Shorter bed lengths were constructed by covering the downstream 12 inches of bed length (for a 2-foot bed) and the downstream and upstream 12 inches of bed length for the basic (middle positioned) 1-foot bed. Steel plates were used for coverage and fuel creep was again observed, although to a lesser degree with the smaller fire sizes. It was assumed that the positioning of the augmented beds on the test stands (and with respect to the viewing ports) was not "a variable", i.e., did not significantly affect extinguishment. Although there is at present no indication that this is not so, some discrepancies were observed for hexane fires with the 9 1/2-inch barrier distance (they are discussed with Results).

Flow Barriers

The basic flow-perturbing obstacle used was a barrier spanning the width of the test stand, normal to the overall flow direction and parallel to the leading edge of the test stand. Simple barrier effect scaling was tried, keeping constant the ratio of barrier height to its upstream distance from fuel bed edge and assuming that fluid-mechanical barrier effects would be felt a certain multiple of barrier heights downstream. Although no correlation was observed, the effect of hexane fuel creep may have affected the correlation and may, similarly, have contributed to the lack of correlation at large (9-1/4-inch) barrier distance (see below). However, after primary flame blowoff, the role of any fuel vapor outside the fuel bed is unclear.

Two basic barrier distances were used: 3-1/4 inches and 9-1/4 inches upstream of the fuel bed edge. With 3-foot hexane beds, the fuel (and flame) creep would probably have effectively reduced the 3 1/4-inch distance to near zero at shock firing, judging from visual observation. For 1- and 2-foot beds and for the 9-1/4-inch barrier distance, the fuel does not necessarily creep all the way to the barrier (in no case did the fuel climb over the barrier).

We considered eliminating the fuel creep toward the barrier either by covering the area between fuel bed and barrier with a strip of inert material that would be removed just before blast arrival, or by preheating the surrounding surface. However, such intervention would change the test conditions somewhat (radiative shielding or preheating alter surface temperature between bed and barrier) and thus was not attempted in this year's effort.

Preburn Time and Initial Conditions

During the tests run in 1979, the preburn time (time interval from ignition to shock firing) used for class B fuels was 30 seconds. In these tests, the preburn time was shortened to 15 seconds for hexane, to limit excessive smoke and heat accumulation. The reduction of preburn time did not have any significant overall effect (at least in the absence of barriers). This agrees with expectation since fuel thermal inertia effects for hexane are small relative to flame heat output [i.e., a high mass transfer (B) number] and steady-state fire is reached quickly. For methanol, however, where fuel thermal inertia is larger relative to the flame heat output (or low B number), the longer (30 s) preburn time was used to obtain a well-developed pool fire.

Similarly, the initial temperature of the fuel and fuel bed was judged not crucial for hexane fires because it alters only slightly the vaporization rate (B number) and was not finely controlled. For such fuels as methanol, however, the initial fuel and bed temperature does matter. For the limited, first-order-of-magnitude tests run, a close control was not attempted. However, if future tests are done with low B number, large thermal inertia fuels, attention to initial thermal conditions and preburn time is warranted.

TEST PROCEDURE FOR CLASS B FUELS

The shocktube is prepared and the diaphragm is mounted (see "Shocktube Preparation"). The barrier (if any) is mounted, and the test bed Marinite board substrate is saturated with fuel. The Detasheet initiator is then attached and the unit is armed. For safety, the area is then secured and all subsequent steps are performed remotely.

When the plenum has been pressurized to the desired level, the fuel in the test bed is ignited with a propane pilot. After a predetermined preburn time, the test section is closed. At test section closure, the high speed camera is actuated and allowed $\approx$ 1.6 s to reach constant speed. At this time, the diaphragm is ruptured to initiate the shock.

The test section is monitored visually to determine whether or not extinguishment of the test bed fire occurs. If the flames are extinguished, the test section is opened. If the flames are not extinguished, the test section remains closed and is purged with $CO_2$.

## RESULTS

The basic quantitative results of these tests are the blast extinction overpressure thresholds, expressed as mean overpressure values measured at the test section. These threshold data are reported below, followed by supplemental diagnostic information obtained from phototransistor records. We then compile all the accompanying qualitative (visual) information. Although it is based on extensive, high-quality high-speed camera coverage (color), the synthesis and interpretation of the photographic material contains, necessarily, a certain amount of subjectivity. Moreover, it is based on events occurring in the field of visibility permitted by the (12-inch) viewing ports, with out-of-view events inferred.

### Extinction Thresholds

Figures 7 through 9 and Tables B.1 through B.3 and B.5 in Appendix B present all class B fuel test results. All these tests were done with short-duration pressure pulses. The integrated (mean) overpressure value for each test, as well as the pressure-integration time intervals and the actual positive-phase durations, are tabulated in Appendix B. Figures 7 through 9 present the hexane data exclusively.

Figure 7 contains data (both 1979 and 1980) on blast extinction of hexane fires with no barrier. The new data confirm the results of last year: the approximate threshold overpressure increases linearly with fuel-

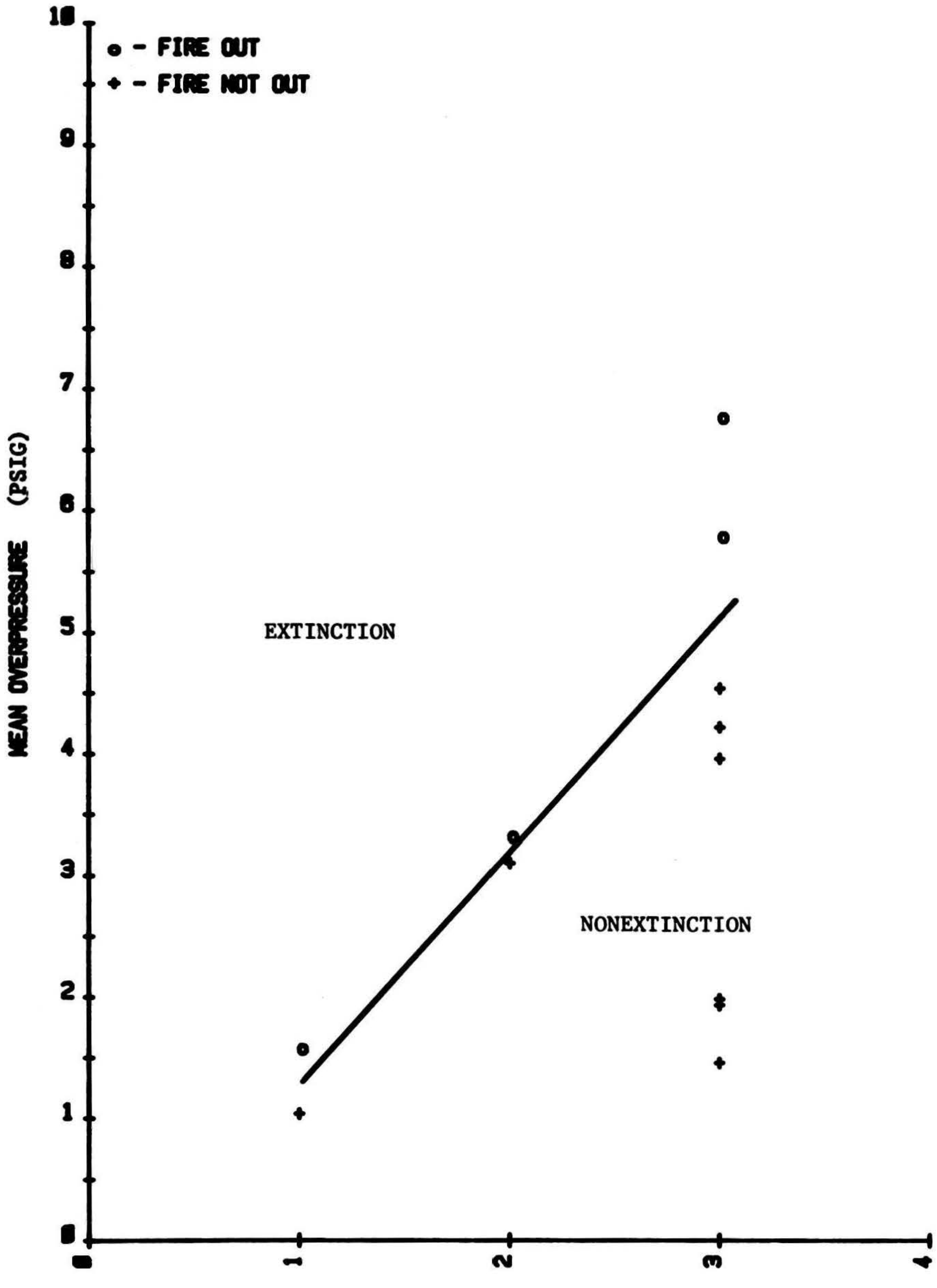


FIGURE 7 BLAST EXTINGUISHMENT OF n-HEXANE FIRES

bed length, at a rate of about 1.9 psi per foot of bed, from the lowest value at 1 foot (1.3 psi) to the highest at 3 feet (5.1 psi) of bed length. The critical ratio of particle displacement to fuel bed length increases from an estimated* 4.0 for a 1-foot bed to about 5.3 for a 3-foot bed, based on the average pressure-integration time interval of 62 ms (as used in calculating pressure thresholds). Reference 1 reports a critical particle displacement about six times the bed length; the lower ratio reported here stems from using essentially the main-pressure-plateau time period (62 ms) as $\Delta t$ rather than the full positive-phase-duration time period.

Table B.1 shows that 3-foot methanol fires were blast-extinguished at overpressure as low as 1.1 psi. Lower overpressures were not tested because, below 1 psi, the explosive charge for diaphragm rupture presents strong interference with such low blast strength, and any simulation is questionable.

Figure 8 shows data on blast extinction of hexane fires with a 1 3/4-inch high barrier located 3-1/4 inches upstream of the upstream fuel-bed edge. Tests were performed with 1-foot and 3-foot beds only (1-foot beds in the "middle position"). The data do not provide an unequivocal threshold at the 3-foot bed length because of data overlap: fire was both sustained at 6.4 psi and blown out at 6.16 psi (see Table B.2). If the lowest mean overpressure needed for fire blowout is taken as the threshold at the 3-foot bed length, the resultant threshold boundary is a line of the same slope as the extinction threshold line with no barriers (Figure 7), but displaced by 1 psi toward a higher overpressure at each bed length. In other words, this barrier configuration appears to cause systematic elevation by 1 psi in the critical overpressure level needed for permanent flame extinction.

The corresponding critical ratios of particle displacement to fuel-bed length are estimated at 8.0 for the 1-foot bed and 6.3 for the 3-foot

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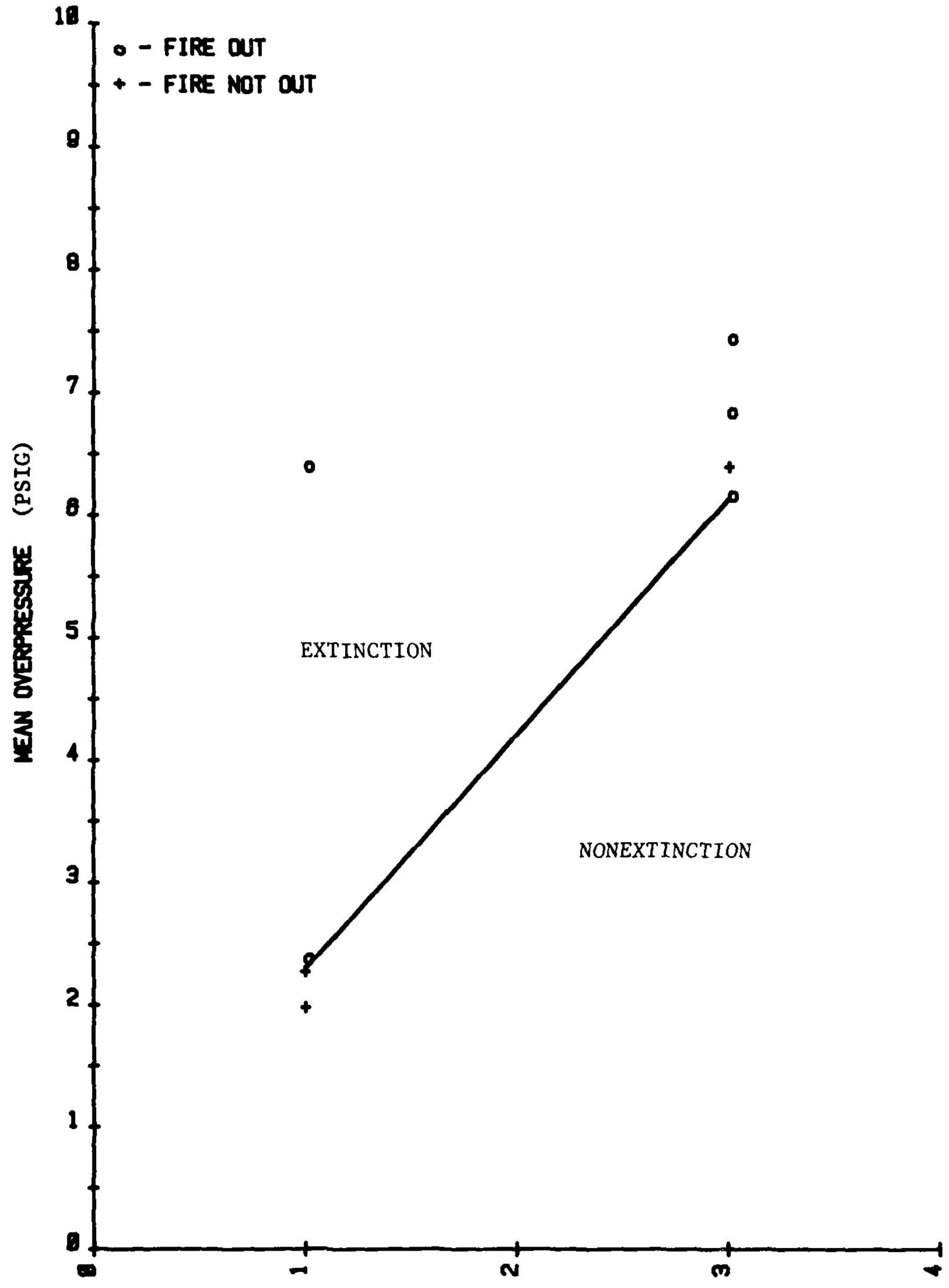
*The critical ratio of particle displacement to fuel-bed length is calculated from the threshold overpressure values and the average pressure-integration time of 62 ms (see Table B.1). The form of the particle displacement equation (Ref. 1) used here is $d_+(ft) = 50\ p\ (psi)\ \Delta t(s)$.




FUEL BED LENGTH (FEET)

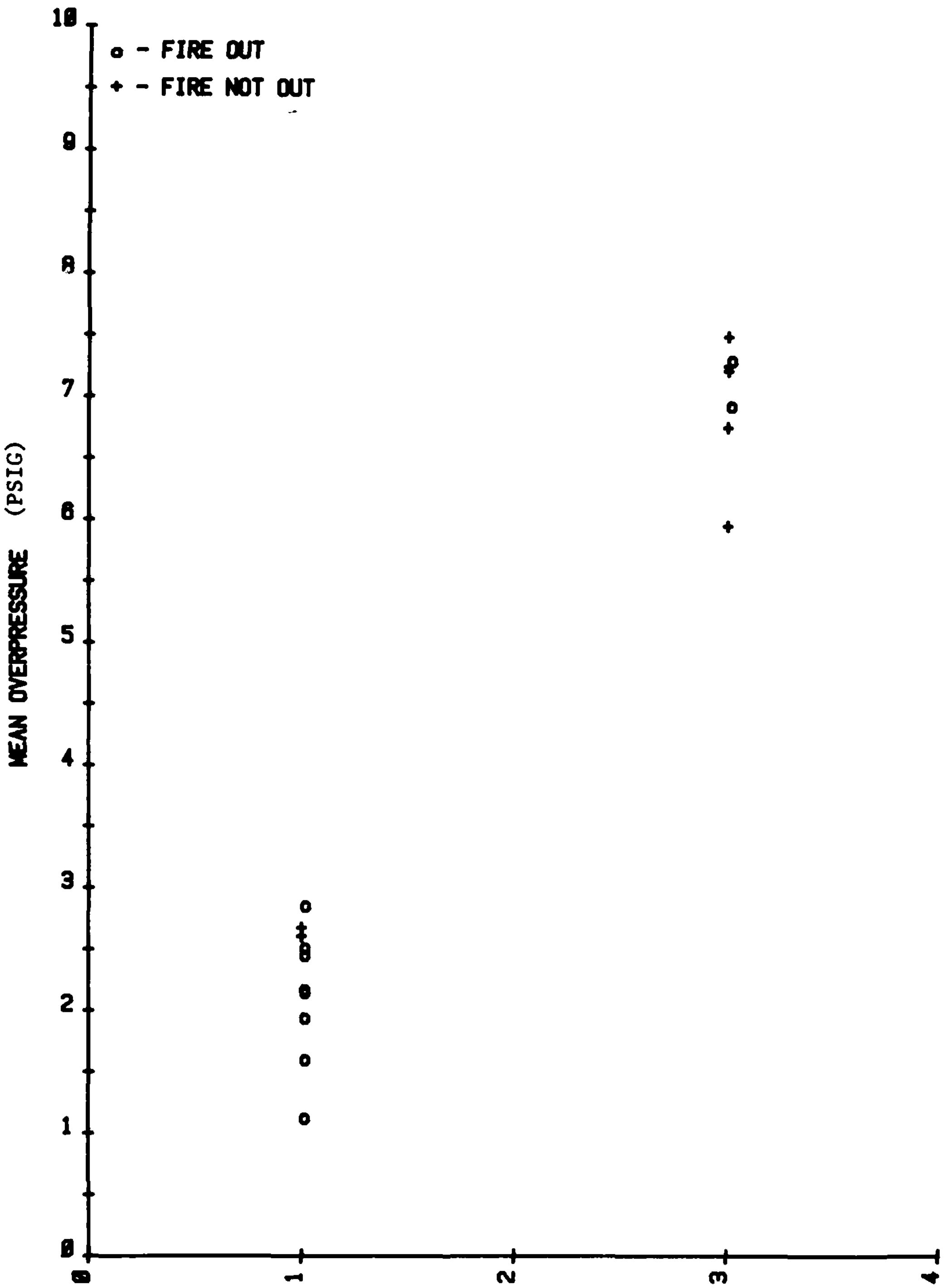
FIGURE 8 BLAST EXTINGUISHMENT OF n-HEXANE FIRES
WITH FLOW BARRIER AT 3-1/4 INCHES

bed, a 75% and 19% increase, respectively, relative to the case with no barrier. In other words, the additional 1 psi in threshold overpressure over the (average) integration time interval of 60 ms results in an additional 3 feet of critical particle displacement, which is equivalent to one bed length for the 3-foot bed, but equivalent to 3 bed lengths for the 1-foot bed.

The effect of the barrier thus is not independent of the bed length, as concerns scaling. As expected, the barrier configuration (height, distance, or both) needs to be related (scaled) fluid-mechanically with respect to the fuel bed or other scale, if small and large scales are to be physically similar. The present results suggest that larger relative shielding is provided (by the same barrier) to the smaller scale. This may be true if the effect of barriers persists, for example, to distances corresponding to a limited multiple of barrier heights downstream of the barrier. The observed mechanistic action of barriers is discussed later in this section.

Surprisingly, the data obtained for hexane fire extinction with the barrier located 9-1/4 inches upstream of the fuel bed are inconclusive. Figure 9 shows data for 17 tests, from which an approximate threshold could not be drawn. As Table B.3 documents for 1-foot bed lengths, both the forward 1-foot section and the middle 1-foot section were used, with the fuel bed position thus slightly changed relative to the test stand and the shocktube. Results were inconsistent from the two positions, whether considered separately or combined. Fire was extinguished in the middle-positioned 1-foot bed for overpressure as low as 1.1 psi. In the front position, two fires were sustained at $\sim$ 2.6 psi, but in two other tests, fires were extinguished at 2.5 and $\sim$ 2.2 psi, again not yielding a threshold.

Although this apparent sensitivity to some unidentified parameter defeated reproducibility, it is unlikely that the fuel-bed positioning would be implicated (although it cannot be ruled out). More likely, the geometrically and chronologically complex flowfield behind the barrier, together with the time-dependent chemical phenomena, may be too much affected by the shock, flow, and fire dynamics. The large




FUEL BED LENGTH (FEET)

FIGURE 9 BLAST EXTINGUISHMENT OF n-HEXANE FIRES WITH FLOW BARRIER AT 9-1/4 INCHES barrier distance may cause the fuel bed to be substantially out of the barrier "shadow" and eddy region and primarily in the complex, large-disturbance flow region downstream of the clearly separated region just after the barrier.*

Phototransistor Records

The main purpose of the phototransistor records was to determine, by direct optical detection, the actual magnitude of flame displacement by blast, and if possible, the rate at which flame displacement occurs. However, not all signals recorded can be interpreted in terms of flame blow-off pertaining to the actual extinction or reignition at the test bed.

Figure 10 illustrates some of the long- and short-term events observed with the phototransistor traces. The figure presents graphically the recorded existence of flame at the various detector locations, with the height of the bar indicating the signal duration. The bottom limit of the vertical bars indicates the first arrival of the flame (the flame "tip") at the given location. The rate of flame arrival at detector stations 1, 3, 5, 7, 9, and 10 occurs at a rate of about 435 ft/s, which is slightly higher than the estimated peak particle velocity of 335 ft/s in initially ambient air, corresponding to the given mean shock overpressure. This is possible because both the shock velocity and the peak particle velocity would be higher in the high-temperature flame gases than in initially ambient air.† Between stations 10, 12, 14, 16, and 19 the flame tip arrives at a speed of 250 ft/s, slightly lower than the peak particle velocity since overpressure particle velocity decreases: i.e., both the flame and flow decelerate. The average flame arrival velocity from station 1 to station 17, however, differs less than 10% from the peak particle velocity based on the mean overpressure. The flame-displacement magnitude in Figure 10 is seen to be more than 8 times the fuel-bed length (or a total of more than 25 ft).

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*Thus, there may be a large stochastic element in the outcome that is insufficiently sampled with the small number of tests represented here.

†Also, the average shock overpressure over the first 20 ms after shock would be higher than the overall, integrated, mean shock overpressure.

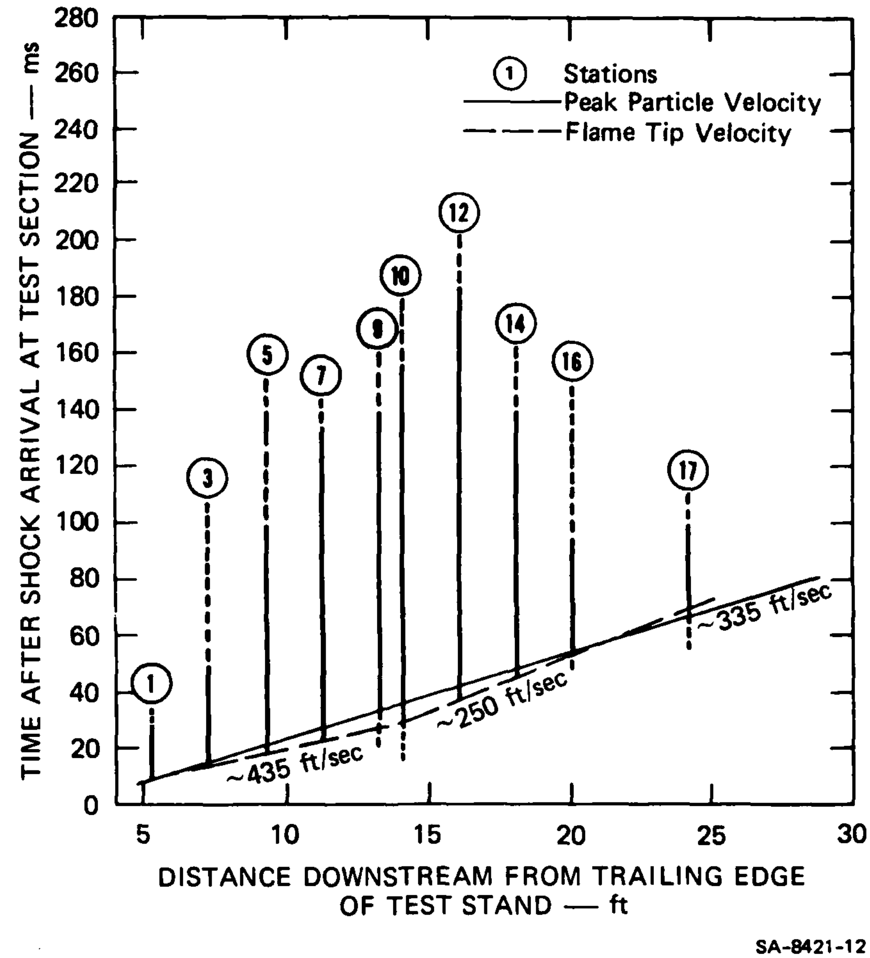


FIGURE 10 HISTORY OF FLAME PRESENCE DOWNSTREAM OF THE TEST SECTION, FROM PHOTOTRANSISTOR RECORDS

The long survival of the flame (e.g., 140 ms at station 12) observed between 8 and 18 feet downstream of the test section may not be peculiar to the degree of confinement of the shocktube gases. Fuel vapors swept downstream from the test section are available for combustion when they are mixed with hot products of combustion from the primary blown-off flame. The high degree of turbulence after shock visibly promotes combustion in the accelerated primary flame, as well as in the combustion waves sweeping the camera's view at later times in tests with no permanent extinction. These combustion waves also attest to the availability, downstream, of a significant volume of gas mixture within combustibility limits.

Although a detailed data reduction was not pursued for these optical records, the flame displacement traces of fires from 1-foot beds support the physical description offered above. In tests 58 and 59, for example, the flame blowoff speeds were about 167 and 133 ft/s, respectively. These speeds are 34% and 27% higher than the peak particle velocity (of initially ambient air) based on the average overpressure. The total flame displacement was about 10 feet.

As expected, there was very little optical output from the methanol flames.

## Film Records

In the hexane tests without barriers, the film records support the flame-displacement mechanism of blowoff and generally confirm the observations offered in Reference 1. The flame is cleanly swept off the fuel bed, trailing a blue and pink flame. Flame return in nonextinction cases typically occurs by flashback.

In tests with barriers, the primary flame is also effectively swept off, but it reignites in the eddy region behind the barrier. There, a sequence of chemical events seems to activate the eddy-entrained fluid (fuel vapor plus possibly some hot gases from the primary flame) to evolve through a clear-blue-flame stage to pink-flame and red-flame stages and finally to luminous yellow flame. These chemical events occur as the fluids rotate through the eddy, the residence time being typically 5-10 ms. Luminous reignition may not always occur in the first reacting eddy formed behind the barrier, because the first (blue or blue and pink) eddy may be displaced downstream without reaching the luminous stage. In this case, reignition occurs also in an immediately following reacting eddy formation; blue and pink flames then occur also along the visible fuel-bed section, and luminous flames arise along the fuel surface as well.

In cases of extinction, this eddy ignition process was not observed or was not distinctly discernible.

## DISCUSSION AND INTERPRETATION

The systematic study of hydrocarbon (hexane) fires showed significant resistance of moderate-size fires to short-duration airblast. Although on 1-foot beds the hexane fires were extinguished at about 1.5 psi mean shock overpressure, extinction on 3-foot beds required mean overpressures greater than 5 psi. The overpressure levels were found to increase uniformly (by 1 psi) for each fire size when a relatively small (1-3/4-inch high) flow-perturbing barrier was placed in the path of the blast near (3-1/4-inches upstream of) the fire.

Although many hydrocarbon fires would likely have similarly high extinction resistance to the short-duration airblasts, it is unclear what the level of resistance would be to longer-duration airblast. Notably, in the early shocktube tests[1] with long-duration pulses, the 3-foot hexane fires were blown out at overpressures down to the 1 psi level. It is similarly undetermined how effective the increased resistance provided by flow barriers would be for the long-duration airblast, although it is still expected to play a role and perhaps be even more significant.

Moreover, it is unclear how airblast blowout of fires on other fuels will compare with the relatively difficult blowout of liquid hydrocarbon fuels. Tests on methanol fires indicated high susceptibility to blowout for even the short-duration pulses. On 3-foot beds, the methanol fires were blown out even at 1.1 psi (mean overpressure, short-duration pulse) without a barrier, whereas with a barrier, the methanol fire was sustained at 1.1 psi but not higher. Hexane and methanol fires probably do not define the extremes of blowout resistance for all liquid fuels, but the range is already considerable. With analytical efforts being in their infancy, the behavior of other liquid fuels cannot at present be easily interpolated or extrapolated from the present data.

In general, the early indications and observation of flame blowout[1] have been borne out by systematic testing. Rapid flame displacement from the fuel bed occurs soon after shock arrival (in 5-10 ms over the 1-foot photographable section). In tests with barriers, this mechanism is augmented by the flow-perturbing effects of the barrier, providing for effective reignition of fuel vapors in the eddy just downstream of the barrier. In many tests, however, momentary (observed or inferred) flame absence from the fuel bed does not lead to permanent extinction; flame flashback is often observed. This is consistent with the observed large downstream displacement of the flame or at least the flame tip, which is 5 to 10 bed-lengths downstream of the fuel bed, depending on conditions.

Field tests will be needed to determine whether free-field air-blast produces similar displacements and permits comparable flame flashback, as observed in the shocktube for the short-duration pulses.* The single previous field test (MIXED COMPANY)[1] failed to produce flame displacement on any of the kerosene fuel beds of various sizes (down to 3-foot beds) at 1, 2, and 5 psi overpressures. The reason is thought to be degradation of the blast at ground level by the terrain.

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*Such liquid-fuel tests were recommended for inclusion in the 1981 MILL RACE event, but were eliminated in the budgetary process.

# CRIB FIRE EXTINGUISHMENT BY BLAST

## ROLE OF CRIB FIRES IN BLAST EFFECTS SIMULATION

Cross piles of wood, called wooden cribs, have often been used in laboratory experiments on fire behavior and fire suppression. Rather than representing models of real configurations, they are usually viewed in fire research as model arrangements offering a problem whose complication is between that of idealized, basic geometries and that of real structures. Moreover, they offer a convenient way of obtaining a controllable and repeatable fire and have served as well-defined source fires in studying fire dynamics in compartments or in studying extinguishment. A schematic of wood cribs used in the shocktube tests is shown in Figure 11. The arrangement of the crib in the shocktube is shown in Figure 12.

Although such cross piles of wood may be viewed as stylized representations of the debris field resulting from nuclear blast damage to a populated (urban) or unpopulated (forested) area, such close analogy was not explicitly made in our present investigation. Such cribs do represent a fuel arrangement that manifests self-sustained burning and, if not extinguished, a fuel load that presents a real fire hazard in buildings. Primarily, however, the crib fires were designed for exploring the upper limit of blast-extinction resistance of a fire of a commonly used material, such as wood, in an arrangement providing self-sustained burning. We have not prescribed the circumstances of ignition and blast arrival by associating these with any hypothetical weapon burst or set of target conditions. Studying crib fire blast extinction is then part of our attempt to identify the conditions characterizing fires that will survive the blast to pose a fire hazard after nuclear explosions. The following features of wood crib fires made them particularly suitable for our shocktube work:*

*The burning behavior of the wood crib fires used in the shocktube tests was determined in preliminary tests and is discussed in Appendix C.

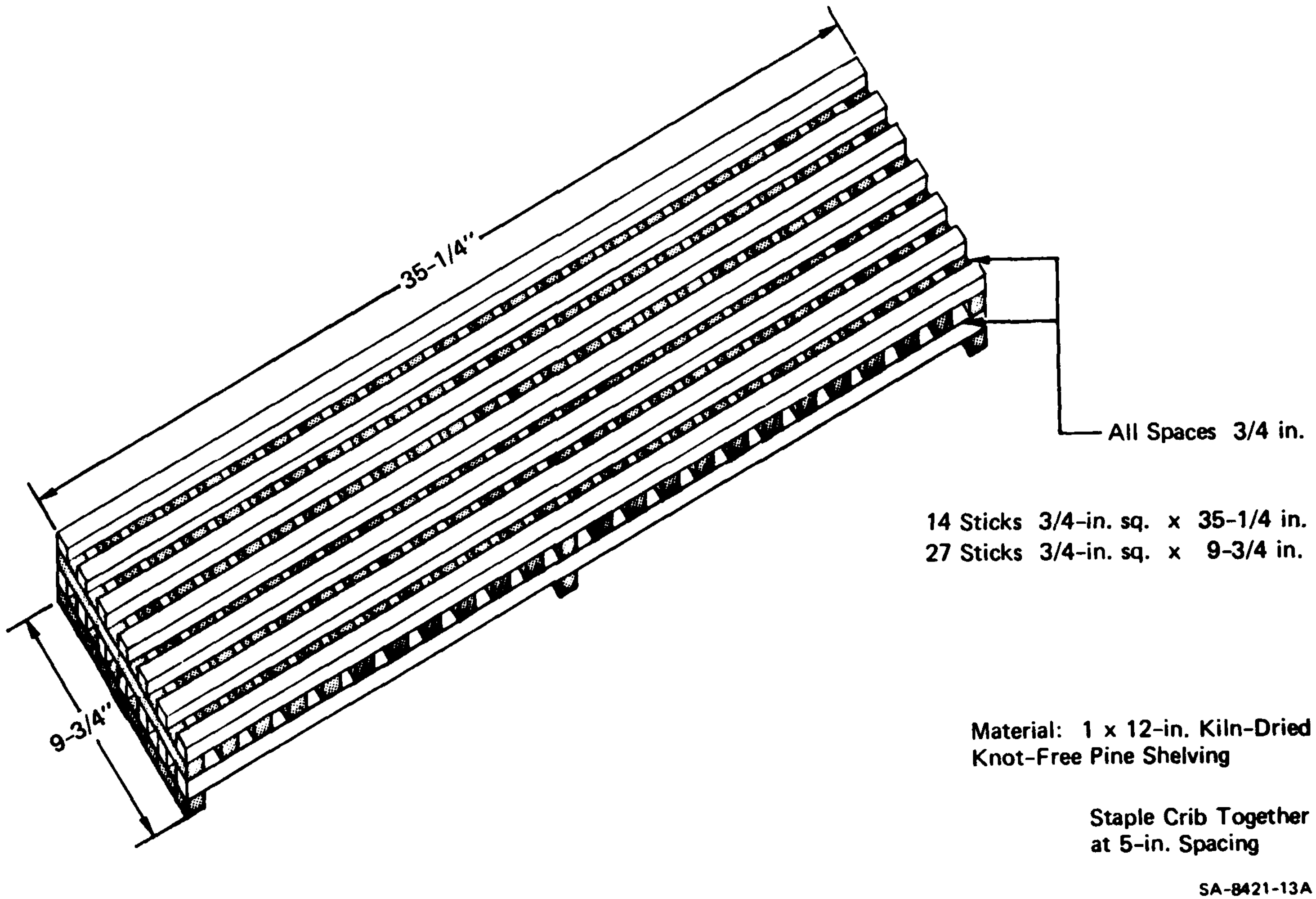


FIGURE 11 WOOD CRIB SPECIFICATIONS

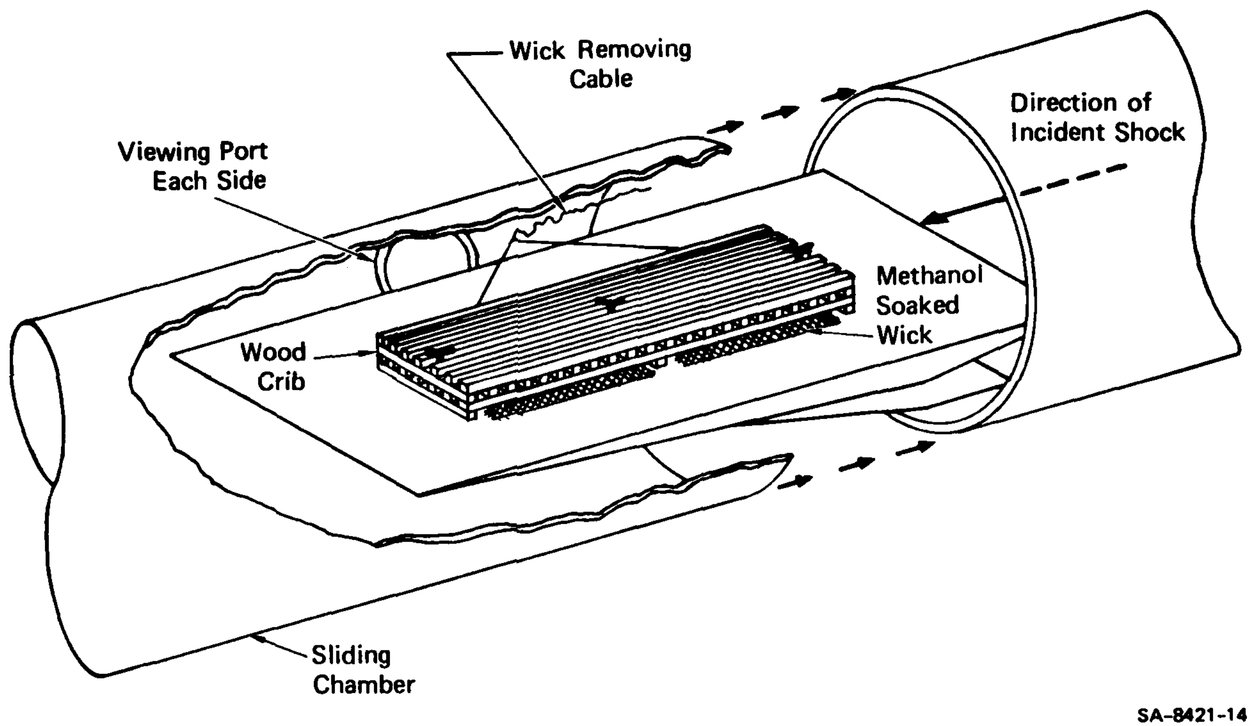


FIGURE 12 SHOCKTUBE TEST SECTION WITH CRIB, BEFORE IGNITION

- Ignition: reliable, repeatable fire start.
- Burning: self-sustained; steady over most of the flaming period; relatively reproducible and constant weight loss rate.
- Fuel: class A, common fuel of low volatility and char forming habit.
- Charring: char thermal inertia; potential for exothermic chemical reaction at surface after flame blow-off, leading to glowing combustion; potential for piloted reignition of volatiles by glowing embers.
- Geometry: major difference in importance of bulk of flame volume, which unlike in pool fires, does not significantly contribute to fuel weight loss; the layered grid structure offers resistance to airblast penetration and blowout of the important, internal flames.

A wood crib fire is mechanistically quite different from the liquid-fuel pool fires discussed previously. The qualitative differences stem from both fuel type and fuel bed geometry. Let us mention briefly what typifies crib burning.

Unlike for liquid pool fires, the flame above the top surface of the crib (referred to here as "top flame") seems to be unimportant in spreading or perpetuating the fire on the crib itself. McCarter and Broido[3] first suggested that the visually impressive flames above burning cribs are considerably less important to fire propagation than was previously assumed. They showed that the energy feedback from the top flames has little effect on volatile evolution and fire zone propagation in a steadily spreading fire in the crib.

Although concerned with fire propagation in cribs, McCarter and Broido's experiments yield an indication of the crucial feedback mechanisms in a steadily burning crib fire and the effect of elimination of the top flame. They examined the parameters affecting the steady, longitudinal flame spread in cribs* and noted that shielding the top surface of the unburnt part of crib from the advancing flame produced little or no decrease in the rate of fire spread. Similarly, when they quenched

*Knot-free, dry western hemlock cribs.

the top flame by $CO_2$ jets, they noted no effect on fire spread. In fact, the observation that the advancing fire front in cribs is vertically planar (with no accelerated spread near the top of crib) attests to the lack of significant energetic enhancement by the top flame. McCarter and Broido support their observations by results from a study on the influence of wind speed on a windblown fire, in which a leaning-over flame caused no increase in fire spread rate in the direction of wind.

The lack of thermal influence of the top flame is supported by studies of steadily burning cribs. Notably, Block,[4] reporting his results on steady, uniform burning of cribs, states that the burning rate is seen as controlling the flame height and not the height controlling the burning rate.

These observations agree with our results on burning of uniformly ignited cribs, obtained in our preliminary test-burning of candidate cribs (described in Appendix C). The purpose of this series of tests was to ascertain the effects of scale on the free burning of cribs. Namely, for the same crib construction (wood type, stick width and spacing, crib height and width, ignition sequence, and so on), we measured the effects on the specific* weight loss rate of increasing the crib length, and with it, the scale of the fire. Interestingly, although the flame volume+ increased, increasing its radiative power, there was no discernible trend in the specific crib mass loss rate. Thomas[5] also reported no effects of scale for 1- to 3-foot cubical cribs.‡ These observations seem to support the claim of the relative unimportance of the top flame to the fuel gasification and fire perpetuation in the crib. This qualitative understanding of the role of the top flame is useful in assigning significance to the blowout of the top flame by blast as compared with the blowout of internal flames and the glowing of embers.

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*Per unit crib length.

+Both flame length and height increased.

‡Thomas's cribs were made of 1-inch-square sticks, spaced 3 inches apart.

To complete the qualitative description of the burning of cribs, we refer to the explanation offered by Harmathy.[6] He stresses that the heat required for volatile evolution is transferred internally to the crib, i.e., within the crib volume, by flames and glowing embers within the crib volume. He points out that, with significant glowing present, the temperature of the internal crib surfaces is higher than the average temperature of the flames above. Consequently, the top flame acts merely to decrease the heat losses from the crib. The heat required for pyrolysis is supplied locally from the internal flames and embers to the component sticks by convection, radiation, and conduction. The rate of pyrolysis is determined by these short-range, high-intensity heat fluxes within the crib volume. The residual effect of these fluxes (thermal inertia) or the persistence of their sources after blast (internal flames or embers) is therefore important for continued volatile production after blast to maintain or reestablish flaming. Thus, the strong thermal interactions within the crib matrix characterize crib burning and, directly or indirectly, crib fire extinction.

The above discussion concerns primarily fully developed, steady-state fires. Nevertheless, the importance of heat fluxes within the crib volume for volatile production starts, in the present test procedure, with ignition. The crib is ignited by a propanol source fire. An alcohol-saturated wick is placed underneath the crib, ignited, and allowed to burn for a predetermined time period (60 seconds). During this period, the alcohol flames bathe the crib underside and the crib interior, protruding above the top crib surface, at most, 15 cm. This traditional choice of ignition arrangement is intended to achieve speedy, full, self-sustained involvement of the crib, minimizing the transient period of weight loss; this, in turn, is achieved by early involvement of the crib interior, which establishes the dominant, interior heat fluxes and results in early onset of the steady weight loss regime. Thus, the crib-interior heat transfer controls the crib mass loss, even in the initial phase of burning. Significantly, when the crib sides start flaming, there is no noticeable increase in the mass loss rate even though some small increase would be expected from its combustible contribution. Essentially the side sticks, lacking the strong multiple heat feedback available in the interior and incurring, moreover, losses to the surroundings, contribute less than the sticks in the crib interior. C nsequently, the involvement of crib side surfaces was not considered important for the present, shocktube application.

The role of the depicted mechanisms controlling sustained crib ignition and burning needs to be clarified in connection with combined nuclear effects, although the present experiments are not intended to directly simulate the thermal-pulse-ignition/blast-extinction sequence of events after a nuclear burst. A wooden crib such as discussed here (Figure 11) is unlikely to experience direct radiant ignition followed by sustained burning, although it will char heavily on exposed surfaces under high fluence. Many studies indicate that in the region lying outside the approximately 20-psi overpressure contour, the free-field thermal fluence will often be insufficient to cause sustained burning of thermally thick fuels (although transient flaming may occur). However, within about the 1 to 2-psi contour, thermally thin fuels (such as papers, rags, leaves, and pine needles) are likely to be ignited and act as potential kindling fuels for involving thicker materials.

Based on the stick dimensions, the crib used in our experiments would be classified (in relation to exposure durations of thermal pulses from nuclear fireballs) as an array of thermally thick fuel elements. However, the exposed, irradiated stick surfaces will lose heat to the surroundings, thus acting (with respect to radiant ignition) as virtually isolated thermally thick elements. The exposed crib sticks will not sustain fire, because there are no opposite facing surfaces to provide multiple thermal interactions (which is the key to sustained burning of piles of wood). Therefore, it is likely that only indirect ignition, such as by kindling fuels, will provide for sustained burning and that sustained burning will, of necessity, involve ignition of the crib interior. Thus, it may be argued that the present (ignition) methodology does not exclude any potentially significant crib fires, because any sustained crib fire requires significant involvement of the crib interior. The present focus is then on the after-blast behavior of a well-defined crib fire with ignition and burning of the crib interior.

## Role of Char and Volatiles in Crib Fires

The role of char in crib burning is not yet well quantified. Harmathy[6] suggests that significant char involvement begins even during the period of active flaming. Figure 13 (taken from Harmathy) typical weight loss curve for a crib compared with Harmathy's model of the partition between the weight loss due to volatile evolution and char oxidation. After an initial transient period of increasing weight loss rate, when the crib weight has decresed to about 0.8 $G_o$ ($G_o$ being its initial weight), the weight loss rate becomes constant until the mass drops to about 0.3 $G_o$. Harmathy suggests that the constancy of the weight loss rate during this period is mainly a result of constancy of the rate of volatile evolution and that char oxidation contributes likewise a small but steady weight loss. His model represents the crib weight loss as a sum* of the two steady weight loss rates, due to volatiles and char, assuming that crib weight loss started effectively some time after ignition and that the char oxidation period is longer than the period of significant volatile production (essentially flaming combustion). Harmathy's argument for the mechanism of burning and his weight loss model is given as follows:

> Fed by air entering the pile, a glowing layer of char at a temperature of about 1000°C develops along the surfaces of wood pieces. The heat released by the oxidation of char (and, to a lesser extent, by volatiles burning inside the pile) and trapped within the pile by the large internal surface areas acts as the factor regulating the rate of volatile evolution. Since the rate of char oxidation depends on the airflow into the pile, which is steady, a steady volatile evolution rate results.

This argument, however, assumes that air entering the crib reaches the char and that char oxidation is responsible for char weight loss. It implies that the char reaches temperature of 1000°C (or some such high value) fairly quickly and that a roughly constant net glowing area or number of embers exists thereafter. This counters intuition and experience, which suggest that the char is only slowly heated and that the volume of embers increases with time as the flow of volatiles diminishes.

*As can be seen from Figure 13, Harmathy assumes that 12.8% of crib mass will be consumed as char, while the rest will leave as volatiles.

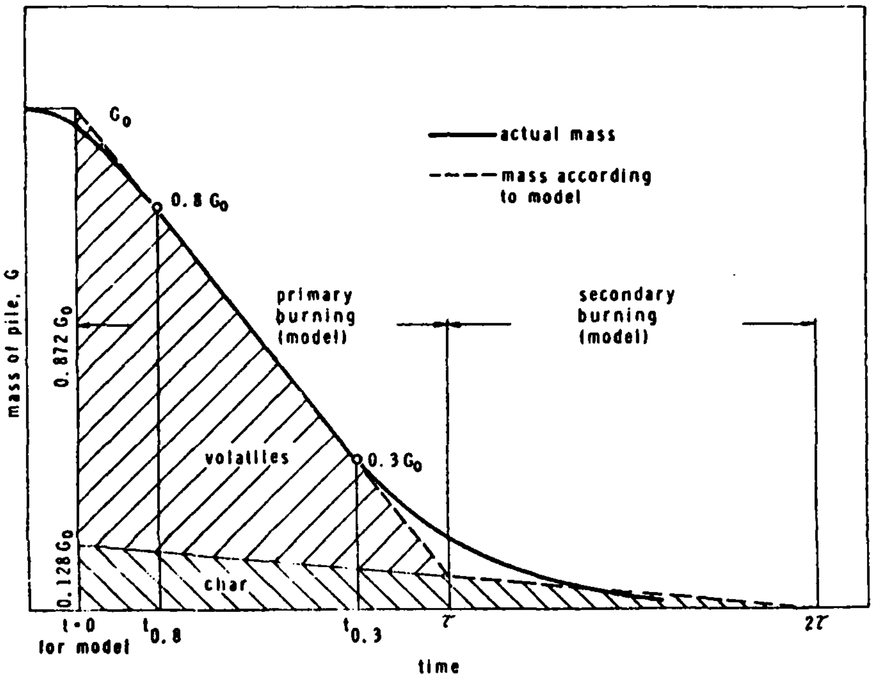


FIG. 13 CHANGE OF WEIGHT OF BURNING WOOD PILE
(Harmathy, Ref. 6)

In the experiments of McCarter and Broido,[3] which measured total radiation of the burning cribs, the attainment of a steady-state radiant power output of the crib fire appeared closely linked to the attainment of a steady-state volume of embers. They note, however, that the steady-state radiation did not coincide with attainment of a steady fire propagation rate, but lagged behind by an interval of 2 to 10 minutes.

In our preliminary crib burns, we have made a similar observation. A radiometer, encompassing in its view the whole crib fire (ignited uniformly), showed radiant flux still increasing 1.5 to 2 minutes after the onset of constant weight loss rate and constant height and luminosity (visual note) of the flame above the top crib surface.

It is possible, however, that significant char weight loss takes place even during the period of high rate of evolution of volatiles (i.e., flaming) but not primarily by oxidation by air, as suggested by Harmathy. Chemical reactions between char and volatiles may occur as the volatiles diffuse through the char, as they flow out through the cracks, or as they move up along and bathe the char surface. Both $CO_2$ and $H_2O$ are important products of pyrolysis and may react to oxidize the char endothermically without the necessity for $O_2$ from air. Thus, during flaming, the air oxidation of char may be prevented fluid-mechanically, by volatiles driving oxygen away from char surface, and chemically, by volatiles competing with char for $O_2$(flame) or with $O_2$ for char (char-volatile surface reactions). Therefore, while possibly reacting chemically, the char may not contribute much as a source of heat for the production of volatiles, especially during intense volatilization.

The char, however, can act as a heat sink (an insulator) and effectively limit the rate of production of volatiles, especially in the later stages of burning. The insulating effect of char has been studied primarily for isolated wooden cylinders, sticks, or planks, with external heat addition if the fuel element was thick and would not otherwise sustain burning or if pyrolysis only was intended.

Kung[7] demonstrates by the use of an analytical model of wood pyrolysis that, in the case of wood boards pyrolyzing under constant external radiant flux, an early period of increasing mass loss rate is followed by steady or declining rate of mass loss, depending on the thickness of the board and char properties (primarily conductivity). He suggests that, as the pyrolysis zone moves inside the wood board, the pyrolysis process is soon impeded by the buildup of the insulating char. Moreover, as the volatiles move through the char, they further remove heat as they leave the surface, reducing pyrolysis. According to Kung then, the net pyrolysis rate is a result of the competition between the accumulated preheat of the virgin wood (which decreases as wood thickness increases) and the impeding effects of char insulation and char cooling by volatiles.

This concept appears to translate directly to crib burning. Thomas[5] reports that, for cribs of wood sticks 1-inch square, the burning rate is constant over approximately three-fourths of the burning time, whereas for 2- and 3-inch square wood, the rate of burning decreases more markedly with time after an initial maximum rate has been reached. He ascribes this to the competition between the increasing heat flux and wood preheat and the increasing insulating effect of the char. With thicker wood elements, the increasing char depth together with the higher conduction losses (lower wood preheat) result in a shorter period near the maximum weight-loss rate.

It appears, therefore, that the stick dimension (3/4-inch-square) in the cribs that we have used (see Figure 11) is such that constant volatile evolution results from the balance of several factors within each fuel element. This constant evolution yields a steady heat feedback upon reaction. Since Thomas[5] obtained a steady crib fire with 1-inch sticks and Fons[8] reports a steadily spreading fire with ½-inch sticks, the steady burning of our 3/4-inch stick cribs is well-supported.

PRELIMINARY TESTS IN SHOCKTUBE

The first three crib fire tests were exploratory and were conducted before the series of free-burning crib tests (Appendix C), i.e., before crib design and ignition were reexamined and finalized. Consequently, the exploratory tests (67-69, see Table B.5) will be described only briefly and qualitatively here; all results and discussions following this section concern the shocktube tests with the standardized cribs (see Table B.4).

The first three tests (67-69) yielded some general observations. The stick spacing was too small to provide ample ventilation for the crib interior, slowing down fire development. However, the close stick spacing and corresponding dense crib construction did not appear to impede the flame blow-off immediately after blast arrival. In tests 67 and 68, this resulted in permanent fire extinguishment. In test 69, a very long preburn time was allowed (15 minutes). At that time, glowing embers were present and were, moreover, enhanced for some time after blast arrival. Flame reappearance was observed in the vicinity of embers or immediately above crib top surface after blast. Some early flamelets were blown out by blast wind of still large velocity, but ultimately the air velocity decreased sufficiently for flames to persist.

Although the above tests pointed out the need for redesigning the cribs to permit practical, shorter preburn times, they did indicate the longer time scale needed for cross piles of wood to achieve full fire involvement with fire-perpetuating active embers (compared with our later results). Moreover, they demonstrated clearly the dual nature of blast/fire interaction in case of a charring material such as wood.

## TEST PROCEDURE FOR CRIB FIRES

The following sequence of events constituted a normal test of blast extinction of a crib fire in the shocktube.

(1) The shocktube is prepared and the diaphragm is mounted (see Shocktube Preparation in the Experimental Approach section).

(2) The crib is weighed and mounted in the shocktube as shown in Figure 12.

(3) The wick is saturated with propyl alcohol ($\sim$ 300 ml) and placed under the crib. The cables for wick removal are attached. The premises are closed off.

(4) Either the short driver section of the shocktube alone or with the tank is pressurized to the desired plenum pressure.

(5) A short pilot-flame pulse (propane jet flame) ignites the alcohol on the wick, marking ignition time (time zero).

(6) Approximately 2.5 s before the end of the desired preburn time, the telescoping section is closed remotely (~ 1 s the camera is started and accelerated to full framing speed (~ 1.6 s), and the shock is fired by diaphragm rupture.

(7) In the case of crib fire extinction (determined visually as no flame present), the telescoping section is opened immediately and the crib is examined for glowing embers. The crib is removed and weighed (the final crib weight is typically obtained within 1 minute after shock).

In the case of no extinction (flaming persists), the telescopic section is kept closed, and a $CO_2$ extinguisher with its nozzle inside the shocktube is used to extintinguish the fire (usually within 5-10 s). The final crib weight is then obtained 1 to 1.5 minutes after blast.

## RESULTS

### Extinction Thresholds

The primary, quantitative results relate the observed fire extinction thresholds, in terms of the magnitude of the appropriate blast parameter, to the fire conditions and vice versa. A map of extinction/nonextinction cases results is shown in Figures 14 and 15; each point, representing the intersection of a blast and a fire condition, corresponds to a single test. Both the blast and the fire conditions are independently variable, with extinction or nonextinction being the outcome determined by a given pair of conditions. The extinction criterion was taken as permanent extinction of flaming on the crib, whether or not smoldering char combustion persisted. All the quantitative results in this section are restricted to the white pine cribs with the standardized design* shown in Figure 11. Tests were done with both short and long positive phase duration pulses; the former comprise all but three tests while the latter were three essentially exploratory tests. Figures 14 and 15 contain data for short-duration pulses only.

*all cribs used were 3-feet long.

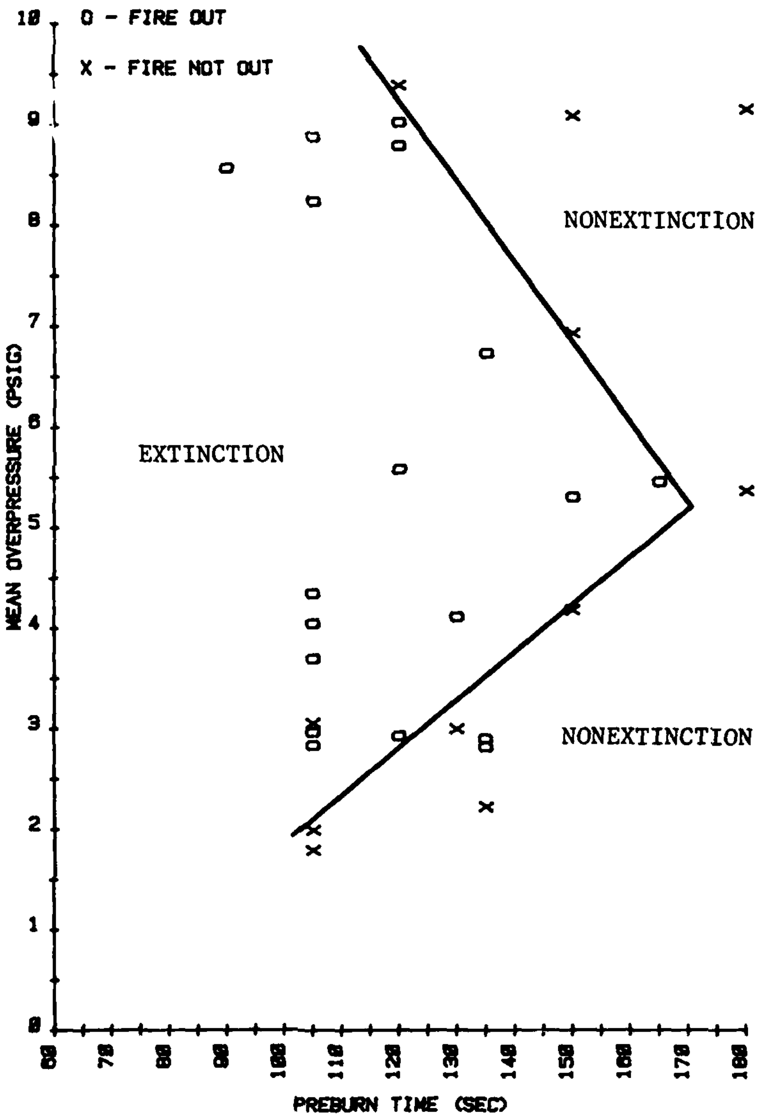


FIGURE 14 BLAST EXTINGUISHMENT OF CRIB FIRES, BASED ON PREBURN TIME

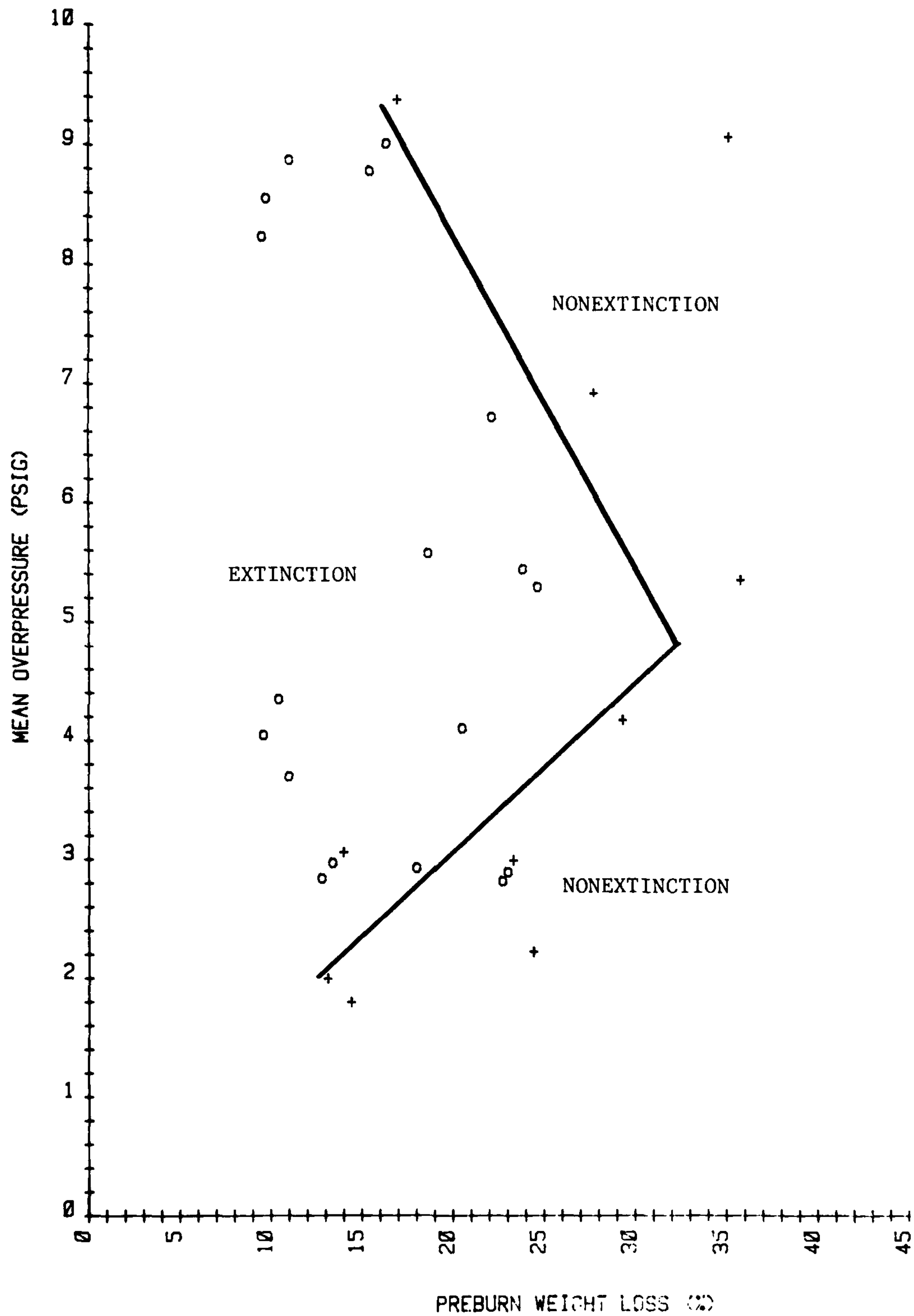


FIGURE 15 BLAST EXTINGUISHMENT OF CRIB FIRES, BASED ON PREBURN WEIGHT LOSS

Short Positive-Phase Duration Airblast. Figure 14 uses an average, time-integrated overpressure value as measured at the test section for the blast variable (ordinate) and the crib preburn time as the fire variable (abscissa). A wedge-shaped region in the figure appears to encompass the extinguished cases. In other words, there does not appear to be a single threshold, as for class B fuels, separating the blast extinguished cases from those that were not extinguished. Instead, there is a curved boundary separating the apparent extinction and non-extinction domains. Two straight lines have been used to roughly separate the two domains.

Figure 14 suggests that, for a given preburn time, the overpressure required for extinction is not a unique function. That is, for each preburn time between about 100 and 700s, there appear to be two extinction thresholds: a first, lower threshold such that, for a blast of an (averaged) overpressure greater than the lower threshold, the fire is put out permanently; and a second, higher threshold such that, for a blast with an overpressure greater than the threshold, the fire persists.

This double-valued threshold was unexpected. It differs both from our experiences with class B (liquid) fuels, where a given fire has only one extinction overpressure threshold, and from such studies as Tramontini and Dahl's,[9] where a unique "blast" property (the maximum air velocity) determined extinction thresholds of various forest-fuel beds. These differences and the suspected underlying causes of the special crib fire behavior under blast will be discussed later.

Since exact reproducibility of burning is hard to achieve during the preburn time period, another representation of crib fire condition, the percent weight loss attained at shock arrival, is also used as a coordinate for the extinction map, Figure 15. The extinction threshold contour appears as a knee-shaped curve, bounding all cases of blast-extinguished fires.

In Figure 14 there appear two "fire-out" points at 135 s preburn time that lie below the approximate (lower) threshold curve and a "fire-not-out" point at 105 s that lies within the extinction region. These data bring up two considerations concerning the extinction thresholds and the overpressures associated with them. First, the magnitude of the overpressure averaged over the positive phase duration may not be the ideal blast parameter for the fire extinction. When a better (controlling) parameter is available, a more clearcut division between the extinction and nonextinction regions may appear. Second, even if such a successful extinction correlation is devised, the threshold may still be fuzzy due to phenomena that are more or less probabilistic (such as turbulence) and due to the complexity of the fuel (charring) and fuel arrangement (ensemble of sticks). This complexity introduces unrecognized or uncontrollable fire variables, in addition to any nonsystematic variations in the imposed airblast.

For the cases where fire was not blast extinguished, the percent weight loss at shock arrival was slightly less than Figure 15 indicates because only the final weight measurement after manual extinction is available. However, because this extinguishment was typically accomplished within 5 s, the additional weight loss is estimated to be about 1%.*

Long Positive-Phase Duration Airblast. Although the positive phase duration was not one of the blast parameters extensively studied in this year's effort, it was desirable to check briefly the effect of long duration airblast on crib fires to see whether our understanding extends qualitatively to such cases or whether the behavior is markedly different. Such long-pulse cases are important because at low overpressure values, near 2 psi, real airblasts from surface or low airbursts of nuclear weapons yield greater than about 16 kilotons of energy are characterized by positive-phase durations of 1 second or more.

Specifically, three tests were run for pairs of overpressure/preburn time values below the lower threshold found for short-pulse blasts (Figure 14) and for which the short-pulse blasts would therefore not be expected to cause extinction. Repeated extinction below that threshold

*Except in tests 91 and 92 where after-test extinction was less rapid. (Test 91 is not plotted in Figure 15.)

in the case of the long pulses would alert us to the possible cumulative consequences of prolonged heat and removal of volatiles from the crib by the blast wind.

The long-pulse data correspond to tests 122, 123, and 124 (Table B.4). The crib fires were not permanently extinguished. In fact, visual indication is that the longer-duration low-overpressure blast promotes refanning of the crib, enhancing char glowing and speedy re-establishment of vigorous crib flaming. (The pressure records for the three tests are given in Figure 5.)

Phototransistor Records

Three optical sensors were used to check the motion of the flame in the direction of shock propagation (downstream) or opposite (upstream). Sensors were located 5.3 and 6.3 ft downstream of the tail end of the crib and 5.3 ft upstream of the front end of the crib. Due to lower fuel pyrolysis rate (gasification) for the crib material (wood) as compared with hexane, the flame mobility or persistence of luminosity of bulk flame after blowoff was expected to be low, or in any case lower than for hexane. Therefore, the sensors were positioned as close as possible to the test section (but far enough so that they would not be damaged during the preburn period).

The displaced flames were detected only by the downstream sensors. Flame presence at the 5.3 ft downstream distance, starting between 21 and 37 ms after shock firing (depending on overpressure) was detected in 5 out of 18 tests. This indicated the primary flame displacement immediately after shock; the flame is blown off the crib, but not necessarily completely. There appears to be no correspondence between the shock magnitude (overpressure) and the signal of flame presence or passage at the 5.3 ft downstream distance. Both large ($\sim$ 9 psi) overpressures and small ( $\sim$ 3.0 psi) shocks can have large primary-blowoff signal, suggesting passage of bulk of the flame, but can also have no signal at all. There are a few signals at times longer than 50 ms after shock firing at both 5.3 and 6.3 ft downstream but, in connection with high-speed camera coverage, these are considered unlikely to be flames and may be flying embers only. Only in Tests 92 and 93 can the large signals at both downstream locations (at 90 and 240 ms, respectively) be considered possible secondary flame blowoff, although films do not directly support that.

The optical sensors have, in the case of crib fires, little consistent and significant output. However, they thereby clearly demonstrate the local nature of flame blowoff in crib fires. The bulk of flaming gases of a crib fire have less unburnt fuel vapor and hence less mobility (or earlier loss of luminosity) upon blowoff than flames from a hydrocarbon pool fire. Were it not for firebrands, the crib fires would have a restricted range of influence as potential fire hazard as pilot flames. However, the production of firebrands by blast, although not a subject of this report, is demonstrable and will be discussed along with the high-speed camera records.

## Film Records and Visual Observation

As was the case with class B fuels, the high-framing-rate camera coverage provided much necessary detailed information. Although limited to viewing the middle 1-foot section of the crib from the side (there is a partial view of the transverse, interior crib stick surfaces) it provides for examination of the after-blast sequence of events on a time scale of 1 ms or less.

The film coverage of crib extinguishment provides a fairly unified and consistent picture that can be chronologically compared with the pressure records. Just after the shock, the "top" flame (above the crib) is swept off cleanly in 5 to 10 ms, depending on the overpressure. The internal crib flames persist a bit longer at the lower overpressures, but are typically all blown out by 20 ms after shock. For short preburn times ( $\lesssim$ 105 s), there is little glowing just after flame blowoff, with proportionately more glowing for the higher preburn times. Glowing intensification begins with or shortly after the onset of the pressure (and velocity) plateau, peaking in the last third of the pressure plateau (between about 40 and 60 ms after shock). Both large preburn time and large overpressure (air velocity) cause the most glowing; especially in nonextinction cases above the second threshold (overpressure > 5 psi), the glowing is very intense. In test 113, with 3 minutes preburn and 5.4 psi shock, the whole crib outline is made visible by the glow.

As the pressure begins to decrease after the end of the pressure plateau, the glowing decreases significantly and, in cases when reignition occurs, it occurs typically by flashback during the rapid pressure decline near the end of the positive-phase duration. The flame flashback often occurs along the bottom crib surface, but has also been observed to occur along the top surface or as a combustion front propagating upstream through the crib volume. The flashback flame appears to propagate easily through the gas phase. Generally there is an indication of generous amounts of volatiles for combustion in the vicinity of the crib or within the crib volume as pressure and velocity decrease.

Since the downstream one-third of the crib is not directly observable, it is not known whether a residual flame initiates the flashback. At the downstream end of the crib, the flow wake would enhance both flame retention and flame reignition from volatiles as air velocity decreases. However, for low overpressure blast ($\sim$ 2 psi) such as in tests 121, 103, and 104 there is indication of tail-end flame retention. Although there was continued volatile evolution from the cribs, the glowing, even when enhanced, was probably too dim or spotty to alone cause reignition in these tests, and flashback from wake-retained flame is credible.

Isolated reignition of volatiles has also been observed (near the center of the crib). Both isolated flamelets, such as formed from volatiles issuing from a crack in the wood stick, and luminous volatiles reignited in an eddy have been observed, but typically these isolated ignitions do not survive and the crib is reignited by a combustion wave spreading through the volatiles in or near the crib matrix.

## DISCUSSION AND INTERPRETATION

The observed conditions for permanent blast extinction of flaming combustion on wooden cribs have been described above. The two overpressure thresholds found have been described, and the increased participation of the solid phase (char) combustion at high airflow rates was suggested as a probable cause of the second threshold.

It is expected that there is a third airblast threshold of higher overpressure and blast wind velocity, above which the smoldering reaction (primarily carbon oxidation) cannot keep up with convective cooling, and even glowing is extinguished. Although it has not been experimentally determined for the crib fires, an experiment conducted by Vulis[10] reports the extinction point of burning carbon. He heated ohmically a rod of electrode carbon to dark red incandescence, after which he directed on the rod an air jet. He reports that, even after the electric current was disconnected, intense combustion started on the carbon surface for a certain airblast velocity and continued to increase with increasing air velocity; its temperature approached theoretical (maximum burning temperature). However, Vulis states that:

> ...a sharp, practically instantaneous, extinction occurred as still higher velocities were reached (of the order of 220 to 250 m/sec); a section of the carbon surface being blasted directly by the air jet darkened instantly and became dark from a dazzling white; the temperature of this section dropped from 2000°K to between 500 and 700°K. Conversely, as the air-jet velocity was subsequently reduced, the combustion of the carbon rod, being continued at a certain distance from the place being blasted directly by the jet, again spread to the dimmed section and a sharp, clearly observable ignition occurred.

This early experiment by Vulis falls into the category of extinction problems where the combustion rate, kinetically controlled, is increased to its maximum and extinction occurs when the cooling rate overcomes the combustion heat release rate. The air velocity threshold reported by Vulis corresponds, by peak particle velocity, to 19.4 to 23 psi. Since the extinction process is not truly instantaneous (and the actual blast velocity would decrease from peak to some lower value in that time), the approximate blast extinction would occur at some value over 20 psi.

Previously, Tramontini and Dahl[9] conducted experiments on blast extinction of forest fuels. Ignition was effected with an intense radiant source (although at a somewhat lower source temperature than that of the nuclear fireball), and their airblast simulation, although it included a shock and brief overpressure, focused on the air velocity and duration characteristics of airblast waves. Overpressures were not maintained throughout the period of blowdown flow as they are in the Camp Parks facility.

Because of the substantially different thermal properties of the fuel arrangements used by Tranmontini and Dahl, only gross similarities and differences will be noted. In both studies, the (lower, in our case) extinction thresholds increased with the preburn time. Their fuel elements were much thinner and the preburn times needed were much shorter ($\sim$ 5 s). All of their fuels, except punky wood, were approaching uniform temperature throughout the thickness of each burning fuel element just before blast arrival. Based on preburn time, the square roots of the Fourier numbers (Fo) for each fuel element were 1.5 for pine needles, 8.9 for newsprint, 3.6 for madrone leaves, and 2 or greater for cheetgrass, i.e., all were thermally thin to greater or lesser extent. Only punky wood, which failed to achieve sustained burning even without blast, had $(Fo)^{1/2}$ less than 1, estimated at $\sim$ 0.08. The individual sticks of the wooden cribs used in our study were thermally thick, with $(Fo)^{1/2} < 1$ even with 3 minutes of preburn time. The large difference in thermal state of the fuels, as well as the difficulty of judging the overall thermal state of the Tramontini and Dahl fuel arrays (as compared with the individual thin fuel elements), makes comparisons in extinction thresholds difficult. One large qualitative difference is presented by the multiple-valued extinction threshold observed for cribs, in particular the second, higher threshold for which no counterpart is yet known for the thinner fuels.

Tramontini and Dahl also studied the effect of airflow duration on the velocity extinction threshold and found that the threshold decreased linearly with flow duration. This dependence has not been systematically studied in this year's experimental work and is planned for future tests. Three tests were made (see 122, 123, 124 in Table B.4) with positive-phase durations from 1.4 to 4.0 s and mean overpressures below the lower extinction threshold, but no effect of increased duration was observed. Fires were not put out, and the longer lasting airflow only intensified the crib fire during blowdown. However, these limited tests do not rule out the effect of long blast durations, which must be addressed.

# CONCLUSIONS AND RECOMMENDATIONS

The processes involved in the extinction of fire by air blast waves and other perturbing effects associated with the interactions are complex in the extreme. Gaining a sufficient understanding of the complexities to permit the development of engineering methods for dealing with the practical problems will require a well-coordinated, multifaceted technical approach. The experimental work to date has been largely exploration. We regard this report as a concluding point in the exploratory phase of the program. It shows the rough outlines of this previously unexplored territory and identifies, at least in a preliminary way, some of the important factors and their interdependencies in the following four parameter categories:

- Airblast characteristics
- Fuel properties
- Scale effects (fire size parameters)
- Target configuration (including the modifying effects of surroundings on the character of the air blast).

The program should now proceed to develop these preliminary findings, concepts, and relationships into reliable, generally applicable engineering tools. To accomplish this in timely fashion will require concerted effort directed along several convergent, mutually supportive paths. Specifically, we recommend the following:

(1) Continue to improve simulation capability. Incorporation of the SAI-designed thermal source as an accessory to the Camp Parks facility should substantially enhance the simulation of the combined processes of fire initiation/extinction. Quantitative flow diagnostics are needed. A modest investment in a more convenient system for changing the duration of the overpressure pulse would soon pay for itself in the increased experimental output made possible by the reduced turnaround time between tests.

(2) Pursue several lines of research concurrently. The ongoing, concurrent efforts in experiment and theory are beginning to show promise for similitude development, and should be continued. More frequent interaction

between the experimenters and theoreticians should be encouraged, possibly formalized. In addition, however, there should be two distinct lines of experimental activity, one applied, the other fundamental. The recent decision by DNA to reactivate its program in fire effects enhances the prospects for joint and complementary efforts of this sort that can have serendipitous consequences for both agencies.

(3) The applied research should seek early answers to practical questions. With the incorporation of a successful thermal radiation accessory to the Camp Parks facility, we can begin testing a variety of representative urban and wildland targets under conditions that essentially duplicate actual nuclear-attack situations. The nearly infinite variety of configurational parameters (i.e., target geometries in combination with different surroundings) precludes testing exhaustively the spectrum of practical situations. Nevertheless, we recommend that practical "shading" rules* and barrier-effect scaling be determined, to give some general information on the effect of our three-dimensional world on blast resistance of fires. A few medium size, representative problems may then guide the intuition in fire assessment modeling. Shocktube experiments, combined with analytical models and aided by basic phenomenological research supported by DNA may then provide practical order-of-magnitude judgment. Such "rules of thumb" could be immensely valuable as interim aids in emergency planning for civil defense.

(4) The basic phenomenological research should be directed at the evolution of similarity principles. This recommendation is broad and necessarily vague at this stage in the research. However, we can recognize several potentially rewarding avenues as a result of our exploratory work, and it will be helpful to structure discussion of this final recommendation in terms of the four parameter categories that we have already addressed.

Airblast Characteristics. At the heart of this research, and critical to the planning for it, lies the question: Is this dynamic problem basically different from the much studied quasi-static one? And along with this key question come several corollaries involving the importance

*As, for example, the following: A 1-foot high wall or pile of debris may shield from extinction, on the windward side, $\underline{x}$ ft of fuel A for a 5 psi blast and $\underline{y}$ ft of fuel A for a 10 psi blast.

of pressure, shock, and pressure/flow decay. To date, we have focused experimental attention on overpressure as characteristic of the intensity (or strength) of the airblast wave. Positive-phase duration has not yet been systematically studied and other properties, such as impulse and dynamic pressure, have been virtually ignored. Similarly, in the theoretical approaches taken to date, quasi-static mechanisms of extinction, which are characterized by critical airflow velocity thresholds, have been the basic premises, with no more justification than scientific intuition and the reasonable view that simple things should be tried first to avoid unnecessary complexity. The importance of the dynamics--the shock and abrupt onset of intense flow, the slower (but still rapid) decay of both air velocity and overpressure--are totally unevaluated at present. An experimental determination of the validity of the quasi-static premise has been proposed as a part of a complementary DNA-funded study, which is planned to be conducted in the Camp Parks Blast/Fire Facility concurrently with further FEMA-sponsored testing.

The resolution of this critical issue, with highly idealized experiments, would greatly enhance the utility of, but not eliminate the necessity for, conducting blast extinction tests on realistic fuels as described in recommendation (3). If the quasi-static premise were shown to be valid, however, simpler, less expensive simulation techniques could readily replace the shocktube.

Fuel Properties. Class A fuels are generally considered the ones of greatest concern in nuclear weapon fire damage, but class B fuels, which are also commonly found in potential urban targets, will continue to be of interest in this research because, in addition to the relative ease with which fuel variables (e.g., combustion revelant properties) can be identified and quantified, and lacking the troublesome complications of solids that pyrolyze and char, a systematic study of their properties compared with their differences in behavior can lead to a fundamental understanding of the mechanics of airblast suppression, which may be quite as relevant to class A as to class B fuels. The basic phenomenological study proposed for DNA sponsorship emphasizes gaseous and liquid fuels and should limit its initial focus to this class of fuels. The companion analytical projects funded by FEMA would help plan and interpret the results and use them to test their hypotheses regarding the fluid mechanical/chemical mechanisms of blast extinction of the basic, volatilizing (class B) fuels.

Scale Effects. When considering scale effects, we must recognize both the inherent effects of scale on the free-burning properties of fires and the extent to which the scale of the fire (fuel bed extent, flame volume) alters the blast/fire interactions. The former has been extensively studied and need only be applied and incorporated into the test rationale. The latter, however, has not been studied, and the shocktube and field tests (e.g., MIXED COMPANY) represent initial efforts with only tentative results. It would appear that the fire size compatible with the Camp Parks shocktube is fairly limited. Although it is true that energy release considerations would practically limit the flame volume for controlled preblast free burning of fuels inside the shocktube, the shocktube, due to its ample length (200 ft), would theoretically permit great exaggeration of the key dimension for flame displacement, that is, in the direction of blast propagation. At some stage in the experimental and analytical work, such partial (one-dimensional) scale modeling may be conceptually supportable and may be suitable for testing in the shocktube.

In the short run, the limited fire scale variation of 1-3 feet in routine tests (extendable perhaps to the full 5-foot length of the test stand), together with the basic parameter study planned for the DNA work, should provide preliminary verification of analytical models including effects of scale. The accurate characterization of airblast as well as fuel parameters should probably be achieved before extending the capability of the shocktube to model more extensive scale effects.

Target Configuration. This point has already been mentioned in the discussion of recommendation (3). Its successful resolution seems to call for greater experimental ingenuity and analytical insight than any other part of the problem. Our experiments planned for the MILL

RACE event are designed to provide an initial assessment of the effect of angle of incidence of the airblast to the burning target surface. Other factors, addressed here, are associated with perturbations in the airblast caused by interactions with surroundings, such as a barrier in the line of advance to the target.

It is reasonable to suppose that a degraded airblast, whose energy has been dissipated through viscous shear and turbulence, is [illegible] effective in blowing out fires. Such degradations may result from airblast approach over rough, dissipative terrain and through the geometrically complex urban environment. The unexpected results obtained at MIXED COMPANY (where kerosene beds as short as 3 feet resisted extinction even at 5 psi) were tentatively explained as resulting from shock degradation near the terrain surface. It may be that flow-perturbing effects of the fire surroundings would, in a real instance, outweigh the effects of fuel type and fire scale. In such a modified flowfield, localized fluid mechanical features such as wakes and eddies behind structures and obstacles (or behind or under debris) may stabilize the flames in essentially the same manner as flameholders do, until the blast wind subsides and the fire re-establishes itself.

We recommend continuation of the work on barrier-effect studies on class B fuels that was started during the project reported here. Close liaison between our experimental findings and the analytical efforts at Notre Dame and TRW can reasonably be expected to bear fruit in the near term.

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## Appendix A

## WORK PLAN

## WORK PLAN

### A. Preliminaries

1. Some exploratory investigations are planned, using a laboratory-scale wind tunnel, to guide the selection of fuels for use in the shocktube. Liquid and possibly gas fuels with wide ranges of potentially pertinent properties (such as flame speed, mass transfer number) will be observed in the wind tunnel for flame extinguishment thresholds under steady and nonsteady flow. Those fuel properties causing a significantly different flame behavior in the wind tunnel may be desirable to be represented in a range of values in the fuels used in the shocktube.

2. For testing of class A fuels, effective methods of igniting and maintaining a steady flame over the whole (flat) surface will be improved or developed. Innovative methods will be designed without recourse to the SAI radiant heat source and may be different for different types of fuels. Nonporous solid fuels may be ignited by a thin liquid film (of, e.g., acetone), while for porous fuels more sophisticated ignition means may be developed (e.g., powders, solid alcohol).

3. During last year's shocktube tests at or near the extinguishment limit for hexane flames, a recursive, upstream and downstream motion of the flame on or downstream of the fuel bed was observed. Parts of this "struggle" of the flame to remain at or return to its original position above the fuel bed were observable through the port hole viewing a section of the fuel bed. The photographic records at this observation station show flame behavior of some complexity and time-variability (changes in flame color and radiant intensity, flame shape, scale of turbulence within the flame), but also yield simple and important features like flame speed and acceleration, as

well as indicating visible extinguishment. While the visible, photographable events at the observable section of the fuel bed will continue to yield indispensable information, photo-optical techniques are being introduced to record the motion and behavior (e.g., sketching) of the flame beyond the test section. These techniques are designed to record flame presence (and optical intensity) by probes at preselected stations downstream of the test section. The high time-resolution of the probes should provide accurate data on the downstream motion in both extinguishment and threshold cases.

4. Development of other diagnostics at or downstream of the test section is planned. The aim is to increase the quantitative and qualitative information on the shock/flame interaction for various shock and flame (fuel) properties and to record or control--for reproducibility--the actual flame conditions just before shock arrival at flame. Our understanding would be furthered by knowledge of the after-shock flow, within or outside of the flame, and of the reflected rarefaction and compression waves resulting from the shock-flame interaction. The planned inclusion of more complex fuel geometries and flow barriers (tasks B and D) would especially benefit from the closer inspection of the flame/shock/flow interaction to which these diagnostics would contribute. Some of the diagnostics that will be investigated are the following:

   - Pressure and flow measurements at or downstream of the test section are planned. The after-shock flow is affected by but not directly discernible from the flame motion, yet it is a necessary input for any companion theoretical effort (which will be difficult enough even without calculating this intermediate result, especially for more complex geometries).
   - Shadowgraphs have had much successful application in shock-tube work and may prove a useful application in this program. They may yield helpful qualitative understanding of shock/flame interaction and of the shock structure downstream of a barrier just before shock impingement on the flame. Reproducibility may also be ascertainable (qualitatively) by shadowgraphs.
   - Particle velocity ahead of or within flame is an important feature as concerns extinguishment, and if time permits, diagnostics will be developed for its evaluation. Streak

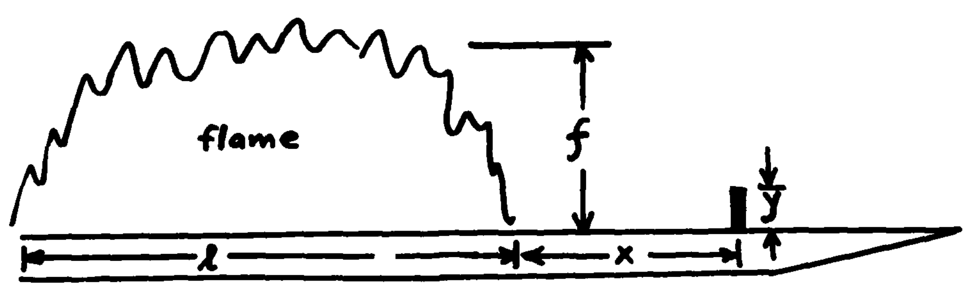
photographs may be obtained with the high-speed camera viewing the test section, with smoke (or other visible) pulses injected upstream of the test section. Barrier effects and aftershock turbulence may also be deduced from such observed streak lines.

- In the case of class A fuels, which may not reach steady-state burning or may not reach it at burning times practical for the shocktube tests, diagnostics will be developed to control the preburn times (i.e., shock firing) to ensure reproducibility and knowledge of burning conditions just before shock arrival. To this end, burning rate measurements (weight loss) or fuel temperature measurements are considered.

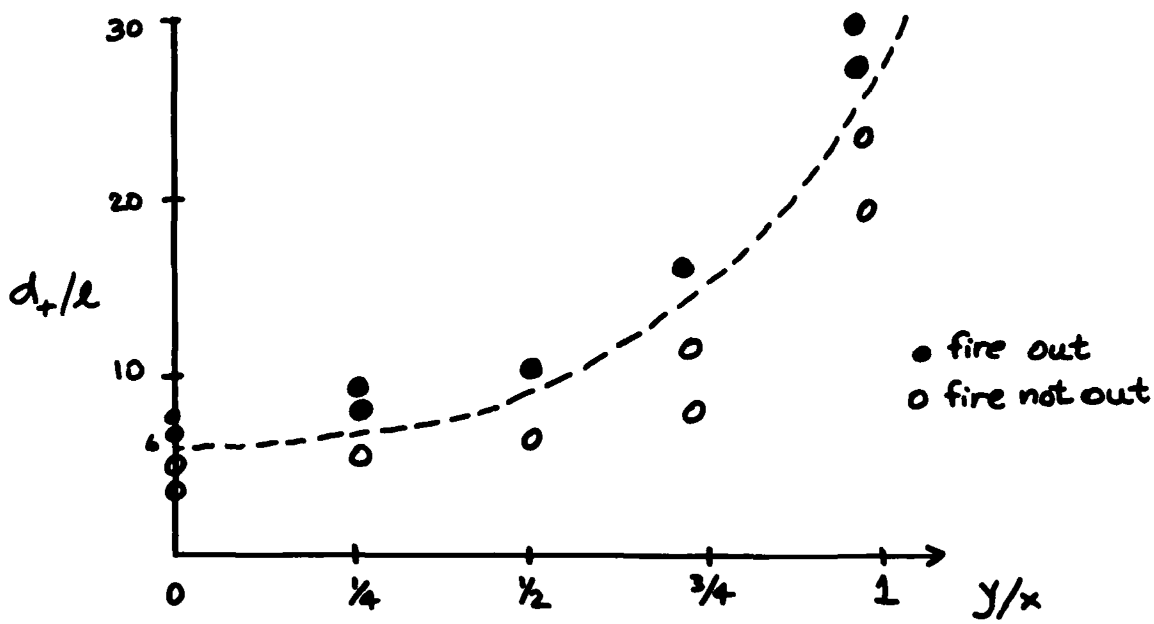
B. Effects of Barriers

1. Exploratory tests in the shocktube are planned for one fuel (hexane on Kaowool substrate) to get a feel for the effect and feasibility to determine extinguishment thresholds in the presence of a barrier upstream of the fuel bed.

2. The barrier effect will be quantified with suitable extinction criteria and key barrier/flame/shock parameters. The barrier parameters may be barrier height/distance of barrier upstream from fuel bed, (y/x); barrier height/flame height, (y/f); barrier height/fuel bed length, (y/ℓ).



The found threshold values are anticipated to relate to, e.g., the barrier parameter (y/x) as shown below.




C. Effects of Fuel Properties

1. Exploratory runs will be made in the shocktube (without barrier) using methanol and possibly other fuel(s). Selection of fuels (through key properties) will be based on empirical findings of their (non-steady flow) extinguishment in the wind tunnel (subtask A.1) and on predictions by Spalding theory (for steady flow). Fuel properties such as flame speed may prove to be important, and fuels with high flame speed (e.g., acetylene) may prove useful at testing such a concept (parameter) of extinguishment.

2. If results warrant it, determination of barrier effects will be repeated in the shocktube, obtaining, e.g., $d_+/\ell$ versus y/x relationship for methanol; thresholds will be compared to hexane results with barriers.

3. Additional fuels will be considered; other liquid fuels, some quasi-class-A solid fuels such as PMMA, or a charring solid such as wood. Fuel bed with considerable surface roughness may be considered if time permits. (As is the case with barrier effects or complex fuel configurations, surface roughness may be a source of flame-stabilizing turbulence.)

D. Effects of Fuel Configuration

1. Fuel geometries with some degree of complexity will be explored in the shocktube for extreme extinguishment conditions. In other words, we will take an exploratory look at what is a hard-to-blow-out fuel and configuration, and what peak overpressures and overpressure durations are needed for extinguishment. Well-established crib fires may be such candidate fires for class-A fuels; other fires (fuels/fuel configurations) will be designed and explored to select the (realistic) extreme hard case.

2. We will develop a reproducible "hard case" situation (e.g., in terms of weight loss or burning rate for crib fires) at shock arrival and determine extinguishment thresholds as was done for hexane. Comparisons will be made with limiting, extreme barrier effects (task B).

# Appendix B

## SHOCKTUBE TESTS - DATA COMPILATION

Table B.1

CLASS-B FUEL TESTS - NO BARRIER

| Test No. | Fuel | Bed Length (inches) | Preburn Time (s) | Mean Over-pressure (psi) | Positive Phase Duration (ms)[a] | Observation |
|---|---|---|---|---|---|---|
| 21[b] | n-Hexane | 36 | 30 | 6.77 | 172 (65) | Fire out |
| 22[b] | n-Hexane | 36 | 30 | 4.55 | 170 (60) | Fire sustained |
| 20[b] | n-Hexane | 36 | 30 | 4.23 | 170 (66) | Fire sustained |
| 19[b] | n-Hexane | 36 | 30 | 1.99 | 170 (60) | Fire sustained |
| 33 | n-Hexane | 36 | 15 | 5.79 | 115 (58) | Fire out |
| 34 | n-Hexane | 36 | 15 | 3.97 | 115 (63) | Fire sustained |
| 35 | n-Hexane | 36 | 15 | 1.94 | 100 (60) | Fire sustained |
| 36 | n-Hexane | 36 | 15 | 1.46 | 90 (60) | Fire sustained |
| 23[b] | n-Hexane | 24 | 30 | 3.11 | 150 (65) | Fire sustained |
| 24[b] | n-Hexane | 24 | 20 | 3.32 | 145 (59) | Fire out |
| 25[b] | n-Hexane | 12 | 20 | 1.57 | 110 (62) | Fire out |
| 26[b] | n-Hexane | 12 | 20 | 1.04 | 70 (68) | Fire sustained |
| 37 | Methanol | 36 | 15 | 3.3 | 77 (55) | Fire out |
| 38 | Methanol | 36 | 30 | 1.4 | 68 (62) | Fire out |
| 40 | Methanol | 36 | 30 | 1.1 | 68 (61) | Fire out |

[a]Numbers in parentheses represent the time over which pressure was averaged.

[b]Tests completed in 1979 and reported in Reference 1.

Table B.2

CLASS-B FUEL TESTS - Barrier Distance = 3.25 inches
Barrier Height = 1.75 inches

| Test No. | Fuel | Bed Length (inches) | Preburn Time (s) | Mean Over-Pressure (psi) | Positive Phase Duration (ms)[a] | Observation |
|---|---|---|---|---|---|---|
| 44 | n-Hexane | 36 | 15 | 7.44 | 120 (61) | Fire out |
| 45 | n-Hexane | 36 | 15 | 6.4 | 120 (60) | Fire sustained |
| 46 | n-Hexane | 36 | 15 | 6.84 | 122 (60) | Fire out |
| 55 | n-Hexane | 36 | 15 | 6.16 | 119 (58) | Fire out |
| 54 | n-Hexane | 12 | 15 | 6.39 | 95 (57) | Fire out |
| 58 | n-Hexane | 12 | 15 | 2.37 | 78 (58) | Fire out |
| 59 | n-Hexane | 12 | 15 | 1.98 | 94 (58) | Fire sustained |
| 60 | n-Hexane | 12 | 15 | 2.27 | 98 (61) | Fire sustained |
| 41 | Methanol | 36 | 30 | 1.1 | 68 (61) | Fire sustained |
| 42 | Methanol | 36 | 30 | 2.4 | 68 (57) | Fire out |
| 43 | Methanol | 36 | 30 | 1.7 | 68 (58) | Fire out |

[a]Numbers in parentheses represent the time over which pressure was averaged.

Table B.3

CLASS B FUEL TESTS - Barrier Distance = 9.25 inches
Barrier Height = 1.75 inches

| Test No. | Fuel | Bed Length (inches) | Preburn Time (s) | Mean Over-Pressure (psi) | Positive Phase Duration (ms)[a] | Observation |
|---|---|---|---|---|---|---|
| 47 | n-Hexane | 36 | 15 | 5.96 | 100 (60) | Fire sustained |
| 49 | n-Hexane | 36 | 15 | 7.26 | 110 (60) | Fire sustained |
| 50 | n-Hexane | 36 | 15 | 7.3 | 120 (62) | Fire out |
| 52 | n-Hexane | 36 | 15 | 7.5 | 100 (60) | Fire sustained |
| 56 | n-Hexane | 36 | 15 | 6.76 | 100 (60) | Fire sustained |
| 57 | n-Hexane | 36 | 15 | 6.93 | 118 (60) | Fire out |
| 76 | n-Hexane | 36 | 15 | 7.22 | 100 (58) | Fire sustained |
| 61 | n-Hexane | 12(M)[b] | 15 | 2.45 | 80 (57) | Fire out |
| 62 | n-Hexane | 12(M) | 15 | 1.94 | 72 (56) | Fire out |
| 63 | n-Hexane | 12(M) | 15 | 1.60 | 73 (56) | Fire out |
| 64 | n-Hexane | 12(M) | 15 | 1.12 | 71 (58) | Fire out |
| 108 | n-Hexane | 12(M) | 15 | 2.17 | 93 (58) | Fire out |
| 77 | n-Hexane | 12(F)[c] | 15 | 2.68 | 78 (57) | Fire sustained |
| 79 | n-Hexane | 12(F) | 15 | 2.61 | 82 (57) | Fire sustained |
| 80 | n-Hexane | 12(F) | 15 | 2.85 | 74 (56) | Fire out |
| 109 | n-Hexane | 12(F) | 15 | 2.51 | 93 (57) | Fire out |
| 110 | n-Hexane | 12(F) | 15 | 2.15 | 93 (58) | Fire out |

[a]Numbers in parentheses represent the time over which the pressure was averaged.

[b](M) means the middle position; i.e., the middle 1-foot section of the basic 3-foot bed was used as the fuel bed.

[c](F) means the front position; i.e., the front (upstream) 1-foot section was used as the fuel bed.

Table B.4

WOOD CRIB TESTS

| Test No. | Preburn Time (s) | Estimated wt. loss (%) | Mean Over-pressure (psi) | Positive Phase Duration (ms)[a] | Observation |
|---|---|---|---|---|---|
| 89 | 90 | 9.5 | 8.56 | 93 (64) | Fire out |
| 90 | 120 | 16.1 | 9.02 | 93 (58) | Fire out |
| 91 | 180 | – | 9.14 | 95 (58) | Fire sustained |
| 92 | 150 | (35.0) | 9.08 | 103 (56) | Fire sustained |
| 93 | 120 | (16.9) | 9.39 | 103 (56) | Fire sustained (flame flashback) |
| 94 | 105 | 9.3 | 8.24 | 95 (56) | Fire out (crib burned poorly) |
| 95 | 105 | 10.8 | 8.88 | 95 (56) | Fire out |
| 96 | 120 | 15.2 | 8.79 | 95 (58) | Fire out |
| 97 | 105 | 9.4 | 4.05 | 85 (57) | Fire out (crib burned poorly) (bad diaphram rupture) |
| 98 | 105 | (14.0) | 3.06 | 117 (57) | Fire sustained |
| 100 | 105 | 10.8 | 3.7 | 81 (57) | Fire out (crib glows after test) |
| 101 | 105 | 10.2 | 4.35 | 83 (56) | Fire out (crib glows brightly) |
| 102 | 105 | 12.6 | 2.84 | 80 (56) | Fire out (no glow visible) |
| 103 | 105 | (14.4) | 1.80 | 73 (56) | Fire sustained |
| 104 | 105 | (13.1) | 2.0 | 72 (57) | Fire sustained |
| 105 | 105 | 13.2 | 2.97 | 78 (57) | Fire out (crib glows brightly) |
| 106 | 120 | 17.8 | 2.93 | 103 (57) | Fire out (crib glows after test) |
| 107 | 135 | 22.8 | 2.9 | 103 (56) | Fire out (crib close to relighting) |
| 111 | 120 | 18.4 | 5.58 | 85 (53) | Fire out (crib glows after test) |
| 112 | 150 | 24.4 | 5.3 | 83 (56) | Fire out/but relighted after door opened ∿ 15 sec |
| 113 | 180 | (35.7) | 5.36 | 81 (56) | Fire sustained |
| 114 | 150 | (27.7) | 6.93 | 98 (56) | Fire sustained |
| 115 | 165 | 23.6 | 5.45 | 95 (57) | Fire out/but relighted after removal |
| 116 | 135 | 21.9 | 6.73 | 82 (57) | Fire out (crib glows after test) |
| 117 | 150 | (29.3) | 4.18 | 83 (57) | Fire sustained |
| 118 | 130 | 20.3 | 4.11 | 83 (60) | Fire out/but close to relighting |
| 119 | 130 | (23.3) | 3.0 | 82 (58) | Fire sustained |
| 120 | 135 | 22.5 | 2.82 | 81 (56) | Fire out (crib glows after test) |
| 121 | 135 | (24.4) | 2.23 | 80 (58) | Fire sustained |
| 122 | 180 | (33.2) | 1.95[c] | 1400 | Fire sustained |
| 123 | 110 | (14.3) | 1.9[c] | 3200 | Fire sustained |
| 124 | 160 | (28.1) | 3.25[c] | 4000 | Fire sustained |

[a]Numbers in parentheses represent the time over which pressure was averaged.

[b]Numbers in parentheses represent weight loss after extinction with $CO_2$.

[c]Pressure history for the long-duration pressure pulses is shown in Figure 5.

Table B.5

NONSTANDARD TESTS

| Test No. | Fuel | Bed Length (in) | Barr. Dist. (in) | Barr. Ht. (in) | Preburn Time (s) | Mean o.p. (psi) | Fire | Comments |
|---|---|---|---|---|---|---|---|---|
| 65 | n-Hexane | 36 | 3.25 | 0.6 | 15 | 5.31 | Out | Decreased barrier height |
| 81 | n-Hexane | 36 | 4.625 | 0.875 | 15 | 7 | Out | Same barricade height:distance ratio as 1.75:9.25 inches. |
| 82 | n-Hexane | 36 | 4.625 | 0.875 | 15 | 6.25 | Out | |
| 83 | None | 24 | — | — | — | ∿ 3.25 | Not lit | Hycam film coverage |
| 84 | None | 24 | 0 | 1.75 | — | ∿ 3.25 | Not lit | Hycam film coverage |
| 85 | None | 24 | 3.25 | 1.75 | — | ∿ 3.25 | Not lit | Hycam film coverage |
| 86 | n-Hexane | 24 | 3.25 | 1.75 | 15 | ∿ 3.25 | Sustained | Hycam film coverage |
| 87 | None | — | (a) | 1.75 | — | ∿ 3.6 | — | Shadowgraph visualization of shock/ barrier interaction |
| 88 | None | — | (a) | 1.75 | — | ∿ 3.5 | — | Particle flow visualization |
| 39 | Methanol | 36 | — | — | 30 | — | Sustained | No tank pressure (detonation only); flame disturbed but not blown off |
| 67 | Redwood crib | 12 | — | — | 120 | 7.34 | Out | Crib burned poorly |
| 68 | Redwood crib | 12 | — | — | 240 | 7.80 | Out | Crib burned poorly |
| 69 | Redwood crib | 24 | — | — | 900 | 8.14 | Sustained | Full crib involvement; some loss of crib integrity |

[a]Barrier was positioned 1.25-in. upstream from center of window.

Tests No. 31, 32, 51, 53, 66, 72, 73, 74, 75, 99: had no or improper diaphram rupture.
Tests No. 30, 48, 71, 78: had improper recorder function.
Test No. 70: Test stand and (Douglas fir, 34½-in. long) crib displacement due to high overpressure (11.6 psi).

# Appendix C

## WOOD CRIB FREEBURN TESTS

## WOOD CRIB FREEBURN TESTS

A series of tests was conducted to ascertain the burning behavior and extinguishment susceptibility of wooden cribs. These crib tests guided the selection of the cribs and burning conditions that would be tested for extinguishment by blast in the shocktube.

The approach was to examine the following factors:

(1) The amount and method of application of the ignitor fuel (methanol).

(2) The seating (housing) of the crib and crib support with their effect on fire ventilation and consequently on burning rate.

(3) Scale (size) of crib.

(4) Wood type.

(5) Reproducibility of crib burning in terms of weight loss as function of time; the length of steady burning period.

(6) The behavior of a crib fire that has flames snuffed out at a given time after ignition and for a specified length of time. The conditions for reflaming of cribs after complete flame extinguishment were looked for because these may indicate a hard-to-blow-out fire in the shocktube.

The first four factors were found to play a significant role with respect to the last two items above. They affected the initial transient burning of the crib and, occasionally, also the steady-state burning regime, altering the time required for the crib to attain a "well-seated" fire. The crib response upon extinction, in turn, depended on whether the fire had attained the "well-seated" stage at the time of flame snuff-out. This critical time ranged from 3 to 4 minutes after ignition depending on the first three factors.*

Nineteen free burning crib tests were made. The first thirteen tests used cribs of three sizes (nominal 1-, 2-, 3-foot lengths) constructed from dry Douglas fir sticks (all of 3/4-inch square cross section). Although the Douglas fir cribs were not finally chosen for use in the

*Critical time also depended on ventilation disturbances; these were not intentionally studied and occurred in only one test, quiescent ambient air being achieved in all other tests.

shocktube tests, they confirmed the independence of the specific* burning (weight loss) rate on the crib size (length was the dimension of interest here). Although the flame height above the crib increased significantly with the crib size, the weight-loss rate was not affected. The Douglas fir cribs were observed to have an approximately 4-minute period of steady burning ($\sim$ 40% of flaming time), with a maximum, constant weight loss rate of 13.5 $\pm$ 1.5% of the initial crib weight per minute, for all three crib sizes used.

During the above tests, various ignition methods were tried to optimize the crib ignition stage to obtain reproducible, uniform, and rapid ignition. Various amounts of methanol in the pan under the crib were used as well as methanol-saturated wicks. Since the burnout time of the alcohol was not exactly reproducible, a method was chosen in which a saturated wick was placed under the crib, allowed to burn a predetermined amount of time, and then rapidly removed from under the crib. This worked very satisfactorily, providing very repeatable crib burning histories. The pan was no longer necessary, which further improved crib burning by allowing proper ventilation. This standardized ignition method was used in the shocktube tests, with propanol substituted for methanol.

After the tests with Douglas fir cribs, three tests were made with redwood cribs (3-foot long, of like construction). Their burning behavior, however, eliminated them as unsuitable.

Lastly, three tests were made with pine cribs made from kiln-dried, cut pine shelving. These cribs burned well and with excellent reproducibility; moreover, they reached the steady burning region within 90 seconds after ignition and supported a maximum, constant weight loss rate of 17.4% of initial weight/min for 3.5 minutes. The final weight loss of these cribs was 77%-79%. The burning (weight loss) history for the pine cribs is shown in Figure C.1. These cribs were chosen for use in the shocktube and were used exclusively. The final crib design and specifications were shown in Figure 11 of the main text.

*Per unit weight.

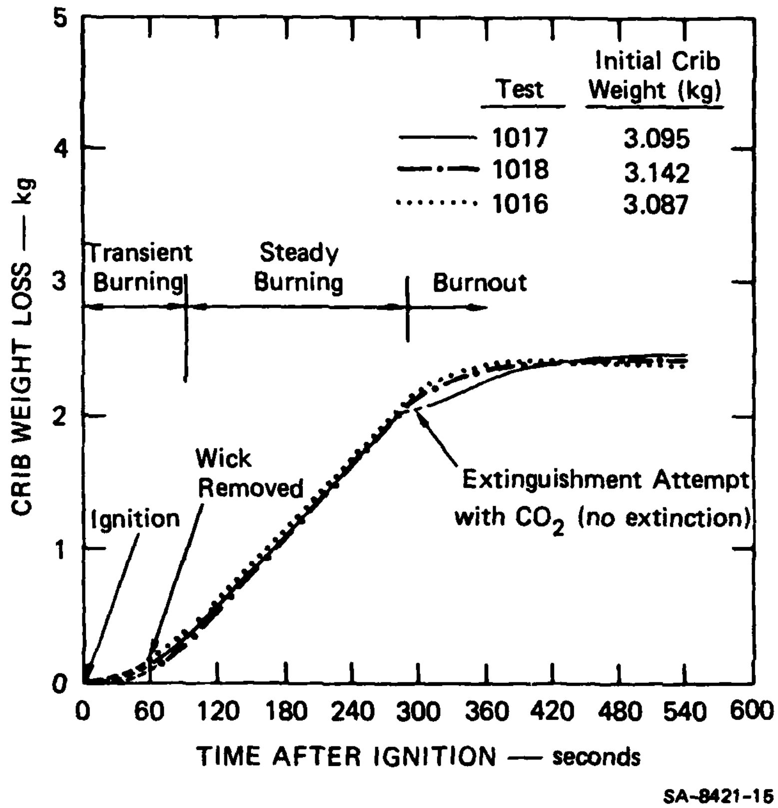



FIGURE C.1 WEIGHT LOSS HISTORY FOR CRIB FIRES

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BLAST EFFECTS ON FIRES: by Jana Backovsky, Stanley Martin, and Robert McKee. SRI Project PYU 8421, 76 pages plus append., Contract No. DCPA01-79-C-0245, FEMA Work Unit No. 2564A, Unclassified (December 1980).

Experiments on extinction of fires by airblast were conducted in the shocktube facility dedicated to blast/fire interaction studies. Three series of tests were conducted to gain practical understanding (quantitative and mechanistic) of *blast effect on fires*, using: (1) liquid-fuel fires of various sizes; (2) liquid-fuel fires, of various sizes, with flow-obstructing barriers upstream of the fuel source; and (3) wood crib fire tests.

Results affirm the concept of flame displacement as a mechanism of extinguishment for liquid-fuel fires on flat surfaces but suggest its limitation in describing blast/fire interactions when flow-perturbing obstacles are present upstream of the fuel bed. Even small barriers are seen to significantly increase the fire resistance to blowout by blast, by providing flame-retentive flow recirculation in their wake and effectively serving as flame-holders. For charring fuels such as wood cribs, after-shock flame displacement is seen to be augmented by sustained, blast-enhanced char involvement. The crib fire history before blast arrival and the extent of char-combustion enhancement (depending on blast strength) determine whether the crib fire is reestablished by rapid rekindling.

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# BLAST EFFECTS ON FIRES

DETACHABLE SUMMARY

December 1980

Annual Report

By

Jana Backovsky
Stanley Martin
Robert McKee

Prepared for:

FEDERAL EMERGENCY MANAGEMENT AGENCY
Office of Mitigation and Research
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## SUMMARY


**Objective and Scope:** The overall objective of this experimental program is to determine and evaluate the physical variables that govern extinction of sustained burning, in representative fuels, caused by simulated airblast characteristic of nuclear explosions. The experiments are also to provide data for analytical models being developed concurrently at Notre Dame and TRW. This year's work included investigations of effects of flow-perturbing barriers on blowout resistance of class B fuels and of the resistance of complex, three-dimensional (class A) fuel arrays (wooden cribs) having gas and solid-phase combustion and charring, with significant heat stored in the char.

**Approach:** The tests of extinction of fires by blast were performed in the SRI-developed shocktube facility. For most of the tests in FY80, the shocktube was used with positive-phase durations between 70 and 133 ms. n-Hexane fires of 1- to 3-foot fuel bed length, with and without flow-barriers, were subjected to blast overpressure extinction thresholds. The barriers were 1-3/4-inch high and were positioned 3-1/4 and 9-1/4 inches upstream of the upstream fuel bed edge, although other barrier heights and distances were tested for simple scaling rules. Methanol fires were tested for contrast with hexane results. With blast extinction of crib fires, the approach has been to design and use fully reproducible, self-sustained class A fires, even though lacking a suitable thermal source, to furnish an easy and sustained ignition simulation of, for example, flat wooden samples. The crib fires were initiated by an alcohol source-fire on a wick placed (for 60 s) under the crib and allowed to burn freely for a predetermined time (1-1/2 to 3 minutes total preburn time). The extent of crib-fire involvement was then correlated with the blast extinction response.

**Significant Results:** Increased fire blowout resistance and an apparently different physical mechanism of fire retention (reestablishment) above the fuel bed were observed with flow barriers, as compared with the flush, basic flat-plate bed configuration. Even with the low (1-3/4-inch high) barrier used in most tests, the flow-perturbing effect is pronounced; at the 3-1/4 inches position upstream the overpressure threshold is effectively increased by 1 psi

at each bed length, compared with the case with no barrier. Photographs of particle-laden after-blast airflow (without fire) show the extent of flow deflection by the barrier and a region of reverse flow behind the barrier; film coverage (with fires) indicates that fuel reignition occurs in the large eddy behind the barrier, showing its function as a flame holder.

The role of char (glowing embers) in crib tests was found to be significant, especially at the higher overpressures and the accompanying high blast winds. Film coverage attests to the strong fanning by blast, causing intense glowing and growth of embers (as well as significant firebrand production). Surprisingly, two extinction overpressure thresholds were observed for the cribs tested: a lower threshold, below which the blast wind apparently does not completely blow off the primary flame, and a higher threshold, above which strong fanning of embers aids the return to flaming combustion. Finally, there appears to be a critical preburn time ($\sim$ 170 s for the cribs tested), after which permanent extinction by blast does not occur at any of the applied overpressures.

In summary, the resistance of initially self-sustained, freely burning fires to relatively short duration blast was found to be substantial, especially with flow disturbances. The effect of intermediate and long-duration pulses has yet to be fully studied, as well as introduction of thermal pulse simulation.