Laboratory Facility for Wind-Aided Firespread along a Fuel Matrix

R. D. FLEETER, F. E. FENDELL, L. M. COHEN, N. GAT, and A. B. WITTE

TRW Electronics and Defense Sector, Redondo Beach, CA 90278

Urban and wildland fires propagate via ignition of discrete fuel elements. Transfer of heat from burning to nonburning fuel is strongly influenced by wind because of its effects on combustion rates, on convective flow patterns, and on radiative transfer owing to its modification of the shape and orientation of the thermal plume. Development of a large low-speed wind tunnel designed expressly for modeling wind-aided firespread, and results of preliminary tests, are described. The tunnel, capable of producing air velocities up to 20 m/s, has a test section of 1.12 x 1.12-m² cross section and 5-m length. A movable ceiling panel allows the plume to rise freely under buoyancy, and affords constant speed for the airflow approaching the propagating flamefront. The plume rises into a straight duct extending 3 m above the fuel matrix. Tests have been carried out with hardwood fuel at loadings of 0.32 and 4.8 kg/m² with air velocity 1.4 m/s. Fuel elements for the tests had total masses of 56.8 and 1500 kg, respectively. Steady-state flame propagation was achieved for the lower fuel loading, with a flame width of 1 m. The 4.8 kg/m² loading did not achieve steady state, and the burning-zone width increased to the entire length of the test section. This difference is attributed to the larger time required to burn the more massive fuel elements. In both cases the propagation was most rapid along the center of the matrix; in the lower-loading case, some unburned fuel remained at the sides of the matrix, possibly as the result of diminished heat transfer to these elements, as well as of radiative losses to the walls. Flame-propagation-rate data from video and thermocouple data for the two cases are compared. Observations of backflow downwind of the flamefront and of plume rise angle are discussed.

INTRODUCTION

The spectacular urban fires of modern times have usually been associated with the occurrence of strong sustained winds (London, 1666; Lisbon, 1775; Moscow, 1812; Chicago, 1871; Boston, 1872; Baltimore, 1904; Tokyo/Yokohama, 1923; Bandon, Oregon, 1936; Tokyo, 1945). Many of the memorable wildlands fires also were consequences of wind-aided flamespread (Miramichi River Valley, New Brunswick, Canada, 1825; Peshtigo, Wisconsin, 1871; Hinckley, Minnesota, 1894; Cloquet, Minnesota, 1918; Tillamook, Oregon, 1933; Shoshone National Forest, Wyoming, 1937; Victoria, Australia, 1938; Maine, New Hampshire, 1947; Sundance Mountain, Idaho, 1967). This list is hardly exhaustive. What it suggests is that ignition often occurs in heavily fuel-laden areas in times of drought, but it is the coincidence of persistent winds of appreciable speed that causes a "blowup." The multiple ignitions may be associated with natural events (lightning, earthquakes) or human intervention (incendiary bombing, campfires); sometimes the resulting fires linger for days without major consequences, until the arising of strong winds precipitates a startling run that ends only when the wind subsides, sustained heavy precipitation arrives, or accessible combustible matter is exhausted. Clearly it is the wind-aiding, not the mode of ignition, that is common to fast spread. Unlike the rare firestorm, wind-aided firespread is the common scenario in an incendiary catastrophe.

Relative to the attention devoted to blast
effects, prompt radiation, and radioactive-material deposition in the aftermath of a thermonuclear event in an urban environment, little attention has been devoted to the incendiary consequences of nuclear weapons [1]. However, propagation of burning from multiple ignitions in the strewn debris of a heavily fuel-laden, severely blasted urban and/or wildlands environment could produce large-area fires. These fires might constitute the primary effect of nuclear weapons over most of the urban area involved. Crutzen and Birks [2] have suggested that lofting of sufficient smoke from urban and wildlands fires can cause significant absorption of solar radiation in the atmosphere to trigger a conjectured global-cooling phenomenon known as nuclear winter.

An important achievement would be the ability to calculate with confidence the rate of flamespread, given the vertical distribution, loading, size spectrum, exothermicity, and moisture content of the fuel; the nature of the topography; and the wind magnitude and direction, temperature, and relative humidity, as a function of pressure, for the ambient atmosphere. If the ability existed to calculate how fast the firefront will advance in a direction normal to its instantaneous locus, then projecting the expected fire position at future time is reduced to an information-management-and-display exercise. This prediction, given all the relevant meteorological, topographical, and fuel-property data, must be executed by a so-called hydrocode. In turn, validation of such hydrocode calculations must be based on comparison with results of smaller-scale experiments, since urban-scale tests are not feasible. Of course, smaller-scale tests almost assuredly do not permit all relevant physical phenomena of the urban-scale fire to be perfectly replicated. Thus, such tests can furnish but a partial (though still relevant and meaningful) challenge to hydrocodes. More specifically, laboratory-scale tests normally do not permit replication of the roles that (for example) radiative transfer and atmospheric stability play in urban-scale fires. Nevertheless, turbulent burning in a well-controlled impressed wind under well-characterized thermodynamic conditions of a well-described fuel distribution permits preliminary verification of a hydrocode over a wide parametric range.

Surprisingly little work has been reported on laboratory experiments modeling wind-aided flamespread across a fuel matrix [3–7]. In present work on measurement of wind-aided flame propagation rate across a well-defined two-dimensional fuel array, the role of the thermal plume in determining flamefront thickness and propagation is recognized, and allowance for unimpeded plume development has received considerable attention in the design.

A plume-dynamics-dominated theory by Carrier et al. [8] of wind-aided spread, inspired by remarks of Taylor [9], is set forth and then applied to a few experimental results, for a preliminary evaluation; far more testing is planned as future work.

**SIMPLISTIC MODEL OF WIND-AIDED FLAMESPREAD ALONG A MATRIX OF DISCRETE FUEL ELEMENTS**

Wishful thinking suggests seeking a simplistic model, which bypasses many details (e.g., concerning the fuel loading) and which concentrates on the dynamics of the convective-plume interaction with a crossflow, to predict quasisteady one-dimensional wind-aided flamespread across a matrix of discrete fuel elements in the open atmosphere [8].

The model may be described thus: the speed of the crosswind implies a rate of entrainment into a two-dimensional plume, if that oncoming wind cannot penetrate the plume. But the entrainment requirements of a maintained buoyant plume over a line-type source is dependent on the strength of the buoyant updraft, according to now classical concepts for maintained plumes. In turn, the strength of the updraft is dependent on the intensity of the line source, i.e., the heat per length per time released (here, by exothermic combustion). And this intensity by definition is simply the product of the mass of thin-fuel loading per unit area, the exothermic heat derived per mass of fuel (after adjustment for
drying and gasification), and the speed of fire propagation. Thus, through intermediate mechanisms, the flame speed is a function of the crosswind speed: the fire spreads at just such a rate that the crosswind modestly tilts, but does not blow over, the (marginally stable) plume.

There are several refinements to the above discussion, some of which are now addressed. For plume-fixed coordinates, the oncoming wind is reduced by the fire-propagation speed. Furthermore, there is inflow into the plume from the downwind side equal to the fire-propagation speed; that is, there is a counterflow on the downwind side of the plume for a plume-fixed observer. Whether entrainment into the plume is quite so predominantly from the upwind side (since the oncoming wind often would far exceed the fire-propagation speed) need not be resolved for present purposes.

Also, the classical entrainment concept relating plume-axis updraft to plume-edge inflow pertains to small density discrepancy between in-column air and surrounding air. For large density discrepancy between in-plume and ambient air, perhaps the relation is more accurately stated in terms of mass flux than volumetric flux. Furthermore, at low altitudes (i.e., in the flaming domain), the entrainment is augmented significantly beyond the classical value, and perhaps another formulation is required. However, no simple refinement of the classical relation has gained widespread acceptance; tentatively the classical entrainment relation is used here.

It is self-consistent to adopt the Boussinesq approximation in the statement of the conservation relations. If \( x \) is the horizontal coordinate, \( y \) is the vertical coordinate, \( u \) is the horizontal velocity component, \( w \) is the vertical velocity component, \( p \) is pressure, \( \rho \) is density, \( T \) is temperature, and subscript infinity denotes the ambient state (for which the density is invariant over the height of interest), then the conservation equations for mass, momentum, and energy for the two-dimensional plume over a line source may be taken in the following form [10]:

\[
\begin{align*}
\frac{du}{dx} + \frac{dw}{dy} &= 0; \\
\frac{dp}{dy} &= -\rho g; \\
\frac{d\rho}{dy} &= \frac{d\rho}{dT} \frac{dT}{dy} = \rho g; \\
\frac{dp}{dy} &= \rho \frac{d\rho}{dT} \frac{dT}{dy} + w(T - T_\infty); \\
\frac{dp}{dy} &= -\rho c_p \left( \frac{dT}{dy} + \frac{g}{c_p} \right); \\
\end{align*}
\]

where, subscripts \( x \) and \( y \) denote partial differentiation. For the Boussinesq approximation,

\[
\frac{d\rho}{dy} = \frac{\partial \rho}{\partial T} \frac{dT}{dy} 
\]

or for a perfect gas,

\[
\frac{d\rho}{dy} = \frac{T - T_\infty}{T_\infty} 
\]

For Gaussian profiles for the dependent variables, the axial values \( W(y) \) and \( R(y) \) and the e-folding distance, or plume width, \( b(y) \) appear as follows:

\[
\begin{align*}
\rho(x, y) &= W(y) \exp\left[-\frac{x^2}{b^2(y)}\right], \\
\rho(x, y) &= R(y) \exp\left[-\frac{x^2}{b^2(y)}\right].
\end{align*}
\]

Application of the integral method to (1), (3), and (4), under (2) and (5)–(8), gives three ordinary differential equations for the three dependent variables \( b(y) \), \( R(y) \), \( W(y) \). That is,

\[
\frac{d}{dy} \int_0^x w(x, y) \, dx = -u(\infty, y) = \frac{d}{dy} \left( \frac{bW}{\pi^{1/2}} \right) = \frac{2}{\pi^{1/2}} \alpha W,
\]

1. The plume probably is cellular and effectively three-dimensional at low levels, so there is likely to be entrainment from all sides; the cells merge to form a two-dimensional plume at some height above the surface.
under the Taylor entrainment hypothesis

\[ -u(\infty, y) = \alpha w(0, y) = \alpha W(y), \]  

(10)

where \( \alpha = 0.16 \) (Lee and Emmons [10]). Similarly,

\[
\frac{d}{dy} \int_0^\infty w^2(x, y) \, dx + u(x, y)w(x, y) \bigg|_{x=0} = \int_0^\infty \frac{\rho_\infty - \rho(x, y)}{\rho_\infty} \, dx = \frac{d}{dy} (bW^2) 
\]

\[ = 2^{1/2} Rb. \]  

(11)

For a dry-adiabatic lapse rate (neutrally stable atmosphere), the right-hand side of (4) vanishes, and

\[
\rho_\infty c_p T_\infty \int_0^\infty w(x, y) \left[ \frac{\rho_\infty - \rho(x, y)}{\rho_\infty} \right] \, dx = \frac{gQ}{2}, 
\]

(12)

where the constant of \( \dot{Q} \) is the full-infinite intensity of the line source; hence by (7) and (8),

\[
bWR = \left( \frac{2}{\pi} \right)^{1/2} \frac{g\dot{Q}}{\rho_\infty c_p T_\infty}. \]  

(13)

Equations (9), (11), and (13) admit solution in the form

\[ b = \beta y, \quad W = \gamma, \quad R = \gamma y^{-1}, \]  

(14)

where the constants \( \beta, \gamma, T \) are identified by

\[
\beta = \frac{2}{\pi^{1/2}} \alpha, \quad \gamma = \left( \frac{g\dot{Q}}{\alpha \rho_\infty c_p T_\infty} \right)^{1/3}, 
\]

\[
T = \frac{1}{2^{1/2}} \left( \frac{g\dot{Q}}{\rho_\infty c_p T_\infty} \right)^{2/3}. \]  

(15)

Thus, the updraft on the axis of the linearly growing plume is invariant with height, but the density discrepancy does decrease inversely with altitude, the model clearly being singular at the source \( z = 0 \).

Under the Taylor hypothesis [9] that the crosswind is compatible with the entrainment requirements, in view of (10) and of the expectation that the entrainment is predominantly from the upwind side of the two-dimensional plume, if \( U \) is the crosswind,

\[ U \geq 2\alpha \left( \frac{Qg}{\alpha \rho_\infty c_p T_\infty} \right)^{1/3}. \]  

(16)

But the fire intensity \( \dot{Q} \) is given by

\[ \dot{Q} = Qav_f, \]  

(17)

where \( Q \) is the effective chemical heat per mass of thin fuel, \( \sigma \) is the mass of thin fuel per area, and \( v_f \) is the fire-propagation speed. Hence,

\[
\frac{v_f}{U} = \frac{\rho_\infty c_p T_\infty U^2}{8\alpha^2 \frac{gQ}{\sigma}}, \]  

(18)

or \( v_f \propto (U^3/\sigma) \), since \( Q \) is relatively invariant for most fuels of interest. The very often cited general relation that buoyant strength \( \dot{Q} \) goes as the cube of the crosswind speed \( U \) in the near-critical (i.e., almost blow-over) condition, as displayed in (16), may be traced to Rouse [11]. The present interpretation permits relating the proportionality factor to a well-known and already measured empirical constant, the entrainment constant \( \alpha \).

According to (18) the flame-propagation speed \( v_f \) increases as the exothermicity \( Q \) and thin-fuel loading \( \sigma \) decrease, but increases as the ambient temperature \( T_\infty \) increases. These proportionalities reflect the requirement to generate sufficient exothermicity per length per time \( Q \) to "match" the crosswind \( U \). The assumption of reaction rate sufficient for the flow rate is implicitly adopted; if the so-called first Damkohler number is not large enough (and forced-convective extinction occurs), one of the bases of (18) is violated and the relation does not hold. Also, if a strong gust of wind arises, the flame-propagation rate cannot adjust instantaneously, the quasi-steady relation (18) is inapplicable, and the plume is blown over; in time, the propagation speed \( v_f \) may increase to restore a fairly vertical plume and (18) holds again (a cycle sometimes referred to as "rolling-type
spread”). Since by measurement \((2\alpha) < 1\), from (16) one expects \(W > U\). Further, if one anticipates \((v_f/U) < 1\), then

\[ U < 2\alpha \left( \frac{2gQ\alpha}{\rho\alpha c_p T_\infty} \right)^{1/2}; \quad (19) \]

that is, for too strong a crosswind, even if the burning rates can keep pace, the exothermicity capacity of the fuel loading cannot, and the plume is blown over.

In view of the approximations (Boussinesq approximation, neutrally stable ambient, line source of heat, etc.), perhaps factor-of-two-like error is to be expected. The point may be worth making that the effect of relaxing the Boussinesq approximation, so the large density discrepancies of a strongly buoyant plume are accounted for, is anticipated to be in the direction of reducing the entrainment, i.e., reducing \(\alpha\). The magnitude of this effect might readily reduce \(\alpha\) to about \((2/3)\alpha_0\), if the reduction goes as \((\rho_{\text{plume}}/\rho_{\text{ambient}})^{1/2}\), as conjectured by Morton [12] on the basis of experimental data with jets, and if (on the basis of pyrolysis temperature for pine needles) one takes averaged plume temperature to be twice the ambient temperature for purposes of this ratio. However, Lee and Emmons [10] arrived at the value \(\alpha = 0.16\) by fitting the simplistic model just presented to experimental data for a laboratory fire; thus, this value for \(\alpha\) in a sense accounts for large-density-variation effects.

Finally, just as (18) may not apply for too strong a wind, so (18) requires modification as \(U \to 0\), for then omitted spread-against-the-wind mechanisms (omitted above because they are negligible in the presence of a significant aiding wind) should be retained. That is, \(v_f\) may well be (modest but) finite for \(U \to 0\).

**TEST FACILITY**

**Design Requirements**

The facility is designed for initiation of a flamefront at the upstream edge (of a fuel matrix) situated perpendicular to the impressed airflow. Experimental repeatability, and tractability for modeling, suggest that the impressed airflow be of low turbulence. Further, the flow is to be uniform so that the flamefront and plume are not driven asymmetrically. Because visual confirmation of plume rise angle, flamefront shape, and propagation is desirable, the test section is fitted with large windows. The matrix of fuel elements forming the floor of the test section is established with clay-filled trays, into which wooden fuel elements (e.g., toothpicks) are placed at regular intervals.

The design differs from conventional wind-tunnel configuration mainly through attention to the dynamics of the thermal plume sustained by exothermic combustion. The argument supporting the propagation-rate scaling law discussed in the previous section proposes that the flame propagation is responsive mainly to the dynamics of plume/crossflow interaction. A classical wind tunnel, with fixed floor, walls, and ceiling, does not allow the plume to rise at the same rate and angle as in an open fire: boundaries force the plume to bend and become horizontal near the ceiling (Fig. 1a); however, a strongly convective plume is envisioned to “block” the region downstream of the flame from the oncoming wind, a picture consistent with downwind-witness accounts of wind shifts toward the flamefront as the flamefront approaches from upwind.

Earlier attempts to mitigate ceiling effects resulted in open channel designs having no test-section ceiling at all (Fig. 1b). While tunnel blockage does not occur, the turbulent mixing region, which begins at the ceiling end point, grows into the test section in only a few tunnel heights downstream of the lip. This limits tests to very short length, probably insufficient to establish steady flame propagation in many cases of interest. More often, longer open sections are used despite the intense turbulent mixing which occurs. This mixing results in jet-type deceleration of the impressed flow such that the flow speed further downwind is reduced from that upwind. With the impressed crosswind acting on the plume continually changing, establishment of a quasi-steady rate of flame propagation (if one exists) is precluded.
The facility developed at TRW mitigates the disadvantages of both the open, and also the closed, devices by using a semiopen channel (Fig. 1c). A movable ceiling is provided; the ceiling position is continuously adjusted so that the ceiling ends just before the rising plume. Significant entrainment by the impressed flow cannot occur upstream of the plume, which rises unperturbed out of the test section. If the plume blocks and diverts the oncoming flow, there is no natural wind downstream of the plume except that induced by combustion and plume entrainment. Thus the lack of a ceiling downstream of the plume does not give rise to a turbulent shear layer. Rather, free convective air motion occurs unimpeded downstream of the plume. The design requires that the blower be situated upstream of the test section, in order to produce the wind upstream of the burning zone and to allow free circulation downstream of the flame-front.

Facility Scale

Dimensioning of the facility is also based on plume dynamics considerations. Wooden toothpicks are taken as the smallest vertical fuel elements with an aspect ratio similar to that of trees or buildings. A fire fueled by a collection of these hardwood sticks standing on edge on 1-cm centers in a clay base is found to produce a flame 25-50 cm high. For further freedom for
the plume in addition to that offered by the sliding ceiling, a test section height of 110 cm is selected.

Test-section length is constrained by the goal of attaining steady flame propagation under wind-aided conditions. The steady-state burning-zone width should be small relative to the test-section length. The burning-zone width may be estimated by matching momenta of the crosswind and of the thermal plume. The plume buoyancy force \( F_b \) is given by

\[
F_b = g(\rho_a - \rho_p)hw_d,
\]

where \( g \) is the magnitude of the gravitational acceleration; \( \rho_a \) and \( \rho_p \), the air density at ambient and plume (hot) conditions, respectively; and \( h \), \( w \), and \( d \), the plume height, width (streamwise) and depth (third-dimension), respectively. The dynamic head of the oncoming flow pushes on the plume with force \( F_p \), where

\[
F_p = \rho_a U^2hw_d,
\]

where \( U \) is the wind speed. If it is taken that the density varies as the inverse of temperature (isobaric conditions) and that the plume temperature is much greater than ambient, so that \( \rho_o \ll \rho_a \), the ratio \( R \) of the inertial to buoyant forces (the Froude number) is given by

\[
R = \frac{U^2}{2g\bar{w}}.
\]

For equilibrium of buoyant and dynamic forces, \( R \) is set equal to unity.

To ensure operation in a wind-aided mode and not in a purely free-convective mode, the wind speed must be large compared with that of thermally induced draft. For this calculation an imposed wind of 5 m/s is assumed. This results in a plume width \( \bar{w} \) of 1.23 m. If this width is identified with the burning-zone thickness, the fuel-bed length must be several times larger than the plume width to permit attainment and observation of steady-state propagation. Hence, a 5-m test-section length is selected. Flame propagation is anticipated to be about an order of magnitude slower than the wind speed, or roughly 50 cm/s for these conditions. Thus, a test section of 5-m length permits a minimum of 10 s of observation time under the fastest expected flame-propagation conditions.

A test section of 5-m length at wind speeds of about 5 m/s will be burdened with thick wall boundary layers. For rough-wall (fully tripped) boundaries, boundary-layer thickness of 20 cm is likely at the end of the 5-m test section. The two sidewall boundary layers thus reduce the depth (available for flame propagation without boundary-layer interference) by 40 cm. A 1.1-m tunnel width is selected to allow an undisturbed flow 60 cm in depth.

Figure 2 shows the final tunnel design schematically, and Fig. 3 is a photograph of the installed apparatus. Prominent in both is the exhaust stack, which rises 6 m above the tunnel floor. The stack allows the combustion gases and blower-impressed wind to exit the facility without altering the plume development in the test section. The long section between the fan and the test section serves as a constant-cross-section settling region. Flow velocity is controlled with manual fan inlet and outlet dampers (not shown).

**Structural and Thermal Design**

The tunnel was designed to accommodate large transient heat loads and to be free from vibration from either the blower or air turbulence. At the highest anticipated fuel loading (about 5 g/cm²) approximately 50 kg of fuel could be consumed in 1 min, with heat release at a rate of almost 17 MW. The tunnel is constructed of 11 identical frame sections constructed of 6.4-mm-thick aluminum. The frames are bolted together, with separation by high-temperature silicon-rubber gaskets. This provision allows thermal expansion of the sections without warpage. The aluminum hood is similarly attached to the top of the frame structure. Upstream of the test section, the frames are closed with 14-gauge aluminum, and also sealed with high-tempera-
Fig. 2. Schematic diagram of the flamespread wind tunnel.
ture gaskets. The 5 frames of the test section are fitted with 11 Pyrex windows (2 on each frame, and a third window on the last frame, for visual access along the tunnel axis). The window frames may all be opened to gain access to the test section.

The movable ceiling is an aluminum plate with rollers set in a track extending along the entire length of the tunnel.

For minimization of transmission of vibration to the tunnel, the blower is mounted outside the test facility; it rests on vibration-isolation mounts on a concrete pad separated from the rest of the facility.

**Turbulence Suppression**

Development of a one-dimensional flamefront is unlikely to occur if the wind arriving at the front is nonuniform across the test-section width. For a satisfactorily uniform flow at the low speeds of interest (up to 8 m/s), a network of honeycomb, screen, and fibrous material is designed for installation upstream of the test section. These measures increase the load on the blower by increasing the pressure drop through the tunnel. For sufficient flow under these conditions, a 45-kW blower capable of providing a 10.4 m³/s airflow through a pressure drop of 3.6 kPa is selected. Flow-conditioning materials are designed according to the concept of turbulent-scale separation. The tests reported below were carried out with only the screen, the coarsest honeycomb, and the polyester material (Fig. 4).

Measurement of turbulence levels in the tunnel was accomplished with a 0.15-mm-diameter hot-film probe operated in the constant-temperature mode. Figure 5 shows the air velocity measured by horizontal traverses at 56 cm above the floor, before and after installation of the flow-conditioning elements. All of the measurements are at the upstream boundary of the test section. The rms flow turbulence at the test conditions is roughly 3% of the mean velocity.
Fig. 4. Arrangement of flow-conditioning elements in the wind-tunnel inlet section. The last flow-conditioning element is 2.2 m upstream of the test section, to allow "imprints" of the elements on the airflow to dissipate.

Fig. 5. Hot-film measurements of the streamwise air speed in the tunnel. Transverse traverses shown are 59 cm above the tunnel floor, at sites 279.4 cm from the leading edge of the test section. Configuration d was used for the flamespread tests.
Before modification of the flow, the tunnel radiated noise to the surroundings at about 90 dB; the noise dropped an estimated 10 dB owing to turbulence suppression. The flow is uniform across the test section except near the walls; the higher velocity and turbulence level near the walls probably are caused by air leakage around the edges of the flow-conditioning elements and from flow tripping along the rough walls.

**Fuel Matrix Base**

Installation of the fuel matrix in the test section entails use of trays packed with moist modeling clay to support the fuel elements. The trays span the full test-section depth (1.1 m) and length (5.0 m). Fuel elements are placed in the clay while it is still malleable (Fig. 6). Through exposure to ambient air, moisture evaporates from the clay so that a hard, nonreactive base is left beneath the fuel. The clay is impermeable to air, so oxygen can reach the fuel from the tunnel airflow only. The clay has a flat (not shiny) grey surface.

**Igniter**

A propane-fueled system is provided for igniting the fuel uniformly along the upwindmost row. The igniter consists of a 1.3-cm-diameter stainless steel tube held horizontally near the floor of the tunnel just upstream of the upwindmost tray. Holes of 1-mm diameter are drilled in the tube at 6.4-mm centers for dispensing the propane. The tube is connected through a solenoid valve to a propane cannister outside the tunnel. A spark transformer provides a high voltage between the tube and a small electrode at one side of the tube about 1.9 cm away. The transformer and the valve are actuated by a single switch so that, at any time propane is dispensed, the propane is ignited and burned. This procedure prevents the...
filling of the tunnel with a large quantity of possibly combustible propane-air mixture. Upon actuation, flame, stabilized in the airflow by the steel tube, propagates rapidly across the tube length so that ignition is essentially simultaneous across the width of the upwindmost row of the fuel matrix.

**Instrumentation**

Data desired from the experiment include the flow conditions upwind of the burning zone (wind speed); the propagation rate, thickness, and shape of the burning front; the effect of the approaching front on the local downwind flow; and the behavior of the thermal plume. To ensure that the moving ceiling has not constrained the plume, data collection includes indication of the leading-edge position of the ceiling relative to the combustion-zone location.

Measurement of the flamefront-propagation speed is accomplished with thermocouples, and by image recording and analysis via video cassette recording. Bare chromel-alumel thermocouples formed of 0.1-mm wire are attached to fuel elements along the axis of the tunnel. Eight thermocouples are spread evenly along the length of the test section at 56-cm intervals. The thermocouple wires are wrapped loosely around the elements, so the bead at the thermocouple front surface is left exposed to the oncoming flow (and to radiation from the approaching flame). An individual thermocouple in place on a wooden fuel element is shown in Fig. 7. The thermocouple voltages are stored by strip-chart recorders for later analysis. No reference junction is provided since the temperatures of interest are far above room temperature (100–1000°C). By recording the temporal interval for successive thermocouples to reach a fixed temperature, a measurement of the rate of axial flamespread is obtained. Recording of images of the combustion zone with a videocassette recorder (VCR) is also used to measure the flamespeed rate. Sufficient resolution is not available in video recording to image the entire

![Fig. 7. A thermocouple mounted on the forward-facing side of a 5-cm-high hardwood stick.](image_url)
test section in each frame and still to resolve the flamefront accurately. The video raster contains roughly 250 lines of resolution; for imaging the entire test section, 5 m in length, one line then corresponds to 2 cm. An uncertainty of 3 lines in image focusing and recording results in an uncertainty of 12 cm in flamefront position. In resolving a bright, rapidly fluctuating flamefront in a moderately lighted field, considerable degradation in resolution is expected from both local camera overexposure and motion-induced blurring of the flamefront image. This problem is compounded by use of modern, self-compensating vidicon color cameras, which adjust their sensitivity for the overall field and thereby incur severe overexposure of the combustion-zone image data. These shortcomings are overcome by using five video cameras, one focused on each windowed section of the tunnel. As the flame transverses the field of each camera, the compensator works to keep the flame image at the correct exposure. The resolution is improved by a factor of five, so that the flame location may be determined with a precision of about 2.4 cm. A switchbox is used to choose manually which camera video signal is to be fed to the VCR. Digital elapsed time is added to the video signal before it reaches the VCR. This provision gives a continuous time reference printed on each "frame" of the recorded image data.

A thermocouple array is also employed to characterize deviation of the flamefront from one-dimensionality. Five thermocouples are placed normal to the flow axis at the downstream side of a fuel tray, 2.8 m from the leading edge of the fuel matrix. They are positioned among the fuel elements at the axial centerline and at 20 and 40 cm to each side of the centerline. Peaking of the thermocouple voltage recorded with strip charts is taken as an indication of flame passage. The difference in time of passage of the flamefront at the five stations indicates the amount of deviation of the flamefront from one-dimensionality.

The effect of the approaching flame on the local airflow is made visible with tufts. A vertical array of double-attached tufts is positioned in the center of the test section. Figure 8 shows the device, which gives a visual indica-

---

Fig. 8. The flow-directional indicator positioned about a fuel matrix ready for a test.
tion of flow direction over the total test-section height. The ladder consists of two parallel rods (diameter 1.6 mm) spanned by gold- and aluminum-coated Kapton strips. The strips billow in either the upstream or the downstream direction, according to the local wind. They are sensitive to wind speeds less than 0.1 m/s. Additional Kapton tufts are attached to identical rod segments, positioned within the fuel matrix and standing 1 cm taller than the fuel elements; these tufts indicate the direction of airflow at various positions relative to the combustion zone.

For recording the position of the leading edge of the ceiling for later correlation with flamefront position, a ceiling-indicator device is provided.

**PRELIMINARY RESULTS**

A wind speed of 1.37 m/s was selected for the multitray tests on the basis of tunnel-sizing calculations and of the propagation rates observed during trials. The rms turbulence level at this speed was 3.0% of the mean velocity (see Fig. 5 for the flow-profile appearance for the tests).

**First Test**

Flat, hardwood toothpicks are spaced axially and transversely on 1.27-cm centers. The fuel elements were of length 5.84 cm, of which 5.52 cm extended above the clay surface. The exposed surface was 2.99 cm² and the mass above the clay was 53 mg, so that each element had a surface-to-mass ratio of 5.64 m²/kg. The loading of exposed fuel (not submerged in clay) was 0.321 kg/m². Figure 8 shows the fuel matrix in place in the tunnel. No sticks were placed on either tray edge within 10 cm of a tunnel wall. This provision limits the amount of flame propagation taking place in the boundary layer, where the velocity field is nonuniform. Also, by keeping the burning region away from the windows, the heat loading on the glass is reduced. The fuel-free zone intentionally was made only half as wide as the expected boundary layer because of wall-quench-layer considerations. The absence of burning elements, and thus of their contribution to convective and radiative heating at one side of the outside columns of fuel elements, is expected to slow combustion and flame propagation near the walls. By providing fuel outside of the uniform-flow corridor, it is possible to mitigate this effect within the corridor.

Figure 9 shows the flame development sequentially. Figure 9a shows the flamefront just after the igniter was extinguished. The front is narrow with only slow burning. The very flat (horizontal) plume is expected because, during the starting transient, appreciable convective updraft has not yet developed and the plume is blown over by the impressed wind. As the flame approaches steady state (Fig. 9b), the combustion zone widens and the plume becomes slightly inclined toward the vertical. The indicator of the position of the leading edge of the ceiling is the ribbon hanging into the field of view of the first window (arrow, Fig. 9a). The outer frames visible in this view hold observer-protective polycarbonate windows. The flow-direction indicator is visible in Fig. 9c (see arrow). It shows a strong streamwise pattern over the upper half of the test section, with backflow and areas of forward flow in the lower half. A single tuft, positioned just above the fuel elements at a site 50 cm downwind of the indicator, shows weak backflow (see arrow). This general pattern continues through Fig. 9g, although, as the flame approaches steady state (Fig. 9b), the backflow appears to weaken, so that in Fig. 9h, only forward flow is observed. The two-dimensionality of the burning zone is apparent in Fig. 9k (arrows show retarded burning near edges). The flame has consumed the fuel along the centerline at the center of the third window from the upwind end of the test section; however, strong burning is still occurring along the edges. The flame width is determined by measuring the length of burning along the centerline of the fuel bed. The curved combustion region shape remains through Fig. 9l. The test ends when the leading edge of the flamefront reaches the end of the last fuel tray, as depicted in Fig. 9l. Approximately 70 s of elapsed time is depicted in this sequence.
Fig. 9. Flamespread over a fuel bed composed of flat hardwood sticks (toothpicks). Fuel loading is 0.321 kg/m²; windspeed, 1.37 m/s.
Fig. 9. (continued).
A portion of the fuel bed after the test is shown in Fig. 10. The fuel in the center of the matrix is almost completely burned. At the upper right-hand side of the figure, a few fuel elements which were only partly burned are visible (see arrow). Small groups of such partially burned fuel elements remained in several areas along the outer edges of the matrix.

Second Test

Trays were used with elements consisting of hardwood sticks, similar to Popsicle sticks; the sticks are 11.4 cm in length, of which 11.1 cm extended above the clay surface. The elements had an exposed surface area of 27.0 cm² and an exposed mass of 1461 mg, so that the fuel-element surface-to-mass ratio was 1.85 m²/kg. The fuel matrix was formed of elements spaced at 1.27-cm centers in the streamwise direction and at 2.5-cm centers in the transverse direction. The loading of the exposed fuel for this geometry is 4.77 kg/m², almost 15 times greater than that of the first test. A portion of the installed fuel matrix is shown in Fig. 11. Leaning of a small number of fuel elements was not considered significant to flame propagation through a matrix of a large number of elements. In this case, the matrix was composed of 35 columns and 387 rows totaling over 13,500 discrete elements. As in the first test, the 10-cm strips nearest to the walls on both sides of the tunnel were left free of fuel elements to avoid boundary-layer affects and to lighten the heat load on the windows.

Figure 12 shows the flame propagation and development for this test. The initial burning zone is narrow and one-dimensional (Fig. 12a) and the plume appears nearly horizontal. A more vertical plume begins to arise as the burning region increases to roughly 50 cm in thickness (Fig. 12b), and the plume clearly is nearly vertical in Fig. 12c. The flame continues to grow in width (Fig. 12d) without reaching a steady state within the length of the test section.

Test Results

Primary determination of the flamefront location and its rate of progress is by temperature measurement made with the thermocouples in the fuel bed. Since the recorded temperature monotonically rises, and then monotonically falls, with the passage of the combustion zone, it is necessary to identify the flamefront with a particular threshold temperature. Figure 13 shows the position of the flame determined with this threshold technique applied at two temperatures, 685 and 1120K, for the first test. The rate of propagation is found to be quite constant along the length of the tunnel. The particular temperature chosen effects only a horizontal shift in the curve and does not alter significantly the estimate of the flame-propagation rate. This rate, found by least-squares fitting to the data, was 7.0 cm/s. The correlation coefficients for the fits were 0.997 or better, an indication of constant flame-propagation rate. The ceiling position is also plotted to show how the leading edge followed the flamefront. At time $t = 37$ s, the ceiling began to lag the flamefront by a greater distance than earlier. The initial lag was recovered at time $t = 65$ s. Significantly, the flame propagation appears unaffected by small variation in the lag distance of the ceiling. This indicates that the ceiling position was not constraining the propagation. VCR image data also was used to measure flame-propagation rate. The image data, which contain time reference, were examined manually at intervals of 10–15 s of elapsed burning time and the flame-leading-edge position was recorded. The consistency of the image data with thermocouple-derived data supports the determination of extremely constant flame propagation at 7.0 cm/s. Figure 14 shows a single video frame. The day (013) and precise time, shown in the upper left-hand corner, is included in each image on the video record. While the leading edge of the flame is clearly visible, the limited resolution, and particularly the limited dynamic range of the video camera, make it difficult to determine whether the flame leading edge shown is actually a site of burning sticks or just a tongue of burning gas blown forward from the true flamefront. For this reason, and because of the need for manual determination of the flamefront position, the video technique was considered inferior to the thermocouple measurements.
Fig. 10. The fuel base after the first test: partially burned fuel elements are visible at the upper right.

Fig. 11. The fuel matrix prepared for the second test (fuel loading is 4.77 kg/m²).
Fig. 12. Flamespread over a fuel bed depicted in Fig. 11. Wind speed is again 1.37 m/s.
Video and film image data showed clearly that while the flamefront propagation was steady, the flamefront was far from one-dimensional during the first test. This observation is confirmed by Fig. 15, which presents the elapsed time to reach particular temperatures at five positions in the fuel array. These positions are all at the same distance downstream (279 cm) from the fuel-bed leading edge, but at transverse positions 20 and 40 cm from the axial centerline.
Fig. 15. Temporal isothermal map shows the retardation of the flamefront away from the tunnel centerline. These measurements are at sites 279.4 cm downwind from the leading edge of the test section.

as well as at the centerline. Each thermocouple reading was normalized by its peak readily during flame passage. The lines connecting the data points indicate the times at which each thermocouple reached its peak reading and its half-peak reading both during the heating (flame-approaching) and cooling (flame-leaving) phases. The lateral lag in the flamefront position decreases from 16 s during the flame-approaching phase, to only 9 s during the flame-leaving phase; this difference indicates that the nonlinearity was actually decreasing as the flame propagated. The 9-s lag corresponds to a variation in flame location of 63 cm.

The plume-dynamics-controlled flame-propagation theory for a line fire in a crosswind was compared with the present results, and with results of coniferous-stand burns carried out in the Canadian National Forest by the Great Lakes Forest Research Center, Sault Ste. Marie, Ontario, Canada (B. Stocks, private communication). The theory allows calculation of the rate of flame propagation \( v_f \), from knowledge of the wind-speed \( U \), and fuel loading and exothermicity \( Q \), via the relation (18). For both the forest-fire data of Stocks and the present data, the ambient air density \( \rho_a \) is taken to be 1.1 kg/m\(^3\); the specific heat capacity of air \( c_p \), 1.004 kJ/kg K; the ambient temperature \( T_a \), 300K; the magnitude of the gravitational acceleration \( g \), 9.8 m/s\(^2\); and the exothermicity of the fuel \( Q \), 18,570 kJ/kg (a value appropriate for dry fuel, so there is no correction for moisture content).

The entrainment factor \( \alpha \) was taken as 0.16. For one laboratory test, the wind speed \( U \) was 1.37 m/s and the fuel loading \( \sigma \) was 0.321 kg/m\(^2\). The calculated flame velocity for the laboratory test is 13 cm/s, a factor of 1.8 greater than the measured 7 cm/s. For the forest-fire data, the wind speed was 6.7 m/s and the fuel loading was 3.0 kg/m\(^2\), for calculated flame velocity of 166 cm/s. The value measured by Stocks was 110 cm/s. While neither calculation indicates that the result following from formula (18) might have predictive power on its own, both calculations suffer from roughly the same fractional error compared with experiment. This indicates that experimental measurement could yield a factor by which (18) might be multiplied. The equation might then have predictive power for wind-aided firespread. Further, it may be useful to recall that the entrainment into the burning zone is enhanced over the classical value [13], so setting the entrainment parameter \( \alpha \) equal to 0.16 may be an underestimation in the present context. In any case, the results are encouraging, since the two experiments are in many ways near antipodes of physically interesting parametric ranges. The forest data was acquired at nine times the fuel loading, and almost five times the wind speed, of the lab test. The size scales of the fuel elements range over almost three orders of magnitude (between trees in the forest and 5-cm fuel elements in the lab test). The remaining error is attributable to uncertainties in the fuel-loading data for the forest, for which an estimate of fuel thin enough to participate in the flame propagation must be made. Exothermicity is also not well known for either
case, since corrections (e.g., for relative humidity and for specific wood type) have not been applied. The wind tunnel permits an order-of-magnitude variation in wind speed and fuel loading, so that tests over a wide range of these parameters could be conducted to evaluate further the adequacy of the formula for correlating experimental data.

CONCLUSION

A laboratory device for measurement of the rate of flame propagation along a two-dimensional discrete fuel matrix under wind-aiding has been described. Special attention in the experimental design was given to achieving unimpeded plume development; in preliminary tests a constant rate of flame propagation was established, with a propagating combustion zone of constant length.

Extension of a suggestion by Taylor (concerning the fluid dynamic criterion for blow-over of a two-dimensional plume in a crossflow) to the case of propagation of a line fire in a wind resulted in a simple expression for roughly estimating firespread rate in such an experiment. The model for the rate of flame propagation also has been applied to field-scale, forest-fire measurements. More definitive and comprehensive results await further experimentation and will be reported in a separate paper.

The authors are deeply indebted to George Carrier of Harvard University for many indispensable discussions on all aspects of the research.

The authors wish to thank Michael Frankel of the Defense Nuclear Agency for the opportunity to pursue this investigation; they are also grateful for assistance from Robert Flory and Ralph Wege. The participation of technicians Frank Farey, Kurt Hoover, Shuzo Sakurai, and Richard Yee is also acknowledged.

Finally, the authors are in indebted to Ann McCollum for preparation of the manuscript and to Asenatha McCauley for preparation of the figures. This work was carried out under Defense Nuclear Agency contracts DNA-001-83-C-0104 and DNA-001-83-C-0228.

REFERENCES


Received 28 March 1984; revised 18 May 1984