THE LARGE URBAN FIRE ENVIRONMENT: TRENDS AND MODEL CITY PREDICTIONS

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ABSTRACT

The urban fire environment that would result from a megaton-yield nuclear weapon burst is considered. The dependence of temperatures and velocities on fire size, burning intensity, turbulence, and radiation is explored, and specific calculations for three model urban areas are presented. In all cases, high velocity fire winds are predicted. The model-city results show the influence of building density and urban sprawl on the fire environment. Additional calculations consider large-area fires with the burning intensity reduced in a blast-damaged urban center.

INTRODUCTION

Large urban fires have resulted from natural disasters, explosions, and wartime actions. In many cases, entire urban areas were totally destroyed despite firefighters' efforts to contain the flames. The World War II fire-bombing raids on European and Japanese population centers caused immense damage and hundreds of thousands of casualties. Several ignited firestorms, with hurricane-force winds, high street-level temperatures, high concentrations of carbon monoxide, and complete burning of all combustible materials within the fire boundaries. Firestorms also produced a high number of casualties, seldom ameliorated even by concerted rescue efforts.

Large urban fires are a much greater threat in the age of nuclear weapons then ever before. Hundreds of square kilometers of an urban (or wildland) area can be ignited simultaneously by a single-megaton nuclear weapon. Indeed, superfires of unprecedented size could dwarf the tremendous fires of World War II.

This paper presents predictions of the temperatures, pressures, and high-speed winds created by large urban fires (1). The dependence of those quantities on fire size, burning rate, and various other parameters is explored, and fires in model U.S. cities are examined. Simulations in which fires are extinguished in the center by blast are compared with those in which the fires continue to burn. The analysis used (2) may also be extended to obtain estimates of oxygen depletion and noxious gas buildup.

MODEL

The predictive model employed (2) focuses on the strongly buoyant flow generated in and around a large area fire. A finite-volume heat source is used to approximate the net effect of the combustion kinetics. A one-parameter eddy-viscosity model describes the turbulent stresses, and a graybody approximation is employed to model hot gas and smoke radiation. Jump conditions describe the rapid changes in physical quantities at the fire periphery. Those conditions allow the induced fire winds to be calculated directly without extensive far-field computations.

The model depends parametrically on the radius R and height H of the fire, the scale Q and spatial distribution q(r, y) of the heat addition rate, the radiation mean-free path $1/k^*$, and the eddy coefficients of momentum and heat transfer $\overline{\mathcal{E}}_1$, $\overline{k}_1$. A range of parameter values are used in the calculations.

SOLUTION DEPENDENCE ON FIRE SIZE, HEAT RELEASE, TURBULENCE, AND RADIATION

As a baseline case, a megaton-yield burst is assumed and the fire characterized by the following parameters (1, 3):

$$R = 10 \text{ km} \quad , \quad H = 100 \text{ m} \quad , \quad QH = 57 \text{ kcal/m}^2\text{-sec}$$

$$q(r, y) = \begin{cases} 1.6 & \text{for } y \leq 25 \text{ m} \\ 1.6\left(\dfrac{100 - y}{75}\right) & \text{for } 25 \text{ m} \leq y \leq 100 \text{ m} \quad , \\ 0 & \text{for } y \geq 100 \text{ m} \end{cases} \tag{1}$$

$$k^{*-1} = 20 \text{ m} \quad , \quad M_1 = K_1 = 0.2 \quad ,$$

M_1 and K_1 are the dimensionless eddy coefficients defined by

$$M_1 = \overline{\mathcal{E}}_1/UR \quad , \quad K_1 = \overline{k}_1/UR \quad , \quad U = (\gamma - 1)QR/\gamma P_a \tag{2}$$

with γ the ratio of specific heats and P_a the ground-level ambient pressure. The above values are representative of the model cities considered in the next section.

The near-fire velocity and temperature fields predicted for the baseline case are shown in Figs. 1 and 2. These plots are typical of the results obtained for the model cities. In all cases, the induced inflow is strongly turned upward across the width of the burning region, and the high temperatures in the fire region decay rapidly with altitude.

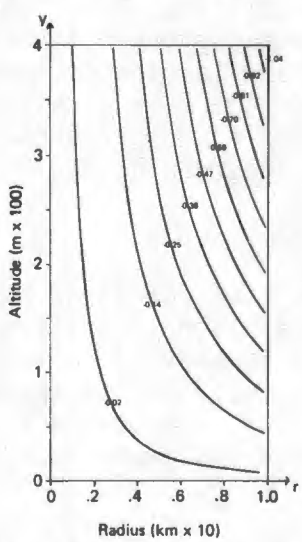

Fig. 1. Flow field streamlines, baseline fire.

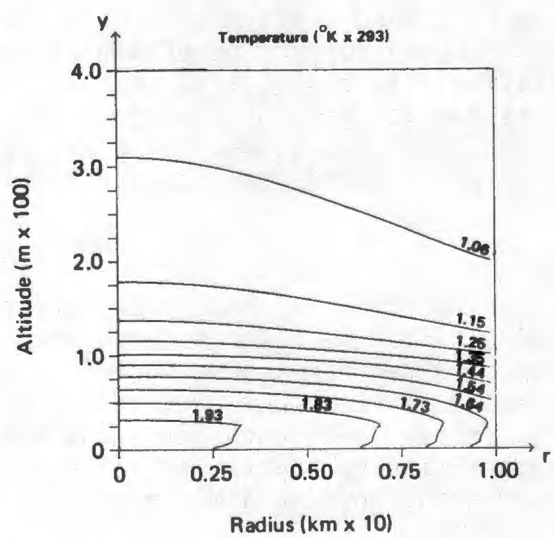

Fig. 2. Temperature contours, baseline fire.

The dependence of the fire-wind velocity and temperature with fire size, heat release, turbulence, and radiation is summarized in Figs. 3 and 4, and Table 1. The maximum induced velocity u_{max} and the maximum temperature T_{max} both increase with either radius (fire size) or intensity (fuel loading). The increases are nearly linear for relatively small radii and heating rates, but tail off markedly at larger radii and higher intensities.

Table 1 describes the basic dependence of fire winds and temperatures on the remaining factors: fire height, spatial distribution of the heat release, turbulence, and radiation. As expected, temperatures and velocities are increased when the radiation is reduced ($1/k^*$ increased (2)), and velocities are decreased when the turbulent stresses (i.e., M_1) are increased. The fire-wind environment is relatively insensitive to changes in the turbulent heat transfer (K_1), implying that the burning-region energy balance is principally controlled by the combustive heat release, convection and radiation. When the fire height H (QH fixed) is increased, temperatures drop. Correspondingly lower velocities do not occur, however, since a smaller fraction of the heat release QH is radiated away at the lower temperatures and higher kinetic energies are supported. This basic dependence on the fire-wind environment on fire height suggests that hydrocode simulations of the environment should employ a volume heat source instead of a prescribed heat influx at the ground surface.

Several variations in heat release distribution have been considered (1). As expected, relatively high frequency perturbations have little effect on the fire-wind environment. At lower frequencies, forced oscillations in the temperature field develop but the velocity field is still relatively unaffected. The gross features of fire-wind flows (e.g., velocity and temperature maxima) are thus primarily dependent on the total heat-release rates and not details of the fuel bed. The data base required to make predictions for specific cities may thus be minimized.

An additional excursion compares the results for the fully-circular (10 km radius) baseline fire with those for a similar but annular fire of inner radius 5 km. The results are quite similar. The annular-fire winds also blow in toward the symmetry axis and upward at all points. This suggests that the environment generated by nuclear-weapon-ignited urban fires may be relatively insensitive to changes in the geometry and loading of the central, blast-damaged region. In addition, as sketched in Fig. 5, a cluster of separated large fires, such as could result from multiple nuclear bursts over a large city, might coalesce and engulf much of the intervening region.

MODEL CITY PREDICTIONS

Predictions of the large-fire environment are made for three model U.S. cities, which we refer to as W, M, and E. City W is lightly built-up, and intended to represent new, sprawling cities. City E is heavily built-up, and intended to represent old, congested cities. City M is of intermediate building density. For each city, two cases are considered: a baseline fire and one modified by blast. In all cases, the fire radius is taken to 12 km (corresponding to a 1 Mt burst (3)).

Few metropolitan areas are axisymmetric. Nevertheless, most cities have a main business district with high-rise office and apartment buildings,

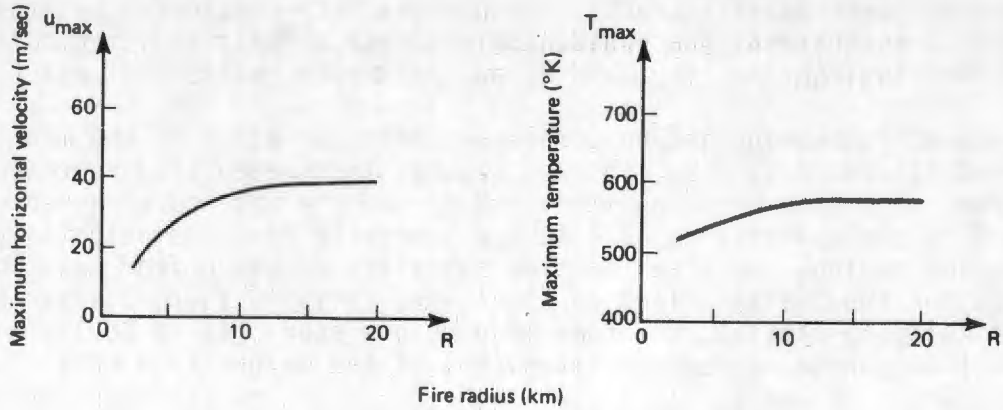

Fig. 3. Dependence of maximum radial velocity and temperature on fire radius.

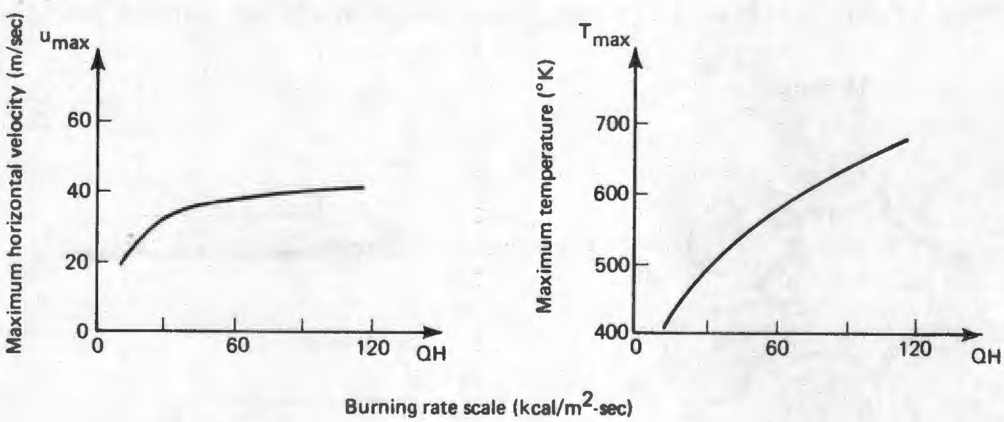

Fig. 4. Dependence of maximum radial velocity and temperature on burning rate scale.

Table 1--Dependence of temperature and radial velocity on other parameters

Parameter	Variation	Resulting Change in T--Temperature	Resulting Change in U--Radial Velocity
H--Fire Height	Increase	Decrease	Increase
q(r, y)--Heat Release Distribution	Radial Oscillations of Various Types	Oscillations	None
M_1--Eddy Coefficient: Momentum	Increase	None	Decrease
K_1--Eddy Coefficient: Heat	Increase	None	None
k^{*-1}--Radiation Mean Free Path	Increase	Increase	Increase

surrounded by lower density tracts. Each model city considered has three regions: a tall central city; a residential/industrial belt of intermediate height around the central city; and a low, primarily residential outer belt.

The basic dimensions and heat release characteristics of the model cities are defined (1) in Figs. 6-8. In each figure, the shaded area represents the assumed fuel zone (one building story ~ 3 m) and the hatched area represents the resulting combustion zone (2.4 to 5.0 times the fuel-bed height). For each baseline region, the areal heating rates are computed from assumed average values for the building land to total land ratio (0.15 to 0.40), the number of building stories, the fuel loading per story (16 to 20 lb/ft^2), and the overall burn rate for combustibles (90% of the weight in 3 hrs).

For the blast-modified cases, the weapon burst is assumed to occur over the city center, leveling many buildings in the central city and inner belt. The height of each fuel zone is thus assumed constant and equal to its baseline outer-belt value. The total height of the combustion zone is chosen similarly. The areal heating rate is not however independent of radius. The combustibles of the central city and inner belt would be spread radially by

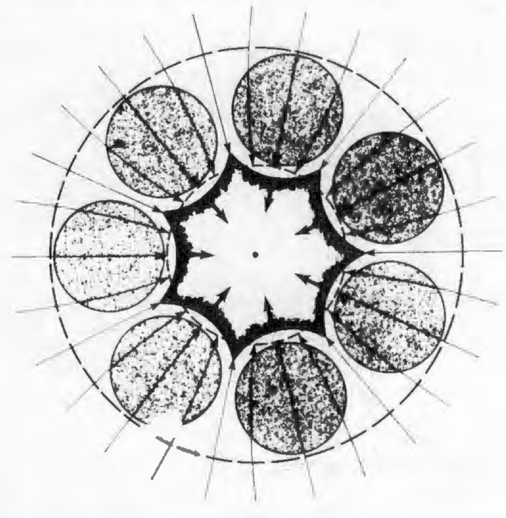

Fig. 5. Radial airflow and fire spread patterns suggested for annular cluster of large area fires.

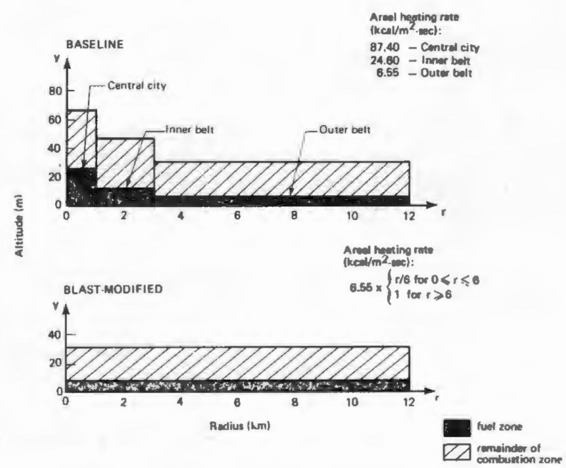

Fig. 6. Fire schematic for baseline and blast-modified city W.

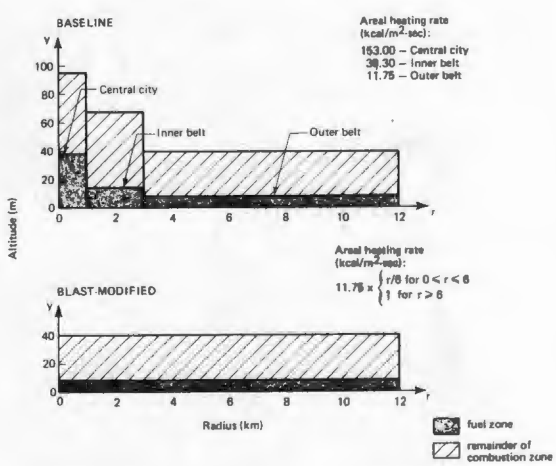

Fig. 7. Fire schematic for baseline and blast-modified city M.

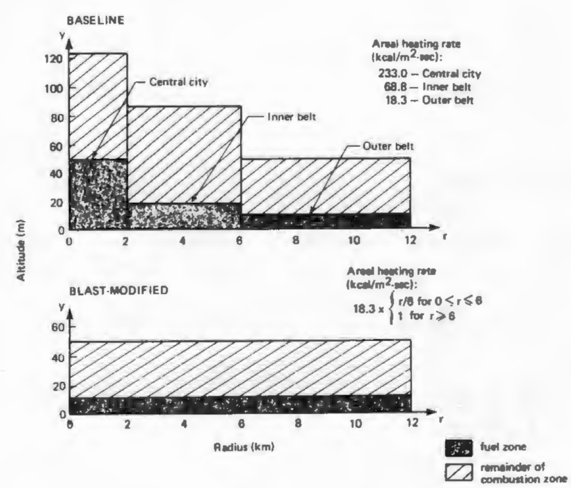

Fig. 8. Fire schematic for baseline and blast-modified city E.

the blast, and piled up in a debris field. Since some combustibles in that zone may be buried under layers of nonflammable materials (e.g., concrete, brick, metal), the areal heating rate is not expected to be correspondingly higher and may in fact be relatively small. We thus assume that the heating rate is zero at the city center, increases linearly with radius over a debris zone extending out 6 km from the center (3), and equals its baseline outer-belt value for radii greater than 6 km.

The resulting model city predictions are summarized in Table 2. As expected, the baseline predictions are uniformly larger than the blast-modified ones. The differences are significant for the temperature, pressure and vertical velocity, but small for the radial velocity. The winds and wind damage resulting from nuclear-weapon-ignited fires may be relatively insensitive to the blast disruption of the fuel bed.

The predictions in Table 2 indicate that the winds generated by a large urban fire will in themselves constitute a major threat. Although most of the velocities in the table are less than hurricane force (more than 30 m/sec), it should be noted that those values represent *means*. Near street level, where fire winds will be channeled between buildings, hurricane force winds may be typical. The winds may be even greater than those encountered in the 1943 Hamburg firestorm (2).

The velocity, temperature, and pressure predictions in Table 2 are all greatest for city E (the tallest and densest) and least for city W (the shortest and sparsest). For a given fire, therefore, the threat will be most severe for the most congested cities. In general, however, the shorter cities sprawl out over greater areas than do taller ones of comparable population, and are thus capable of supporting more widespread fires. Multiple weapon bursts can greatly increase the fire severity in such cities.

Table 2--Velocity, temperature, and perturbation pressure maxima in model city simulations

	City			City		
	W	M	E	W	M	E
	Radial Velocity (m/sec)			*Vertical Velocity (m/sec)*		
Baseline	20.2	26.3	39.0	0.89	3.12	12.48
Blast-Modified	17.9	23.9	28.5	0.37	1.56	4.32
	Temperature (°K)			*Perturbation Pressure (psi)*		
Baseline	577	619	704	0.056	0.113	0.271
Blast-Modified	455	485	510	0.011	0.044	0.076

DISCUSSION

The results presented here provide basic predictions of the fire-wind velocities and temperatures that would occur in and around large urban fires caused by megaton-yield nuclear weapon bursts. The dependence of winds and temperatures on fire size, heat release, and other parameters is described, and model-city simulations are summarized. The results should be applicable to fire damage evaluations, rescue planning, and definition of shelter requirements.

In general, hurricane-force winds are predicted. Velocities increase with fire width and the magnitude of the heat-release rate, but are rather insensitive to spatial variations in that rate. Predicted flow fields are all qualitatively the same, with the fire winds directed (radially) inward and upward everywhere. Such winds are expected to spread the flames into central, blast-extinguished regions, and to foster fire spread between clusters of fires caused by multiple weapon bursts.

In the model-city simulations, a range of fuel distributions and heat-release rates were developed to explore the effects of varying city construction and fuel loading. Those distributions and rates were sectionally uniform, but could easily be replaced in further simulations by more refined quantities based on surveys of actual cities. The most severe fires should occur in the higher density cities, though even low density regions can support hurricane-force winds if they are large enough. Application of these results to definition of shelter hardness (thermal) would imply different criteria for the different types of cities.

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