CRITERIA FOR ONSET OF FIRESTORMS

G. F. Carrier, F. E. Fendell, and P. S. Feldman
TRW Space and Technology Group, Redondo Beach, CA 90278

Quantitative criteria are evolved for onset of firestorms, severe stationary (nonpropagating) holocausts arising via merger of fires from multiple simultaneous ignitions in a heavily fuel-laden urban environment. Within an hour, surface-level radial inflow from all directions sustains a large-diameter convective column that eventually reaches altitude of about 10 km (e.g., Hamburg, Dresden, Hiroshima). As the firestorm achieves peak intensity (2-3 hours after the ignitions), inflow speeds are inferred to attain 25-50 m/s; typically 12 km^2 are reduced to ashes, before winds relax to ambient levels in six-to-nine hours. Here the firestorm is interpreted to be a mesocyclone (rotating severe local storm). Even with exceedingly large heat release sustained over a concentrated area, in the presence of a very nearly autoconvectively unstable atmospheric stratification, onset of vigorous swirling on the scale of two hours requires more than concentration of circulation associated with the rotation of the earth; rather, a preexisting, if weak, circulation appears necessary for firestorm cyclogenesis.

NOMENCLATURE

$B(z,t)$ = radius of preexisting mesoscale vortex, m
$B_o(z) = B(z,0)$, m
$b(z,t)$ = e-folding radial distance for plume variables, m
$b_i = b(0,t)$, m
c_p = specific heat capacity at constant pressure for air, m^2/s^2-K
E = time-average strength of maintained heat source, W
g = gravitational acceleration, m/s^2
r = cylindrical radial coordinate, m
$S(z,t)$ = angular momentum per mass derived from earth rotation, m^2/s
$T(r,z,t)$ = temperature, K
t = time, s
$V(z)$ = swirl speed of preexisting mesoscale vortex, m/s
$v(r,z,t)$ = azimuthal velocity component, m/s
$W(z,t)$ = centerline axial velocity component, m/s
z = axial distance above ground, m
z_i = distance from subterranean point source to ground, m

GREEK

$\alpha(r,z,t)$ = entrainment functional
α_o = value of α in the absence of rotation
$\Gamma_o(z) = B_o(z)\,V(z)$, m^2/s
ε = volumetric-flux equivalent of E, m^3/s
$\rho(r,z,t)$ = density, kg/m^3
Ω = component of angular velocity of earth locally perpendicular to surface, s^{-1}

SUBSCRIPTS

a = ambient quantity (function of z only)
i = initial, i.e., pertaining to z = 0
o = ambient quantity (function of z only)

INTRODUCTION

In the aftermath of the atomic bombing of Hiroshima, (1,2) and of the massive incendiary bombing of Hamburg (3-6) and Dresden (7), particularly virulent, long-lived, uncontrolled burning occurred that had few if any recorded precedents. About one-half hour after multiple simultaneous ignitions (in a heavily fuel-laden urban environment)(2,8), the fires merged to form a rather uniformly burning area of many square kilometers. Whereas the ambient winds were less than 5-6 m/s, the mass fire engendered radially inward winds at street level from all directions; about 2-3 hours after the initiating bombing, these winds reached a peak intensity of about 20 m/s, with some estimates by professional firefighters of 50 m/s. The radially inward wind apparently precluded spread beyond the initially ignited area, though virtually everything combustible within this region was burned before the winds subsided to moderate in speed and variable in direction about six hours after initiation. A single huge central convective column, into which the hot product gases flowed, rose to about 10 km. This rare nonpropagating fire, so distinct from more common ambient-wind-aided spreads, is termed a firestorm. The goal of the present investigation is to delineate, from thermohydrodynamic modeling, quantitative criteria for the onset of a firestorm; detailed description of the event at peak intensity is not the prime objective.

In the interpretation given here, the term firestrom is apt. In a conventional meteorological context, storm suggests cyclonic wind about a center of low surface pressure, with precipitation from convectively induced advection [i.e., from buoyancy-caused ascent and saturation of warm moist air, with (1) radial influx under continuity, and (2) possible attendant spin-up under conservation of angular momentum associated with earth rotation or some locally enhanced level]. Hence a firestorm is a "heat cyclone" (9), a mesolow in which the exothermicity of combustion, as distinguished from the condensation of water vapor, induces free convection. Just as firestorms are exceptional fire events, so mesolows (thunderstorms with organized rotation, also referred to as tornado cyclones and supercells) are uncommon relative to the total number of thunderstorms, and are characterized by horizontal scale of several kilometers and lifespan of about six hours (10). Further, just as the mesolow is characterized by towering cumulonimbi ascending through the depth of the troposphere to the tropopause, so the firestorm is characterized by a convective column ascending to exceptionally great height, e.g., 10-13 km at Hamburg.

The observation at low altitudes of appreciable radial influx from all directions toward the base of the centrally sited convective column corroborates, rather than contradicts, the primarily rotating nature of the bulk of the air motion. Investigation of the near-surface inflow layer near the center of a vigorously rotating airmass over a fixed flat surface shows that strong, purely swirling motion is altered to equally strong, purely radial influx near the ground, though immediately at the ground the non-slip constraint holds (11-13).

The firestorm is the exceptional event in that diffusive mechanisms normally relax spin-up, such that swirling is either modest or nil (14). Allusions to the parallel between firestorms and tropospheric storms in the general sense of strong convection accompanied by strong surface winds are frequent. However, pertinence of the dynamic characteristics of a rapidly rotating airmass above a relatively fixed flat surface plane has been emphasized by Ebert (9), Emmons (15) and Long (16); Ebert and Emmons suggest that the rotation of the air surrounding the plume suppresses entrainment such that the buoyant plume rises to exceptional altitude, while Emmons and Long note that radial near-surface inflow is consistent with rapid higher-level swirling. Here, quantitative description seeking onset criteria is undertaken. It may be remarked that the well-known propensity for long-range, spotting-type (discontinuous) spread of free-burning fire via firebrands in the event of firewhirls (17, 18) suggests that the spatially confined character of recorded firestorms yet may have exceptions.

ANALYSIS

If one neglects plume-scale rotation during spin-up, then, for adopted Gaussian-type profiles, the angular momentum is

$$rv(r,z,t)=S(z,t)\left\{1-\exp[-r^2/b^2(z,t)]\right\} + \Gamma_0(z)\left\{1-\exp[-r^2/B^2(z,t)]\right\},$$

where the angular momentum $\Gamma_0(z)$ of a (prescribed) preexisting mesoscale vortex is taken as invariant in time over the span of interest in firestorm onset. Applying conservation of angular momentum yields

$$\frac{\partial S}{\partial t} = 2\Omega\alpha bW, \quad \frac{\partial B^2}{\partial t} = -2\alpha bW. \qquad (2)$$

Since initially, $B(z,0) = B_0(z)$ and $\Gamma_0(z)$ is finite (see Table 1 for parameter values), since $S(z,0) = 0$ and $\Omega = O[(6h)^{-1}]$, and since the entrainment constant $\alpha = O(0.1)$ in a nonrotating atmosphere, it follows that spin-up times based on concentrating angular momentum derived from earth rotation occurs over too long a span to explain reported firestorm phenomena. Thus, the term involving S in (1) is discarded; the convectively induced advection engendered by the intense exothermicity serves to concentrate a preexisting vortex. Plausibility for such a preexisting vortex at Hamburg (derived in part from earlier air raids) is furnished by the fact that prior winds of 4-6 m/s were reported about 10 km from the firestorm site, but the site itself was in virtual calm (6,9).

The similarity solution for a buoyant plume from a point source of heat at $z = z_i$ in an adiabatic (neutrally stable) atmosphere (in which density variation with altitude is ignored to afford a closed-formed expression) is given by (19)

$$b = \frac{6}{5}\alpha_0(z+z_i), \quad W = \frac{5}{6\alpha_0}\left[\frac{18}{5\pi}\left(\frac{\alpha_0 \varepsilon g}{z+z_i}\right)\right]^{1/3}, \qquad (3)$$

where the entrainment constant α is given its classical value, and

$$\varepsilon = \frac{\bar{E}}{\rho_a(0)c_pT_a(0)}, \quad b_i = \frac{6}{5}\alpha_0 z_i. \qquad (4)$$

The subterranean site of the virtual source $(-z_i)$ has been chosen such that plume has (assigned) plausible radial scale b_i at ground level z=0; this procedure does admit finite mass and momentum flux, as well as buoyant flux. Equations (3)-(4) are used in (2) over the time interval before spin-up alters plume structure via introduction of an axial pressure gradient. The decrease of B^2 in time at fixed z, from (2), implies increased swirl v in time at fixed r and z, from (1). Computations for the parametric assignments of Table 1 suggest swirl speeds of O(20 m/s) are readily achieved for the lower troposphere just outside the plume. Presumably $\alpha = O(\alpha_0/10^2)$ after spin-up, such that reduction in entrainment results in roughly a doubling of the plume height. Some results are given in Figure 1.

CONCLUSIONS

Current estimates for firestorm-onset criteria are as follows: "(1) at least 8 pounds of combustible per square foot of fire area, (2) at least half of the structures in the area on fire simultaneously, (3) a wind of less than 8 miles per hour at the time, and (4) a minimum burning area of about half a square mile" (2, pp. 299-300). On the basis of the study described above, the following alternate criteria are proposed: (1) a localized heat release of order 10^{19} ergs/s sustained for at least 2-3 hours; (2) a preexisting weak vortex characterized near ground level by swirl of 4 m/s at about 8 km, such that preexisting angular momentum (per unit mass) near ground level is $3.2 \cdot 10^4$ m^2/s; (3) absence of a strong ambient crosswind, with less than 4 m/s perhaps being adequate constraint, but with total absence being even more conducive to firestorm onset; and (4) a very nearly dry-adiabatic lapse rate holding for the lowest few kilometers of the atmosphere. Lower-tropospheric spin-up to about 20 m/s within 2-3 h seems plausible under such criteria. If the exothermicity of combustibles is taken to be that of dry woody matter consumed readily in forest fires, which is $1.86 \cdot 10^4$ J/g or so, then the requisite fuel loading appears to be about four times the 8 pounds per square foot cited earlier, if an area of 12 km^2 is entailed and the burning continues at high intensity for 6 h (as reported at Hamburg). The onset of swirling near the convective-column edge may be abrupt in that it can rise from nearly nil levels to 20 m/s or so within a half hour. The background angular momentum associated with the rotation of the earth is inadequate for spin-up to the cited swirl speed on the scale of 2 hours or so.

Further work on plumes whose base temperatures are $O(10^3 K)$ and which are accompanied by significant swirl is impeded by the current absence of answers to the questions: (1) is the entrainment rate more properly related to mass entrainment [i.e., $\rho_a \lim_{r\to\infty} (ru)$] per unit of axial mass flux [$bW \lim_{r\to 0} \rho$], or to volume entrained [$\lim_{r\to\infty} (ru)$] per unit of axial volume flux (bW); (2) by how much is the entrainment coefficient reduced by an increase in swirl. Answers can be furnished experimentally only. In fact, it is clear from already published laboratory experiments on firewhirls (20) that reduction in entrainment with swirl is highly significant.

ACKNOWLEDGMENT

The authors are grateful to technical monitors Mike Frankel and Tom Kennedy for the opportunity to pursue this investigation. This work was supported by the Defense Nuclear Agency under contract DNA001-81-C-0111.

REFERENCES

1. H. Bond, ed., Fire and the Air War (National Fire Protection Agency, Boston, MA, 1946).

2. S. Glasstone and P. J. Dolan, eds., The Effects of Nuclear Weapons, 3rd ed. (U.S. Department of Defense and U.S. Department of Energy, Washington, D.C., 1977).

3. M. Caidin, The Night Hamburg Died (Ballantine, New York, NY, 1960).

4. G. Musgrove, Operation Gomorrah--The Hamburg Firestorm Raids (Jane's, New York, NY, 1981).

5. M. Middlebrook, The Battle of Hamburg--Allied Bombers against a German City in 1943 (Charles Scribner's Sons, New York, NY, 1981).

6. H. Brunswig, Feuersturm über Hamburg (Motorbuch, Stuttgart, Germany, 1981).

7. D. Irving, The Destruction of Dresden (Ballantine, New York, NY, 1965).

8. G. J. B. Fisher Incendiary Warfare (McGraw-Hill, New York, NY, 1946).

9. C. H. V. Ebert, "The Meteorological Factor in the Hamburg Fire Storm," Weatherwise 16, 70-75 (1963).

10. E. Brandes, "Mesocyclone Evolution and Tornadogenesis," Monthly Weather Review 106, 995-1011 (1978).

11. G. F. Carrier, "Swirling Flow Boundary Layers," Journal of Fluid Mechanics 49, 133-144 (1971).

12. O. R. Burggraf, K. Stewartson, and R. Belcher, "Boundary Layer Induced by a Potential Vortex," Physics of Fluids 14, 1821-1833 (1971).

13. G. F. Carrier and F. E. Fendell, "Analysis of the Near-Ground Wind Field of a Tornado with Steady and Spatially Varying Eddy Viscosity," in Wind Field and Trajectory Models for Tornado-Propelled Objects, Electric Power Research Institute, Palo Alto, CA, Report NP-748 (1978), pp. A-1--A-45.

14. P. Dergarabedian and F. Fendell, "Parameters Governing the Generation of Free Vortices," Physics of Fluids 10, 2293-2299 (1965).

15. H. W. Emmons, "Fundamental Problems of the Free Burning Fire," in Tenth Symposium (International) on Combustion (Combustion Institute, Pittsburgh, PA, 1965), pp. 951-964.

16. R. R. Long, "Fire Storms," Fire Research Abstracts and Reviews 9, 53-68 (1966).

17. H. E. Graham, "Fire Whirlwinds," Bulletin of the American Meteorological Society 36, 99-103 (1955).

18. S. L. Lee and J. M. Hellman, "Heat and Mass Transfer in Fire Research," in Advances in Heat Transfer, Vol. 10 (Academic, New York, NY, 1974), pp. 219-284.

19. B. R. Morton, G. Taylor, and J. S. Turner, "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proceedings of the Royal Society A234, 1-23 (1956).

20. H. W. Emmons and S.-J. Ying, "The Fire Whirl," in Eleventh Symposium (International) on Combustion (Combustion Institute, Pittsburgh, PA, 1967), pp. 475-488.

21. S.-J. Ying, "The Fire Whirl," Engineering Sciences Laboratory, Division of

Engineering and Applied Physics, Harvard University, Cambridge, MA (1965).

22. R. Schubert, "Examination of the Building Density and Fuel Loading in the Districts Eimsbüttel and Hammerbrook in the City of Hamburg as of July 1948," Stanford Research Institute, Menlo Park, CA, translation under Project MU-6464 (1969).

Table 1 NOMINAL VALUES FOR PARAMETERS

$B_o(0)$	$8.00 \cdot 10^5$ cm	α_o	$9.30 \cdot 10^{-2}$
b_i	$5.00 \cdot 10^4$ cm	$\Gamma_o(0)$	$3.20 \cdot 10^8$ cm^2/s
c_p	$1.00 \cdot 10^7$ cm^2/s^2-K	ε	$2.60 \cdot 10^{12}$ cm^3/s
E	$9.05 \cdot 10^{18}$ erg/s	γ	1.40
g	$9.80 \cdot 10^2$ cm/s^2	$\rho_a(0)$	$1.16 \cdot 10^{-3}$ g/cm^3
$T_a(0)$	$3.00 \cdot 10^2$ K		

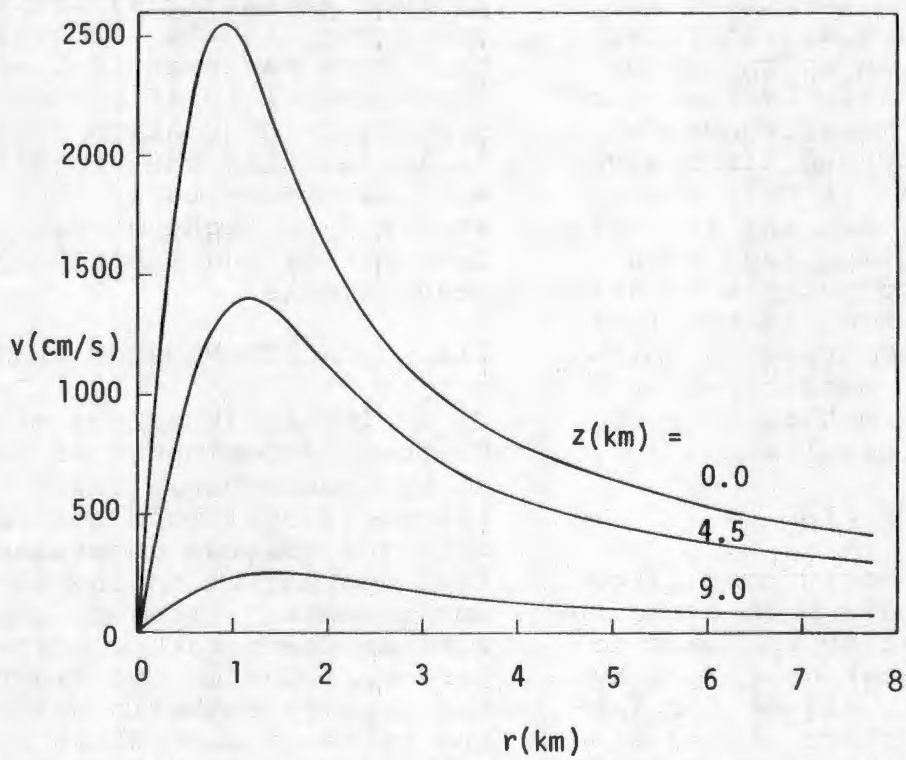

Figure 1 Swirl speed v, at time t=2.5 h at three altitudes z, vs. radial distance from the axis of symmetry r. The peak swirl occurs at r=1.12B, for fixed altitude and time, for the Oseen-type vortex adopted. Parameter values are those of Table 1 except here the volumetric flux of the heat source $\varepsilon = 2.586 \cdot 10^{12}$ cm^3/s.