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MASS FIRE MODEL CONCEPT

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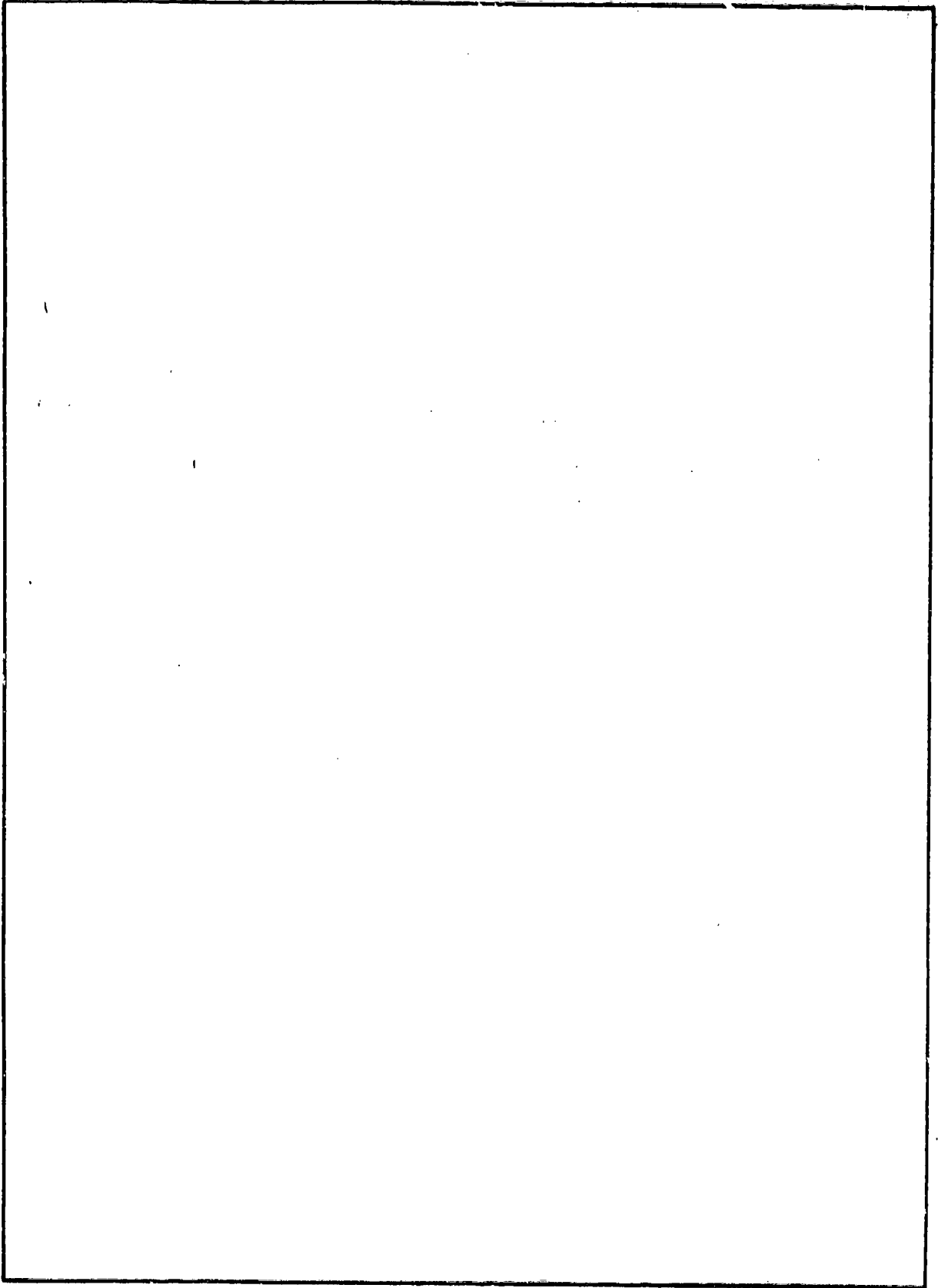
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SECTION 1

INTRODUCTION

This section presents information that is introductory to the following sections. However, it goes beyond a simple introduction by incorporating a summary of this report together with conclusions drawn from the work performed, and recommendations regarding future related work.

1.1 BACKGROUND

The purpose of developing a model of urban mass fires is to predict the spread, development, and ultimate effects of uncontrolled urban fires. The model predictions need to be in sufficient detail and accuracy to provide decision makers with information regarding the mitigation and/or encouragement of selected mass fire effects. As always, the ideal is precise and accurate predictions. However, the detail and precision that can be useful to decision makers may be far less than that required by fire phenomenology researchers.

For these reasons, and in the interest of providing decision makers with a (minimally useful) model as early as possible, we have defined a mass fire model concept and developed a demonstration implementation of the concept. It is anticipated that the phenomenology models employed may be criticized as being premature, imprecise, and/or insufficiently substantiated by empirical data. We agree, beforehand, with these allegations. The evolutionary concept of simulation development demands that the physical models be continuously subject to improvement.

This work is concerned with simulating fires initiated in urban areas by nuclear detonations. Such fires are characterized by a large number of more or less simultaneous ignitions distributed over an area perhaps hundreds of square kilometers in extent. The only fire behavior experience, which approaches these circumstances, is limited to the mass fires of World War II. These mass fires resulted from conventional incendiary bombing of German and Japanese cities and from the nuclear detonations over Hiroshima and Nagasaki. In addition, some large wildland fires, burning in heavy fuels and rapidly propagating by branding far ahead of the main fire front, may have produced sufficient densities of discrete ignitions to have approximated mass fire conditions.

Observer reports and ex post facto reconstructions of these events establish some qualitative and semiquantitative features of mass fires, which a valid model must replicate, but which alone cannot furnish a sufficient basis for developing a model of mass fire behavior. A model of urban mass fire behavior, thus, cannot be totally based upon the results of full scale empirical observations. The data are either inadequate or nonexistent, and are likely to remain so. Enough documented fire behavior experience does exist, however, to provide critical checks upon the results of any mass fire behavior model. For example, a useful fire behavior model should replicate the development of the Hamburg fire storm, as well as the failure of fire storms to develop in Berlin.

In the development of a computerized simulation of physical phenomena, it is important to address the computational basis of the simulation as well as its physical basis. Complete knowledge of the relevant physical processes will not assure development of a useful simulation, unless suitably timely, detailed, accurate, and economical computations are possible.

The work described in this report addresses both of these aspects of the problem by describing a concept for a computerized simulation of mass fire behavior, which incorporates physically based fire phenomenology models.

1.2 CONCLUSIONS AND RECOMMENDATIONS

The most important results of this work are the model concept and the demonstration model. The demonstration model is an implementation of the model concept in simplified form. The demonstration model shows the feasibility of developing a computerized simulation of mass fires based on the concept described in Section 4. Additionally, the demonstration model has potential for both short-term and long-term utility.

In the short term, it is recommended that the physical realism of the fire phenomenology models be improved, that the simulation be calibrated and that parametric results be generated. In the construction of the demonstration model, it was not possible to address the fire phenomenology models in the required detail. Consequently, a great deal of improvement in overall model realism can be accomplished with a modest investment to improve the phenomenology models.

1.2.1 Hydrodynamic Modeling

The total atmospheric perturbation, and the part of it describing street level winds, is essential not only to describe mass fire conditions but also to model the spread and development of an urban mass fire. The coarse resolution global atmospheric hydrodynamics of a large area fire is a useful, but limited, approach. Both experimental and theoretical evidence indicates that the actual distribution of separated fires, and the spontaneous breakup of area fires into separate columns exercise major influence upon fire-induced winds. Not necessarily to the

exclusion of other approaches, our model concept opts for a hydrocalculation based upon parameterized multiple plume properties, which can incorporate the requisite resolution. The feasibility, in principle, of this approach is shown by the demonstration model, but further investigation and theoretical study is required to develop these ideas into reliable computational procedures.

1.2.2 Branding and Contagion

Limits of spatial resolution, uncertainties of fuel properties, and insufficient understanding of phenomenology are difficulties that models of spread mechanisms in urban fires must confront, even when hydrodynamic flow fields are specified. Our demonstration model includes the two propagation mechanisms of branding and contagion (flaming contact). Radiative ignition is omitted, but could be included as well. Some aspects of these spread mechanisms are amenable to simple physical estimation. An important goal is to improve the estimates and extend the areas in which estimates can be made beyond the level presently employed in the demonstration model. Where possible, physical estimates inspire confidence not otherwise obtainable. In view of the difficulties mentioned above, there are definite limits upon these physical refinements and the degree to which they could be used to model propagation mechanisms. Recognition of these limits and their implications for modeling procedures is an important research effort in model development.

1.2.3 Simulation Grid and Subgrid Characteristics

From consideration of the tradeoffs between the desire for detail and accuracy, and the need for computational economy and storage efficiency, it was decided that the demonstration model would employ a spatial grid of city block sized elements (i.e., cells). Over these cells, uniform values of variables and effects would be assumed. For

example, a cell would be characterized by a fuel type, the wind velocity would be constant over a cell, and combustion would be (spatially) uniform over a cell. City block sized grid cells are physically appropriate in that each cell is, thus, surrounded by a line fuel break (i.e., street) of specifiable width. In this grid configuration, the fire, in order to spread, must be able to propagate over the streets. In the process of developing and debugging the demonstration simulation, it became clear that the city block sized resolution was insufficient to describe effects to a city block sized level of detail. For example, ignition of a non-burning cell by a burning cell depends on how and where the fuel is burning within the ignited cell. Indeed, it was necessary to incorporate some subgrid detail in the demonstration model. The grid structure employed and the nature and detail of the subgrid calculations can significantly impact the computational economy and storage efficiency of any mass fire model. For these reasons, it is recommended that a more detailed study be made of the simulation grid structure and the nature and detail of the subgrid calculations to be employed. This study should recognize that these two subjects are not independent and that they both relate to the problem of fuel specification.

The simulation can be calibrated against historical data on large fires and should be able to replicate at least gross details of known situations. A model, calibrated to even this degree, is of potential use to decision makers. Parametric studies of historical fires in which selected parameters are varied to produce fire effects as a function of the varied parameter will provide additional, sensitivity information for use by decision makers.

In the long term, the structure of the demonstration model will provide the vehicle for an evolving mass fire simulation. An intimate understanding of the need for, and the nature of evolving simulations is explicit in the design of the demonstration model structure. It readily

allows for modification of existing, or incorporation of new, computation processes and data types.

1.3 SUMMARY

Section 2 presents a succinct description of the state-of-the-art in urban mass fire modeling. An exhaustive review of the literature was not attempted; however, the important sources are discussed and referenced. It was found that, although work is in progress on the constituent parts of a mass fire behavior model, no satisfactory model exists.

Section 3 describes the USDA Forest Service-developed Rothermel model that has been used to predict the behavior of fires in lower level (grass, brush, etc.) wildland fuels. The Rothermel model is described in considerable detail in order to clearly point out why it is considered inappropriate for describing fires in an urban environment.

Section 4 presents the physical basis for a computerized simulation of the initialization and spread of uncontrolled urban fires, including the onset and development of mass fires. Such a simulation must incorporate physically based models of all the pertinent phenomena. These models must parametrically define cause-effect relationships for all of the important variables and variable interactions involved in the effects to be simulated. The required physically-based phenomenology models are described and discussed in detail. Particular emphasis is placed on the development of useful (as opposed to ideal) phenomenological models for timely incorporation in a mass fire simulation.

Section 5 presents the computational basis for a computerized simulation of urban mass fires. A demonstration version of the simulation is described in terms of the overall simulation structure, the mathematical and logic structure of each major model, and data entry, management, and output.

Section 6 presents sample results for eleven example cases. These cases involve different initial ignition densities and patterns, together with different initial ambient wind conditions. These results show the initiation and development of uncontrolled urban fires in terms of fire geometry, heat production rates, and wind velocities.

SECTION 2

MASS FIRE MODELING (STATE-OF-THE-ART)

2.1 SUMMARY

There presently exists no satisfactory model by which the development of nuclear-induced urban fires may be described. Research into the constituent mechanisms required as components of such a model is in progress, but model development need not wait for this research to be completed. Modeling is possible at any state of knowledge, and, with proper structuring, can be done in an open-ended fashion to incorporate new knowledge when it develops.

Significant advances of understanding have been acquired since the existing models were devised. The need to incorporate fire spread and mass fire phenomena as related parts of a unified simulation is the major requirement, which can be met at this time. The potentially lengthy and costly effort to determine fuel properties and inventories can be guided by the degree to which any practical model can make use of them.

2.2 BACKGROUND

The initiation, development, and effects of mass fires resulting from nuclear attack on urban areas has been a problem of concern since the advent of nuclear weapons. Investigations motivated by this problem have amassed a volume of material, dealing with its various aspects, which is summarized in the review of Martin (Reference 1), supplemented by the recent report of Small and Brode (Reference 2). Both of these documents

contain extensive bibliographies. Since 1978, the Defense Civil Preparedness Agency, now part of the Federal Emergency Management Agency, has sponsored an integrated research program aimed at achieving a reliable method for predicting the incendiary outcome of nuclear attack. A periodic report and assessment of this program has been published yearly (References 3 and 4). The following discussion here does not attempt to repeat these general surveys, but focuses specifically upon certain modeling problems.

2.3 INITIAL CONDITIONS

Much of the previous and presently ongoing research is devoted to establishing the initial fire conditions resulting from nuclear attack. The effect of the thermal pulse, as modified by distance and atmospheric conditions, in producing ignition of various inflammable materials exposed to it; the potential of these ignitions to spread and result in full building involvement; and the effect of blast to (1) alter substantially the fuel properties and distribution; (2) to extinguish or enhance primary ignitions; and (3) to produce secondary ignitions by breakage of gas and power lines are all important aspects of the initiation problem (Reference 4). These very important processes, which others are investigating, are not our direct concern here. Given the initial conditions (of both ignitions and fuel), we are interested in modeling the fire development.

Though not our immediate concern, the faithful incorporation of these very detailed mechanisms to initialize a model is an outstanding problem. Given uncertainties of structural behavior and the impossibility of resolving small detail in a city-wide simulation, some judicious modeling choices are required, even assuming adequate understanding of basic mechanisms.

2.4 SPREAD MODELS

Existing fire spread models are reviewed by Weisbecker and Lee (Reference 5) and Alger and Martin (Reference 3). Many models of fire spread within compartments and buildings have been built, but attempts at spread models on a city-wide scale are limited to three models. These are the SSI (Scientific Services, Inc.), the URS (URS Research Company), and the IITRI (Illinois Institute of Technology Research Institute) models and their modifications. Relying upon the conclusions of the papers cited above, it appears that all of these models (which were developed in the late 1960's) may suffer serious defects.

All of these models stress fuel distributions, which are incorporated at a level of detail ranging from high detail (actual building and content surveys) in the SSI model to use-factor classification of areas in the URS and IITRI models. Fuel representation does not account for blast damage, which is viewed as a serious restriction. The basic spread mechanism of all these models is radiative contagion, with some simplified spread by firebrands in the IITRI and URS models. The failure to adequately model fire parameters, upon which these processes depend, is considered a shortcoming. In practice these models spread the fire in a stochastic manner, based upon fuel type. A final, and perhaps decisive, criticism of these pioneering models is their lack of any interactive features of mass fire phenomena, fire-induced winds, their effect upon spread, and plume coalescence.

Consistent with the Project Flambeau results, we do not agree with the emphasis upon radiation as a primary spread mechanism, but believe that both branding and flame contact are of equal, if not greater, importance. Mass fire phenomena are essential to determine spread. Without minimizing the true role of fuel properties, it may be that this problem aspect has been overemphasized in the past. Resolution limitations will, in any model, limit the detail of fuel descriptions.

In any case, the accumulation of understanding permits substantial improvement upon these early spread models.

2.5 FIRESTORM MODELS

The presence of strong, hurricane-force winds directed radially inward toward the large urban fires of WWII has prompted diverse attempts to understand and model this phenomenon, called a "firestorm."

An analysis of historical experience (Reference 6) established some preliminary conditions thought necessary for firestorm phenomena. By employing historical analysis in conjunction with modeling, Lommanssen, et al (Reference 7) developed buildup and existence criteria for firestorms. Firestorm criteria were also developed (Reference 8) on the basis of WWII experience and empirical data on flame merging.

The need for experimental data motivated two programs to test the behavior of large fires: the Flambeau program (References 9 and 10), and the Euroka fire in Australia (Reference 11), a fire of 260 meter radius. The data from these fires, though none were as large as an urban mass fire, fills an important gap between historical mass fires and laboratory fires. We have found the insights reported by Countryman from the Flambeau program especially valuable.

Aside from fire plume modeling, done by several investigators, the theoretical work of Nielsen (Reference 12) and Nielsen and Tao (Reference 13) specifically models the global hydrodynamics of a large urban fire. Recently, a new approach to atmospheric disturbances and physical parameters of large area fires has been initiated (Reference 2). Some detailed, two-dimensional analytic models of fire plumes in the atmosphere have been published (References 14 through 17).

We believe the hydrodynamic properties of urban mass fires to be of central importance. The extent to which global (low-resolution) hydrodynamics is sufficient needs further examination. The firestorm phenomenon, however, is only one aspect of the problem. The hydrodynamic modeling must be broadly enough structured to encompass any developmental behavior which occurs. A good part of the problem is to understand what can happen.

2.6 WILDLAND FIRES

Our task excludes wildland fires, but any discussion of the state-of-the-art for modeling large fires must take cognizance of the Rothermel Model (Reference 18), which occupies a unique status as the only well-verified spread model in existence. This model, its limitations, and possible applicability to the urban fire problem, are examined in detail in Section 3.

SECTION 3

ANALYSIS OF ROTHERMEL RATE OF SPREAD EQUATION

3.1 SUMMARY AND CONCLUSIONS

The Rothermel rate of spread (RROS) equation (Reference 18) for estimating localized rate of fire spread in a homogeneous fuel bed is described in terms of a qualitative theoretical basis and a quantitative empirical definition. Generalizations of the basic rate of spread equation are described that allow estimation of fire spread rates over an area of interest in heterogeneous, natural understory fuels. It is shown that local scalar spread rate is necessary but insufficient to allow fire growth estimates to be made. A fire front propagation algorithm and a local directional spread rate algorithm are described, together with local scalar spread rate, that provide a computational procedure for estimating the growth of wildland fires. Difficulties associated with input data acquisition and data management resulting from the fuel characteristics required by the rate of spread equation are discussed and their resolution is described.

The Rothermel rate of spread equation is demonstrably suitable (Reference 19) for estimating the growth of free burning fires in lower story, natural fuels. From the analyses described here, and in the referenced report, it is concluded that the Rothermel equation is of limited utility in estimating the growth of urban fires for the following reasons:

1. The quantitative coefficients of the RROS equation are valid only for understory natural fuels (i.e., grass, brush, etc.). They were experimentally determined from

laboratory fires in continuous fuel beds where the fuel was simulated by uniform, homogeneous constructs of uniform fuel particles and the environment was simulated by a wind tunnel.

2. The fire front propagation and local directional spread rate algorithms, required for wildland fire growth estimates were developed specifically for understory natural fuels and are not applicable to estimating the growth of fires in an urban fire environment.
3. It is explicit in the quantitative coefficients of the RROS equation that wildland fires in natural understory fuels are largely propagated by the combustion of loosely packed fine fuels at the periphery of the fire; loosely packed fine fuels do not occur in significant quantities in urban fuel beds.
4. The RROS equation describes a free burning fire in which venting effects are quantitatively controlled by fuel packing. In an urban fire venting effects are generally controlled by the building structure within which the fire is burning.
5. Wind effects in the RROS equation are open loop; it has wind-fire coupling, but no fire-wind coupling.
6. The effects of branding are not addressed by the RROS equation.
7. It is not economically nor physically practicable to experimentally quantify the detailed interparticle heat exchange mechanisms for all urban fuels of interest in analogy with the experiments that were performed for natural fuels.
8. There is no mechanism in the RROS for allowing fire propagation across a break in the fuel bed, analogous to a street in the urban environment.

The RROS can be used to describe fire growth in significant areas of natural fuels within the urban environments of interest. Even for this purpose, however, modifications will be necessary to account for trees and the energy release rate of unconsumed fuels burning within the fire perimeter. These conclusions regarding the inapplicability of the RROS equation to the growth of urban fires contribute nothing positive toward the solution of this problem. However, Section 4 of this report presents a methodology for describing the growth of fires in urban environments of interest.

3.2 THEORETICAL BASIS

The theoretical basis of the RROS is largely due to Fons (Reference 20), Tarifa and Torralbo (Reference 21), and Frandsen (Reference 22). Fons was the first to describe fire spread by a mathematical model. The Fons model embodied a contagion concept in which fire spread in a fuel bed is considered to consist of successive ignitions occurring at a rate controlled primarily by the ignition times and distances between successive fuel particles. Tarifa and Torralbo confirmed Fons' ideas by showing that heating of the fuel ahead of a progressing flame front is the first and most essential process of the flame propagation mechanism. Frandsen applied the principle of energy conservation to a unit volume of fuel ahead of an advancing flame front in a homogeneous fuel bed to obtain the following expression for the quasi-steady rate of fire spread:

$$R = \frac{I_{xig} + \int_{-\infty}^0 (\partial I_z / \partial z)_{z_c} dx}{\rho_{be} Q_{ig}} \quad (3-1)$$

where

R = quasi-steady rate of spread (ft/min)

I_{xig} = horizontal heat flux absorbed by a unit volume of fuel at the time of ignition (Btu/ft²-min)

ρ_{be} = effective bulk density (the amount of fuel per unit volume of the fuel bed raised to ignition temperature ahead of the advancing fire) (lb/ft³)

$(\partial I_z / \partial z)_{z_c}$ = the gradient of the vertical intensity evaluated in a plane at a constant depth, z_c , of the fuel bed (Btu/ft-min)

Q_{ig} = heat of ignition of unit volume of fuel (Btu/lb).

Equation 3-1 is a theoretically rigorous description of the rate of spread of a line fire through a homogeneous fuel bed of uniform depth in terms of a ratio of the heat flux received by, to the heat required for ignition of, a unit volume of fuel ahead of the advancing flame front. Equation 3-1 contains heat flux terms for which the mechanisms of heat transfer are not known, and consequently, it cannot be solved analytically. Definition of an approximate form of Equation 3-1 that can be solved analytically resulted from examination of each term and determination of analytical and empirical methods for evaluating the unknown mechanisms of heat transfer (Reference 18).

The form of Equation 3-1 was simplified by the definition of the following set of terms.

3.2.1 Effective Heating Number

The amount of fuel involved in the ignition process is specified in the denominator of Equation 3-1 as the effective bulk density ρ_{be} . The effective heating number ϵ is defined as the dimensionless ratio of the effective bulk density to the actual bulk density. Hence,

$$\epsilon = \rho_{be} / \rho_b \quad (3-2)$$

3.2.2 Propagating Flux

The numerator of 3-1 is defined to be the propagating flux I_p where

$$I_p = I_{xig} + \int_{-\infty}^0 (\partial I_z / \partial z)_{z_c} dx \quad (3-3)$$

The propagating flux consists of two terms, the horizontal flux and the cumulative gradient of the vertical flux up to the fire front. The vertical flux is most significant for wind driven and upslope fires, for which there is an effective flame tilt and an increased heat transfer to the unignited fuel by radiation, convection, and conduction. It is assumed that the vertical flux is small for no slope, no wind fires; and the heat flux for these conditions is defined as

$$(I_p)_0 = I_{xig} \quad (3-4)$$

3.2.3 Reaction Intensity

The energy release rate of the fire front produced by burning gases resulting from pyrolysis of the fuel bed ahead of the fire front is defined as the reaction intensity I_r where

$$I_r = -h(dw/dt) \quad (3-5)$$

and

dw/dt = mass loss rate per unit area in the fire front, (lb/ft²-min)

h = heat content of fuel (Btu/lb).

The reaction intensity is the source of the no wind propagating flux, $(I_p)_0$, and it is assumed that the no wind propagating flux and the reaction intensity I_r can be evaluated independently and then correlated. Thus, the coefficient relating $(I_p)_0$ and I_r is

$$\xi = \frac{(I_p)_0}{I_r} \quad (3-6)$$

Knowledge of this correlation will allow $(I_p)_0$ to be determined from I_r , which can be determined from parameters that describe the fuel bed complex.

3.2.4 The Effects of Wind and Slope

The effects of wind and slope are defined as changes in the propagating heat flux, that alter the heat received by potential fuels due to convection and radiation. Based on the assumptions that the contribution of the vertical intensity $(\partial I/\partial z)$ to $(I_p)_0$ is small and that the effects of wind and slope on the propagating flux are independent, the total propagating flux is defined to be of the form

$$I_p = (I_p)_0 \cdot (1 + \phi_w + \phi_s) \quad (3-7)$$

where

ϕ_w = a dimensionless coefficient dependent on wind speed,

ϕ_s = a dimensionless coefficient dependent on slope.

3.3 EMPIRICAL DEFINITIONS

Substitution of Equations 3-2 through 3-7 into Equation 3-1 yields the Rothermel rate of spread (RROS) equation in the form

$$R = I_r \epsilon \frac{(1 + \phi_w + \phi_s)}{\rho_b \epsilon Q_{fg}} \quad (\text{ft/min}) \quad (3-8)$$

Each term of Equation 3-7 was analyzed and transformed into a format appropriate for experimental quantification. This resulted in a set of experimentally determined relationships by which rate of spread estimates can be obtained from 3-8 in terms of parameters describing the fuel bed, terrain slope, and wind speed (Reference 18). These experimentally determined relationships (Reference 7) are given in Table 3-1.

The use of Equations 3-8 through 3-26 to provide estimation of fire spread rate requires specification of the parameters shown in Table 3-2.

3.4 GENERALIZATION OF THE ROTHERMEL RATE OF SPREAD (RROS) EQUATION

The RROS equation given by Equations 3-8 through 3-26 provides local rate of spread in a homogeneous fuel bed. Use of the RROS equation in describing a propagating fire front necessitates generalization to include spread rates for heterogeneous fuels distributed over an area.

Table 3-1. Defining equations for RROS equation.

Equation	Description	Equation Number
$I_r = r'_w \eta_n \eta_M \eta_s$	Reaction intensity (Btu/ft ² -min)	(3-9)
where:		
$r' = r'_{\max} (\beta/\beta_{op})^A \exp[A(1-\beta/\beta_{op})]$	Optimum reaction velocity (min ⁻¹)	(3-10)
$r'_{\max} = \sigma^{1.5} (495 + .0594\sigma^{1.5})^{-1}$	Maximum reaction velocity (min ⁻¹)	(3-11)
$\beta_{op} = 3.348\sigma^{-.8189}$	Optimum packing ratio	(3-12)
$A = 1/(4.774\sigma^{.1} - 7.27)$		(3-13)
$\eta_M = 1 - 2.59 \frac{M_f}{M_x} + 5.11 \left(\frac{M_f}{M_x}\right)^2 - 3.52 \left(\frac{M_f}{M_x}\right)^3$	Moisture dampening coefficient	(3-14)
$\eta_s = 0.174 e_S^{-.19}$	Mineral damping coefficient	(3-15)
$\xi = (192 + 0.2595\sigma)^{-1} \times \exp[0.792 + 0.681\sigma^{.5}](\beta + 0.1)]$	Propagating flux ratio	(3-16)
$\phi_w = CU^B \left(\frac{\beta}{\beta_{op}}\right)^{-E}$	Wind coefficient	(3-17)
$C = 7.47 \exp(-0.133\sigma^{.55})$		(3-18)
$B = 0.02526\sigma^{.54}$		(3-19)
$E = 0.715 \exp(-3.59 \times 10^{-4}\sigma)$		(3-20)

Table 3-1. Defining equations for RROS equations (concluded).

$W_n = \frac{w_o}{1 + S_T}$	Net fuel loading (lb/ft ²)	(3-21)
$\phi_s = 5.275 \beta^{-.3} (\tan \phi)^2$	Slope factor	(3-22)
$\rho_b = w_o / \delta$	Ovendry bulk density (lb/ft ³)	(3-23)
$\epsilon = \exp(-138/\sigma)$	Effective heating number	(3-24)
$Q_{ig} = 250 + 1,116 M_f$	Heat of pre- ignition (Btu/lb)	(3-25)
$\beta = \frac{\rho_b}{\rho_p}$	Packing ratio	(3-26)

Table 3-2. PROS equation input parameters.

Parameter	Description
w_o	oven dry fuel loading (lb/ft ²)
h	fuel particle low heat content (Btu/lb)
ρ_p	ovendry particle density (lb/ft ³)
M_f	fuel particle moisture content ($\frac{\text{lb moisture}}{\text{lb ovendry wood}}$)
S_T	fuel particle total mineral content ($\frac{\text{lb minerals}}{\text{lb ovendry wood}}$)
S_e	fuel particle effective material content ($\frac{\text{lb silica-free minerals}}{\text{ovendry wood}}$)
U	wind velocity at midflame height (ft/min)
$\tan \phi$	slope, vertical rise/horizontal distance
M_x	moisture content of extinction.

A generalization of the RROS equation to include heterogeneous fuels is described in Reference 18 (pp. 28-33). This generalization allows definition of an arbitrary number of uniformly distributed fuel categories and size classes. For natural, understory fuels, two categories (live and dead) and four to five size classes are used. Since neither all size classes nor all categories are equally effective in fire front propagation, a weighting procedure is described in Reference 18 for combining the descriptions of understory fuel size classes and categories into a single spread rate.

A generalization to allow computation of spread rates over an area is accomplished by defining a computational mesh over the area of interest and specifying all of the parameters required for the RROS equation in each cell of the mesh. The specification of mean parameter values for the i -th fuel category and j -th fuel size class requires estimation of each input parameter shown in Table 3-3 for each cell of the computational mesh.

Two weighting parameters based on the surface area of the fuel within each category and size class are defined by

$$f_{ij} = \frac{\bar{A}_{ij}}{\bar{A}_i} \quad \text{Ratio of surface area of the } j\text{-th size class to total surface of the } i\text{-th category per unit fuel cell} \quad (3-27)$$

and

$$f_i = \frac{\bar{A}_i}{\bar{A}_T} \quad \text{Ratio of surface area of the } i\text{-th category to total surface area per unit fuel cell.} \quad (3-28)$$

Table 3-3. RR0S equation input parameters within the i-th fuel category and j-th fuel size class of each fuel cell.

Parameter	Description
$(\bar{w}_o)_{ij}$	= ovendry loading (lb/ft ²)
$(\bar{\sigma})_{ij}$	= surface-area-to-volume ratio (ft ² /ft ³)
$(\bar{S}_T)_{ij}$	= mineral content (lb minerals/lb wood)
$(\bar{S}_e)_{ij}$	= effective mineral content $\left(\frac{\text{lb minerals} - \text{lb silica}}{\text{lb wood}}\right)$
$(\bar{h})_{ij}$	= low heat value (Btu/lb)
$(\bar{M}_F)_{ij}$	= moisture content (lb moisture/lb wood)
$(\bar{\rho}_p)_{ij}$	= ovendry particle density (lb/ft ³)
Mean value within the i-th category:	
$(\bar{M}_X)_i$	= moisture content of extinction (lb moisture/ovendry wood)
Mean fuel array properties:	
$\bar{\delta}$	= depth of fuel (ft)
$\tan \phi$	= slope (ft vertical rise/ft horizontal)
U	= wind velocity at midflame height (ft/min)
m	= total number of categories
n	= number of size classes within the i-th category.

where

$$\bar{A} = \frac{(\bar{\sigma})_{ij} (\bar{w}_o)_{ij}}{(\rho_p)_{ij}}$$

Mean total surface area of fuel of i-th category and j-th size class per unit fuel cell (3-29)

$$\bar{A}_i = \sum_{j=1}^{j=n} \bar{A}_{ij}$$

Mean total surface area of fuel of i-th category per unit fuel cell. (3-30)

$$\bar{A}_T = \sum_{i=1}^{i=m} \bar{A}_i$$

Mean total surface area of fuel per unit cell. (3-31)

In terms of the above weighting factors and the parameters defined in Table 3-3, the reaction intensity is given by

$$I_R = r' \sum_{i=1}^{i=m} f(\tilde{w}_n)_i \tilde{h}_i (\tilde{n}_d)_i (\tilde{n}_M)_i \quad , \quad (3-32)$$

where the characteristic parameters weighted by surface area are as follows:

$$(\tilde{w}_n)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{w}_n)_{ij}$$

Net loading of i-th category (3-33)

$$(\bar{w}_n)_{ij} = \frac{(\bar{w}_o)}{1 + (\bar{S}_T)_{ij}}$$

Net loading of j-th class (3-34)

$$\bar{h}_i = \sum_{j=1}^{j=n} f_{ij} \bar{h}_{ij} \quad \text{Low heat content value of } i\text{-th category} \quad (3-35)$$

$$(\bar{\eta}_s)_i = 0.174(\bar{S}_e)_i^{-.19} \quad \text{Mineral damping coefficient of } i\text{-th category} \quad (3-36)$$

$$(\bar{S}_e)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{S}_e)_{ij} \quad \text{Characteristic effective mineral coefficient of } i\text{-th category} \quad (3-37)$$

$$(\bar{\eta}_M)_i = 1 - 2.59(\bar{r}_M)_i + 5.11(\bar{r}_M)_i^2 - 3.52(\bar{r}_M)_i^3 \quad (3-38)$$

Moisture damping co-efficient of i -th category

$$(\bar{r}_M)_i = \frac{(\bar{M}_f)_i}{(\bar{M}_{ext})_i} \quad \text{Moisture ratio of } i\text{-th category.} \quad (3-39)$$

$$(\bar{M}_f)_i = \sum_{j=1}^{j=n} f_{ij} (\bar{M}_f)_{ij} \quad \text{Moisture content of } i\text{-th category.} \quad (3-40)$$

The potential reaction velocity (r') is an experimentally determined function of the fuel bed packing ratio (β) and fuel particle size as characterized by fuel particle surface-to-volume ratio (σ). Thus,

$$r' = r'_{\max} (\bar{\beta}/\bar{\beta}_{op})^A \exp[A(1 - \bar{\beta}/\bar{\beta}_{op})] \quad (3-41)$$

where

$$r'_{\max} = (\bar{\sigma})^{1.5} / (495 + 0.0594 (\sigma)^{1.5}) \quad (3-42)$$

$$\bar{\rho}_{op} = 3.348 (\bar{\sigma})^{0.8189} \quad (3-43)$$

$$A = (4.774 (\bar{\sigma})^{0.1} - 7.27)^{-1} \quad (3-44)$$

and where

$$\bar{\sigma} = \sum_{i=1}^{i=m} f_i \bar{\sigma}_i \quad \text{Characteristic surface-area-to-volume ratio of the fuel complex.} \quad (3-45)$$

$$\bar{\sigma}_i = \sum_{j=1}^{j=n} f_{ij} \bar{\sigma}_{ij} \quad \text{Characteristic surface area-to-volume of } i\text{-th fuel ratio category.} \quad (3-46)$$

$$\bar{\rho} = \frac{1}{\bar{\sigma}} \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} \frac{(\bar{w}_o)_{ij}}{(\rho_p)_{ij}} \quad \text{Mean packing ratio} \quad (3-47)$$

$$\bar{\rho}_b = \frac{1}{\bar{\sigma}} \sum_{i=1}^{i=m} \sum_{j=1}^{j=n} (\bar{w}_o)_{ij} \quad (3-48)$$

This completes the calculations for the reaction intensity (I_r) term of the RROS Equation 3-8 for nonhomogeneous fuels. The remaining terms are treated similarly. The no-wind propagating flux ratio is given by

$$\xi = (192 + 0.2595 \bar{\sigma})^{-1} \exp[(0.792 + 0.681 \bar{\sigma}^{.5})(\bar{\beta} + 0.1)] \quad (3-49)$$

The denominator of Equation (8), which contains the heat sink terms, is given by

$$\rho_b \epsilon Q_{ig} = \bar{\rho}_b \sum_{i=1}^{i=m} f_i \sum_{j=1}^{j=n} f_{ij} \left[\exp\left(\frac{-138}{\bar{\sigma}_{ij}}\right) \right] (\bar{Q}_{ig})_{ij} \quad (3-50)$$

where

$$(\bar{Q}_{ig})_{ij} = 250 + 1,116 (\bar{M}_f)_{ij} \quad \begin{array}{l} \text{The heat of pre-ignition (3-51)} \\ \text{for j-th size class within} \\ \text{the i-th category.} \end{array}$$

The wind and slope multiplication factors are given by

$$\phi_w = CU^B (\bar{\beta}/\bar{\beta}_{op})^{-E} \quad (3-52)$$

$$\phi_s = 5.275 (\bar{\beta})^{-0.3} (\tan \phi)^2 \quad (3-53)$$

where,

U = mean windspeed at midflame height (ft/min)

$$C = 7.47 \exp(-.133 \bar{\sigma}^{.55}) \quad (3-54)$$

$$B = 0.02526 \bar{\sigma}^{.54} \quad (3-55)$$

$$E = 0.715 \exp(-3.59 \times 10^{-4} \bar{\sigma}) \quad (3-56)$$

3.5 PROPAGATION MODEL EMBODYING THE RROS EQUATION

The generalized RROS equation provides estimates of local rate of fire spread in heterogeneous fuels over an area of interest. This is, however, insufficient to allow estimates of fire growth, which require in addition a fire front propagation algorithm and a local directional spread rate algorithm.

3.5.1 Fire Front Propagation Algorithm (FFPA)

The FFPA described here was developed specifically for fires in understory wildland fuels (Reference 19) and is probably not applicable to urban fuels. It is described, however, as an example of the types of considerations involved in applying the RROS equation to fire growth estimates.

It is assumed that all propagation interactions occur at the perimeter of a wildland fire at the interface between the flame front and unignited fuel. FFPA has these characteristics:

1. The algorithm must accept required data and provide results of variable, user specified resolution.
2. Perimeter resolution must be variable from fire-to-fire, perimeter-to-perimeter, and point-to-point within a perimeter.
3. A perimeter should not cross an earlier perimeter or itself. That is, a fire is assumed to always grow toward unburned fuel.
4. The algorithm should be able to simulate fires burning through nonhomogeneous, discontinuous wildland fuels in uneven terrain.
5. The shape of the fire should be a priori, indeterminate, and dependent upon local fuel, topographical and meteorological conditions

over the region within which the fire is situated.

6. It should be possible to initiate the model from an arbitrary perimeter definition (a point, geometric shape, set of points, etc.).

In the FFPA, each perimeter is described by a set of points connected by straight-line segments. The basic function of the propagation model is to estimate the location and shape of the next perimeter by an outward propagation of the points that define segments of the current perimeter. The use of variable (i.e., segment length) resolution over each perimeter permits detailed description of the perimeter where desired while allowing a significant reduction in the total number of calculations and the amount of data required to describe the perimeter.

The user specifies a minimum (δs) and a maximum (Δs) allowable spacing between any two adjacent points within a perimeter. An internal algorithm defines the spacing between each successive pair of points such that

1. The spacing falls within the specified limits,
2. The spacing is a function of the maximum of the propagation rates at the two points, and
3. The greatest density of points occurs where the fire front propagation rates are highest.

Thus, the spacing ds_{ij} between two adjacent points p_i and p_j is given by

$$ds_{ij} = f(\max[R_i, R_j]) \quad (3-57)$$

and

$$\delta s \leq ds_{ij} \leq \Delta s \quad , \quad (3-58)$$

where

R_i = propagation rate at point p_i ,

R_j = propagation rate at point p_j .

Let a perimeter at time T_0 be completely defined by the set of 10 points shown in Figure 3-1. By completely defined, we mean that no further operations are required upon the specified set of points to complete the description of the perimeter. Since the function of the propagation model is to estimate the next perimeter in terms of the set of points that define the current perimeter, it does not matter how the perimeter at T_0 was obtained. It could have been calculated from an earlier perimeter, it could have been estimated, or it could have been obtained as input from measured data. Given the perimeter at T_0 , we will very briefly describe the sequence of operations required to estimate the next perimeter.

The outward direction at each point of the perimeter is defined as the bisector of the angle formed by the two line segments intersecting at each point, as shown in Figure 3-2. The directional spread rate is calculated at each point; the propagation direction is determined at each point (the outward direction is used in this example); and each point is propagated in the specified direction, at the specified rate over a specified interval to the next perimeter at T_1 as shown in Figure 3-3.

The newly defined set of points that describe the perimeter at T_1 are tested to determine if Equations 3-1 and 3-2 are satisfied for each candidate perimeter segment, and

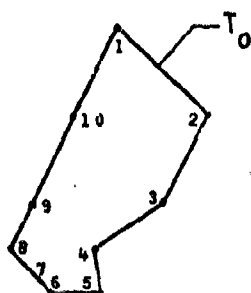


Figure 3-1. The set of points defining the perimeter at T_0 .

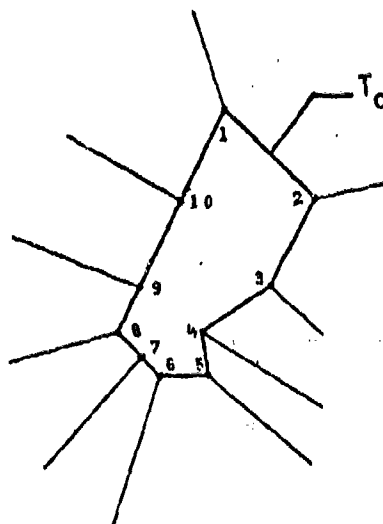


Figure 3-2. The outward direction at each point.

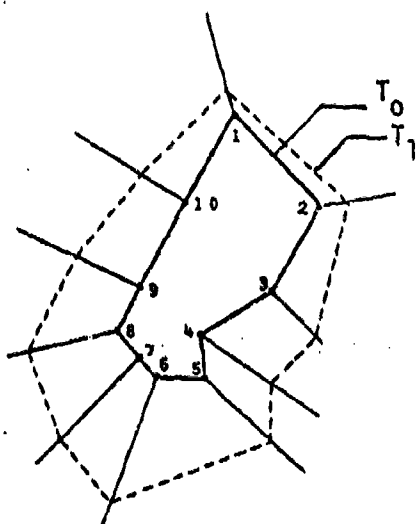


Figure 3-3. Preliminary perimeter at T_1 .

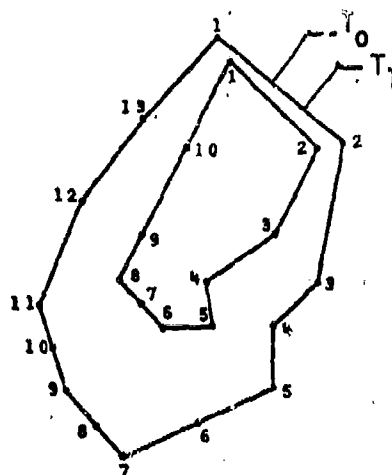


Figure 3-4. Final perimeter at T_1 .

1. a new point is added at the center of each segment that is too long,
2. a point is deleted from each segment that is too short, and
3. the process is repeated until all segments satisfy the above together with Equations 3-1 and 3-2.

For this example a point was added to each of segments (5,6), (7,8), and (8,9), as shown in Figure 3-4.

The collection of points is then tested to determine if the perimeter contains any loops (i.e., crosses itself). If such a condition is detected, the points contained within each minor loop are deleted. The remaining points are enumerated, and the current perimeter is by definition completely described by this set of points, as shown in Figure 3-4, and the entire sequence of operations is repeated to obtain the next perimeter.

3.5.2 Local Directional Spread Rate Algorithm (LDSRA)

Local spread rate estimates are based on the RROS Equation 3-8, which is rewritten for convenience in the form (Reference 5)

$$R(q_1, q_2, \dots, q_N, u, \phi) = R_0(q_1) [1.0 + \phi_w(u, q_1) + \phi_s(\phi, \beta)] , \quad (3-59)$$

where

$R(q_1, q_2, \dots, q_N, u, \phi)$ = spread rate in direction of local wind velocity,

q_N = fuel parameters,

u = local wind speed

ϕ = angle of local slope measured from the local horizontal,

$R_0(q_i)$ = no wind, no slope spread rate,

$\phi_w(u, q_i)$ = wind function

q_i = fuel particle area-to-volume ratio,

$\phi_s(\phi, \beta)$ = slope function,

β = fuel packing ratio.

There is no explicit directional dependence in the RROS equation. However, development of the RROS equation was heavily dependent upon empirical data obtained from wind tunnel simulations of wildland fires. The empirically deduced effects of wind (ϕ_w) and slope (ϕ_s) are, thus, defined to be for the down-wind and up-slope directions, respectively.

The RROS Equation 3-59 predicts that, in the absence of wind and slope, a point fire will spread circularly at the rate R_0 . The qualitative basis for a local directional spread rate is the assumption that, in the presence of wind and/or slope, a point fire will spread elliptically as a function of R_0 , $\vec{\phi}_w = \phi_w \hat{a}_w$, and $\vec{\phi}_s = \phi_s \hat{a}_s$ where $\hat{a}_w$ and $\hat{a}_s$ are unit vectors in the directions of down-wind and up-slope, respectively.

The components obtained from the RROS model are shown in Figure 3-5 in a two-dimensional reference frame with origin at the point of interest. It is assumed that the data upon which R_0 , $\vec{\phi}_w$ and $\vec{\phi}_s$ are based apply at least to the point of interest. The reference frame used consists of earth-tangent-plane coordinates E (east) and N (north), so that the angles α_s and α_w are azimuthal angles. The unit vector $\hat{a}_w$ is in the direction toward which the wind is blowing (opposite to common, meteorological convention). The unit vector $\hat{a}_s$ is the negative horizontal

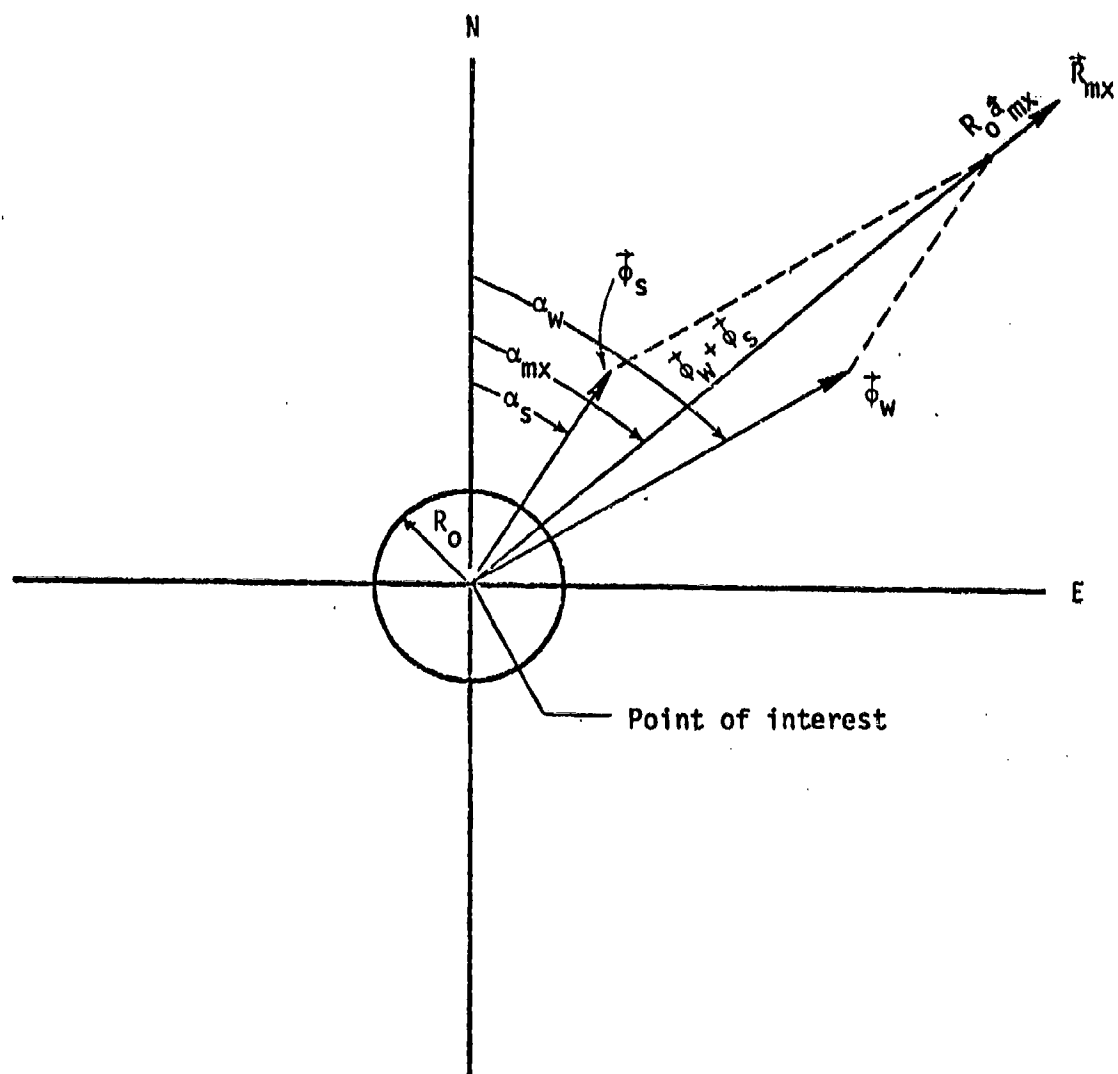


Figure 3-5. Graphical representation of RROS model output components.

projection of the local surface normal, and thus points in the up-slope direction.

An ellipse can be completely defined in terms of the location of one focus, the line of apsides, the apoapsis distance, and the semi-latus rectum. Define the point of interest as the location of the occupied focus. Define the line of apsides along a unit vector $\hat{a}_{mx}$ where

$$\hat{a}_{mx} = (\phi_w + \phi_s) / |\phi_w + \phi_s|. \quad (3-60)$$

Define the semi-latus rectum R_N by

$$R_N = R_O + |\phi_w \times \hat{a}_{mx}| + |\phi_s \times \hat{a}_{mx}| \quad (3-61)$$

Define the apoapsis distance R_{mx} as shown in Figure 3-5 by

$$R_{mx} = R_O + (\phi_w \cdot \hat{a}_{mx}) + (\phi_s \cdot \hat{a}_{mx}) \quad (3-62)$$

where,

$\hat{a}_{mx}$ = a unit vector in the direction of maximum spread area,

R_{mx} = the magnitude of maximum spread rate,

R_N = spread rate in the direction normal to maximum spread rate.

The azimuthal angle α_{mx} of R_{mx} as shown in Figure 3-5 is given by

$$\alpha_{mx} = \arctan [(\phi_w \sin \alpha_w + \phi_s \sin \alpha_s) / (\phi_w \cos \alpha_w + \phi_s \cos \alpha_s)]. \quad (3-63)$$

The eccentricity of the ellipse is by definition

$$e = 1 - R_N/R_{mx} \quad (3-64)$$

and the directional spread rate in the azimuthal direction (θ) is then given by

$$R(\theta) = R_{mx} (1-e)/(1 + e \cos \theta) \quad (3-65)$$

where $\theta = \pi + \alpha - \alpha_{mx}$

An important characteristic of Equation 3-65 is that it preserves the magnitude of spread rate in the direction implied by Equation 3-59.

It was determined from comparing computational results with actual wildland fire growth data that the LDSRA defined by Equation 3-65 predicts local elliptical spread rate patterns exhibiting excessive eccentricity. This was considered to be a result of the dependence of Equation 3-59 upon experimental data from simulated fires in laminar wind fields. Laminar wind flow is rare in nature, particularly near the ground in rough terrain and vegetation. The effect of local turbulence is considered to decrease the eccentricity of the local directional spread rate pattern as a function of local wind speed. The eccentricity of the local spread rate ellipse was, thus, modified in accordance with wildland fire growth data. The resulting LDSRA is given by

$$R(\alpha) = R_{mx} (1 - e')/(1 + e' \cos \alpha) \quad (3-66)$$

where

$$e' = ef(u) \quad (3-67)$$

and

$$f(u) = 1.0 - 0.02u, \quad 0 \leq u < 10 \text{ (mph)} \quad (3-68)$$

$$f(u) = 0.8 - 0.0054(u - 10), \quad 10 \leq u \leq 80 \text{ (mph)} \quad (3-69)$$

3.6 ANALYSIS OF THE RROS EQUATION

Formulation of a computational procedure embodying the RROS equation for estimating the growth of wildland fires revealed problems related to input data, computation, and data management requirements. These problems derive from the use of a grid structure over the potential burn area and the detailed fuel descriptions specified for the RROS equation.

The required cell size and expected fire size define the amount of data to be entered, the computational detail required, and the amounts of data to be accessed and stored. Cell size is determined by the most limiting of the rate of change of terrain slope, wind velocity, fuel diversity and desired firefront resolution. Consideration of these parameters indicated a minimum practical cell size of about one acre for wildland fires. The historical data on wildland fires of interest implied that a potential burn area of about 10^4 cells would not be unreasonable. Reference to Table 3-3 for two fuel categories and six size classes shows that 98 fuel parameters plus five additional parameters are required as input data for each cell. For 10^4 cells this is a very large amount of data and is comprised largely of detailed fuel characteristics. For this reason, the RROS equation was analyzed to determine the sensitivity of spread rate estimates to each of the input data elements.

An initial analysis (Reference 23) examined the sensitivity of RROS equation results to independent changes in each variable over the range of values that each variable might exhibit. This analysis partitioned the RROS equation variables into two sets, strong and weak variables. Each strong variable resulted in a maximum rate of change of estimated rate of spread with respect to the value of the subject variable that was greater than ten percent. Weak variables were below this threshold.

The strong variables were identified to be u , σ , δ , M_f , and M_x and the weak variables were W_0 , h , ρ_p , S_T , S_E , and $\tan \phi$ (see Table 3-2 for variable definitions). A subsequent analysis examined the effects upon RROS equation results of all independent variables, all physically realizable couplings between strong variables, all weak variables combined and all strong variables combined. The results of this analysis are shown in Table 3-4. Examination of the standard deviation of the distribution of percentage change in estimated spread rate for each tested variable set reveals that

1. There are three strong variables (u , σ , and M_f)
2. The weak variables W_0 , h , ρ_p , S_T , S_E , and $\tan \phi$ can be treated as constants
3. The two intermediate variables δ and M_x can be accommodated with two levels of quantization.

As a result of these analyses, it was possible to reduce the number of data elements required per cell from approximately 100 to 6. All of the fuel characteristics were determined in terms of the fuel type within a cell and its age. The remaining four data elements consisted of the wind velocity components and the slope components. This reduction in the

Table 3-4. RROS equation variables summary.

CASE	MEAN (R/R̄)	MODE (R/R)	STD. DEV. σ _{R/R̄}	80% CONF. LIMITS	
				R/R̄ (10)	R/R̄ (20)
<u>WEAK VARIABLES</u>					
W ₀	1.00	1.00	0.01	0.99	1.01
h	1.00	1.02	0.07	0.89	1.09
ρ _p	1.00	1.00	0.007	0.99	1.01
S _T	1.00	0.99	0.02	0.97	1.03
S _e	1.01	0.99	0.07	0.93	1.08
tan φ	1.00	1.01	0.05	0.94	1.06
<u>STRONG VARIABLES</u>					
u	1.18	0.74	0.68	0.30	2.01
σ	1.06	1.12	0.42	0.49	1.56
δ	1.00	1.03	0.15	0.78	1.18
M _f	1.07	0.93	0.40	0.63	1.52
M _x	0.99	1.00	0.14	0.88	1.07
<u>COUPLED STRONG VARIABLES</u>					
u, σ	1.22	0.38	0.91	0.26	2.45
u, δ	0.96	1.11	0.56	0.23	1.76
σ, δ	1.06	0.96	0.45	0.46	1.69
u, σ, δ	1.24	0.32	0.97	0.19	2.52
M _f , M _x	1.10	0.94	0.43	0.67	1.66
<u>COUPLED STRONG, WEAK AND ALL VARIABLES</u>					
All Weak	1.03	1.01	0.11	0.85	1.14
All Strong	1.34	0.34	1.28	0.12	2.89
All Variables	1.29	0.62	1.13	0.16	2.99

amount of data to be processed, coupled with the use of the segmented perimeter propagation model described in Section 4, allowed efficient simulation of large wildland fires.

SECTION 4

URBAN MASS FIRE BEHAVIOR MODEL CONCEPT

4.1 INTRODUCTION

No conventional state-of-the-art exists, in either a theoretical or empirical sense, which suffices to immediately construct an urban mass fire behavior model. Previous investigations provide a foundation, but in themselves are insufficient for the purpose. Consequently, a model concept must have a high judgemental content based upon assessment of the most important physical processes and factors together with extrapolation from better understood situations. The present, or reasonably short-range, possibility for computing or estimating the major physical processes is a necessity. Simulation of a complex interactive situation is, however, something more than straightforward computation. The organizational structure, which chooses and sequences the separate aspects and their interactions, can equal the physical calculations in importance. The unique model structure described in Section 5 is an essential part of our model concept. The present section concentrates on physical aspects of the model.

Our concept aims at a model description of the behavior and propagation of a mass urban fire in order to assess its ultimate effect and to explore the requisite conditions in which various modes of development (propagating line fire, firestorm, etc.) occur. This emphasis upon fire development elevates propagation mechanisms to primary importance.

We consider mass fire propagation mechanisms, in order of spread potential, to be

1. Firebrand transport (transport of burning material)
~ 0-5 km
2. Contiguous spread or pilot ignition (flame and hot gas contact, convection) ~ 0-50 m
3. Flame radiation ~ 0-10 m
4. Heat conduction ~ cm.

Heat conduction influences pyrolysis rate (burning rate) of already ignited material, but is otherwise negligible. Flame radiation provides an essential feedback of heat to burning material, but propagation by this mechanism is rather short range. It becomes important only when view factors approach a solid angle of 4π , as in closed compartments or dense fuel beds. Fire spread between closely spaced buildings may occur by flame radiation, although, in this case, it may be obscured by convective mechanisms. Only in the absence of other propagation mechanisms does flame radiation become significant. The important feature of the remaining major propagation mechanisms, branding and convection, is their dependence upon the details of the gaseous hydrodynamics.

Hydrodynamic motions of ambient atmosphere (wind and updrafts), flame columns, and fire plumes are determined by the background meteorology as well as the state of the fire, which includes the spatial distribution and intensity of burning, both current and past. In turn, the burning state and its changes are determined by hydrodynamic (wind and convection) effects upon burning rate and propagation. Despite the fact that any fire involves hydrodynamics, small scale burning in the open apparently does not require explicit consideration of the mutual, two-way interaction between fire and wind. The small scale fire is affected by

the wind, but the perturbation of wind by the fire is negligible. The success of the Rothermel Spread Model (Reference 18) description of fire propagation demonstrates the validity of neglecting the reverse effect of open fires upon wind, at least for brush fires, which, in this sense, are small scale. On the other hand, models of compartment fires in still intact buildings require a hydrodynamic description of the interaction between air flow (ventilation) and burning rate. In the case of open fires, as the number, intensity, and areal distribution of burning regions grow, the atmospheric perturbation increases to the point where fire development becomes substantially influenced by the fire itself. Our concept of an urban mass fire model emphasizes this reciprocal interactive effect, which we expect to assume significance in conflagrations on the scale to be considered. The potential presence of a high-velocity fire-induced wind as a damage mechanism is also of interest in itself.

In addition to the fire-hydrodynamic reciprocal interaction, mass fire behavior, of course, depends upon the effective (after blast) initial ignitions (spatial and temporal distribution) and other factors, all of which can be considered fuel parameters. Fuel loadings of burnable material and its effective heat content, rates of combustion, fuel distribution (building heights and spacing, streets, and open areas as firebreaks, vegetation, etc.) are all essentially fuel descriptors. These parameters, perhaps drastically modified by air blast, clearly underlie the behavior of nuclear-induced urban mass fires, and define the modeled situation. Recall that the major research effort in producing the Rothermel model was quantification of the effects of fuel parameters, which are central to it. In the urban model context one requires fuel parameters in sufficient detail to define the situation, but propagation (branding, pilot ignitions) and burning characteristics, insofar as they are fuel dependent, must be handled partly parametrically since detailed information is lacking. We advocate reasonable functional behavior and idealized physical models to estimate these effects. Any model of urban

fire development, whether it includes reciprocal fire-wind interaction or not would, at the present level of knowledge, suffer equally from these fuel-related uncertainties.

Once the reciprocal fire-hydrodynamic (fire-wind, for short) interaction is selected as the central aspect of urban mass-fire behavior, we must consider methods for its calculation and exploitation. Our concept is essentially the choice of an approach to this problem.

4.2 MODEL ALTERNATIVES

Mass fire development, considered as an interactive fire-wind problem, demands a three-dimensional description of the flow of hot gases and ambient air. Although heat sources are localized on or near the surface, brand transport depends upon velocities aloft, and winds near the surface--important for pilot ignitions--are only a special part of the unified total flow. Later we will examine some evidence from the Flambeau tests which indicates the need for three-dimensional resolution even in the near-surface region of heat production and active flaming.

4.2.1 Detailed Hydrodynamic Calculation

A detailed 3-d hydrodynamic calculation, based upon fundamental equations of motion, could in principle be used to determine the flow field. A major practical problem with this approach is the need for high spatial resolution, sufficient to resolve irregularities and discontinuities in zones of burning and convection, which are certainly present at ignition and immediately after, and which may persist for extended periods. Such calculations of detailed 3-d flow fields would be expensive and lengthy to perform, even if sufficient memory capacity for the computer calculations were available.

A physical problem with this approach arises in the need to compute the effects of turbulence, which, in this case, is largely produced by buoyancy of hot gases. It is not clear whether there is an expeditious method for calculating the behavior of buoyant, turbulent flows directly from fundamental principles. Second-order closure schemes of turbulence modeling are far too demanding to be practical in a model which, in addition, performs many other types of calculation and which must be repetitively run to assess the effects of varying conditions. At this level of detail, turbulent exchange approximations based upon mixing length hypotheses do not alleviate the computational burden significantly and of themselves introduce large uncertainties.

Numerical computation of detailed flow fields at high resolution is perhaps a last resort, and other avenues should be explored first.

4.2.2 Low-Resolution (Lumped-Parameter) Hydrodynamic Calculations

At the other extreme, we might consider only a global, comparatively low resolution description of the flow field. Previous approaches to the mass fire problem have calculated the axially symmetric flow field resulting from a single large area circular fire (with assumed smoothed and uniform heat production rates per unit surface area). By invoking either mixing length assumptions or turbulent entrainment assumptions, the calculations have produced reasonable solutions for the single large fire plume in the asymptotic region at large altitudes above the source. These calculations, however, typically yield unrealistic behavior in the region near the ground. One effect (Reference 12) is rapid convergence of the rising hot gases to the center of the burning area to form a narrow plume, which then expands normally in its subsequent rise. This exaggerated behavior is not necessarily inherent in the model type, being, we believe, a consequence of oversimple assumptions. The single plume formed at high altitudes by coalescence of hot turbulent gases from many separate heat

sources may be adequately represented by this type calculation. The coalescence process itself and the detail of wind fields at lower elevations resulting from discrete burning zones requires something in addition, or perhaps a different approach. Though potentially useful for determining large scale atmospheric perturbations and overall flow fields, these low resolution hydrodynamic models fall short of providing the crucial small scale structure needed to model fire development.

4.2.3 Parameterized Multiple Plumes

In the face of the limited understanding of mass fire phenomena and the recognized inadequacy of previous approaches to the problem, we have evolved a concept for modeling fire development, which does not attempt a first principles calculation of the hydrodynamics. Instead, the flow fields are deduced as a superposition of velocities resulting from the actual distribution of segmented burning zones and their attendant entraining plumes. This approach requires that the major features of individual burning zones and fire plumes be parameterized in terms of comparatively few variables: heat production rate per unit area, areal extent, and wind description being the principal variables. Heavy reliance is placed upon similarity solutions together with laboratory and field experiments, supplemented by physical arguments and scaled to mass fire conditions. In situations where this procedure is considered inadequate, parameterized functional relations, which summarize results of off-line hydrocode calculations of single plumes, could be employed. Essentially each burning zone (or subdivision) is represented by sources and sinks of mass distributed in three dimensions. From this distribution, atmospheric flow external to plumes and flames can be calculated. The external flow reacts back upon the plumes to establish the location of the source-sink distribution in a self-consistent manner. Once established, the wind field determines burning rates and propagation to advance the fire development.

The approach is not without difficulties and leads to several problem areas, which require investigation. However, it exploits experimental measurements and qualitative insights obtained in previous research, avoids the inherent difficulty of turbulence calculations, and can achieve detail and resolution without excessive computation.

By keying the description to a simple demonstration model, the following sections illustrate the model concept and clarify the procedure to implement it. Problem areas are discussed as they are encountered.

4.3 ATMOSPHERIC MOTION

First, we briefly sketch our conception of the relevant phenomenology of fires burning in the open as derived from previous research and observations. From the standpoint of urban mass fires, all detailed tests have been small fires. Leaving aside, for the moment, the effects of atmospheric stratification and scale height, these small fires are governed by the same physical parameters as larger ones. The effect of larger distance scales is quantitative, not qualitative, and we presume relations between nondimensioned groups of variables may be used in large scale as well as small scale fires.

Figures 4-1(a) and 4-1(b) picture the features of a small area laboratory fire. Vertically, the fire consists of a flame zone, a zone of intermittent flaming, and a buoyant plume, which quickly assumes the asymptotic behavior of a weakly buoyant plume, since mixing with cool ambient air is rapid. At small burning rates $\dot{Q}$ (J/s), the flame column shows convergence, but at higher burning rates the flame column diverges almost immediately as it rises. This distinct behavior must depend upon both $\dot{Q}$ and the fire area A ; but as long as the area is small enough, the burning takes place in a simple flame column. The work of McCaffrey

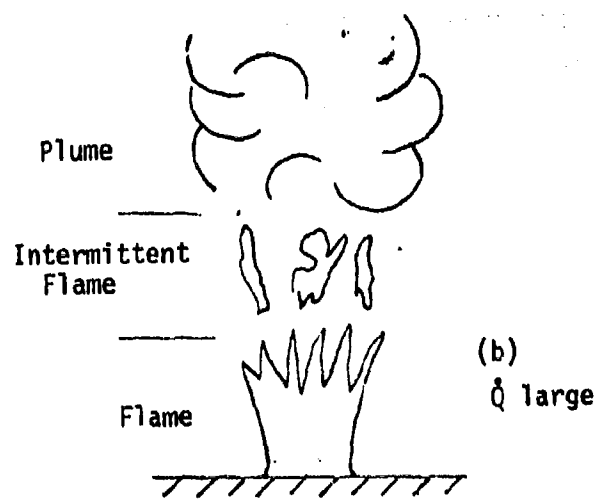
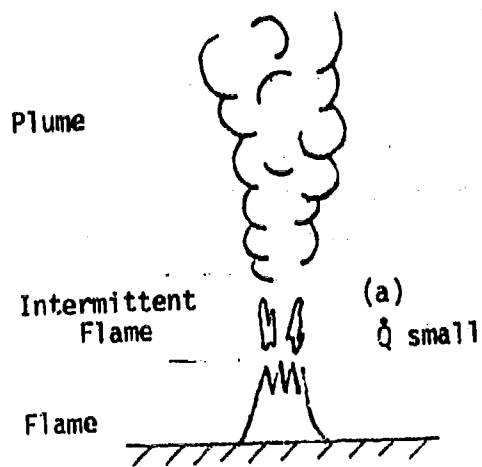


Figure 4-1(a) and (b). Small area fire.

(Reference 24) and Cox and Chitty (Reference 25) has provided reliable parameterizations of these single fires, but the area effect awaits investigation.

When several small area fires are burning in proximity, one expects the situation shown in Figure 4-2. Each separate fire and its plume entrains air. The effective "sinks" of all plumes produce an air velocity, which tips the plumes inward and brings them together at a coalescence height, after which the buoyant gases form a single plume. We encounter here a fire-induced wind, strongest at the location of the peripheral fires, which may influence their spread.

If all the small area fires coalesce, or if a large area is burning without gaps, the situation approaches that illustrated in Figure 4-3. In this case, according to the observation of Countryman (Reference 9) in the Flambeau tests, a single flame column does not persist. Instead, the fire spontaneously divides into separate flame columns and plumes, which maintain their identity through a short transition zone before combining into a simple plume. Although detailed analysis of the reason for this behavior is lacking, it clearly is a manifestation of the dynamic instability of a single flame column in certain conditions. It may be related to the Raleigh-Taylor buoyancy instability, or to the requirement of an air supply for burning, which may favor the large surface/volume ratio of multiple flame columns. Here again, the fire character must depend not only upon the total $\dot{Q}$ but also upon the fire area, A . This behavior has a strong effect upon fire-induced winds, since a large amount of entrainment must occur in the transition and flame zones below the base of the combined plume. Wind estimates depend upon resolution of these features.

The configuration of Figure 4-3 is similar to that of Figure 4-2, but the separate columns have different origins. In the one case, they are imposed by physical separation of the fires, and in the other are

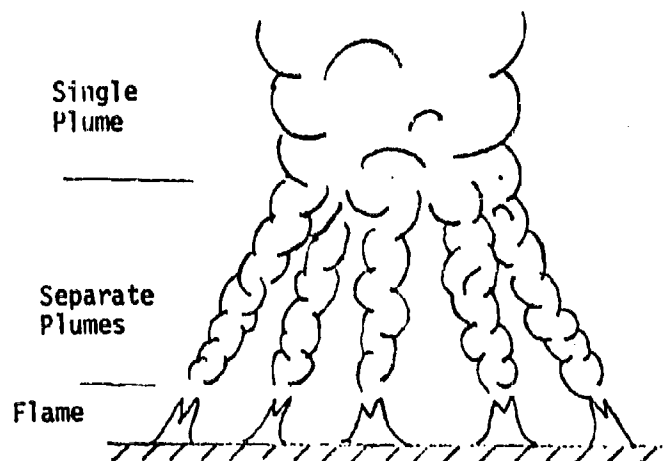


Figure 4-2. Separated small area fires.

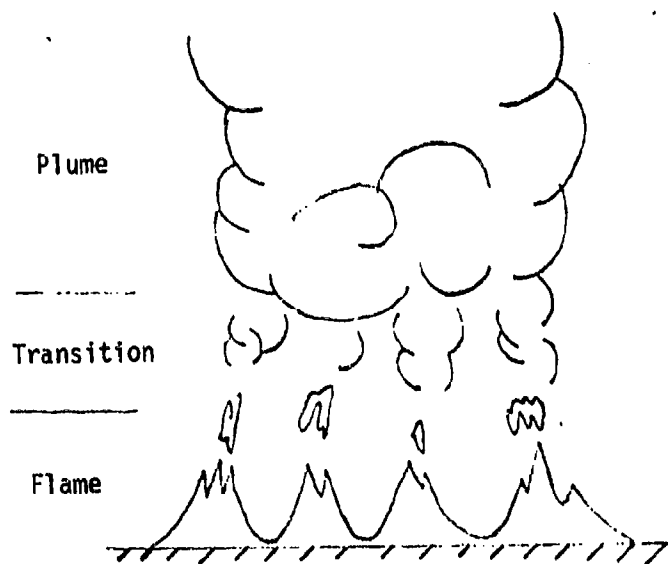


Figure 4-3. Large area fire (spontaneous break-up into separate flame columns). "Countryman Descriptive Model."

a result of fire dynamics. In either case, or in a possible combination of the two, the atmospheric motion and plume character are interactively determined. Plumes as effective sinks of ambient air determine fire winds, but winds affect the plume (or sink) distribution.

The illustrations of Figures 4-2 through 4-4 depict some of the effects of atmospheric fire plumes in the absence of an ambient wind. Both ambient winds and atmospheric stratification can modify the picture. Since we have by no means solved these problems, we describe in the following paragraphs some partial features to illustrate the concept. Most of these features have been incorporated as elements in the interactive demonstration model.

4.3.1 Single Fire Plumes

A single weakly buoyant plume, in a uniform atmosphere and in the absence of wind, approximates the form of a right circular cone. Taking the apex of the cone at the ground, the similarity solution of the buoyant plume (References 26 and 27) requires

$$w = a Z^{-1/3} \quad (4-1)$$

$$Z_B = n r_B ,$$

where w is the mean upward velocity in the plume and the ratio Z_B/r_B between the height and radius of the plume has the constant empirical value, $n = 5.51$. The constant, a , is a function of the buoyancy flux in the plume, which is directly related to the heat production rate $\dot{Q}$ if the plume is fire driven. By assuming $3w = w_{\max}$, the plume centerline velocity, the plume measurements of Cox and Chitty (Reference 25) permit computation of the relation

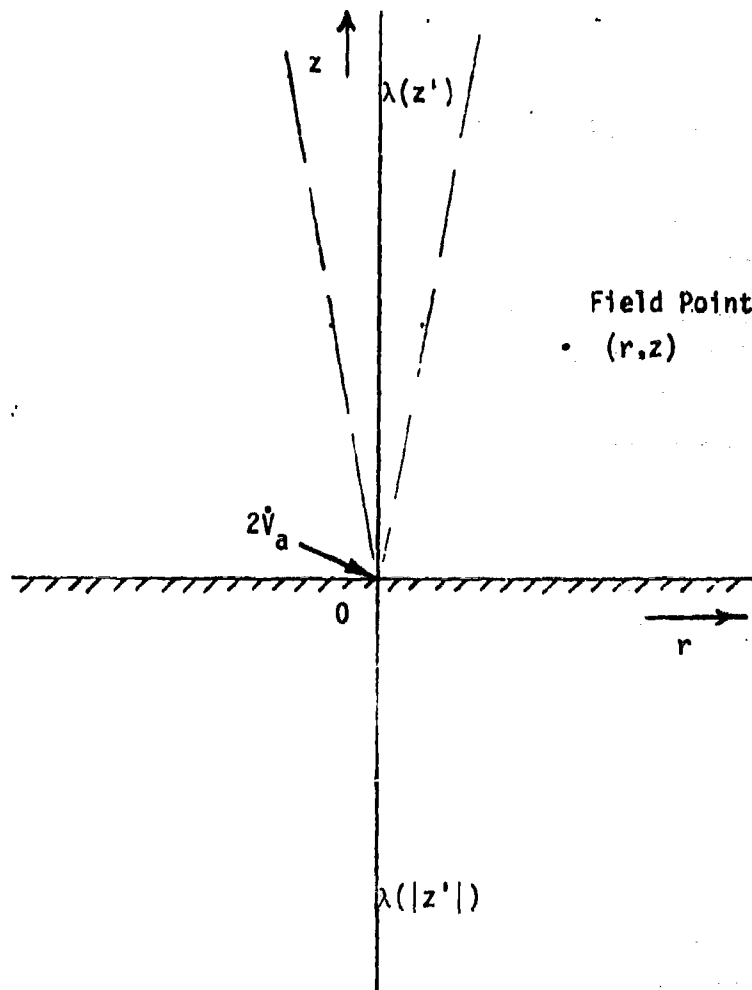


Figure 4-4. Plume geometry and sinks.

$$\alpha = 3.897(10)^{-2} \dot{Q}^{1/3} \quad (4-2)$$

where units are mks and $\dot{Q}$ is heat production in watts. An entrainment constant α (defined as the constant of proportionality between the mean upward plume velocity and the indraft velocity of ambient air through the sides of the plume), $u = \alpha w$, can be calculated from these relations, by using mass conservation and the assumption of incompressible flow. The result, $\alpha = 5/(6n) = 0.151$, does not agree with measured values, which are near 0.1. We use $\alpha = 0.1$.

Outside the plume, the ambient air motion may be modeled as the flow induced by a distribution of sinks located along the plume axis. The entrainment sink density λ is

$$\lambda(Z') = \frac{d\dot{V}}{dZ} = -2\pi\alpha\alpha(Z')^{2/3}/n$$

where Z' is the vertical coordinate of the source point and $\dot{V}$ (m^3/s) is volume flow rate. In addition, we account for the air supply necessary for combustion by placing a point sink of magnitude $\dot{V}_a$ on the ground at the cone apex:

$$\dot{V}_a = -k \dot{Q}/(h_0 \rho_0) = -5.5(10)^{-7} \dot{Q}$$

Here h_0 is the heat of combustion of the fuel (incomplete combustion of wood, $\sim 1(10)^7$ J/kg), k is the mass of air required to burn a unit mass of fuel ($\sim 7-10$ kg-air/kg-fuel) and $\rho_0 = 1.27$ kg/ m^3 , the ambient air density. $\dot{Q}$ is the burning intensity in watts.

The plume geometry and sink distribution are shown in Figure 4-4, where in order to fit the boundary condition at the ground (zero

vertical velocity), a below-ground image distribution is added. This doubles $\dot{V}_a$, the magnitude of the point sink at the ground.

Before continuing, we note that this model includes only sinks, although one would expect the effect of heat addition to be gas expansion and, hence, a net overall source. The source is present at the plume cap in a developing plume, and must be considered while the plume is being established. Sudden, quasi-explosive increases of burning rate can also produce transient outdrafts by this mechanism. Here we consider a steady, established plume; place the plume cap at infinite height; and neglect its effect.

The velocity field external to the plume is given by integration over the sink densities. In the cylindrical coordinates chosen, the results take the form

$$\begin{aligned} v_r(r, \beta) &= \dot{V}_a / [2\pi r^2(1+\beta^2)^{3/2}] - \alpha a f_r(\beta) / [2 \pi r^{1/3}] \\ v_z(r, \beta) &= \dot{V}_a \beta / [2\pi r^2(1+\beta^2)^{3/2}] + \alpha a f_z(\beta) / [2 \pi r^{1/3}] \end{aligned} \quad (4-3)$$

where $\beta = Z/r$, and units are mks throughout. The nondimensional functions $f_r(\beta)$ and $f_z(\beta)$, obtained by integration of the plume sinks between $Z' = \pm \infty$, are shown in Figure 4-5. Values of β are restricted to the interval, $0 < \beta < 5.51$, the region outside the plume. At fixed β , the atmospheric velocities induced by plume entrainment fall off at the slow rate of $r^{-1/3}$, a result of the infinite plume length. The horizontal velocities directed radially inward always exceed vertical velocities except very near the origin where effects of the point sink dominate. Throughout most of the external region, turbulent entrainment by the plume is a far stronger driver of the flow than is the sink of combustion air.

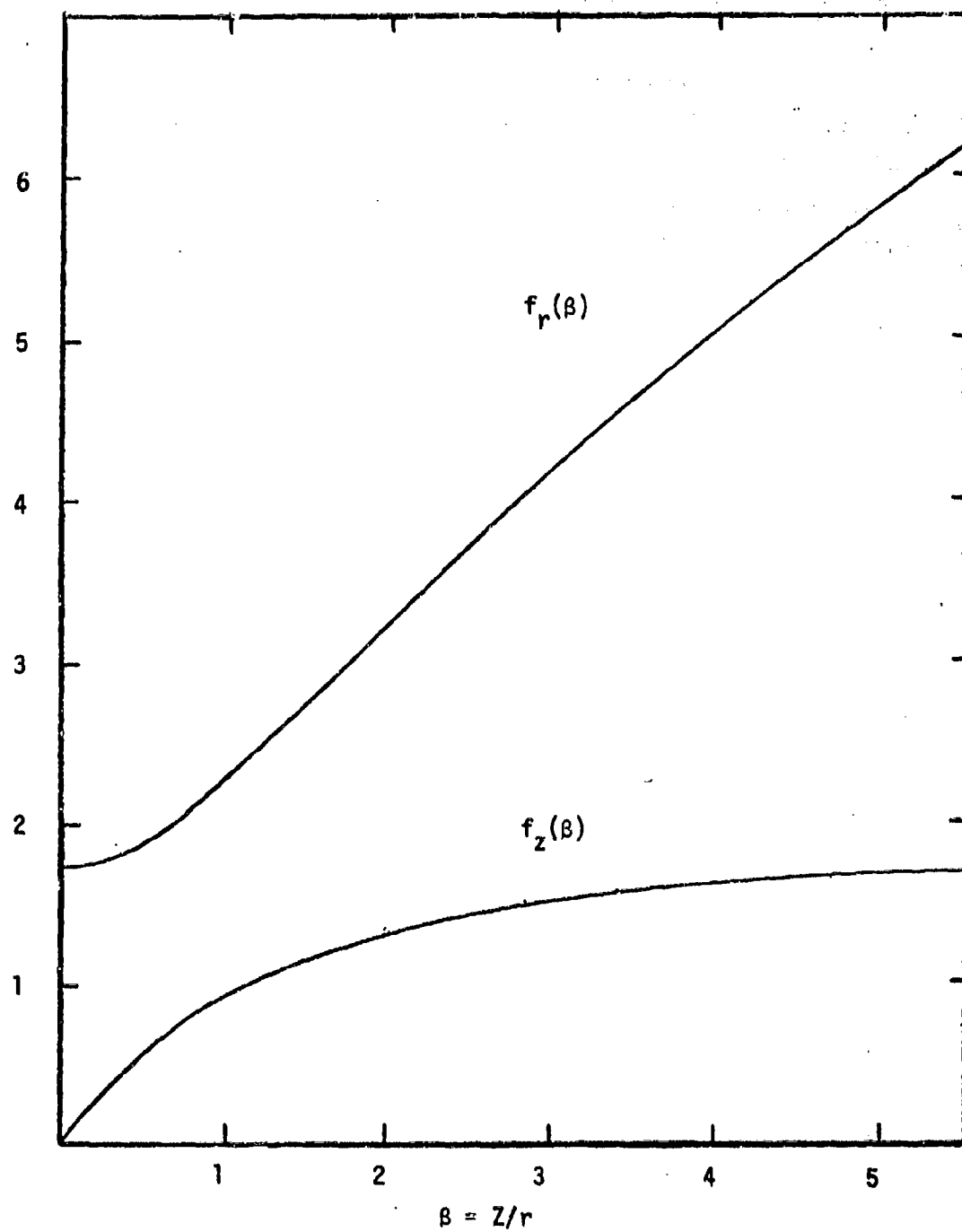


Figure 4-5. Non-dimensional velocity functions of single vertical plume.

This analysis, though very simple, illustrates the technique of calculating induced atmospheric motion from plume parameters. In this case, the sole free parameter is $\dot{Q}$, the power of the fire. Clearly, atmospheric stratification, which not only modifies the plume but also, in stable conditions, restricts vertical flow in the ambient atmosphere, would alter these results. Plume bending in a wind, either ambient or induced by other plumes, would change both the magnitude and location of sinks. These questions need to be addressed in a complete model.

A simple algorithm to demonstrate our conceptual approach specializes the above analysis to calculate ground level wind. Each separate fire plume acts as a partial source for the ground level wind and contributes a velocity,

$$v_r(r) = \dot{V}_a / (2\pi r^2) - 0.862 \alpha a / (nr^{1/3}) \quad , \quad (4-4)$$

directed toward the plume origin. The numerical factor 0.862 is half the value of $f_r(\beta)$ at $\beta = 0$. This formula applies to a developed plume of infinite height. To account for the plume formation transient, important in the initial stages, we extend the integral of plume entrainment sinks only over the actual vertical height of the plume. (The source at the cap is still neglected for simplicity.) The height of the plume cap for a steady burning rate starting at $t=0$ is approximately,

$$Z_c = 0.234 \dot{Q}^{1/4} t^{3/4}$$

again in mks units. A numerical integration over plume sinks to this height introduces a function of $Z_c/r = \gamma$ in the place of the constant, 0.862. This function is fitted by the approximate formula,

$$0.862 + g(\gamma) = 0.862 \gamma^{1.59} / (1.328 + \gamma^{1.59}) \quad (4-5)$$

which plays the role of a build-up function for the plume-induced surface wind fields. Close to the plume, winds build up to their final steady value more quickly than at larger distances.

4.3.2 Multiple Fire Plumes and Area Fires

If a mass urban fire were to consist of separate point fires of prescribed burning rate whose plumes remained vertical, separate, and independent, the fire-induced ground level wind could be obtained as a superposition of contributions from each fire given by the formulas of the previous section. This, perhaps zeroth order, approximation is in fact the general method used to calculate wind fields in our demonstration model. However, the model does not operate with point fires, but with square grid cells (modeling city blocks), and carries the total burning rate of each cell. A "fire" is defined as a group of contiguous burning cells, separated from other fires by unignited areas. In turn, each fire may be divided, on a geometrical basis, into "sub-fires," the two horizontal dimensions of which are approximately equal. This procedure permits computation of the fire-induced wind by a superposition of effects from each "sub-fire." Outside the sub-fire, its effect is that of an equivalent plume at its center, and the shape of each sub-fire may be approximated as a circle of radius, r_f .

In order to perform the wind calculation, the number of plumes or, what is the same thing, the number of equivalent point fires in the burning area of the sub-fire must be determined. This is the problem mentioned in Section 4.3 and illustrated in Figures 4-2 and 4-3 relating to the spontaneous breakup of an area fire into separate flame columns and plumes. Its importance stems from the fact that air entrainment into a plume is governed by the factor a defined in Equation 4-2, which is

proportional to $\dot{Q}^{1/3}$. A given total $\dot{Q}$ of an area fire, divided into N flame plumes entrains at a rate proportional to $N(\dot{Q}/N)^{1/3}$. Entrainment is, thus, proportional to $N^{2/3}$. Many separate plumes produce more atmospheric perturbation (fire-induced winds) than does a single fire of the same total power. This reasoning supports the contention that resolution of separate fires and burning areas is essential in a mass fire model. On the basis of these ideas, multiple separated ignitions may be more likely to generate firestorm conditions than area burning.

Our analysis of these features has hardly begun. To implement the demonstration model we estimate the number of plumes, N , present in a sub-fire of radius r_f with a total power $\dot{Q}$ as

$$N = 4.94(10)^3 \dot{Q}^{-2/3} r_f^{5/3} \quad (4-6)$$

This expression has only scant justification, based upon inexact estimates of flow conditions required to minimize pressure gradients, which we do not reproduce here. It is expected that the number of plumes (or flame columns) increase with fire dimensions, and decrease with burning rate. No obviously ridiculous results occur within the ranges of the variables employed.

Each sub-fire is assumed to consist of the number of plumes given by Equation 4-6, which are uniformly distributed over the quasi-circular area of the sub-fire. The effects of each plume, given by terms of the form of Equation 4-4, are superimposed. The total combustion air sink $\dot{V}_a$ is placed at the fire center, and the weak $r^{1/3}$ dependence upon distance away from the plume center is neglected inside the sub-fire. There results a simple formula, used in the demonstration model, for the contribution of each sub-fire to the total fire-induced surface wind:

$$\text{for } r > r_f \quad v_r(r) = -\dot{V}_a / (2\pi r^2) - g(\gamma) \dot{Q}^{-1/9} r_f^{10/9} r^{-1/3}$$

$$\text{for } r < r_f \quad v_r(r) = -\dot{V}_a r / (2\pi r_f^3) - g(\gamma) \dot{Q}^{-1/9} r_f^{10/9} r^{-1} \quad (4-7)$$

$$\left\{ \pi - 2 \cos^{-1} \left(\frac{r}{r_f} \right) + \frac{2r}{r_f} \sqrt{1 - \left(\frac{r}{r_f} \right)^2} \right\}$$

where $\dot{Q}$, $\dot{V}_a$, and r_f are the respective total power, combustion air flow, and radius of the sub-fire. The distance r is the radial distance from the sub-fire center and the build-up function $g(\gamma)$ is given by Equation 4-5 computed on the basis of the total $\dot{Q}$ of the largest fire (not sub-fire) in the grid. The total fire-wind at any point is the vector sum of these contributions, each of which is directed toward the center of its sub-fire source.

The fire-induced wind at ground level obtained this way is an overestimate, especially in the region outside of sub-fires, since, in reality, separate plumes coalesce into a single plume whose entrainment is less. (See Figures 4-2 and 4-3.) The far outside region is influenced more by the single plume at high elevations than by the multiple plumes lower down. The reverse effect of the winds upon plume location and entrainment rate is also neglected. By contrast, very near to and inside of sub-fires, the winds may be more realistic. If an ambient wind is present, its velocity is simply added vectorially to the fire-induced wind.

In general, the demonstration model neglects the essential interaction between fire plumes, as well as the effects of plume tilt and atmospheric stratification. These matters require further analysis, but from the foregoing, the necessity of resolving these details and the efficacy of this approach may be appreciated.

4.4 PROPAGATION BY BRANDING

Winds are important because of their influence upon propagation mechanisms. In this section, we develop a simplified branding algorithm, used in the demonstration model, which illustrates the problem areas and general features of fire propagation by branding.

4.4.1 Brand Transport

According to the experiments of Tarifa (Reference 28), the vertical component of firebrand motion can be described by a terminal velocity, with respect to surrounding air, which is a function of time. We approximate the families of curves obtained in his experiments by a simple linear function for the terminal velocity, w_T ,

$$w_T = w_i - kt$$

where w_T is parameterized by w_i , the initial terminal velocity of the brand, which expresses the effect of brand size and geometry. The constant, $k = 1/12 \text{ m/s}^2$, is the same for all brands. At $t_b = w_i/k$, the terminal velocity is zero, which is taken as the time of brand burnout.

The updraft velocity of a fire plume reaches its maximum, w_0 , in the region of intermittent flaming at a height, Z_0 , after which the velocity decreases as $w = aZ^{-1/3}$. The values of a , Z_0 , and w_0 are determined by the power of the fire, $\dot{Q}$, using the measurements of Cox and Chitty (Reference 25). We assume these relations to apply for the vertical component of plume motion, even in the presence of a wind. In a wind, which is needed for brand transport, both the horizontal plume and brand velocity are taken as equal to the wind velocity. These plume velocities are used as the mechanism for brand lifting. The potentially important-brand lifting mechanism of strong fire whirls is neglected.

In a plume the vertical velocity of a brand is,

$$\dot{Z} = aZ^{-1/3} - (w_i - kt); \quad Z = Z_0 \text{ at } t = 0 \quad (4-8)$$

We take the condition $\dot{Z} = 0$ as the condition for the brand to fall out of the plume. An integration of this equation would determine the height and time at which a brand leaves the plume or whether it burns out before leaving the plume. Clearly, small brands will burn out inside the plume before the condition is met. An upper limit of brand size is fixed by the lofting condition, $w_i < w_0$. The fire parameters determine a range of relevant initial terminal velocities, $w_{\min} < w_i < w_0$, of brands that can be both lofted and fall out while still burning.

For expediency, we do not perform the integration. Instead, a series of linear approximations are employed to estimate the time of fallout and the lofting height of the brands. We characterize a brand by the parameter n defined in terms of its initial terminal velocity and the range of relevant terminal velocities:

$$n = (w_0 - w_i)/(w_0 - w_{\min}) \quad ; \quad 0 < n < 1$$

A brand will stay in the plume for a time $t_F = nt_T$, where t_T is the time of fallout of the smallest brand that falls out. The height of fallout Z_F is given by linear interpolation of $Z^{-1/3}$, on the height Z_T to which the smallest brand rises,

$$Z_F^{-1/3} = (1 - n) Z_0^{-1/3} + nZ_T^{-1/3}$$

When a brand leaves the plume, its initial terminal velocity for vertical fall through the air is $w' = w_i - kt_F$, and for the period of its fall

to the ground, its vertical velocity is $\dot{Z} = -(w' - kt)$. The time interval required to fall to the ground from the height Z_F is

$$\Delta t = \frac{w'}{k} [1 - (1 - f)^{1/2}] ,$$

where $f = 2kZ_F/(w')^2$. Provided $f < 1$, a real solution exists and the brand reaches the ground before burnout. For the approximations chosen below, this condition is always met for the range of brand sizes, which fall out after lofting.

The total flight time of a brand, $t_G = t_F + \Delta t$, is less than its burning time, t_B . Our simplified algorithm assumes the horizontal transport of a brand takes place in a uniform wind, $\vec{V}$, the value of the surface wind field at the point of brand origin. (The result of this approximation can be grossly unrealistic in some cases. One needs to determine the brand trajectory with the complete 3-d wind field.) With this simplification, the brand reaches the ground at a point displaced a distance $\vec{D} = \vec{V} t_G$ from its point of production.

One would expect the probability for a grounded firebrand to produce a new ignition to depend upon the fuel present and the brand's remaining burning time, $\tau = t_B - t_G$. This clearly stochastic event is modeled with the ignition probability

$$P_i = 0.3[1 - \exp(\tau/60)] ,$$

where times are in seconds. We have found no data on this process, so this arbitrary expression is justified only by its reasonableness. In fact, it likely overestimates ignition probability.

4.4.2 Fire Parameters and Brand Production

To implement the transport calculation described above, the values of several quantities must be determined from the fire characteristics. The maximum updraft velocity, w_0 , of each flame column is the decisive quantity for brand lofting. The formula, Equation 4-6, for the number of flame columns in a area fire is employed to determine the burning rate of each flame column in a single burning cell. (We use the burning cells of the model, instead of sub-fires, to compute brand transport.) The plume parameters of each flame column turn out to depend upon the ratio $q = (\dot{Q}_c/r_c)^{1/3}$, where $\dot{Q}_c$ is the power of the cell burning and r_c is the radius of a circle whose area is equal to the area of the square cell. From the numerical values measured by Cox and Chitty (Reference 25), we compute

$$\begin{aligned}w_0 &= 9.17(10)^{-2} q \\Z_0 &= 4.20(10)^{-4} q^2\end{aligned}\tag{4-9}$$

in mks units. On the basis of a rough approximation to the solution of Equation 4-8, the brand related quantities are

$$\begin{aligned}w_{\min} &= 4.74(10)^{-2} q \\Z_T &= 5.82(10)^{-3} q \\t_T &= 4.44(10)^{-1} q\end{aligned}\tag{4-10}$$

again in mks units.

The transport of a brand with parameter, η_K , produced in a burning cell of given q can be determined with the sequence of calculations outlined in the preceding section. The results of the algebra are

$$\begin{aligned} t_G &= q(0.444\eta_K + 1.100f'_K - 0.975\eta_K f'_K) \\ t_B &= q(1.100 - 0.531\eta_K) \end{aligned} \quad (4-11)$$

where

$$f_K = 4.726(10)^{-4}(1 - 0.887\eta_K)^{-2}(1 - 0.482\eta_K)^{-3}$$

and

$$f'_K = 1 - (1 - f_K)^{1/2}.$$

There remains the critical question of how many, and what size, brands are produced per unit time by the burning cell. Since little is known of this, we assume the number of effective brands produced in the time interval, T , is proportional to T and to the burning rate,

$$N = 10^{-11} \dot{Q}_C T$$

where the constant of proportionality is frankly arbitrary, but which, in reality, must be fuel dependent. A brand parameter $\eta = 1$ corresponds to the smallest relevant brand. Small brands are assumed to be more likely than large ones, so a linear probability distribution of η is postulated:

$$P(\eta)d\eta = 2\eta d\eta \quad ; \quad 0 < \eta < 1.$$

During a time interval T , the model selects N values of η_k from this distribution for each burning cell and computes the transport of each brand. If the brand grounds in unignited fuel, ignition at this location either occurs or does not, as determined on the basis of the ignition probability. Should the computed number of brands N be less than one, the number is interpreted as the probability for producing one brand in the chosen time interval.

4.4.3 Branding Discussion

Stochastic elements play a large role in fire propagation by branding. Their origin is in part physical (random brand shape and size, turbulent fluctuations), but they chiefly originate from areas of ignorance. To a good approximation, given adequate hydrodynamics, brand transport can be modeled deterministically. The simple algorithms developed above demonstrate this. However, both ends of the branding process encounter more serious areas of ignorance--brand production estimation and brand ignition estimation. Limits of resolution of fuel properties and actual lack of knowledge will likely conspire to perpetuate this situation. Any branding model we can imagine will have a significant probabilistic content.

These considerations make it appropriate to emphasize at this point some modeling philosophy, which pertains to branding, but which also applies generally to our total model concept. In the first place, probabilistic elements of a model do not always imply that its overall behavior is random. Provided the basic underlying probability distributions are narrow enough or provided choices from broad probability distributions are made often enough, the overall aggregate results will display only a finite and acceptable scatter. In effect, the results are deterministic.

In the second place, the basic probability distributions governing modeling choices and logic can themselves be conditioned and changed by current values of physical parameters. Partial and qualitative knowledge, even intuition, can in this manner be incorporated with effect, meaning, and interactive potential. Absence of a precise, deterministic description of a process is no license to model it by a rigid and immutable random choice.

4.5 CONTIGUOUS FIRE SPREAD (CONTAGION)

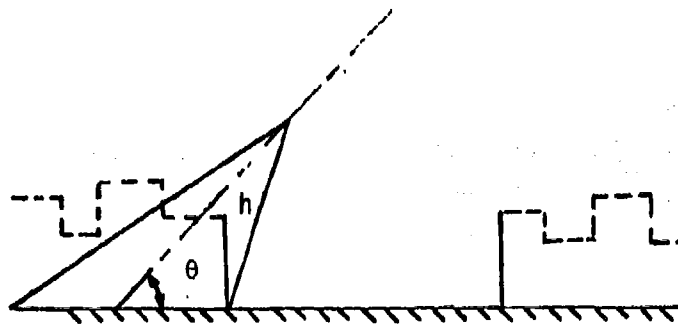
Contiguous fire spread--local spread from ignited fuel to adjacent unignited fuel--is a possible spread mechanism whether branding occurs or not. In the context of wildland fires, the Rothermel model successfully models spread in continuous fuel beds on the basis of local fuel parameters, together with the local terrain slope and wind. The physical framework of the Rothermel model is a spread rate determined by the ratio of emitted heat flux to heat required to ignite new fuel, but the numerical implementation of this idea required extensive tests to quantify fuel characteristics.

In the urban mass-fire context, fuel types and distributions are probably less well quantified than in wildlands and are certainly distinctly different. Also, building separation and the effect of streets as firebreaks may control spread (even after possible fuel scattering and modification by blast effects). Because of these distinctions, the short-range fire propagation across firebreaks is judged the most important mechanism to be modeled in the urban mass fire context. This process depends upon the local wind field and may be far less dependent upon detailed fuel parameters than spread in continuous fuel beds. These statements outline our conception of the proper modeling approach to contiguous fire spread in the urban mass-fire model.

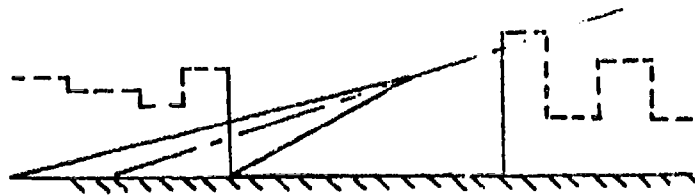
In the following, we briefly outline the very approximate calculation of contiguous spread which we employ in the demonstration model. Contiguous spread is specialized to spread between city blocks (the basic grid cells of the model) across streets, which are assumed devoid of fuel. No inter-building spread is explicitly modeled, since city blocks are the basic units. Spread between separated buildings within a block needs more investigation, along with several other "sub-grid" effects, which must be parameterized. Minimal cell size is limited by the large area of the simulation. If ignited anywhere, an entire city block in the demonstration model eventually burns. Multiple ignitions of the same block are possible and result in faster burning. The rate of burning is proportional to the number of ignitions of the block.

4.5.1 Summary of Contagion Concepts

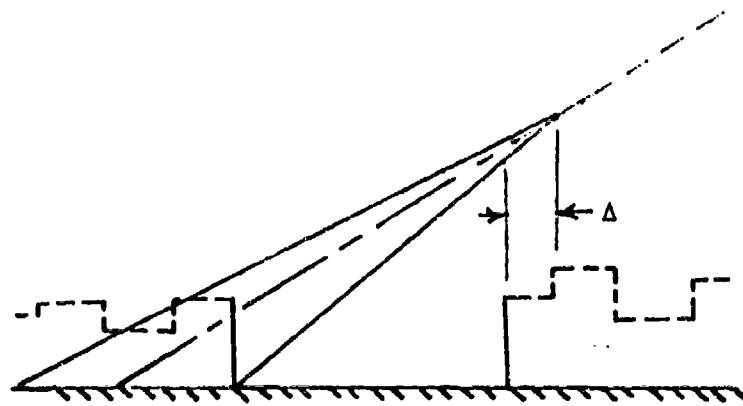
An important observation of the Flambeau tests (Reference 9) was that no fires were ignited outside the original fuel beds except within the horizontal distance determined by the vertical projection of the flaming volume onto the ground. Hence, ignitions only occurred on the lee side of the fire in a wind. We model spread across streets by estimating the configuration of tilted flame columns in the presence of a wind. Each flame column has the assumed shape of a cone with a circular base whose axis length and tilt are functions of burning rate and wind velocity. Figure 4-6 shows some possible relations of a flame column, burning at the edge of a block, to an open street in the downwind direction. Structures are suggested by the dotted outlines, and the flame column is represented by ground-based triangles. If the flame column does not overlap the adjacent block and its projected axis does not intersect buildings across the street, Figure 4-6(a), no contagion is possible and the adjacent block remains unignited. A finite ignition probability per unit time is calculated for the two cases of Figure 4-6(b) and 4-6(c). Figure 4-6(b) provides a mechanism for propagation between tall buildings separated by



a. No contagion. No overlap. No axis intersection.



b. Contagion probability finite.
Flame axis intersects buildings across street.



c. Contagion probability finite.
Flame column overlaps buildings across street.

Figure 4-6. Contagion across streets.

narrow streets, and makes explicit use of building height. The configuration of Figure 4-6(c) allows for propagation in accord with the Flambeau observations, and an ignition probability proportional to the overlap Δ is calculated.

The formulas and algorithms used by the demonstration model to implement these concepts are described in detail in Section 5. These methods may require substantial revision, so our summary description here includes only general features to indicate our concept of the physical factors involved.

Given the power $\dot{Q}$ of a fire and its area, $A = \pi r_0^2$, where r_0 is the effective radius of the cone base, the conical flame volume is computed from the air supply required for combustion $\dot{V}_a \sim \dot{Q}$ and an assumed entrainment velocity 1.0 (m/s) through the lateral surface of the cone. From the volume and base area, the axial slant height, h , of the cone is computed. The angle θ of the cone axis is determined from the ratio of the net vertical force on the flame, its buoyancy, to the net horizontal force. The buoyancy of the flame equals $V_f g (\rho_a - \rho)$ where V_f is flame volume, g is the acceleration of gravity, and $\rho_a - \rho$ is the difference between ambient air density and flame density. The horizontal force equals $\rho_a \dot{V}_a v$ where $\dot{V}_a$ is the total rate of air entrainment and v is the local wind velocity. These rough estimates establish the flame geometry shown in Figure 4-6.

A problem arises because the model carries only the burning rate $\dot{Q}$ of an entire city block. If the base area of the single conical flame equals the area of the block, only rarely is $\dot{Q}$ large enough to result in a flame tip located outside the base area. Here again, we encounter another aspect of the "sub-grid" problem and the need to estimate the number of flame columns in area burning. To resolve this problem

(somewhat inconsistently with procedures of the wind calculation) all the burning is assumed to take place within an area such that $h > r_0$. Since, in this case, the location of the burning sub-area within the block is not known, one employs a probability that it is located on the downwind periphery adjacent to unignited cells.

The geometry of the wind direction and the flame column in conjunction with the position of burning cells in relation to unignited ones forms the basis for calculating spread probability. These probabilities are, in fact, probabilities per unit time. Probabilities are computed at time steps internally determined on the basis of burning rate $\dot{Q}$ and its derivative $\ddot{Q}$. Furthermore, these probabilities are accumulated so that when the time integral of the probability per unit time equals one, ignition is certain.

A more physical contagion algorithm, based upon a ratio of heat flux to heat of ignition as in the Rothermel model, might be preferable to the one we have used in the demonstration model. Also, recall that short-range branding may play a major role in contagion. In general, we feel the demonstration model exaggerates spread by contagion. However, it does capture the dependence of this propagation mechanism upon wind speed, wind direction, and upon burning rate.

4.6 CONCEPT SUMMARY

The preceding sections have emphasized the salient aspects of our urban fire behavior concept. Fire development takes place by the principal spread mechanisms of contagion and branding, which are governed by atmospheric motion, a major component of which can be generated by the fire itself. The demonstration model, which has guided the discussion, provides an explicit framework illustrating the implementation of these concepts. The meaning of the demonstration model, we emphasize, does not

extend any farther. Narrowly viewed, it only provides a suitable structure and classifies the areas requiring further refinement.

A measure of uncertainty must be accepted in a model of urban mass fires. Not only are there limits of resolution of basic fuel and structural data, but also there are limits in the understanding of basic mechanisms all the way through the causal chain of events that occur. This circumstance requires a judicious selection and balance of model elements and model structure in order to minimize the uncertainties. The concept presented is our approach to this problem.

SECTION 5

DESCRIPTION OF DEMONSTRATION URBAN FIRE SIMULATION

The demonstration version of the Urban Fire Simulation embodies the range of phenomenology together with the logic and data management structures needed to implement the simulation concept described in Section 4. However, the phenomenology models are simplified versions of those described in Section 4. Development of a demonstration version of the simulation concept was undertaken to demonstrate the feasibility of implementing the concept, to qualitatively demonstrate simple regimes of behavior for the concept, and to identify areas in which modeling problems might exist. This section describes the structure and operation of the demonstration simulation. Simulation results are presented in Section 6, and a discussion of modeling problems is included in Section 1.

5.1 DEMONSTRATION SIMULATION STRUCTURE AND OPERATION

The demonstration simulation structure is designed to provide flexibility and simplicity of maintenance. The simulation is modular, event sequenced, and autointeractive. The simulation is asynchronously stepped forward in time through execution of events sequentially selected from an event list. Autointeraction is achieved by allowing each module to insert events in the event list.

The overall structure of the Demonstration Urban Fire Simulation is shown by the block diagram of Figure 5-1. The meanings of the blocks shown in Figure 5-1 are defined below:

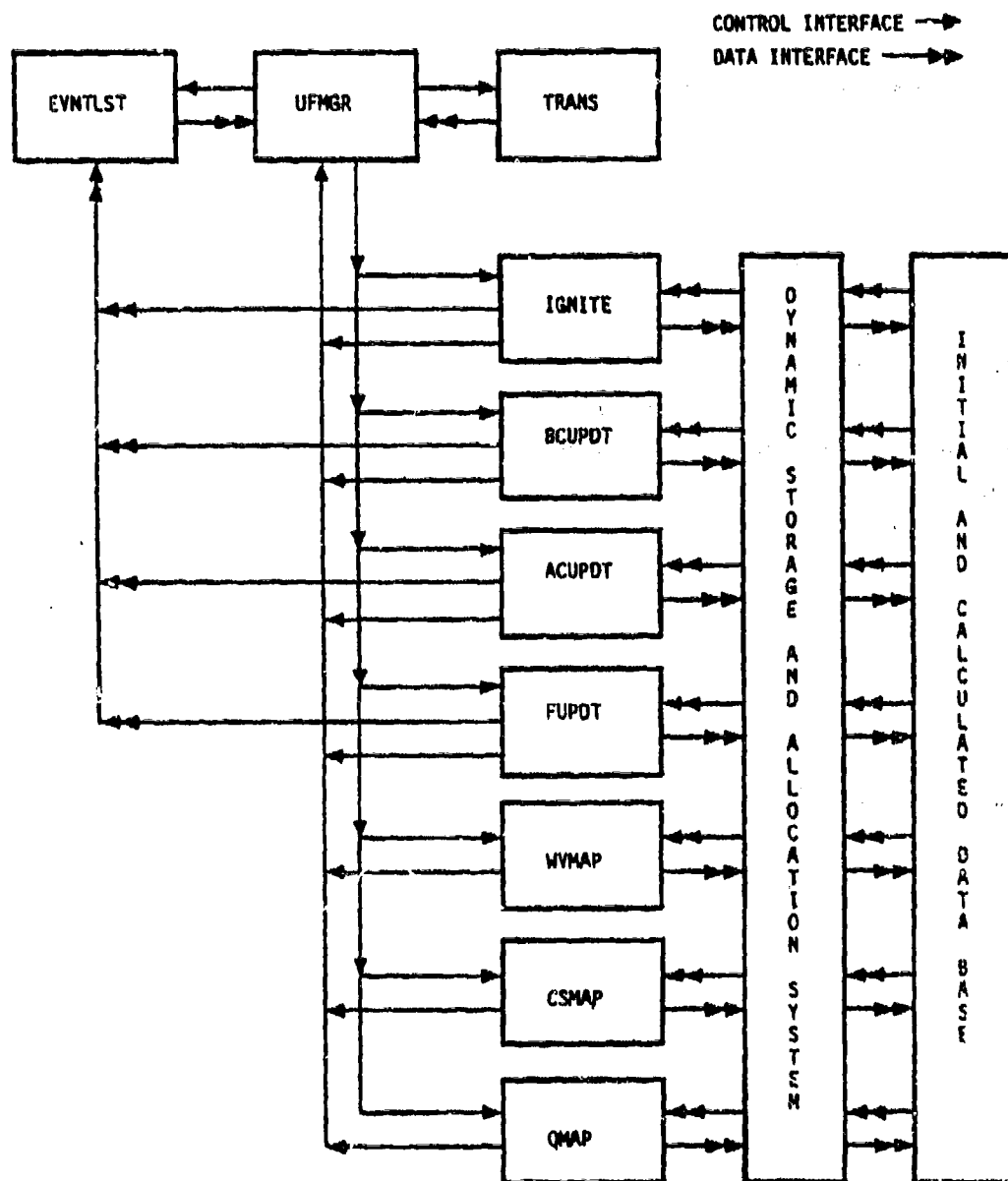


Figure 5-1. Block diagram of demonstration urban fire model.

- ENVTLS - the list (queue) of events to be executed
- UFMGR - the Urban Fire Manager (i.e., the executive structure)
- TRANS - the event module transfer list
- IGNITE - the functional module, which ignites unignited cells
- BCUPDT - the functional module, which updates burning cells
- ACUPDT - the functional module, which updates unignited cells adjacent to ignited cells
- FUPDT - the functional module, which updates the status of fires
- BRNDNG - the functional module, which determines if branding occurs
- WVMAP - the data processing module, which produces wind velocity maps
- CSMAP - the data processing module, which produces cell state maps
- QMAP - the data processing module, which produces heat production maps.

The Dynamic Storage and Allocation System (DSAS) provides for user interface to and management of the Data Base. The Data Base includes input data, interim calculations, and final results. In Figure 5-1, single and double headed arrows are used to indicate interfaces between the blocks. Single headed arrows denote control interfaces and double headed arrows denote data interfaces.

The simulation structure allows a simple executive procedure, which consists largely of two nested sequences of operations as described below. The Urban Fire Manager accesses the Event List and obtains the event in the list having the earliest execution time. With this event, the Urban Fire Manager accesses the Transfer List and obtains the sequence of modules, which must be processed to execute the subject event. The Urban Fire Manager transfers control to the first module in the sequence. The module accesses the Data Base through the Dynamic Storage and Allocation System to obtain its current input data, performs the computations

required by its function, stores an event in the Event List as appropriate, stores the results of its computations in the Data Base, and returns control to the Urban Fire Manager. The Urban Fire Manager continues to transfer control to the modules in sequence until all the modules in the sequence have been processed. When all of the modules in the sequence have been processed, event execution is, by definition, completed. The Urban Fire Manager then accesses the Event List to obtain the event having the earliest execution time and the event execution process is repeated until all events in the Event List have been executed. This executive procedure is both simple and flexible. It allows for altering events, adding events, and adding modules without any coding changes.

The demonstration model computation process is based on a two-dimensional grid structure, which is superimposed on the urban area of interest. The grid partitions the urban area into approximately city block sized square cells (i.e., 150 x 150 meters). As will be seen in the module descriptions, the grid-cell structure provides an organizational medium for the input data, the computational processes, and intermediate and final results. A description of the dynamic data base, which is used by each module, is presented in the next paragraph. This is followed in subsequent paragraphs by descriptions of each of the modules in Figure 5-1.

5.2 DYNAMIC DATA BASE DESCRIPTION

The dynamic data base is keyed to the grid-cell structure and partitioned into data sets consistent with the types of data required or produced by the modules. These data sets are described below.

Grid Data: The grid data are used to define the grid dimensions for a specific simulation execution and can be changed between simulation executions. The grid data are as follows:

1. The cell dimension (assumes square cells)
2. The location of the rectangular coordinate system origin
3. The maximum number of cells in each of the two dimensions.

Cell State Data: Each cell in the grid may, at any time, be in one of the following five states:

1. Unignited
2. Unignited, but adjacent to a burning cell (Adjacent)
3. Ignited and on a fire periphery (Peripheral)
4. Ignited and in a fire interior (Interior)
5. Burned out.

The cell state data are an array containing the state of each cell in the grid. This array is updated each time a cell changes state.

Fuel Data: The fuel within each cell is assumed to be uniform and the fuel type within each cell is identified in terms of an occupancy class. An arbitrary number of occupancy classes can be defined, ranging from heavy industrial through single family residential to parks and unimproved areas. The fuel data specified for each occupancy class are:

1. Fuel loading(kg/cell)
2. Fuel heat content (J/kg)
3. Fuel height (m)
4. No wind combustion rate (m/s)
5. Scale factor for time of maximum heat production.

Event List: The event list is a queue of all the events that have been scheduled for execution and is updated each time an event is taken from or added to the queue.

Burning Cell Data: The burning cell data consist of a sequence of three data sets for each ignited cell. Each cell is assigned a unique identification number (ID) based upon its row-column location in the grid. The cell ID is used to access the cell state data, and the cell state together with cell ID are used to access data for both ignited and unignited cells. The following burning cell data are maintained for each ignited cell:

1. Entry ID (1)
2. Occupancy class (fuel type)
3. Cell topographic height (m)
4. Time of cell ignition (s)
5. Number of times cell has been ignited
6. Cell ID
7. Entry ID (2 or 3)
8. Current cell heat production rate (J/s)
9. Maximum cell heat production rate (J/s)
10. Current cell burn time (s)
11. Time of cell maximum rate of heat production (s)
12. Time at which these data are valid.

Data elements 2 through 6 do not change, and entry ID = 1 denotes this subset of a burning cell data set. Data elements 8 through 12 may change at each calculation time, and this is denoted by entry ID = 2 or 3. Subsets of calculated burning cell data are maintained at two times, which always subtend the simulation time. Data required at any other times are obtained by interpolating between the data stored at these two times. Entry ID = 2 denotes the earlier, and entry ID = 3 denotes the later of these two data subsets.

Adjacent Cell Data: Adjacent cell data consist of a sequence of data sets for each unignited cell that is adjacent to a burning cell. The following information is maintained for each adjacent cell:

1. Entry ID (1)
2. Occupancy class (fuel type)
3. Cell topographic height (m)
4. Time of last cell update
5. Cumulative probability of cell ignition
6. Cell ID

Data for entry ID = 1 are included in this case because the data for an adjacent cell will be used to form the first subset of data for a burning cell. When the cell is ignited, the entry ID = 1 subset will be updated, and subsets for entry levels 2 and 3 will be generated.

Unignited Cell Data: Unignited cell data consist of a sequence of data sets for each unignited cell in the grid that is not adjacent to a burning cell. The following quantities are maintained for each unignited cell:

1. Entry ID (1)
2. Occupancy class (fuel type)
3. Cell topographic height (m).

Data for entry ID = 1 are included in this case because the data for an unignited cell will be used to form the entry ID = 1 subset of data for an adjacent cell when the subject cell becomes adjacent to a burning cell.

Fire Data: A fire is defined to consist of a set of contiguous burning cells. Depending upon its geometry, a fire may be partitioned into subfires that are reasonably symmetrical. This is done because some

of the phenomenology models include assumptions regarding geometric symmetry of the fires they describe. The following data are maintained for each defined fire:

1. Fire ID
2. Location of the effective center of the fire (x,y coordinates - m)
3. Effective radius of the fire (m)
4. Fire heat production rate (J/s)
5. Fire area (m^2)
6. Volume rate of surface air inflow to fire (m^3/s)
7. Time at which these data were calculated (s)
8. Number of cells in fire at the time given in (7)
9. List of cells currently in fire.

The use of an effective center and radius for each fire recognizes that the rate of heat production over a fire will generally not be uniform. Each time a cell is added to (ignited) or deleted from (burned out) the fire data, element 9 is updated. The other eight data elements may be updated much less frequently for reasons of computational efficiency.

The data sets described above constitute most of the dynamic data base, which is accessible to and updated by the simulation models. The remaining data consist of flags, constants, and other numerical quantities that are not generally part of the dynamic data base. The following paragraphs describe the logic flow and data interfaces within the modules shown in Figure 5-1.

5.3 IGNITE MODULE

The IGNITE module initializes burning in cells that have been determined to have been ignited. As shown in Figure 5-2, the event data

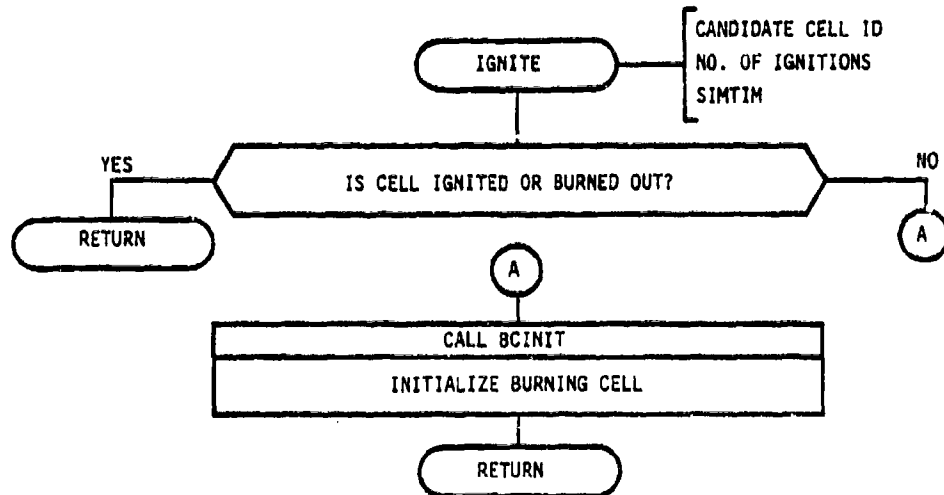


Figure 5-2. Logic flow of IGNITE module.

passed to IGNITE are the identity of the candidate cell, the number of ignitions and the current simulation time (SIMTIM). The candidate cell status is tested to determine if the cell can be ignited. If the cell is already ignited or burned out, it cannot be ignited and IGNITE returns control to UFMGR. If the candidate cell is unignited, the Burning Cell Initialization Subroutine is called and then control is returned to UFMGR.

The Burning Cell Initialization Subroutine (BCINIT) performs the tasks associated with changing the status of a cell from unignited to ignited as shown in Figure 5-3. BCINIT ignites the candidate cell at SIMTIM and changes the cell state from unignited to ignited. While the cell was unignited, the entry ID = 2 and 3 cell data subsets did not exist. The entry ID = 1 cell data subset is initialized at SIMTIM with all zero values. The wind velocity in the just ignited cell is calculated at SIMTIM + 360 seconds by the Wind Velocity Subroutine (WINDV). The entry ID = 2 data subset is initialized at SIMTIM + 360 seconds with values calculated for that time, and a burning cell update event is placed in the event list for execution time at SIMTIM + 360 seconds. Any subroutine requiring data on this cell between the current time and current time plus 360 seconds will obtain it by interpolating between these two data subsets. At current time plus 360 seconds, execution of the burning cell update event will reset data subset ID = 2 to ID = 1, generate a new data subset ID = 2 at a future time dependent upon cell heat production rate, and place an update event in the event list for execution at the same future time. In this way, two data subsets that always subtend SIMTIM are maintained for each burning cell .

The cell state and the fire to which it belongs (if burning) are identified for each of the eight cells adjacent to the just ignited cell. Also, the oldest fire represented among the eight adjacent cells is identified. Fires are assigned unique ID numbers in sequential order, so that older fires have lower ID numbers. When fires are merged, younger

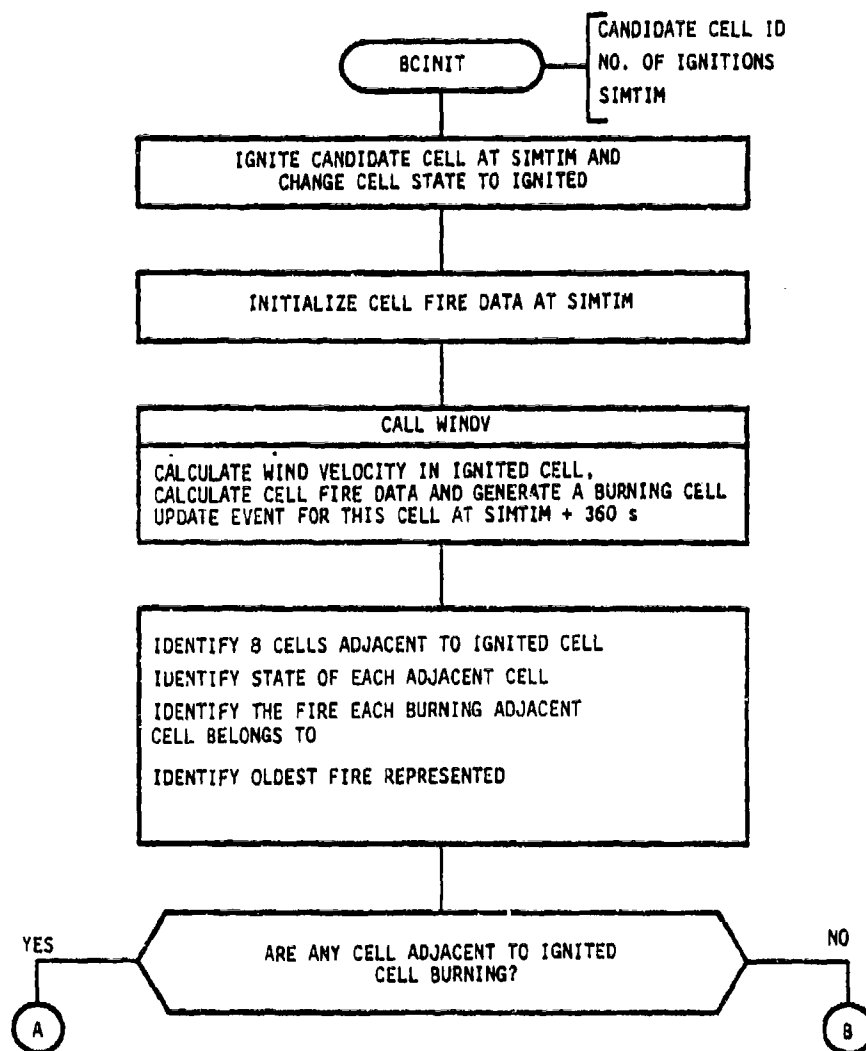


Figure 5-3. Logic flow of burning cell initialization module.

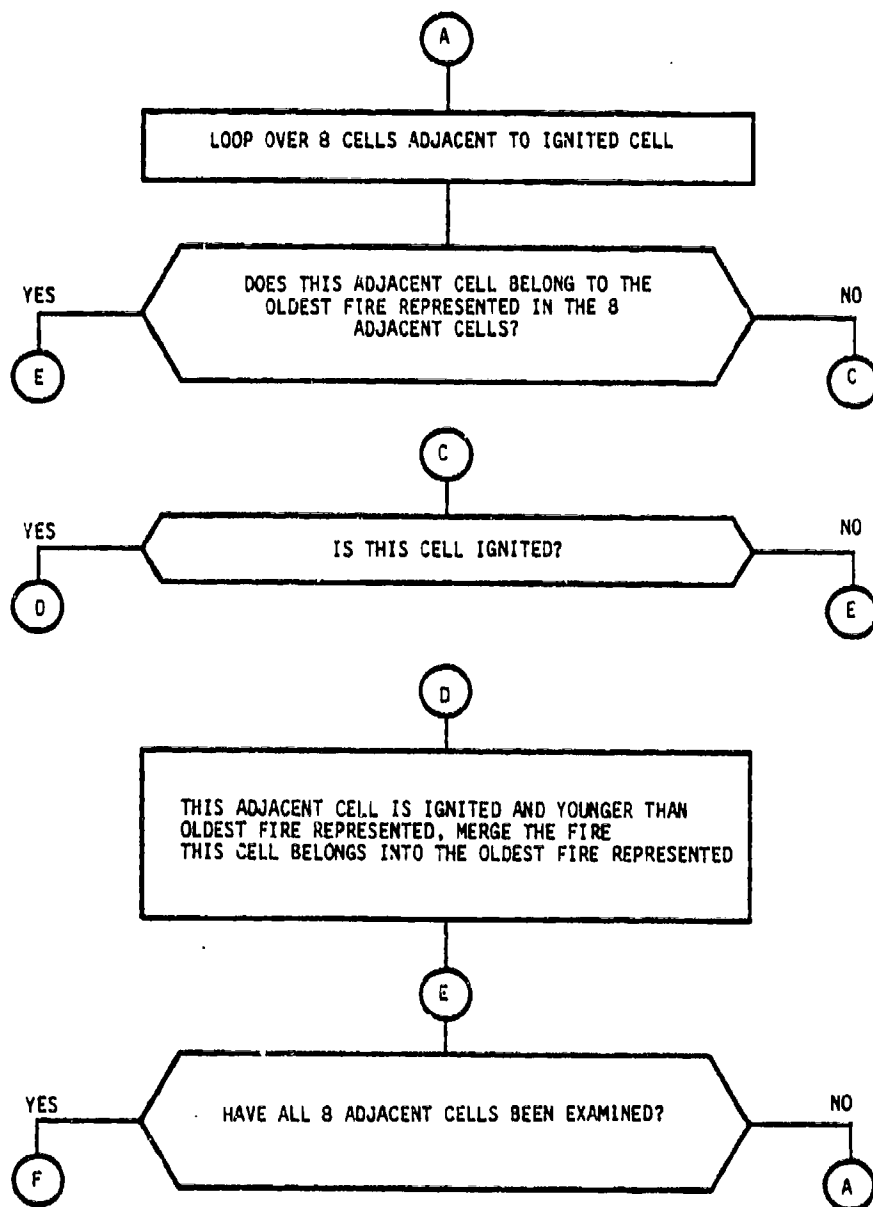


Figure 5-3. Logic flow of burning cell initialization module (continued).

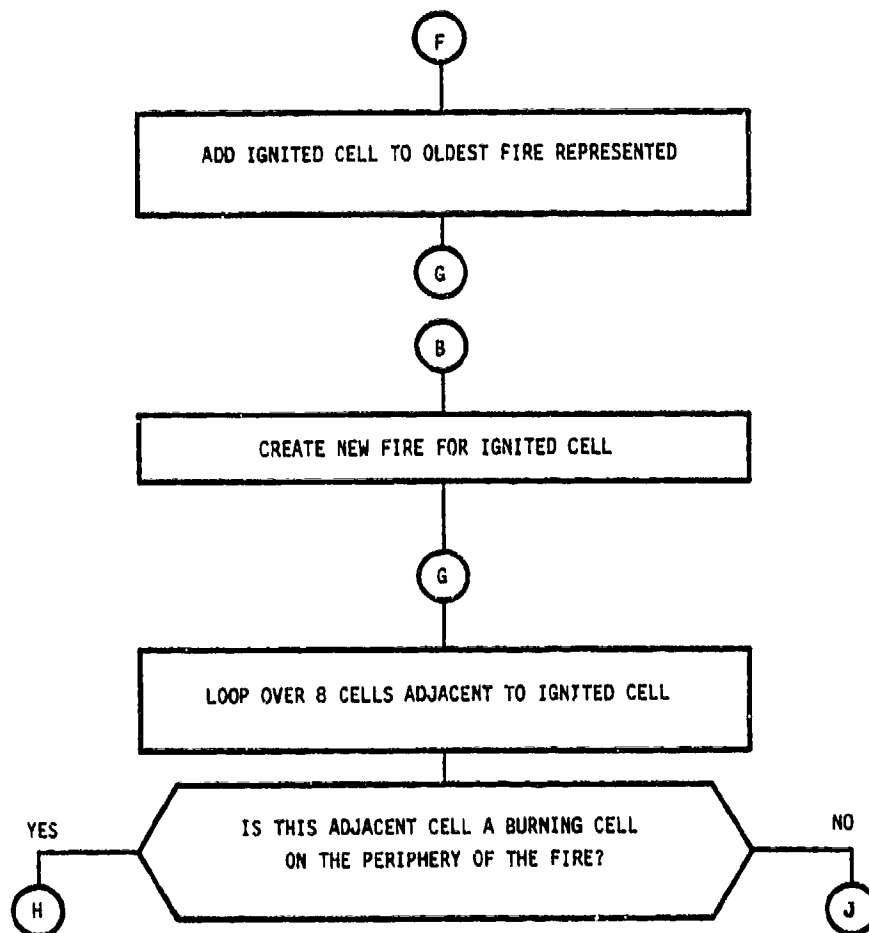


Figure 5-3. Logic flow of burning cell initialization module (continued).

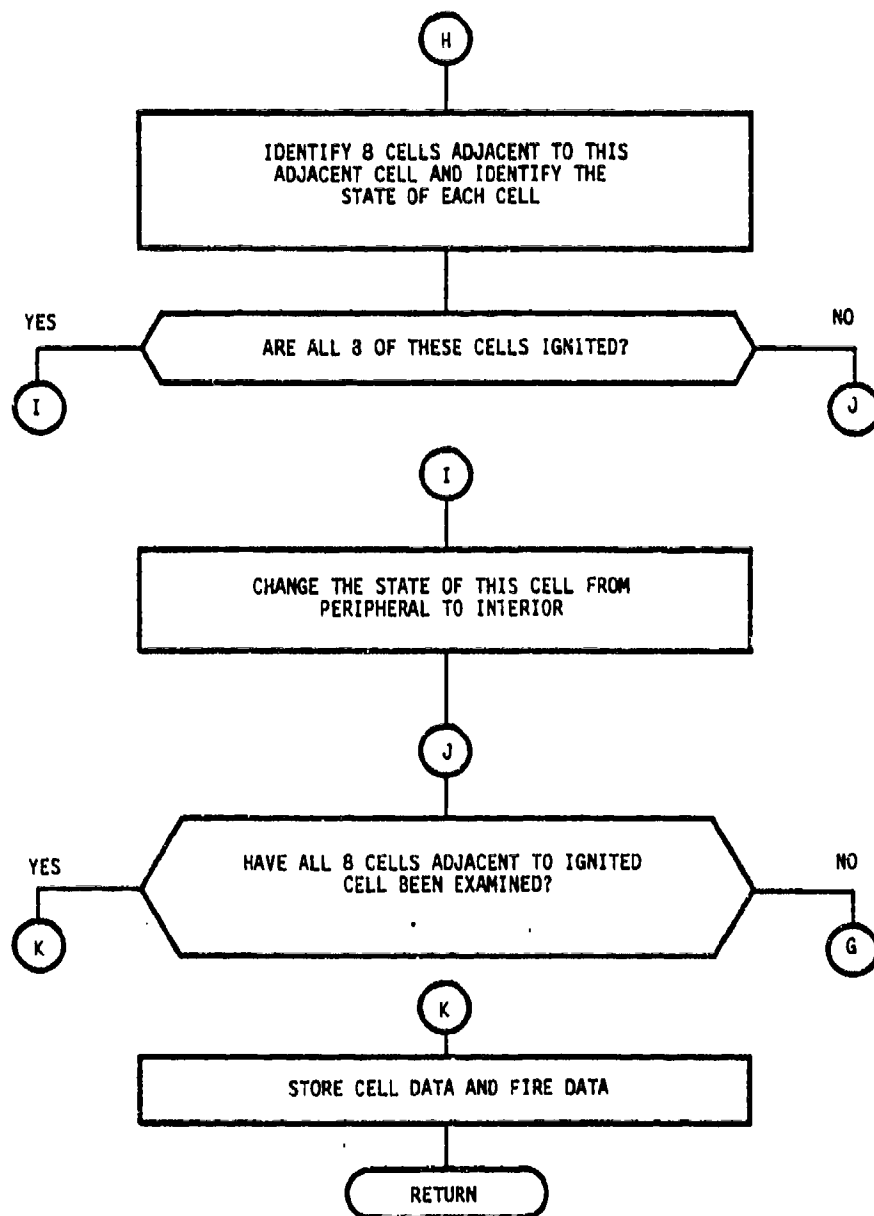


Figure 5-3. Logic flow of burning cell initialization module (concluded).

fires are always merged into older fires to maintain continuity of (older) fire identities.

If at least one cell adjacent to the just ignited cell is burning, BCINIT transfers to label (A), otherwise transfer is to label (B). At label (A), the fire identities of all of the ignited adjacent cells are examined. If the fire ID of an ignited cell is different from the ID of the oldest fire represented among the adjacent cells, transfer is to label (D). At label (D), the fire that the subject burning cell, adjacent to the just ignited cell belongs to, is merged with the oldest fire represented among the eight adjacent cells. Merging the two fires involves combining the burning and adjacent unignited cell lists of the younger fire with the burning and adjacent unignited cell lists of the older fire, updating the fire geometry partitioning, and updating the fire physical data. After all of the required mergers have been performed, the just ignited cell is added to the oldest fire represented among its eight adjacent cells and a transfer is made to label (E).

At label (B), none of the eight cells adjacent to the just ignited cell were found to be ignited. This is the definition of an isolated fire. Thus, a new fire is created for the just ignited cell. This involves assigning to this cell the next fire ID number, creating burning and adjacent unignited cell lists, and initializing the fire physical data.

The Wind Velocity Subroutine (WINDV) calculates the wind velocity at a specified point due to all fires in the grid area and due to the ambient wind. The wind velocity calculation assumes a flux sink at the center of each circularly symmetrical subfire. As mentioned before, fires consist of sets of contiguous burning cells, which are partitioned into subfires that are approximately symmetrical. Thus, each fire, even if not partitioned, includes one subfire (i.e., the whole). As shown in the

logic flowchart of Figure 5-4, WINDV loops over all fires and subfires in the grid and calculates the contribution of each subfire to the fire induced wind velocity at a specified field point. Three cases are considered in this calculation: (1) the field point is located at the center of the subfire under consideration; (2) the field point is inside the subfire under consideration; and (3) the field point is outside of the subfire under consideration. Upon completion of the fire induced wind calculations, the ambient wind velocity is added to the fire induced wind velocity to define the total wind velocity at the specified point.

Calculation of the fire induced wind velocity is based on the following equations.

$$\vec{v}_F(\vec{r}_p) = \sum_{f=1}^N \vec{v}_r(\vec{r}_p) + \sum_{f'=1}^M \vec{v}_f(\vec{r}_p) \quad (5-1)$$

where

$\vec{v}_F(\vec{r}_p)$ = the fire induced wind velocity at the grid point $\vec{r}_p$,

$f=1, N$ are the subfires that do not contain grid point $\vec{r}_p$,

$f'=1, M$ are the subfires that do contain grid point $\vec{r}_p$.

The contribution to the fire induced wind at point $\vec{r}_p$ due to subfire f , which does not contain grid point $\vec{r}_p$, is given by

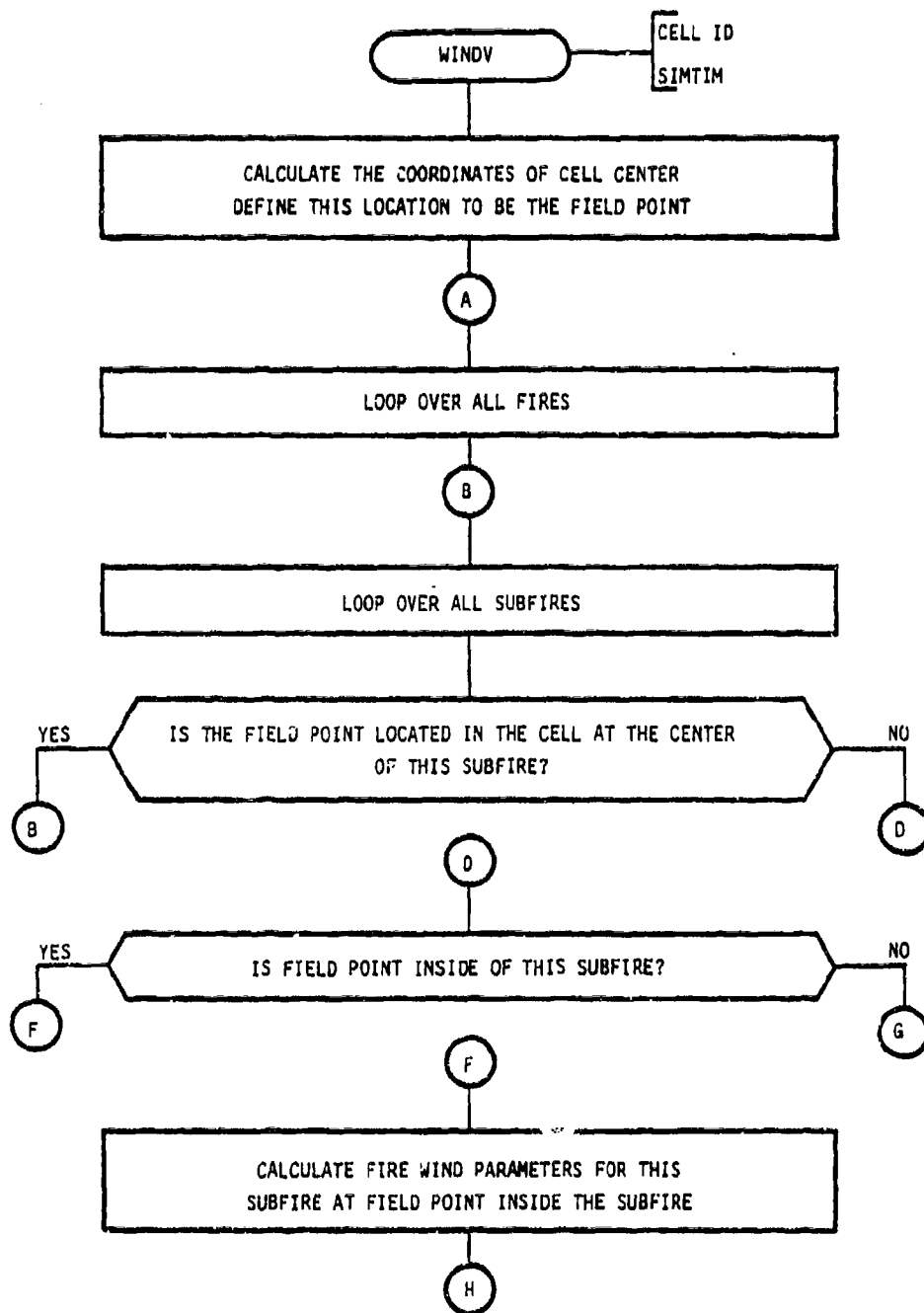


Figure 5-4. Logic flow of wind velocity subroutine.

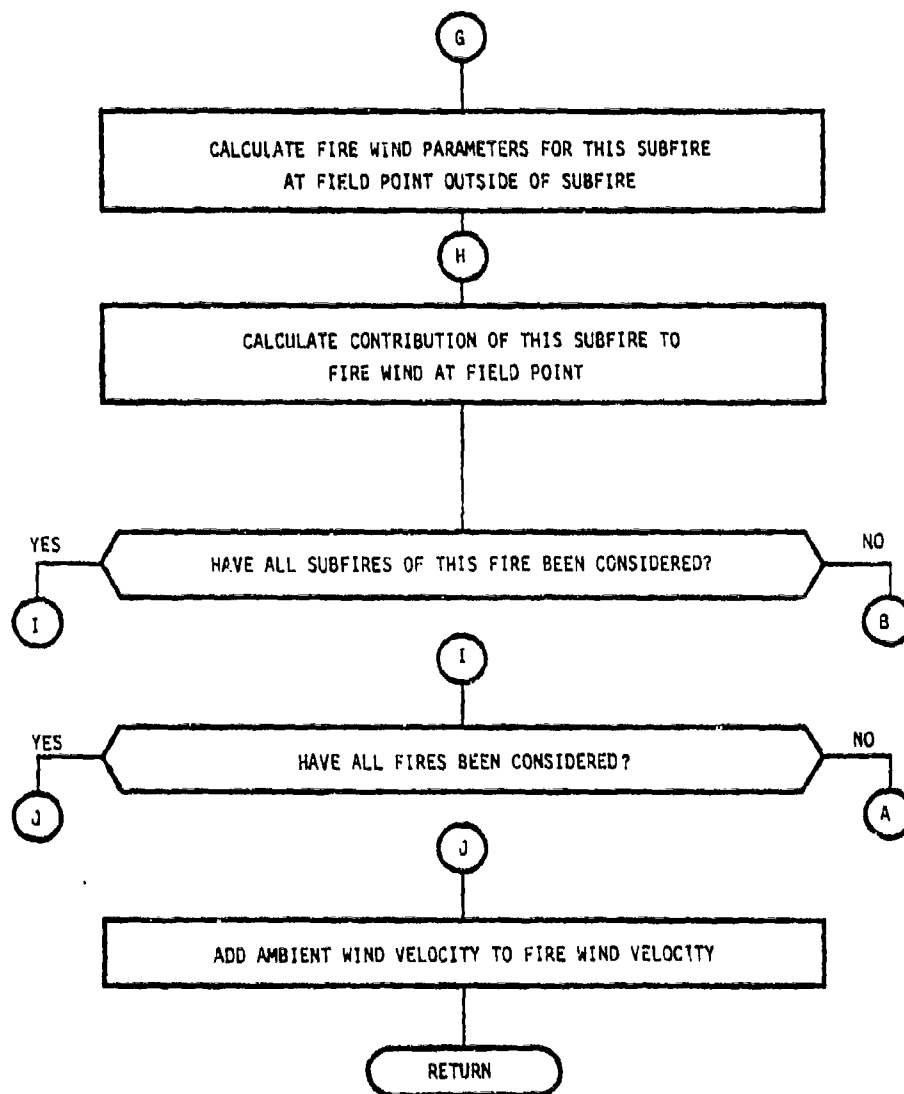


Figure 5-4. Logic flow of wind velocity subroutine (concluded).

$$\vec{v}_f(\vec{r}_p) = \left[\frac{\dot{V}_f}{2\pi v |\vec{a}_f|^3} + \frac{g(\gamma) \dot{Q}_f^{-1/9} r_f^{10/9}}{|\vec{a}_f|^{4/3}} \right] \vec{a}_f. \quad (5-2)$$

The contribution to the fire induced wind at point $\vec{r}_p$ due to subfire f , which does contain grid point $\vec{r}_p$, is given by

$$\vec{v}_{f'}(\vec{r}_p) = \left[\frac{\dot{V}_{f'}}{2\pi r_{f'}^3} + g(W)h \left(\frac{|\vec{a}_{f'}|}{r_{f'}} \right) \dot{Q}_{f'}^{-1/9} r_{f'}^{7/9} \right] \vec{a}_{f'}, \quad (5-3)$$

where

$\dot{V}_{f'}$ = volume rate of air inflow to subfire f' ,

$\vec{a}_{f'} = \vec{r}_{cf'} - \vec{r}_p$,

$\vec{r}_{cf'}$ = location of the effective center of subfire f' ,

$\dot{Q}_{f'}$ = total energy release rate of subfire f' ,

$r_{f'}$ = effective radius of subfire f' .

The function $g(\gamma)$ is given by

$$g(\gamma) = 0.5298 \gamma^{1.5863} / (1.3285 + \gamma^{1.5863}) \quad (5-4)$$

where

$$\gamma = Z_c / |\vec{a}_f| \quad \text{if} \quad |\vec{a}_f| > r_f \quad \text{or} \quad (5-5)$$

$$Z_c/r_f \quad \text{if } |\vec{a}_f| < r_f ,$$

$$Z_c = 0.23376 \dot{Q}_{mx}^{1/4} t^{3/4} \quad (5-6)$$

$\dot{Q}_{mx}$ = total energy release rate of the largest fire in the grid

t = simulation time.

The function $h(|\vec{a}_f|/r_f)$ is given by

$$h\left(\frac{|\vec{a}_f|}{r_f}\right) = \pi - 2 \cos^{-1}\left(\frac{|\vec{a}_f|}{r_f}\right) + 2\left(\frac{|\vec{a}_f|}{r_f}\right) \sqrt{1 - \left(\frac{|\vec{a}_f|}{r_f}\right)^2} . \quad (5-7)$$

5.4 BURNING CELL UPDATE (BCUPDT) MODULE

The Burning Cell Update Module maintains dynamic cell data that provide the characteristics of a burning cell. Two dynamic cell data lists are maintained that always subtend SIMTIM. Characteristics at any SIMTIM are determined by interpolating with respect to time between these two data lists.

The energy production rate of a burning cell is defined by

$$\dot{q}_c = \frac{Q_c}{\tau_{mx}} \tau e^{-\tau/\tau_{mx}} \quad (\text{J/s}) \quad (5-8)$$

where

- $\dot{q}_c$ = energy production rate of cell c (J/s)
- Q_c = total energy content of cell (J)
- t_{mx} = cell time of maximum energy production (s)
- t = cell burn time (s).

The total cell energy content is given by

$$Q_c = H_F L_F A_c \quad , \quad (j) \quad (5-9)$$

where

- H_F = fuel heat content (J/kg)
- L_F = fuel loading (kg/m²)
- A_c = cell area (m²).

The cell heat production rate given by Equation 5-8 rises to a peak value at $\tau = \tau_{mx}$ and then decays as shown in Figure 5-5.

As shown in the logic flowchart of Figure 5-6, the information transferred to BCUPDT by the update event is the ID of the burning cell and the current SIMTIM.

BCUPDT identifies the fire the burning cell belongs to by referring to the cell state map. In this map, a burning cell is identified by the ID of the fire to which it belongs.

The fraction of the cell that has been burned at current SIMTIM is calculated. As shown in Equation 5-8 and Figure 5-5, the cell combustion function is characterized by a maximum heat production rate $(\dot{q}_c)_{mx}$, which occurs at time τ_{mx} . Cell burnout is defined to occur at $\tau = 4 \tau_{mx}$, at which time the cell is approximately 90 percent

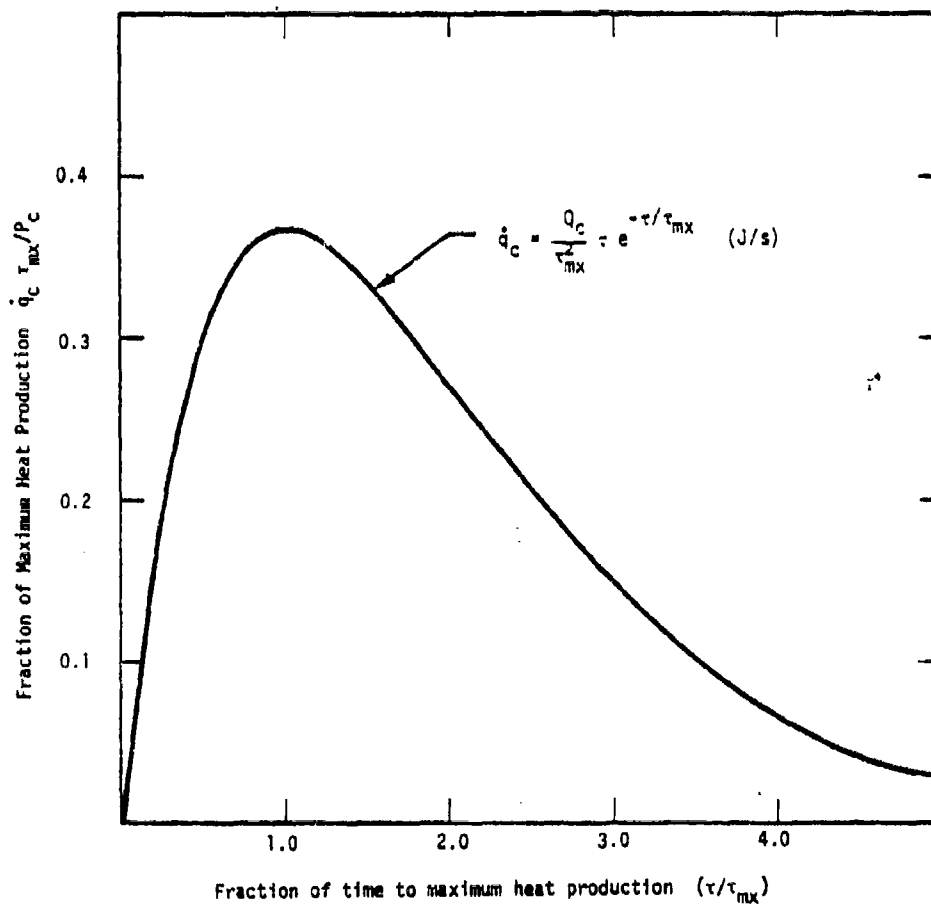


Figure 5-5. Functional form of cell heat production rate.

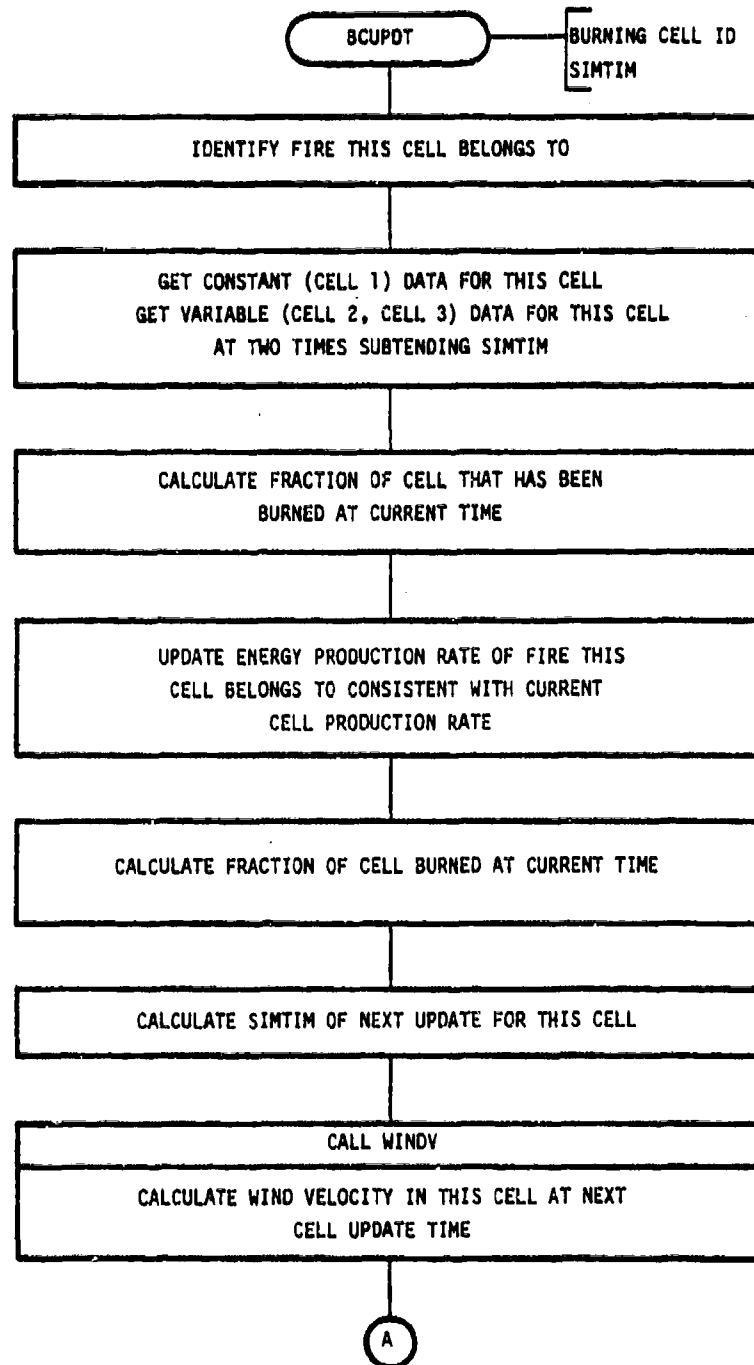


Figure 5-6. Logic flow of burning cell update module.

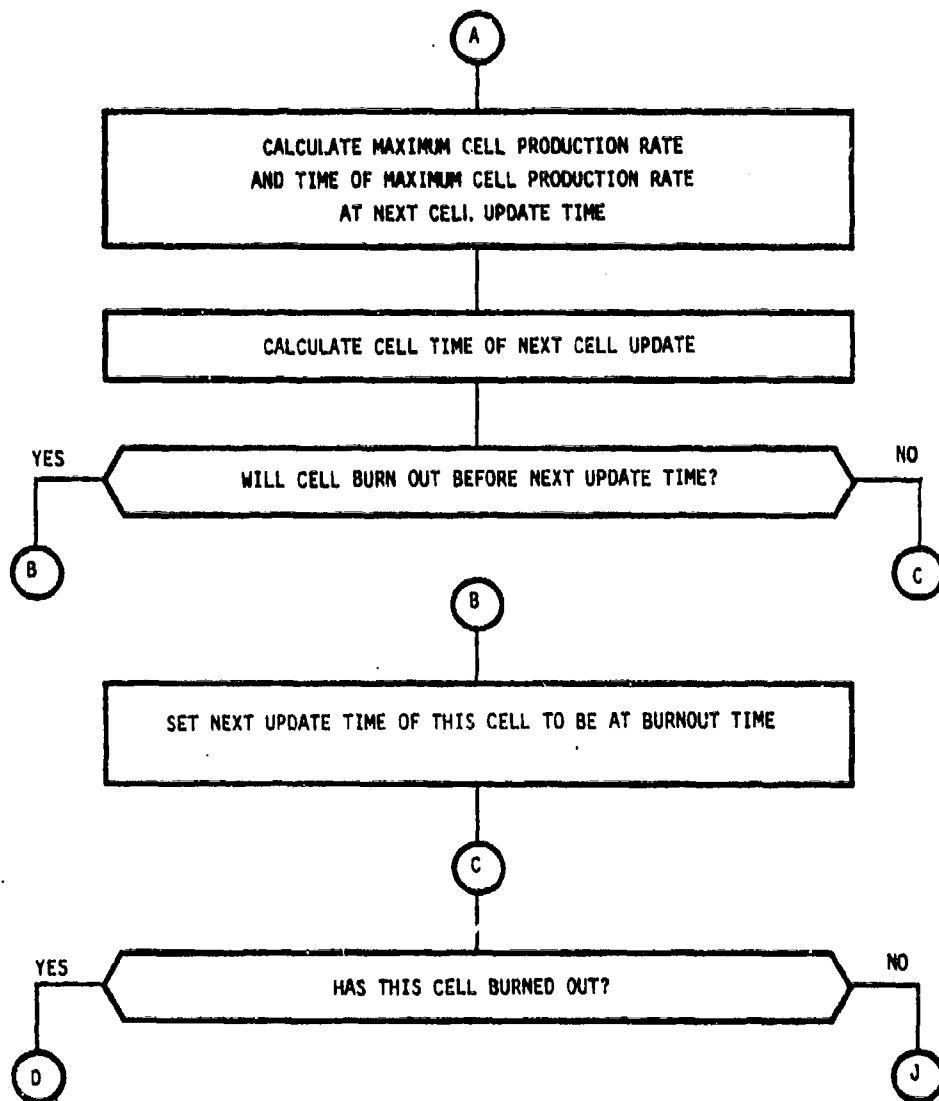


Figure 5-6. Logic flow of burning cell update module (continued).

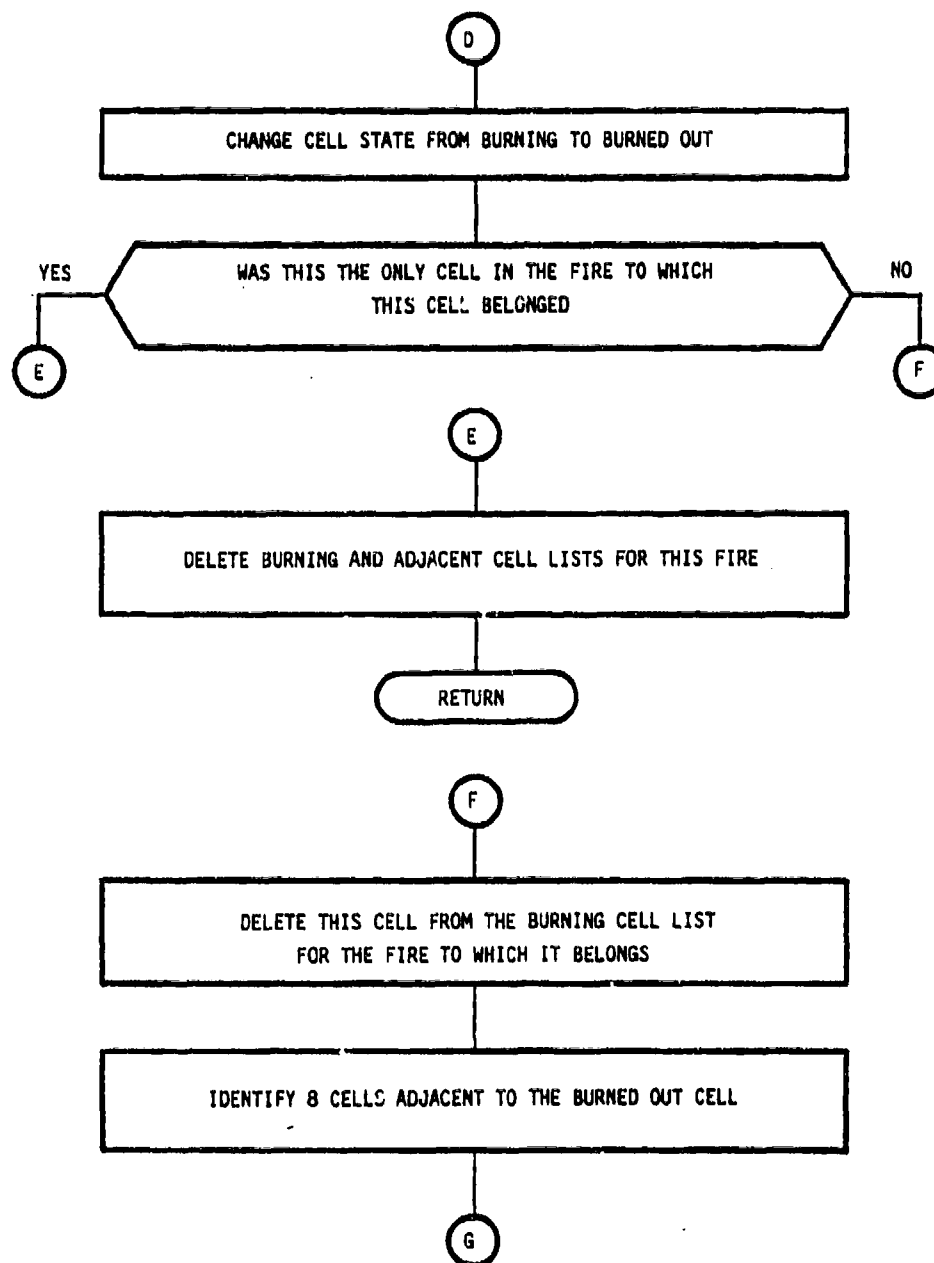


Figure 5-6. Logic flow of burning cell update module (continued).

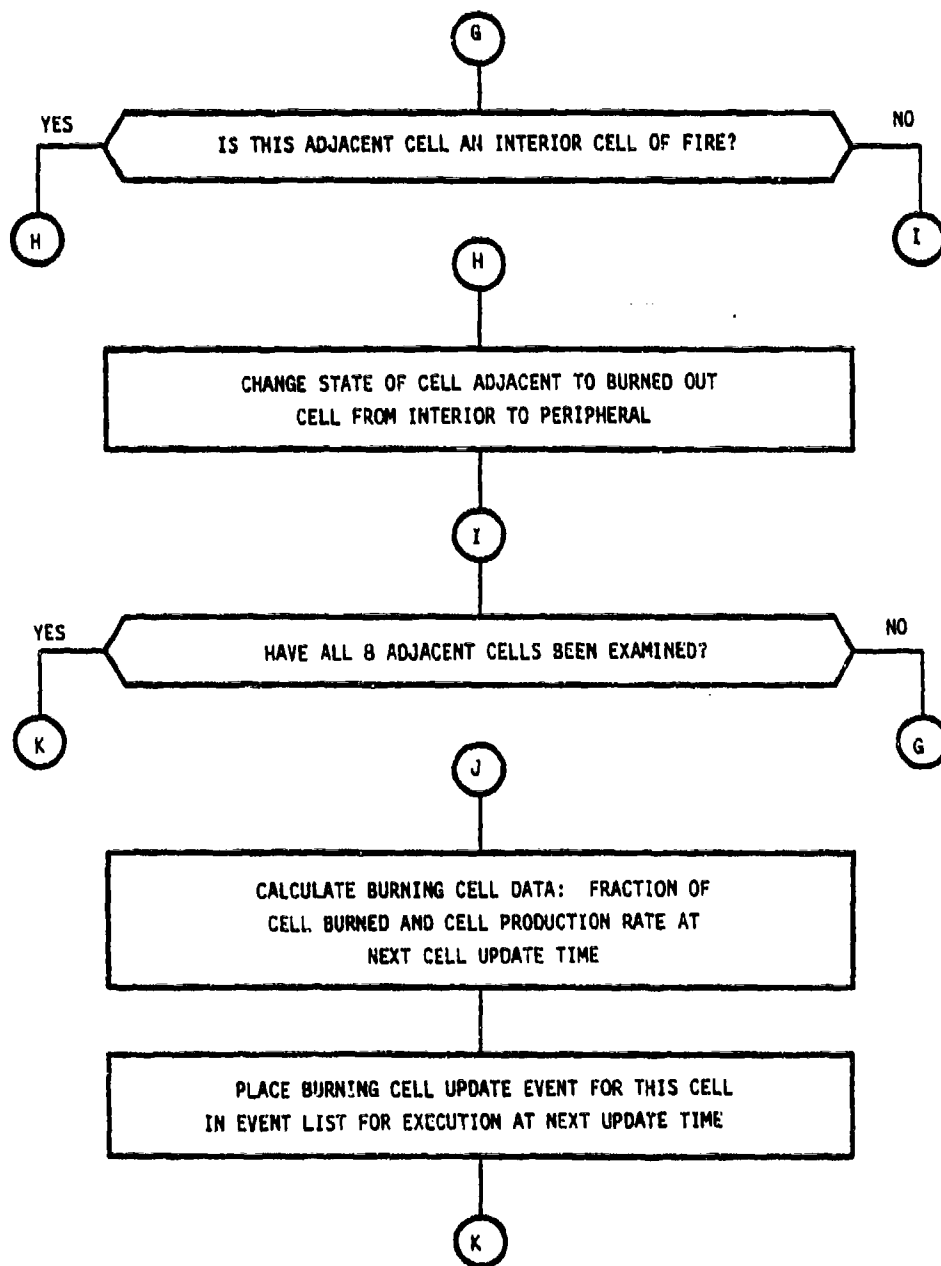


Figure 5-6. Logic flow of burning cell update module (continued).

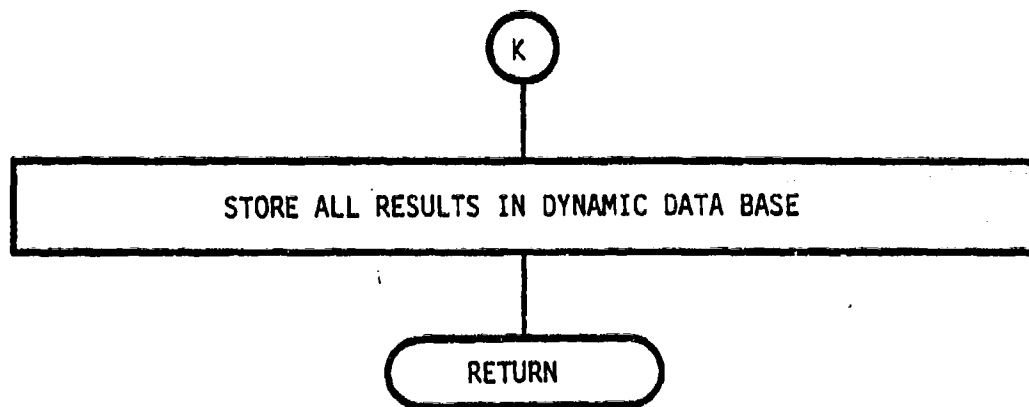


Figure 5-6. Logic flow of burning cell update module (concluded).

consumed, according to Equation 5-8. Thus, a measure of the fraction of the cell that has been burned is given by $\tau/4\tau_{mx}$.

The current energy production rate of the cell is calculated from the dynamic cell data. This cell production rate is used to update the energy production rate of the fire to which the cell belongs. In the case of fires (as opposed to cells), only one set of data is maintained to describe the fire status. In between fire update events, the fire state is assumed not to change, except for fire heat production rate, which is adjusted each time one of the fire's constituent cells is updated.

A burning cell update event is always scheduled to occur when SIMTIM is equal to the time of the most recent dynamic set of cell data. A significant function of the burning cell update is to determine the next update time, project dynamic cell data to that time, and arrange for a cell update at that time.

The time to be associated with the new data set and with the next update of the burning cell is based on the current rate of change of cell heat production rate. The time increment to the next update is given by

$$d\tau = 0.5 \tau_{mx} (1 - q/q_0) \quad (s), \quad (5-10)$$

where $\ddot{q}_0 = \ddot{q}/(t=0)$. This provides for updates at approximately 2000 second intervals when $\tau > \tau_{mx}$ and provides more frequent updates when $\tau < \tau_{mx}$. The rate of change of cell heat production rate with respect to time (q_c) is from Equation 5-8

$$q_c = (Q_c/\tau_{mx}^2)(1 - \tau/\tau_{mx}) e^{-\tau/\tau_{mx}} \quad (5-11)$$

A call is made to WINDV to calculate the wind velocity in the burning cell at $\tau' = \tau + d\tau$, the time of the next cell update.

At label (A) of Figure 5-6, the time of maximum cell heat production is calculated from

$$\tau_{mx} = k L_c / (N_{ig} h_f (a + S_w)) \quad (s), \quad (5-12)$$

where

k = fuel constant

L_c = cell dimension (m)

N_{ig} = number of ignitions in cell

h_f = fuel height (m)

a = zero-wind spread rate coefficient (m/s)

S_w = total wind speed in cell (m/s).

The effects of increasing wind speed upon cell combustion are, thus, to increase the maximum cell heat production rate and to cause its occurrence at an earlier time. Maximum cell heat production rate occurs at $\tau = \tau_{mx}$, which from Equation 5-8 yields

$$(\dot{q}_c)_{mx} = 0.368 Q_c / \tau_{mx} \quad , \quad (5-13)$$

where Q_c is defined by Equation 5-9 and τ_{mx} by Equation 5-12.

The time of maximum heat production is a function of total wind speed in the cell, which is a function of the geometry and intensity of all the fires in the grid, together with the ambient wind. The wind in the cell may, thus, fluctuate and cause both the time and level of maximum heat production rate to fluctuate. These fluctuations are acceptable and represent an important part of the fire wind interaction.

A change in wind speed affects τ_{mx} , $(\dot{q}_c)_{mx}$, q_c and burnout time, together with other cell and fire variables. Given a change in τ_{mx} , we must, to be physically consistent, require the cumulative heat production to be unchanged. The cumulative heat production rate $(\dot{Q}_c)$ is, from Equation 5-8, given by

$$\dot{Q}_c(\tau) = \int_0^\tau \dot{q} dt = Q[1 - (1 + \frac{\tau}{\tau_{mx}}) e^{-\tau/\tau_{mx}}] , \quad (5-14)$$

which we write in the form

$$\dot{Q}_c(f) = Q[1 - (1 + f) e^{-f}] , \quad (5-15)$$

where $f = \tau/\tau_{mx}$ is a measure of the fraction of the cell that has been burned. The cumulative cell heat production is held constant under varying τ_{mx} by also varying τ so that f remains constant. The fraction burned at the next cell update time (τ') with the current value of τ_{mx} is

$$f_1 = \tau'/\tau_{mx} . \quad (5-16)$$

The fraction burned at the next cell update time with the value of τ'_{mx} at that time is

$$f_2 = \tau'(\tau'_{mx}/\tau_{mx}) . \quad (5-17)$$

Calculate the new value of cell time at the next update (τ'') of this cell as

$$\tau'' = \tau'(\tau'_{mx}/\tau_{mx}) \quad (5-18)$$

by requiring that $f_1 = f_2$. The manipulation at cell time is possible without affecting simulation time because the cell time is coupled to SIMTIM only by

$$\text{SIMTIM} = t_{ig} < \tau < 4\tau_{mx} = \text{SIMTIM} \quad . \quad (5-19)$$

Within the limitations imposed by Equation 5-19, τ may advance or regress, as required by Equation 5-18, without affecting SIMTIM.

Given the adjusted time of the next cell update (τ''), the test $\tau'' > 4\tau_{mx}$ is performed. If the update time is after cell burnout, the update time is adjusted at label (B) to coincide with cell burnout.

If $\tau'' < 4\tau_{mx}$, transfer is made to label (C). If $\tau'' = 4\tau_{mx}$, transfer is to label (D), otherwise transfer is to label (J).

At Label (D), a burned out cell has been identified. The state of the subject cell is changed from burning to burned out, and adjustments are made to the related fire data.

At label (E) the subject cell was the only burning cell in the related fire; thus, the fire is deleted by deleting its burning cell and adjacent cell lists. Processing of this cell is then complete and BCUPDT returns control to UFMGR.

At label (F) the subject cell was not the only burning cell in the related fire; thus, the subject cell is deleted from the burning cell list. The 8 cells adjacent to the subject cell are identified to determine if their state has been changed by the state change of the subject cell. All burning cells are either interior cells or peripheral cells.

An interior cell is one that has 8 burning adjacent cells and a peripheral cell is one that has at least one nonburning (unignited or burned out) adjacent cell. Thus, the only state change possible for a cell adjacent to a newly burned out cell is a change from an interior cell to a peripheral cell. In labels (G) through (I) all adjacent cells of the subject cell that were interior cells are changed to peripheral cells.

At label (J) all fire data manipulations have been completed. The burning cell heat production rate at the adjusted time of next cell update is calculated. A burning cell update event for the subject cell is placed in the event list for execution at the SIMTIM corresponding to the adjusted cell update time. At label (K) the new set of dynamic cell data are stored in the dynamic data base in place of the older of the two existing sets of dynamic cell data for this cell. The data stored are Entry ID, Heat Production Rate, Maximum Heat Production Rate, Cell Time of These Data, Cell Time of Maximum Heat Production Rate, and SIMTIM of these data. After storing these data in the dynamic data base, BCUPDT returns control to UFMGR.

5.5 ADJACENT CELL UPDATE (ACUPDT) MODULE

As shown in Figure 5-7, the information passed to the ACUPDT module by the update event is the current SIMTIM and the ID of the cell to be updated. The cell to be updated is called an adjacent cell because it is adjacent to a fire. We will also be concerned with the eight cells adjacent to the cell to be updated. To prevent confusion, the cell to be updated is referred to here and in Figure 5-7 as the subject cell.

An unignited cell adjacent to a fire may experience a state change by becoming ignited. Ignition may result from branding or from contagion. Branding is defined as ignition due to the physical transport of burning material and will be discussed in a later section. Contagion

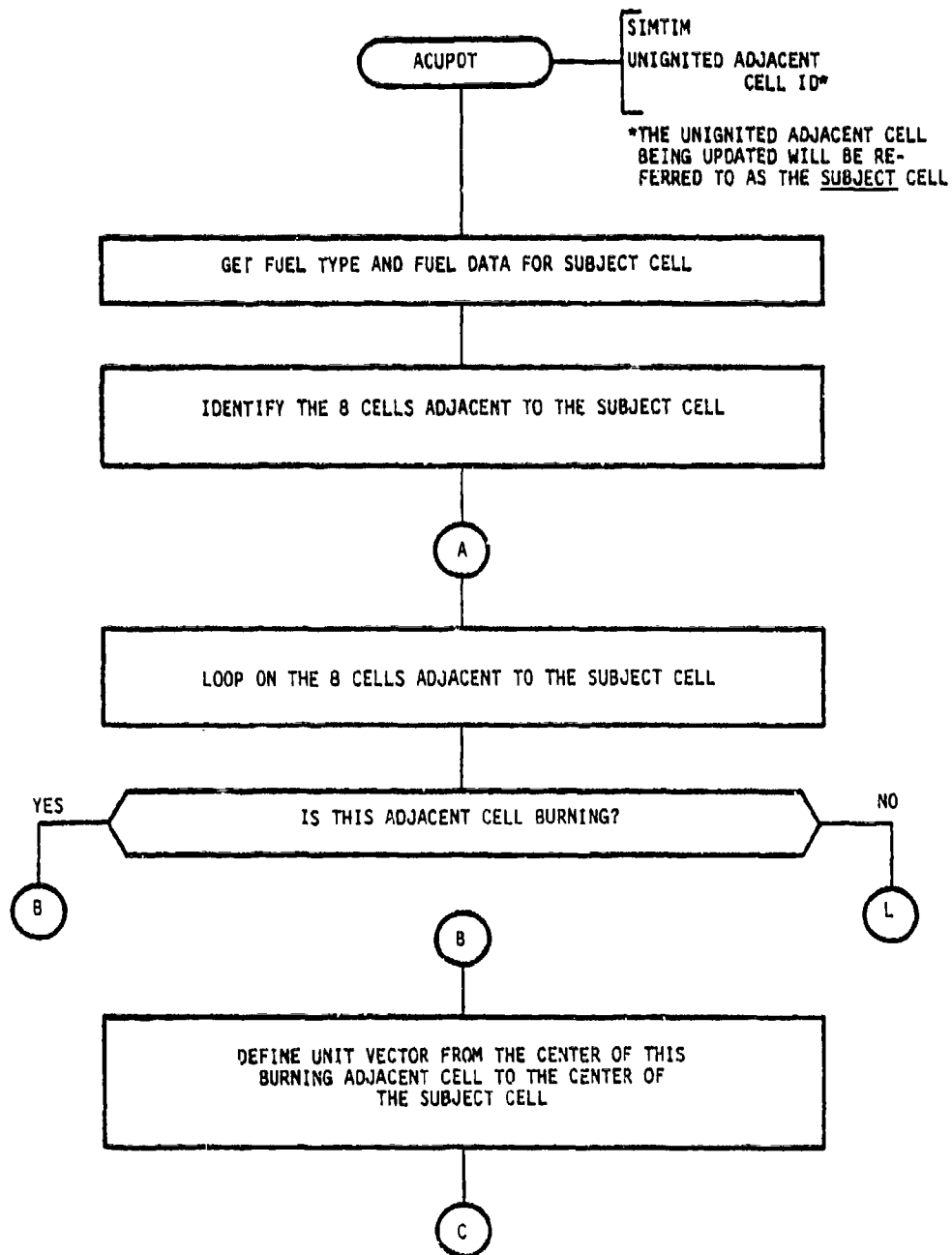


Figure 5-7. Adjacent cell update module.

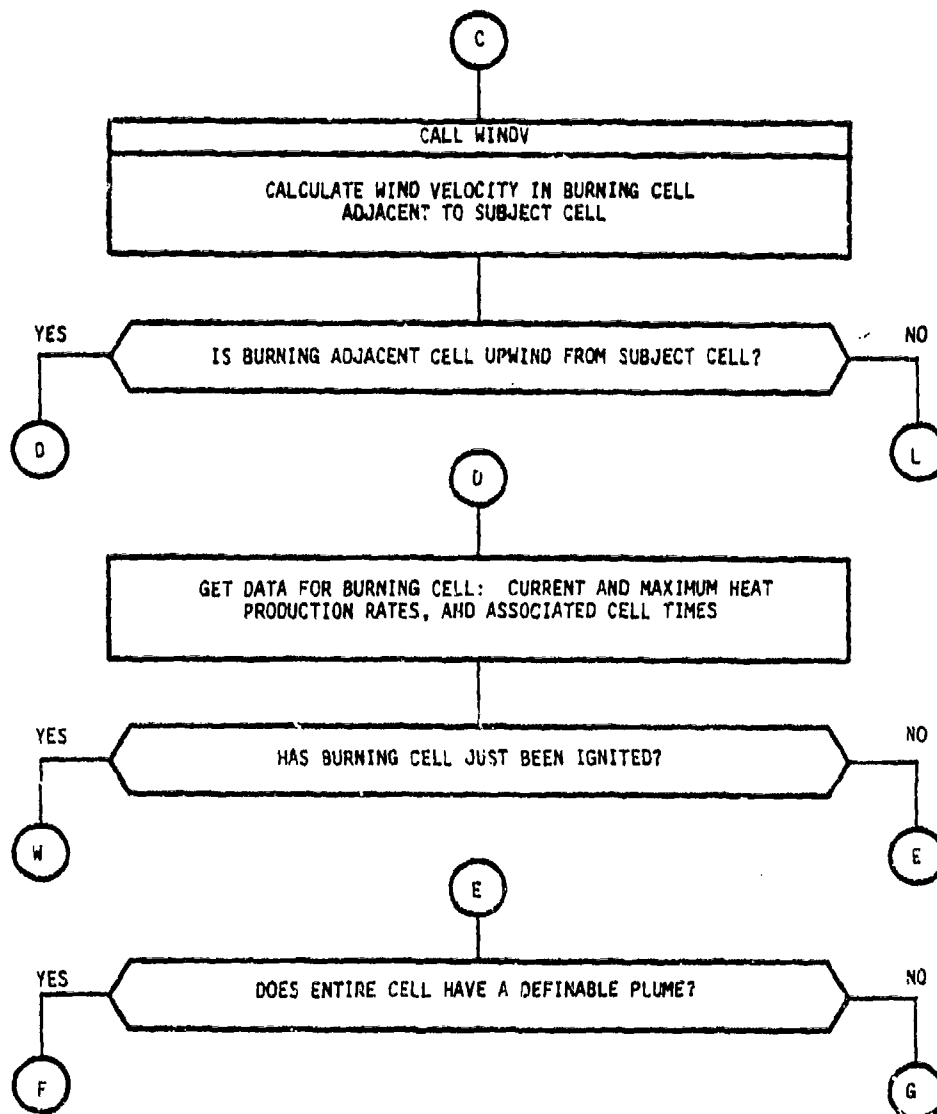


Figure 5-7. Adjacent cell update module (continued).

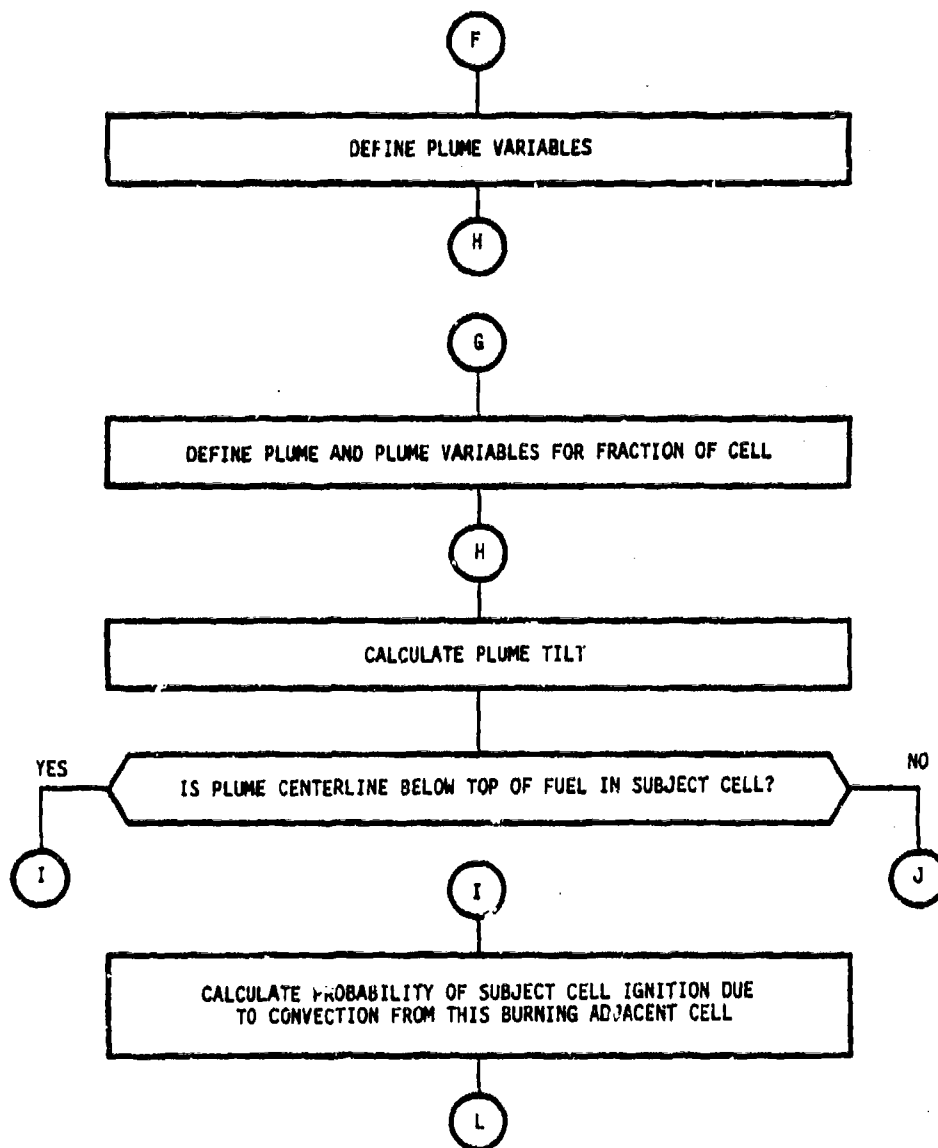


Figure 5-7. Adjacent cell update module (continued).

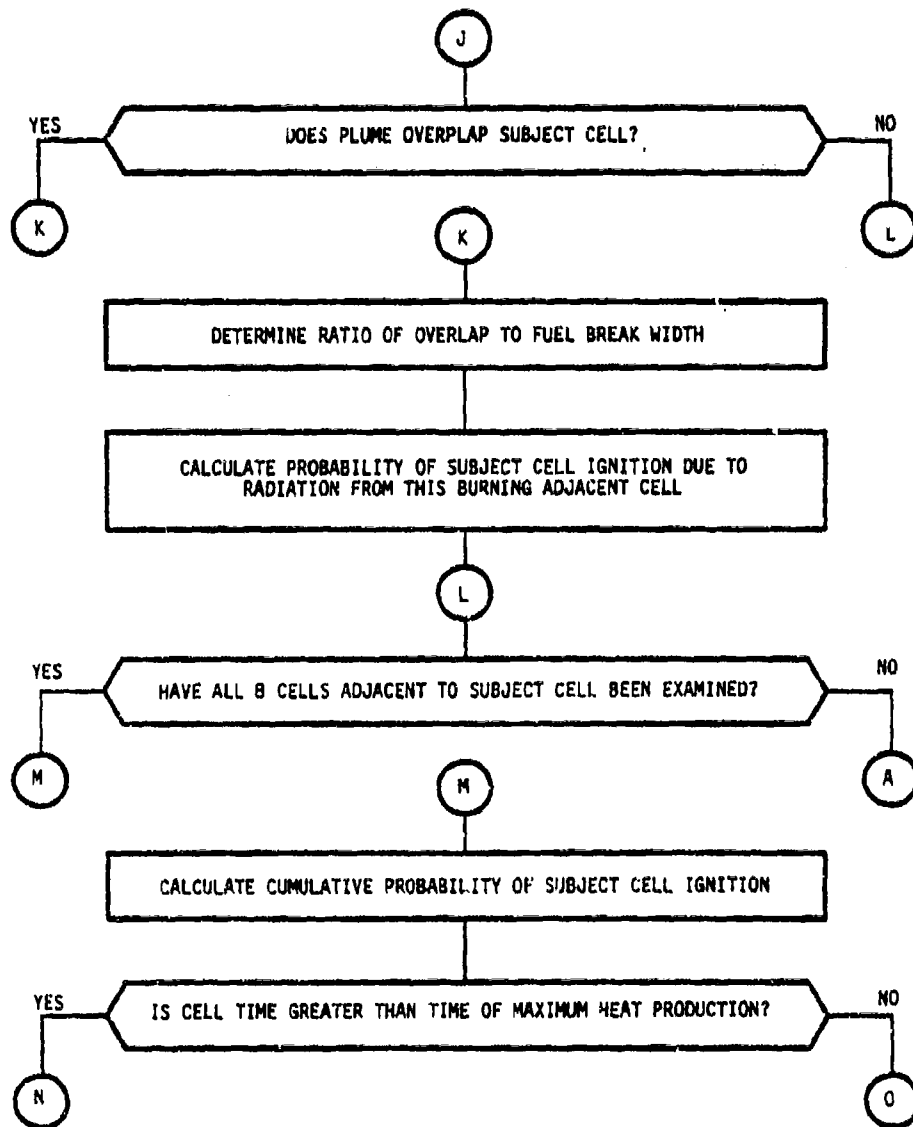


Figure 5-7. Adjacent cell update module (continued).

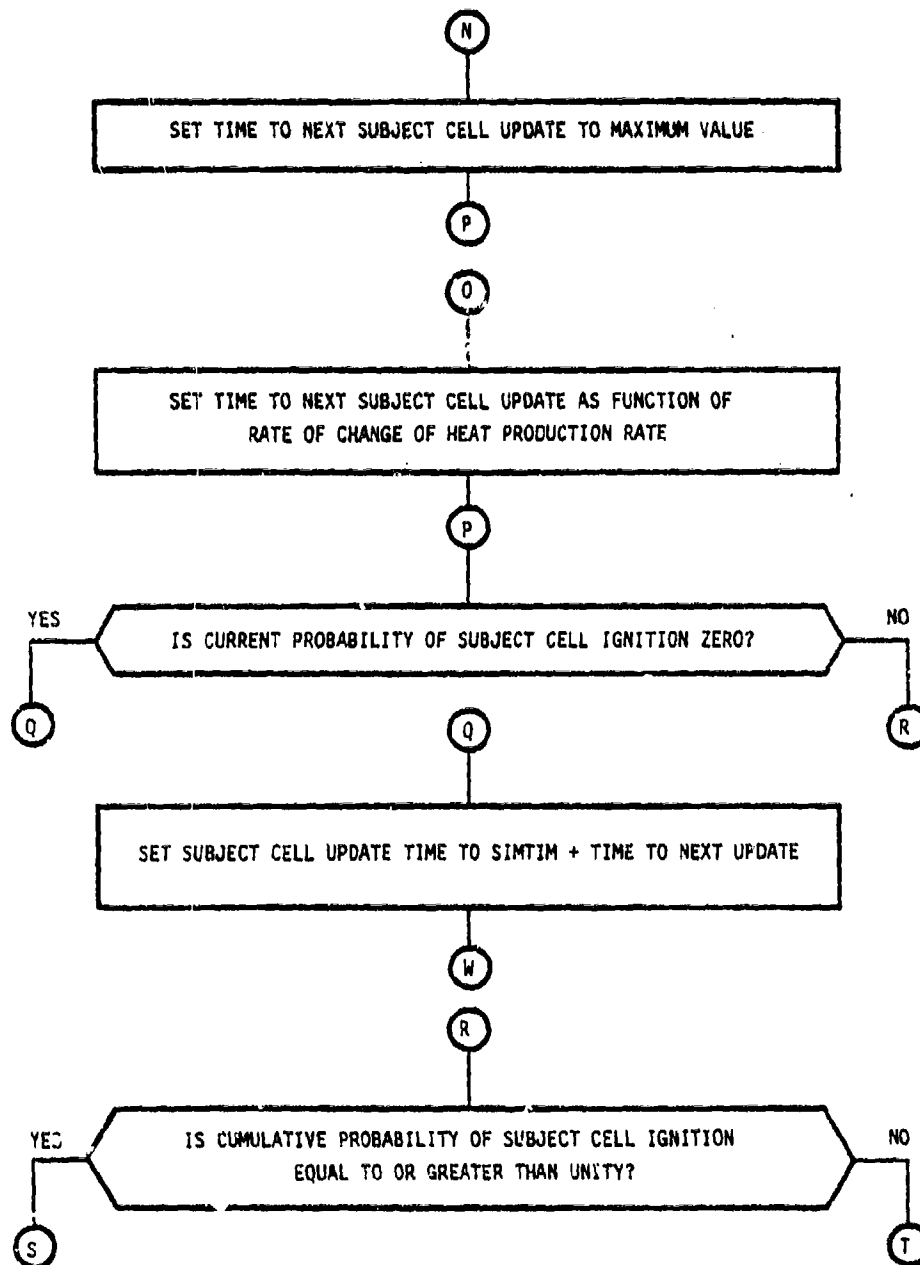


Figure 5-7. Adjacent cell update module (continued).

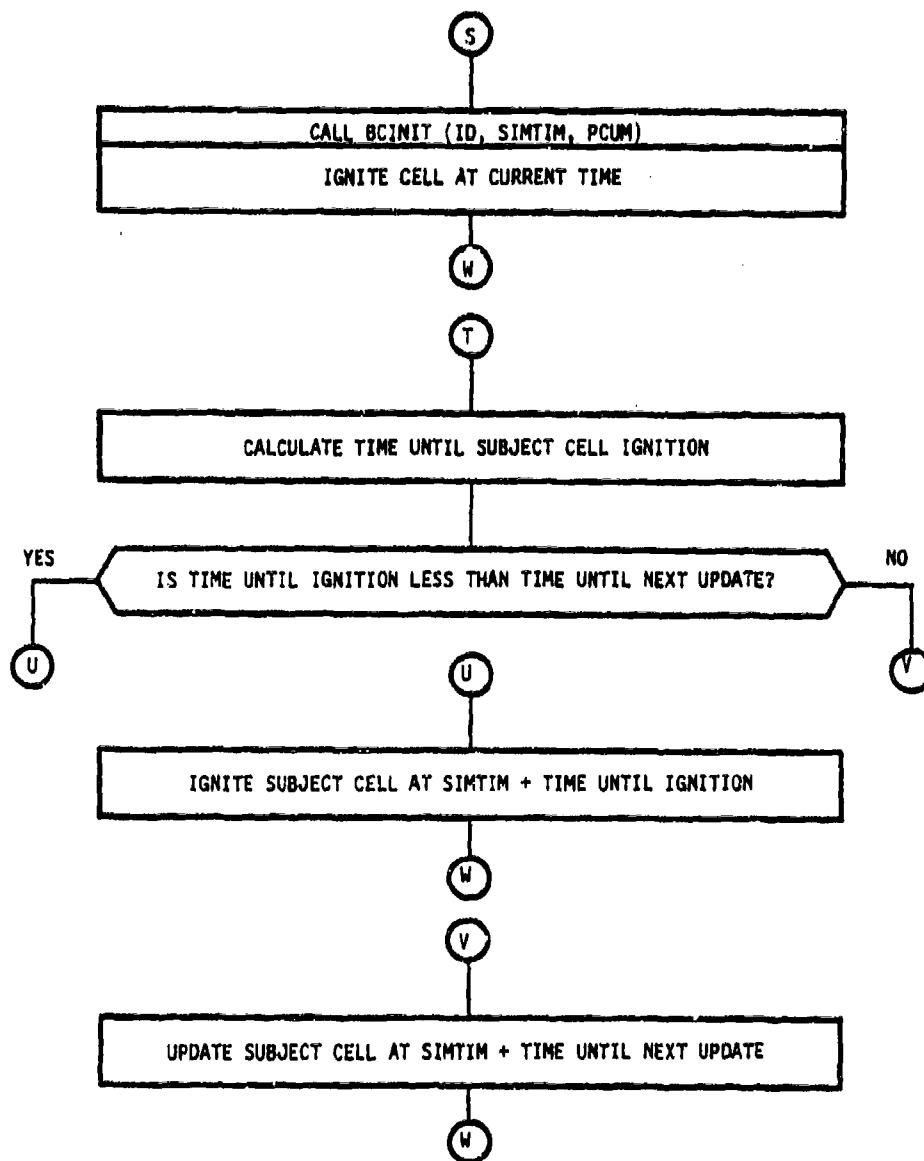


Figure 5-7. Adjacent cell update module (continued).

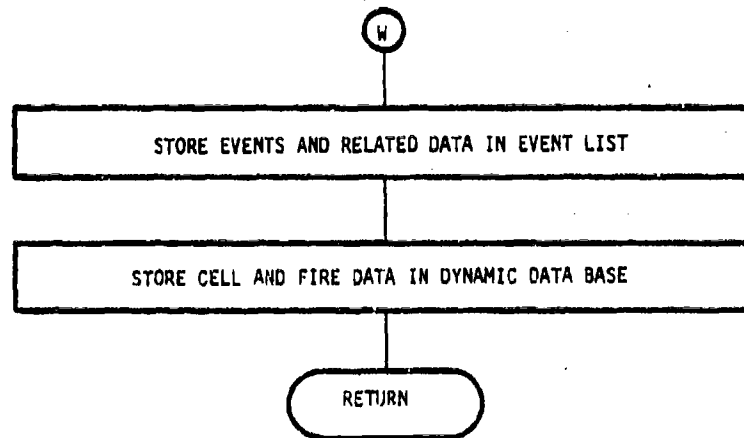


Figure 5-7. Adjacent cell update module (concluded).

is defined as ignition due to the transport of thermal energy by conduction, convection, or radiation. The purpose of ACUPDT is to determine if and when the subject will be ignited by contagion.

The subject cell ID provides access to the appropriate cell data, which contains the cell fuel type ID. The fuel type ID provides access to the fuel characteristics associated with that fuel type. The eight cells adjacent to the subject cell are identified.

Label (A) is the beginning of a loop over the eight cells adjacent to the subject cell in which only burning cells will be examined. Observe that since the subject cell is adjacent to a fire, at least one of its adjacent cells must be ignited. Each adjacent cell is tested (via the cell state matrix) to determine if it is burning. If it is not, the next cell is examined via label (L). If the cell is burning, transfer is to label (B).

At label (B) the unit vector is calculated in the direction from the center of the burning adjacent cell to the center of the subject cell. At label (C) a call is made to WINDV to calculate the wind velocity in the burning adjacent cell. Examination of the scalar product of the unit vector and wind velocity reveals if a wind component exists in the direction from the burning adjacent cell to the subject cell. If there is no wind component in the direction of the subject cell, the next adjacent cell is examined via label (L). If there is a wind component in the direction of the subject cell, transfer is to label (D).

At label (D) the dynamic cell data are accessed for the burning cell adjacent to, and upwind of, the subject cell. If this cell has just been ignited (at the current SIMTIM), its heat production rate is still zero and the next adjacent cell is examined via label (L). If the cell was ignited prior to the current SIMTIM, transfer is to label (E).

At label (E) all of the preliminary conditions have been satisfied for contagion to occur. An ignited cell with nonzero heat production has been identified adjacent to, and upwind of, the subject cell. A test is performed to determine if a plume can be defined for the entire burning cell. The plume test assumes a uniformly burning circular area of radius r_0 , a constant entrainment velocity v_e , and a conical plume of base radius r_0 and height h . The volume rate of air entrained by the plume ($\dot{V}_G$) is

$$\dot{V}_G = A_p v_e \quad , \quad (5-20)$$

where the cone area A_p is given by

$$A_p = \pi r_0 (r_0^2 + h^2)^{1/2} \quad . \quad (5-21)$$

Combine Equations 5-20 and 5-21 and solve for the plume height h to obtain

$$h = r_0 \left[\left(\frac{\dot{V}_G}{\pi r_0^2 v_e} \right)^2 - 1 \right]^{1/2} \quad . \quad (5-22)$$

The total heat production $\dot{Q}_c$ of the cell is

$$\dot{Q}_c = \left(\frac{q_0 \rho_a}{k} \right) \dot{V}_G \quad , \quad (5-23)$$

where

q_0 = heat content of fuel (J/kg)

ρ_a = air density (kg/m³)

k = mass of air per mass of fuel.

The average heat production rate over the cell ($\bar{q}$) is

$$\bar{q} = \dot{Q}_c / A_c \quad (5-24)$$

where A_c = base area of conical plume. From Equations 5-23 and 5-24, Equation 5-22 can be written in the form

$$h = r_o \left[\left(\frac{k_1 \bar{q}}{v_e} \right)^2 - 1 \right]^{1/2} \quad (5-25)$$

where

$$k_1 = \frac{k}{q_0 \rho_a}$$

$\bar{q}$ = average heat production rate per unit cell area.

The condition for a cell to have a definable plume is that the plume height (h) as defined by Equation 5-25 be real valued. For h to be real, we must have

$$\left(\frac{k_1 \bar{q}}{v_e} \right) > 1 \quad (5-26)$$

If Equation 5-26 is satisfied, transfer is to label (F), else transfer is to label (G).

At label (F) the base area, base radius, and height of the conical plume are defined from Equation 5-25 and the cell area, and transfer is to label (H).

At label (G) a plume cannot be defined for the entire cell. It is assumed that, since the cell is burning, a plume exists and can be defined for some fraction of the cell. The appropriate cell fraction is defined by requiring that the minimum plume height h_{mn} be equal to the radius of the burning cell fraction responsible for its generation. In terms of a fraction f of cell area $A_c = L_c^2$, Equation 5-25 can be written

$$h_{mn} = r_{mn} \left[\left(\frac{k_1 \bar{q} L_c^2}{f L_c^2 v_e} \right)^2 - 1 \right]^{1/2}, \quad (5-27)$$

where the effective cell fraction in plume generation is obtained by partitioning $\bar{q}$ and assuming that $\dot{q}$ is uniform over the cell. The requirement for $h_{mn} = r_{mn}$ yields, from Equation 5-27, a definition of the cell fraction f , which is

$$f = (k_1 \bar{q}) / (2 v_e) \quad (5-28)$$

The plume base area, base radius and height are defined as

$$A_p = f A_c, \quad (5-29)$$

$$r_0 = (A_p/\pi)^{1/2} , \quad (5-30)$$

$$h = r_p , \quad (5-31)$$

respectively, and transfer is to label (H).

At label (H) a plume has been defined, either for the entire cell or for a fraction of the cell, and we desire to calculate the plume tilt resulting from wind velocity in the burning cell adjacent to the subject cell. The horizontal ambient wind force F_x is given by

$$F_x = \dot{V}_G \rho_a v_e \quad (5-32)$$

and the vertical buoyancy force F_z is given by

$$F_z = V_p g (\rho_a - \rho_i) , \quad (5-33)$$

where

$\dot{V}_G$ = volume rate of air entrained (m^3/s)

v_e = entrainment velocity (m/s)

ρ_a = ambient air density (kg/m^3)

V_p = plume volume (m^3)

g = gravitational acceleration (m/s^2)

ρ_i = air density inside plume (kg/m^3) .

The inclination θ of the force vector measured from the horizontal is

$$\tan \theta = F_z/F_x = (0.8 V_p g)/(\dot{V}_G v_e) \quad (5-34)$$

where

$$(\rho_a - \rho_i)/\rho_a = 0.8 \quad .$$

The velocity (V_p) of a conical plume tilted $(\pi/2 - \theta)$ radians from the vertical is

$$V_p = (1/3)hA_b \sin \theta \quad (5-35)$$

where

h = cone height (m)

A_b = cone base area (m).

Combine Equations 5-34 and 5-35 to obtain

$$\frac{1}{\cos \theta} = \frac{\tan \theta}{\sin \theta} = \frac{0.8}{3} \frac{hA_b g}{\dot{V}_G v_e} \quad (5-36)$$

Substitution of Equations 5-23, 5-24, and 5-25 into 5-36 and simplifying yields

$$\frac{1}{\cos \theta} = \frac{0.8}{3} \frac{g r_o}{v_e} \left[\left(\frac{1}{v_e} \right)^2 - \left(\frac{1}{k_1 \frac{r}{q}} \right)^2 \right]^{1/2} \quad (5-37)$$

The angle θ given by Equation 5-37 is defined to be the plume tilt angle. It can be seen that Equation 5-37 may be imaginary and that the condition

for Equation 5-37 to be real valued is the same as the condition for Equation 5-25 to be real valued. Thus, the plume definition tests, which define h to be real valued, also assure that θ is real valued.

The cells in the grid are considered to be separated by streets, which are lines of specified width that contain no fuel. The ACUPDT module considers two methods by which heat from a burning cell may ignite an adjacent unignited cell across a street. The method considered depends upon whether the plume centerline lies above (label I) or below (label J) the top of the fuel in the unignited adjacent cell.

At label (I) the plume is tilted sufficiently far from the vertical that the plume centerline lies below the top of the fuel in the adjacent cell. In this case, it is assumed that the plume is blowing directly on the unignited fuel in the adjacent cell, and the probability of ignition of the subject cell is calculated as

$$P_{ig} = \min(\tau/\tau_{mx}, 1.0) \left(\frac{\hat{u} \cdot \vec{v}_G}{|\vec{v}_G|} \right) \left(\frac{\cos(\theta)}{\cos(\theta_{mx})} \right), \quad (5-38)$$

where

τ/τ_{mx} = ratio of cell burntime to time of maximum heat production

$\hat{u}$ = unit vector from the burning cell center to the unignited adjacent cell center

$\vec{v}_G$ = wind velocity in the burning cell

θ = plume tilt angle

θ_{mx} = angle to the top of fuel in adjacent unignited cell.

Transfer is then made to label (L).

At label (J) the plume is not tilted enough for the plume centerline to lie below the top of the fuel in the subject cell. In this case the plume is required to extend across the intervening street and overlap the fuel in the adjacent cell for ignition to be considered. If overlap occurs, transfer is to label K, else transfer is to label L.

At label (K) the probability of ignition of the subject cell due to radiation from the overlapping plume of the burning cell is calculated as

$$P_{ig} = \min\left(\frac{\tau}{\tau_{mx}}, 1\right) \left(\frac{A_p}{A_c}\right) \left(\frac{\hat{u} \cdot \vec{v}_G}{|\vec{v}_G|}\right) \quad (5-39)$$

where

A_p/A_c = fraction of cell (f) for which plume is defined.

Transfer is then made to label (L).

At label (I) as at label (J), prior to the transfer to label L, the probability of subject cell ignition is calculated by Equations 5-38 and 5-39, respectively and accumulated for each appropriate burning cell adjacent to the subject cell. This accumulation, when performed for all cells adjacent to the subject cell, represents the spatial accumulation of probability of ignition for all burning cells surrounding the subject cell.

At label (L) a test is made to determine if all eight cells adjacent to the subject cell have been examined. If all adjacent cells have not been examined, transfer is to label (A) where the next cell is selected, else transfer is to label (M).

At label (M) the just calculated cumulative probability of ignition over the cells surrounding the subject cell is accumulated to the probability of ignition calculated at the last subject cell update. If the minimum value of τ/τ_{mx} for the eight adjacent cells $(\tau/\tau_{mx})_{mn}$ is greater than four, transfer is to label (N), else transfer is to label (O).

At label (N), $(\tau/\tau_{mx})_{mn}$ is greater than four, which means that all burning cells adjacent to the subject cell are beyond the time of burnout. Under these conditions, no increase will occur in the cumulative probability of subject cell ignition. For these reasons, the time interval to the next examination of the subject cell by ACUPDT is set at the maximum allowable value.

At label (O), (τ/τ_{mx}) is less than or equal to four. Thus, at least one of the cells adjacent to the subject cell is currently burning. The time interval to the next examination of the subject cell by ACUPDT is scheduled in accordance with the maximum rate of change of the heat production rates of the cells surrounding the subject cell by the relation

$$DT = (1/2)(1 - q_{mv})(\tau_{mx})_{mn} \quad (5-40)$$

where

$$q_{mx} = [(1 - (\tau/\tau_{mx})_{mn})] \exp(\tau/\tau_{mx})_{mn} \quad (5-41)$$

Control is then transferred to label (W).

At label (P) the just calculated probability of cell ignition P_{ig} is tested. If P_{ig} is zero, transfer is to label (Q), else transfer is to label (R).

At label (R) the just calculated cumulative probability of cell ignition (P_{cum}) is tested. If P_{cum} is equal to or greater than unity, transfer is to label (S), else transfer is to label (T).

At label (S), ignition is certain and the subject cell is ignited by a call to BCINIT. The cumulative probability of ignition is allowed to exceed unity in cases where ignition conditions are appropriately severe. The value of P_{cum} is passed to BCINIT in such cases as the number (real valued) of simultaneous ignitions, thus allowing for multiple (fractional) ignitions. The effect of multiple ignitions is to cause the cell to burn hotter and faster than it otherwise would. These effects are implemented as shown in Equations 5-12 by making τ_{mx} an inverse function of the number of ignitions N_{ig} in the cell and in Equation 5-8 by making $\dot{q}_c$ a function of $1/\tau_{mx}$.

At label T the cumulative probability of ignition for the subject cell is greater than zero but not certain. The determination of what to do in this case is based on a definition of the rate of change of cumulative probability of cell ignition per unit time. The cumulative probability of cell ignition P_{cum} is

$$P_{cum} = \sum_{j=1}^N (P_{ig})_j \quad (5-42)$$

where $(P_{ig})_j$ is the probability of ignition associated with the j -th cell update time interval Δt_j and where the time interval ΔT_{cum} over which probability of ignition has been accumulated is

$$\Delta T_{cum} = \sum_{j=1}^N \Delta T_j \quad (5-43)$$

The increment of cumulative probability remaining until cell ignition is certain ($\Delta P'$) is given by

$$\Delta P' = 1 - P_{\text{cum}} \quad . \quad (5-44)$$

Denote the time interval until ignition is certain by $\Delta T'$ and define the average rate of change of cumulative probability of cell ignition dP_{cum}/dt over the interval $\Delta T'$ by

$$\frac{d}{dt} (P_{\text{cum}}) = \frac{\Delta P'}{\Delta T'} \quad . \quad (5-45)$$

Define the current rate of change in cumulative probability of cell ignition in terms of the most recently calculated values as

$$\frac{d(P_{\text{cum}})}{dt} = \frac{(P_{\text{ig}})_N}{\Delta T_N} \quad . \quad (5-46)$$

At the current rate of change, the time interval until cell ignition is certain is given by Equations 5-45 and 5-46 as

$$\Delta T' = \frac{\Delta P'}{(P_{\text{ig}})_N} \Delta T \quad , \quad (5-47)$$

which is called the projected time to ignition. The interval until the next scheduled cell update ΔT_{N+1} has already been calculated at either label (N) or label (0). If $\Delta T'$ is less than ΔT_{N+1} transfer is to label (U), else transfer is to label (V).

At label (U) the projected time to ignition is less than the time to the next scheduled update. The cell is, thus, scheduled for ignition at the projected ignition time.

At label (V) the time to the next cell update is less than the projected time to ignition. The cell is, thus, scheduled to be updated at the calculated update time.

At label (W) all events that have been scheduled by ACUPDT are placed in the Event List and all new cell and fire data calculated by ACUPDT are stored in the Dynamic Data Base. Control is then returned by ACUPDT to the UFMGR.

5.6 FIRE UPDATE (FUPDT) MODULE

The logical organization of the Fire Update Module (FUPDT) is shown in Figure 5-8. The FUPDT module deals primarily with the problem of scheduling the next update of the subject fire. The mechanics of the update process are performed by the Fire Geometry (FGEOM) and Fire Physical Data (FPHYSD) subroutines, which will be described next.

During initialization, all ignitions need not occur simultaneously, but can be spread over a specified interval. This can initially cause many small independent fires with rapidly changing sizes and heat production rates which can result in the necessity for many fire updates early in the simulation. These updates occur over time intervals that are significant to each fire but are not significant over all of the fires. To satisfy the tradeoff between frequency and significance, all fire updates are constrained by the FUPDT module to occur at intervals that are consistent with significant changes in global fire characteristics.

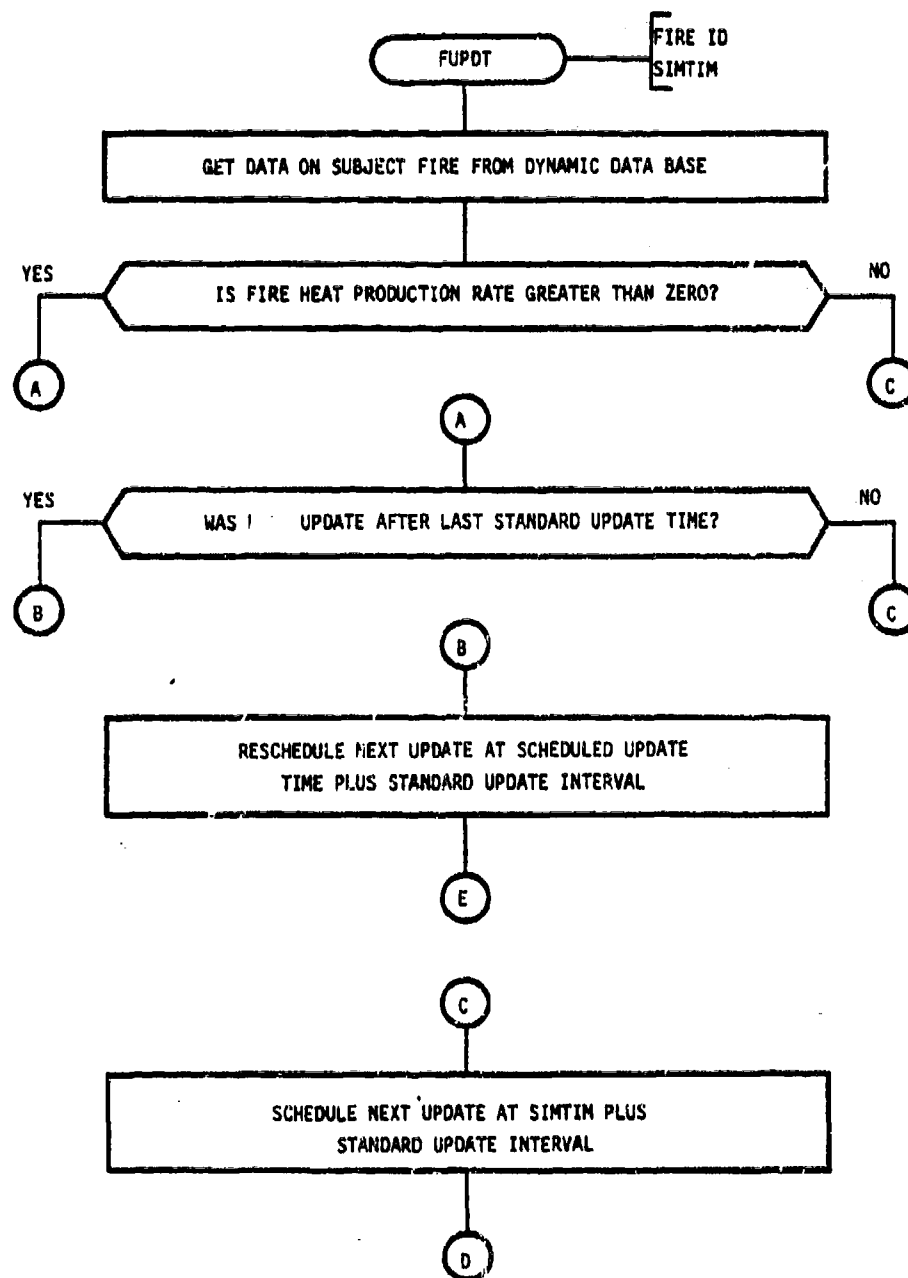


Figure 5-8. Logic flow of fire update module.

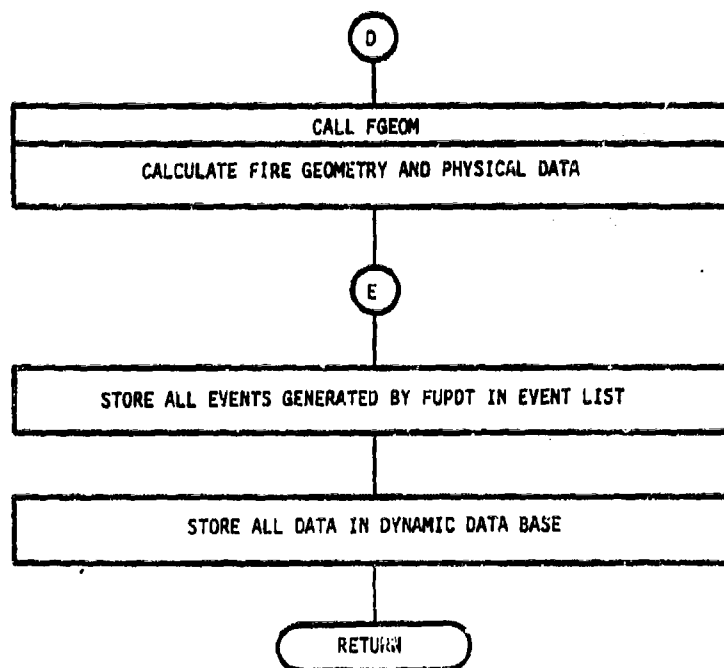


Figure 5-8. Logic flow of fire update module (concluded).

Fire data are treated in two parts, physical data and geometrical data. The fire physical data consist of the burning characteristics of the aggregate of cells that make up the fire. The geometrical data consist of a partitioning of the fire into a set of suitably symmetric subfires. To maintain physically significant fire data, the following fire update criterion are employed:

1. A fire physical update occurs whenever the fire heat production rate has changed by ten percent relative to the value at the last update time.
2. A fire geometry update occurs whenever the fire area has changed by ten percent relative to the area at the last update time.
3. A fire physical data update can occur without an accompanying geometry update.
4. A fire geometry data update must be accompanied by a physical data update.
5. No fire may be updated more frequently than once each 360 seconds.

The period of 360 seconds was chosen as the standard update interval because it represents 10 percent of the minimum time in which an ignited cell can reach maximum rate of heat production.

Fire updates, thus, occur whenever the heat production rate or the size of the fire are changed by ten percent relative to the respective values at the last update. The Burning Cell Update (BCUPDT) module is responsible for maintenance of heat production rate values for burning

cells. It, thus, incrementally changes the heat production rates of fires and determines if a fire update is required under the change in fire heat production-rate criterion. In the process of updating burning cells, the BCUPDT module also identifies cells that burn out. It, thus, decrements fire size as cells burn out, and determines if a fire update is required under the change-in-fire-area criterion. The Ignition (IGNITE) module is responsible for igniting cells. It, thus, increments fire area and determines if a fire update is required under the change-in-fire-area criterion.

Upon entry to the FUPDT module, shown in Figure 5-8, fire data for the subject fire are accessed. If the fire heat production rate is greater than zero, transfer is to label (A), else transfer is to label (C).

At label (A) the most recent update of the subject fire is compared with the last standard update time. If the most recent update was later than the last standard update time, transfer is to label (B), else transfer is to label (C).

At label (B) the fire has been updated since the last standard update time. The current update is, thus, rescheduled to occur at the time of the last update plus the standard fire update interval. Control is transferred to label (E).

At label (C) either the fire heat production rate is zero or the last update was at or before the last standard update. In the first case, the initial update is required and in the second case, the next update is required. In either case, an update is currently required, and the next update is scheduled to occur at SIMTIM plus the standard fire update interval.

At label (D), the geometry and physical data for the fire are calculated by the Fire Geometry subroutine.

At label (E), all events scheduled by the FUPDT module are stored in the Event List, all data are stored in the dynamic data base, and the FUPDT module returns control to the UFMGR module.

5.6.1 Fire Geometry (FGEOM) Subroutine

The algorithm used for fire induced wind velocity calculations assumes that the fires involved are circular. In the processes of initialization and propagation, high aspect (length-width) ratio fires can be generated, which violate this assumption. The fire geometry subroutine employs a simple pattern recognition algorithm to identify long thin fires and partitions them into sets of approximately square subfires, as a suitable representation of the circular fires expected by the fire induced wind model.

Upon entry to the FGEOM subroutine shown in Figure 5-9, the existing physical and geometrical fire data for the subject fire are deleted. The overall fire physical data are independent of the fire geometry. Thus, the Fire Physical Data (FPHYSD) subroutine is entered to calculate physical data for the entire fire. Upon return from the FPHYSD subroutine, the number of cells in the fire is tested. If the fire contains four or more cells, transfer is to label (A), else transfer is to label (J).

At label (A), the fire has been found to have four or more cells. Fires smaller than four cells are not examined for elongation. This is consistent with the attempt to maintain the aspect ratio of involved fires to be no greater than four. The number of candidate subfires is set to zero (i.e., the entire fire), and all cells in the fire are assigned to this subfire.

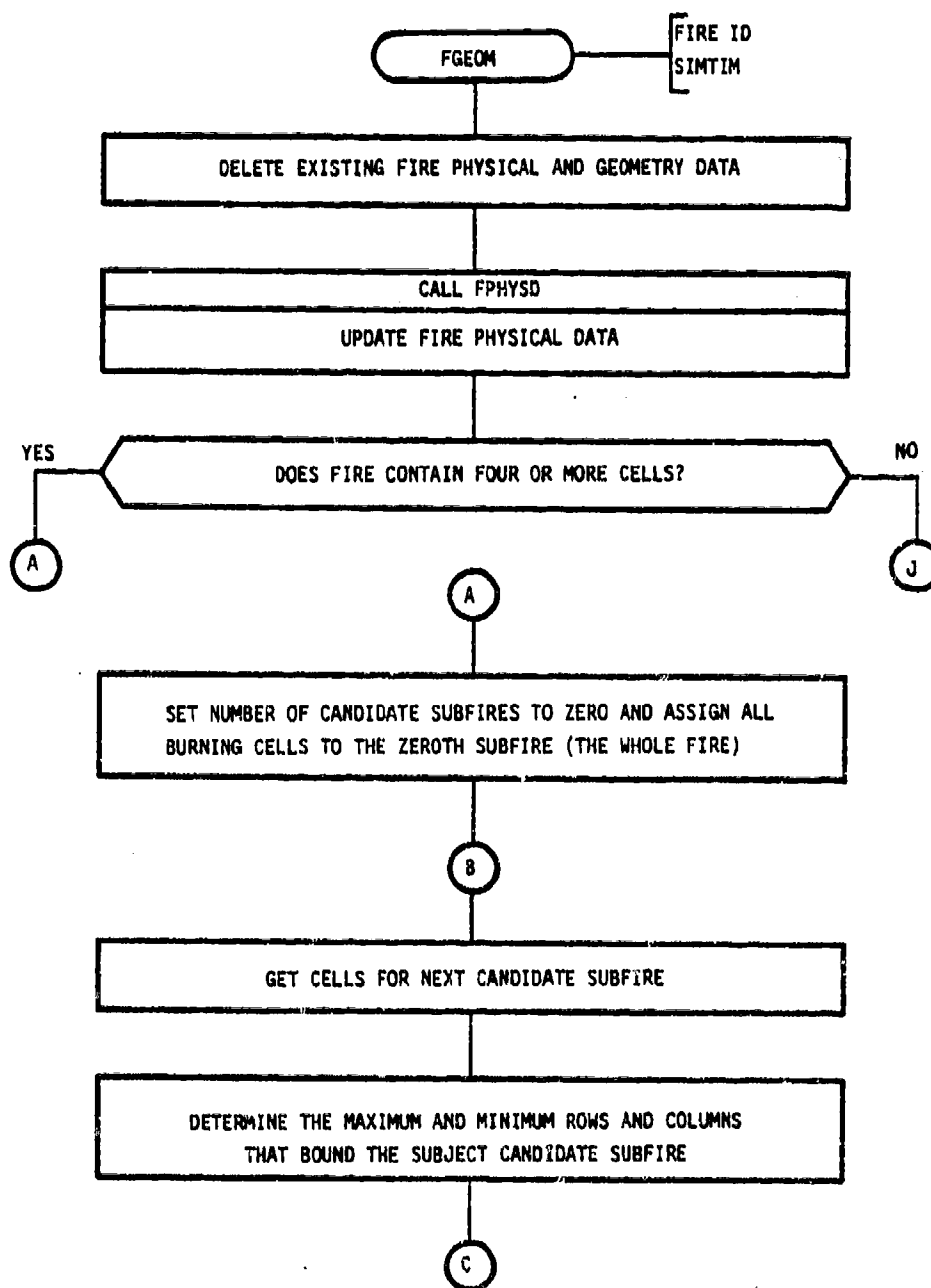


Figure 5-9. Logic flow of fire geometry subroutine.

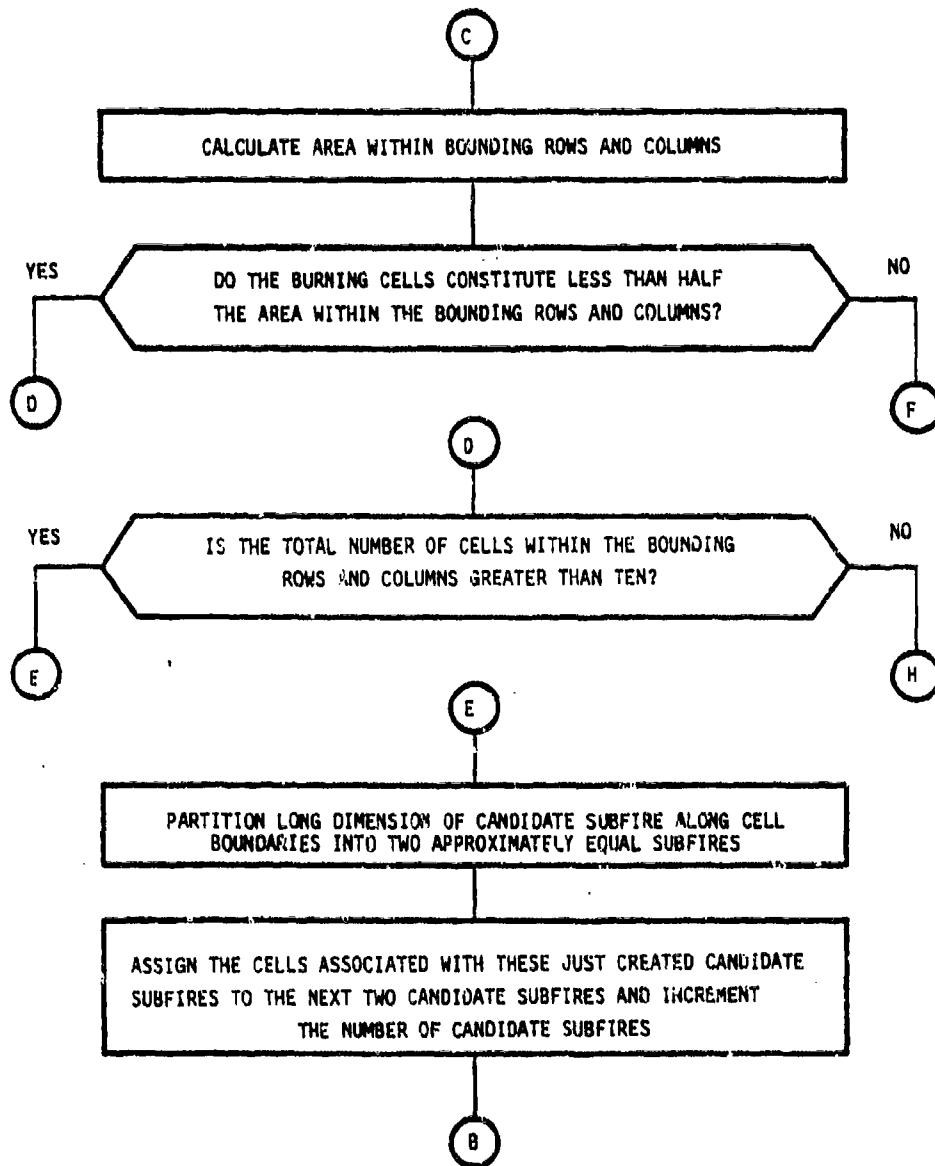


Figure 5-9. Logic flow of fire geometry subroutine (continued).

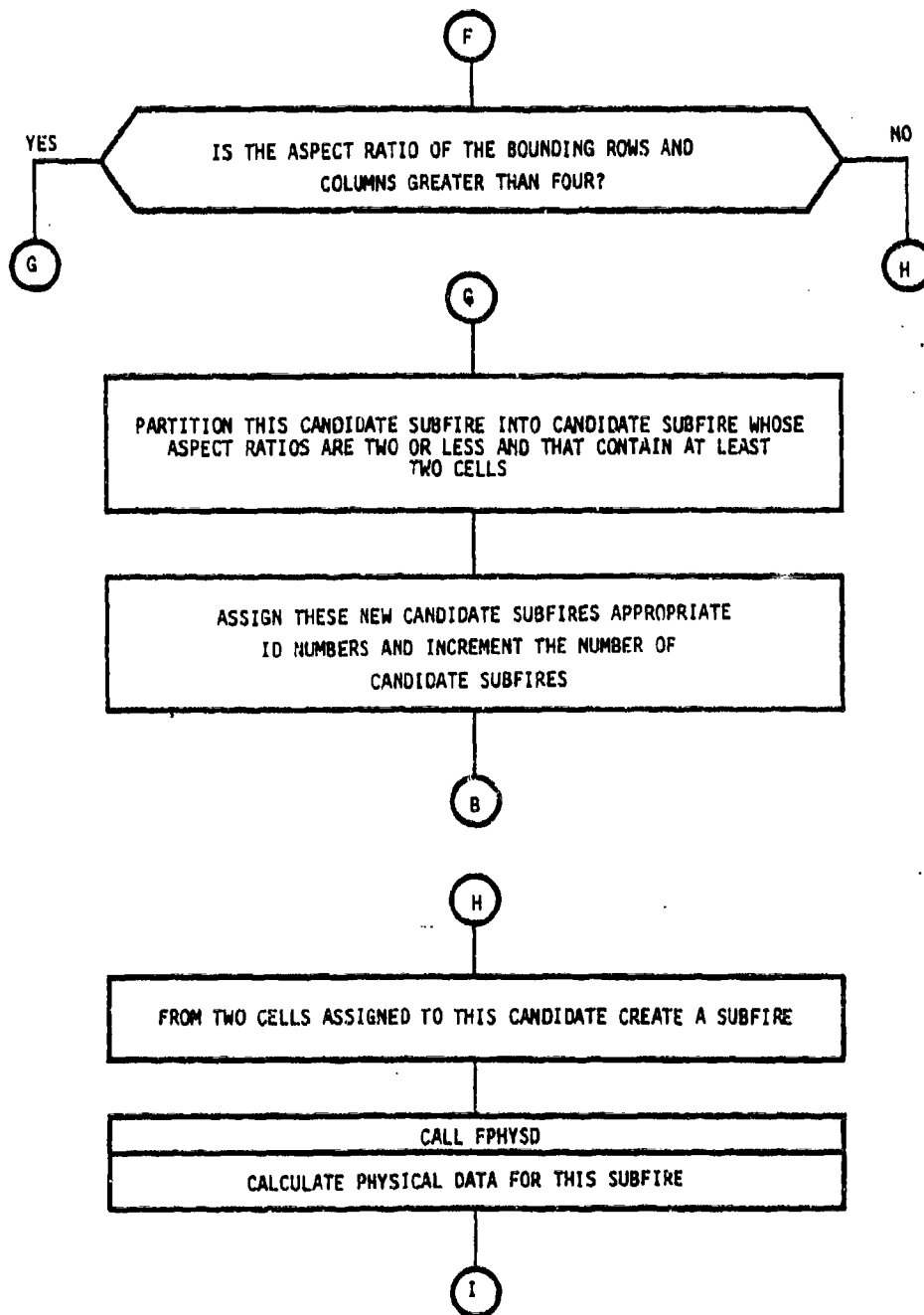


Figure 5-9. Logic flow of fire geometry subroutine (continued).

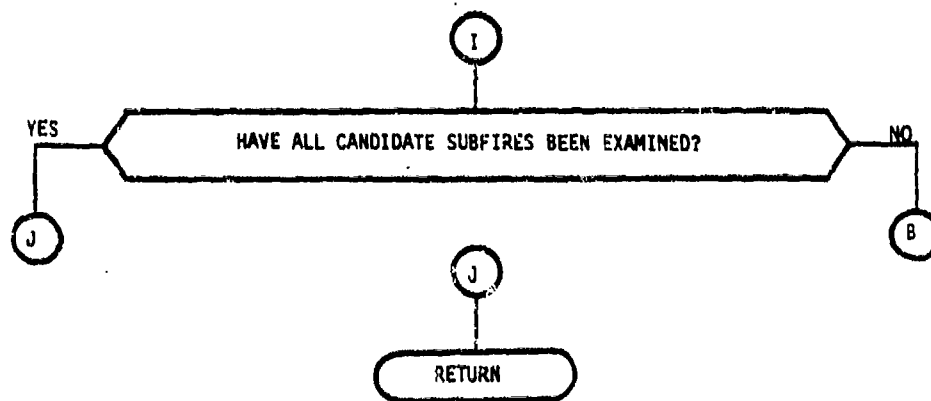


Figure 5-9. Logic flow of fire geometry subroutine (concluded).

At label (B) the cells for the next candidate subfire are accessed. At the first entry to label (B), the only candidate is the whole fire (i.e., zeroth subfire), and all of the cells in the fire are accessed. A subfire consists of a set of contiguous burning cells, cells are identified by their row-column indices, and the rectilinear boundary of a subfire is defined by the maximum and minimum row and column indices exhibited by the set of cells in the candidate subfire. These indices identify the rows and columns that bound the candidate subfire.

At label (C) the area within the bounding rows and columns is calculated. If the burning cells constitute less than half the bounded area, transfer is to label (D), else transfer is to label (F).

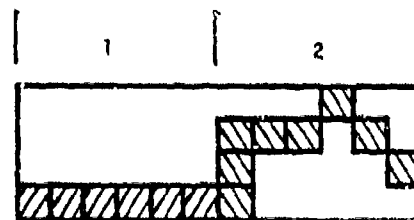
At label (D), if the total number of cells within the bounding rows and columns is greater than ten, transfer is to label (E), else transfer is to label (H).

At label (E) the bounded area is less than half filled by the burning cells and the total number of burning cells is greater than ten. The intent here is to identify subfires represented as sparsely filled bounded areas. The long dimension of these candidate subfires is approximately halved along cell boundaries to create two potentially less sparsely filled subfires. A simple example of such a fire is shown in Figure 5-10, where it can be seen in (a) that the burning cells (shaded) constitute only 30 percent of the bounded cells. The largest dimension of the fire is, thus, partitioned as shown in Figure 5-10(b), creating candidate subfires 1 and 2.

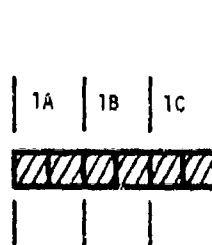
The partitioning of the example fire shown in Figure 5-10 will be described here, although some of the logic will not be encountered



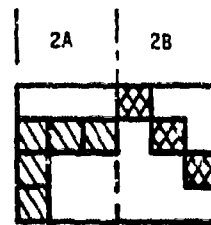
(a) Entire Fire



(b) Subfires 1 and 2



(c) Subfires 1A, 1B, and 1C



(d) Subfires 2A and 2B



(e) Subfire 2A



(f) Subfire 2B

Figure 5-10. Example of fire-subfire partitioning.

until later. One of the reasons for re-examining each newly created candidate subfire by a subsequent entry to label (B) is clearly shown in Figure 5-10(c) and is as follows. As shown in Figure 5-10(b), the burning cells of candidate subfire 1 only occupy 25 percent of its portion of the bounded area. However, when the boundary for candidate subfire 1 is redefined at label (C), the burning cells constitute 100 percent of the bounded area as shown in Figure 5-10(c). Candidate subfire 1 will be identified as an elongated subfire and appropriately subpartitioned. Candidate subfire 2 of Figure 5-10(b) has only 30 percent burning occupancy and is subpartitioned into candidate subfires 2A and 2B. In a subsequent entry to label (B), candidate subfire 2A will be found acceptable with respect to burning cell occupancy and elongation, and will be made into a subfire. Candidate subfire 2B will be found unacceptable with respect to occupancy (33 percent), but too small (less than 10 cells) to subdivide, and will also be made into a subfire.

The candidate subfire under examination has been subpartitioned, the new candidate subfires, thus, created have been assigned IDs, and the total number of subfires included in this fire has been appropriately incremented. At this point, transfer is back to label (B) where the next subfire will be accessed and the above described tests will be repeated.

At label (F) the bounded area of the candidate subfire is 50 percent or more filled with burning cells. The ratio of the longer to the shorter rectilinear boundary lengths (aspect ratio) is calculated for the candidate subfire. If the aspect ratio is greater than four, transfer is to label (G), else transfer is to label (H).

At label (G) an elongated candidate subfire has been identified and the degree of elongation quantified. The candidate subfire is partitioned into subfires each having an aspect ratio no greater than two. An example elongated subfire is shown in Figure 5-10(c) as subfire 1. It can

be seen that subfire 1 has an aspect ratio of six and has been partitioned into three subfires (1A, 1B, and 1C) each having aspect ratios of two. After the new subfires have been defined and the number of subfires appropriately incremented, transfer is back to label (B) where the next subfire is accessed.

At label (H) the candidate subfire has failed the occupancy test at label (C), failed the size test at label (D), or failed the elongation test at label (F). In any of these cases, the candidate requires no further modifications to become a subfire. The cells are assigned to a subfire and physical fire data are calculated by the FPHYSD subroutine for this subfire. Transfer is then to label (I).

At label (I), if all candidate subfires that have been identified have also been examined, transfer is to label (J) where control is returned to the FUPDT module, else transfer is to label (B) where the next subfire is accessed.

5.6.2 Fire Physical Data (FPHYSD) Subroutine

The Fire Physical Data subroutine calculates current values for the specified physical parameters of a fire or subfire. The fire physical (and geometrical) data are an exception to the rule of maintaining two sets of data subtending current time and interpolating between them to obtain current values of specified variables. It is not possible, in this case, because changes in the fire geometry may not allow correlation between the subfires existing at different times. Fire physical data are, thus, updated more frequently than interpolated data, but are held constant between updates.

The logic flow of the FPHYSD subroutine is shown in Figure 5-11, where it can be seen to be devoid of logic branches and to consist simply

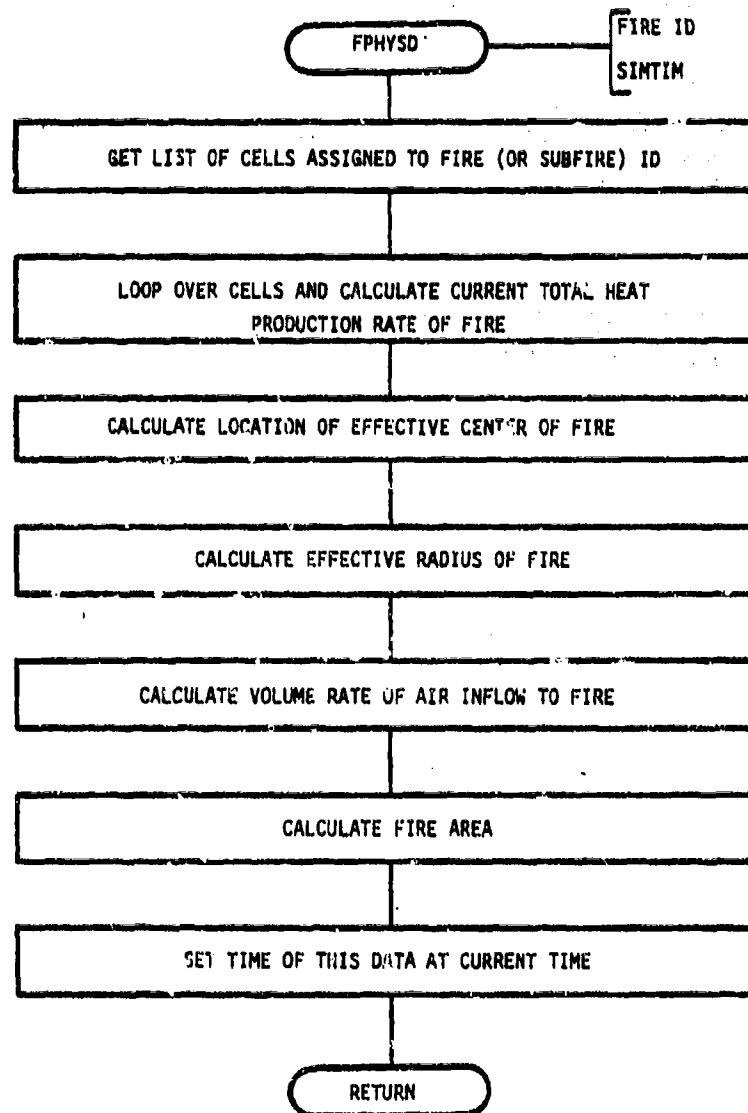


Figure 5-11. Logic flow of fire physical data subroutine.

of a sequence of calculations. Upon entry to the FPHYSO subroutine, the list of cells assigned to the subject fire (or subfire) is accessed and the total heat production rate is calculated from

$$\dot{Q}_k = \sum_{i=1}^{N_k} \dot{q}_i \quad (\text{J/s}) \quad (5-48)$$

where

$\dot{Q}_k$ = total heat production rate of fire k
 N_k = number of cells in fire k
 $\dot{q}_i$ = heat production rate of the i-th cell in fire k.

The location of the effective fire center is calculated in terms of the fire extent weighted by local heat production rate, and is used in the fire induced wind velocity calculations. The coordinates of the effective center of fire k, $(\bar{x}_k, \bar{y}_k)$, are given by

$$(\bar{x}_k, \bar{y}_k) = \left(\sum_{i=1}^{N_k} \dot{q}_i x_i, \sum_{i=1}^{N_k} \dot{q}_i y_i \right) \quad (\text{m}) \quad (5-49)$$

where x_i, y_i = coordinates of the center of the i-th cell of fire k.

The effective radius $(r_o)_k$ of fire k, also used in fire induced wind velocity calculations, is calculated from

$$(r_o)_k = \left\{ \frac{1}{\dot{Q}_k} \sum_{i=1}^{N_k} \left[(x_i - \bar{x}_k)^2 + (y_i - \bar{y}_k)^2 \right] \dot{q}_i \right\}^{1/2} (\text{m}). \quad (5-50)$$

The volume rate of air inflow $(\dot{V}_k)$ to fire k is calculated from

$$\dot{V}_k = a\dot{Q}_k/bc \quad (\text{m}^3/\text{sec}) \quad (5-51)$$

where

a = mass of air required to burn a mass of fuel,
(kg air/kg fuel)

b = heat produced per weight of fuel (J/kg)

c = air density (kg/m³).

The area (A_k) of fire k is given by

$$A_k = N_k A_c, \quad (5-52)$$

where A_c is the specified cell area. The cell area cannot be changed during an execution, but may be changed between executions. The time these data were calculated is denoted as SIMTIM, and control is returned to the calling routines.

5.7 BRANDING (BRANDG) MODULE

The execution of a burning cell update event consists of sequentially processing the BCUPDT module (Subsection 5.4) and the BRANDG module. Thus, upon entry to the BRANDG model, current BCUPDT data are available.

The logic flow diagram of the BRANDG module is shown in Figure 5-12, where the event data are shown to include the (burning) cell ID, SIMTIM, cell heat production rate, and the time of the next cell update. Only burning cells can launch brands, and this is assured by making the test for branding a part of each burning cell update event. The time of the next cell update is calculated by the BCUPDT module and passed to the BRANDG module.

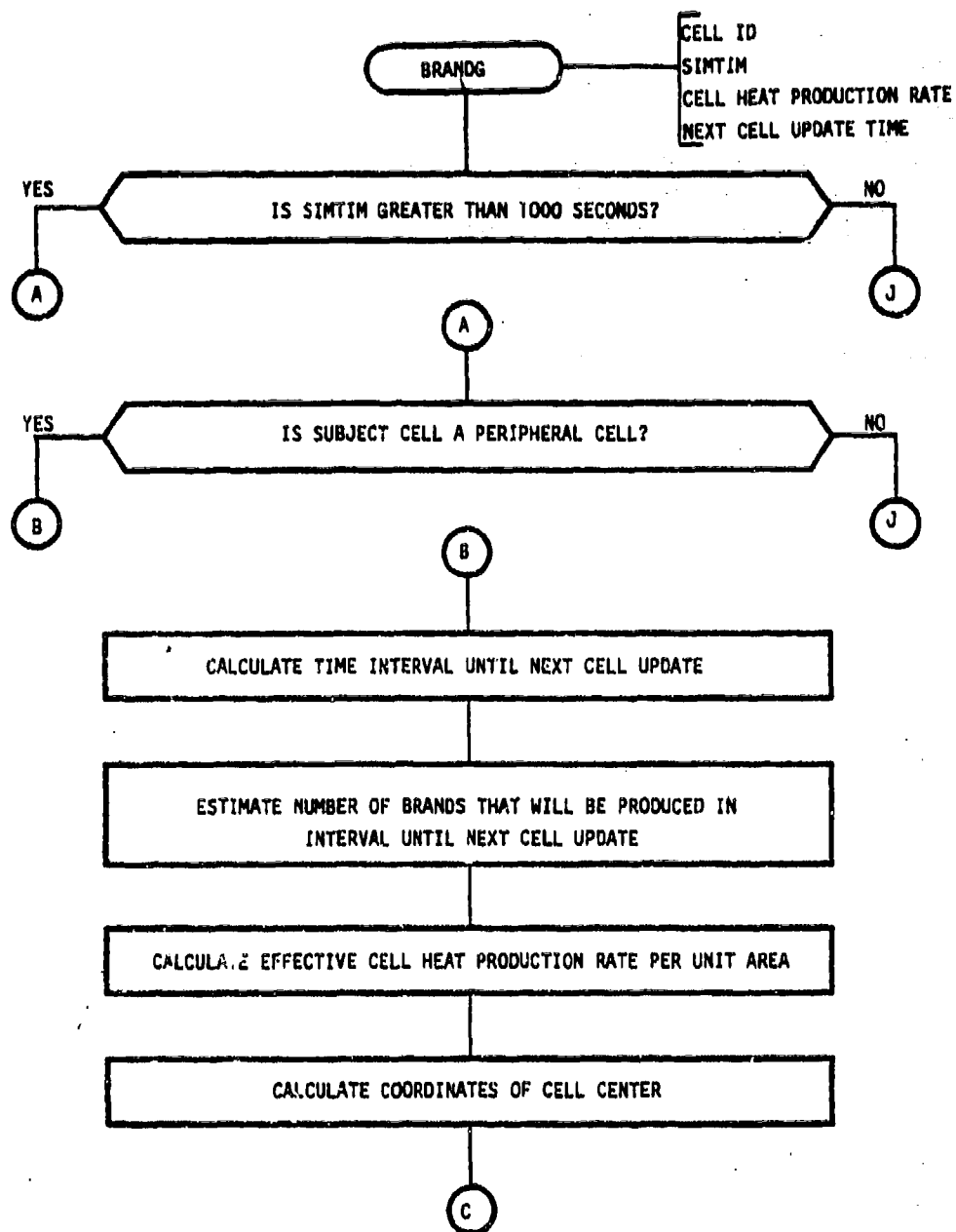


Figure 5-12. Logic flow for branding module.

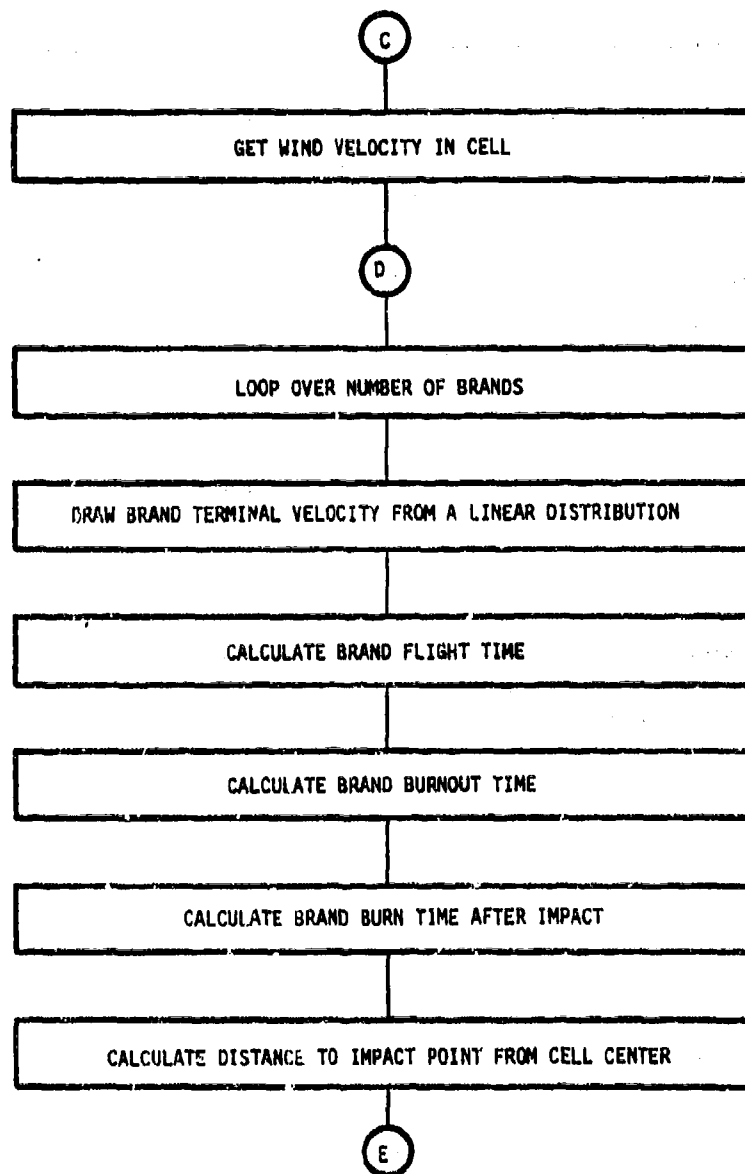


Figure 5-12. Logic flow for branding module (continued).

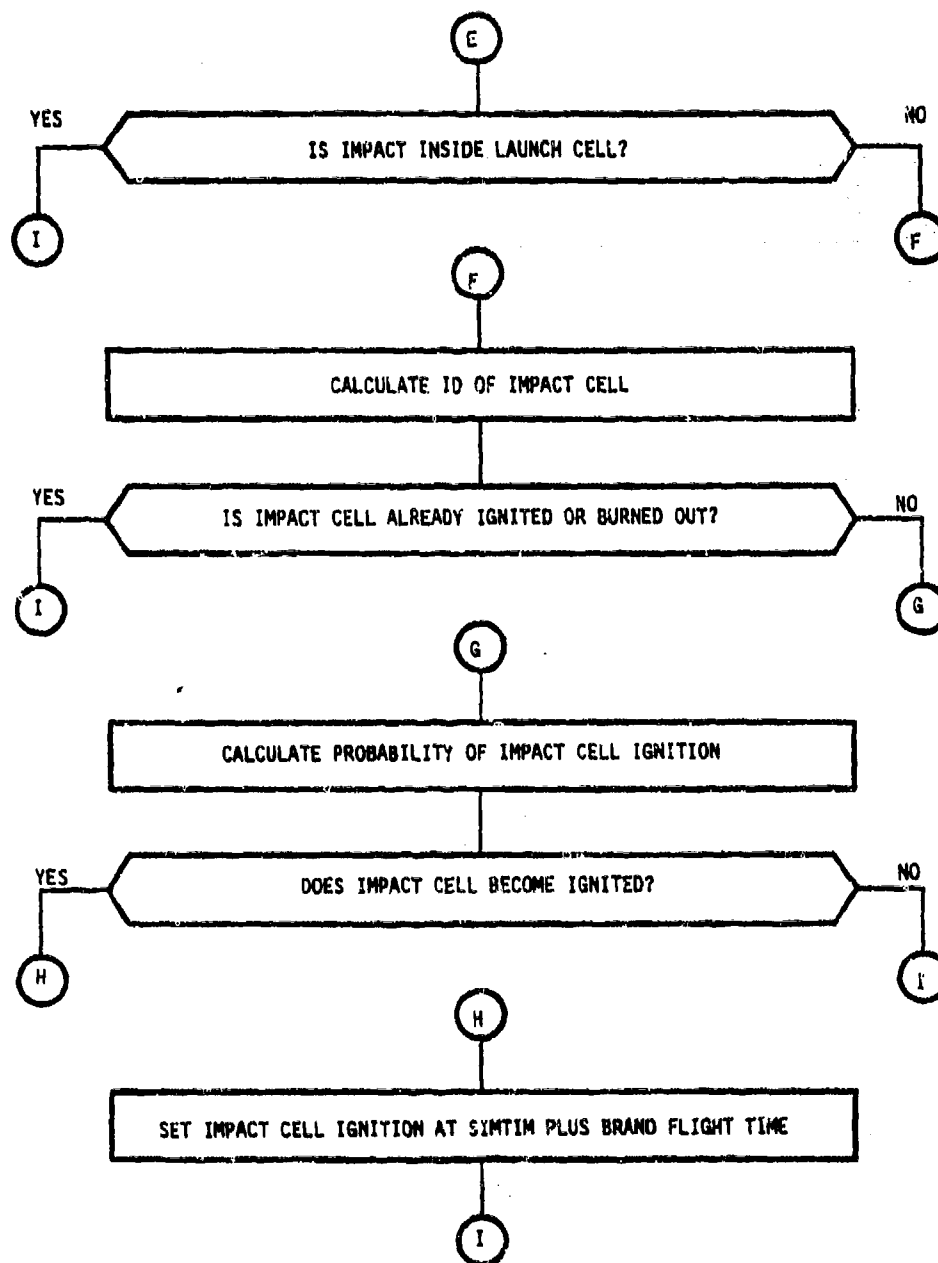


Figure 5-12. Logic flow for branding module (continued).

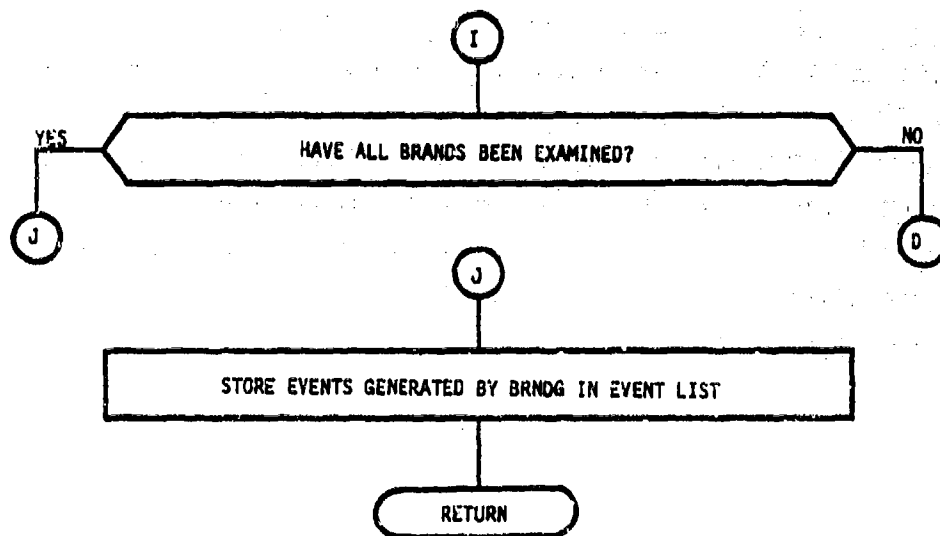


Figure 5-12. Logic flow for branding module (concluded).

Upon entry to the BRANDG module, SIMTIM is tested, and if SIMTIM is greater than 1000 seconds, transfer is to label (A), else transfer is to label (J) where control is returned to the UFMGR. Branding is not allowed for the first 1000 seconds (≈ 17 min) of a simulation for both physical and computational reasons. In the cases that have been run, initialization (i.e., initial ignitions) have been allowed to occur over the first 1000 seconds of simulation time. Thus, cells are being ignited throughout this interval. In general, large numbers of cells are initialized, and all have very low probabilities of branding over the first 1000 seconds. Significant computational resources are saved by not examining these low probability occurrences.

At label (A), if the subject cell is a peripheral cell of the fire to which it belongs, transfer is to label (B), else transfer is to label (J). Only peripheral cells are tested for branding. It is assumed that brands launched by interior cell plumes will, if they fall out, be caught up in, and consumed by the plume of an adjacent burning cell.

At label (B) the time interval until the next cell update Δt is calculated, and the number of brands that will be produced in the interval until the next cell update N_B is estimated as

$$N_B = \dot{q} \Delta t / (1.63 \times 10^{11}) \quad , \quad (5-53)$$

where $\dot{q}$ = cell heat production rate. The constant includes the nature of the fuel in the cell, which can be made explicit. The effective heat production rate per unit cell area is calculated from

$$q_A = \left(\frac{\dot{q}}{L_C \pi^{1/2}} \right)^{1/3} \quad , \quad (5-54)$$

where L_c = the cell linear dimension. From the cell ID, the coordinates of the cell center are calculated.

At label (C) the wind velocity (calculated in the BCUPDT module) is accessed. A loop is formed over the estimated number of brands. Each brand is characterized by its terminal velocity, which is obtained by a random draw from a linear distribution. A linear distribution fits empirical data and produces many more smaller, than larger, brands. From the terminal velocity of the k-th brand η_k , the brand flight time T_k is calculated as

$$T_k = \dot{q}(0.444 \eta_k + 1.10 f'_k - 0.975 \eta_k f'_k) \quad (s) \quad , \quad (5-55)$$

where

$$f'_k = 1.0 - (1 - f_k)^{1/2} \quad (5-56)$$

and

$$f_k = 4.726 \times 10^{-4} (1 - 0.887 \eta_k)^{-2} (1 - 0.482 \eta_k)^{-3} \quad . \quad (5-57)$$

The time at which the brand will burn out is calculated as

$$T_{BO} = \dot{q}(1.1000 - 0.5314 \eta_k) \quad (s) \quad , \quad (5-58)$$

and the amount of time the brand will burn after impact is given by $T_{BI} = T_{BO} - T_k$ (s). The distance the brand is transported from the cell center is given by

$$\Delta \vec{r} = \vec{v}_G T_k \quad (m) \quad , \quad (5-59)$$

where $\vec{v}_G$ = surface wind velocity at cell center.

At label (E), if the brand transport distance, $|\Delta \vec{r}|$, is such that impact is within the launch cell, transfer is to label (I), else transfer is to label (F).

At label (F) the impact coordinates and the ID of the impact cell are calculated. If the impact cell is already ignited or burned out, transfer is to label (I), else transfer is to label (G).

At label (G) the probability that the brand will ignite the impact cell is calculated by

$$P_{ig} = 1 - \exp(-T_{BI}/60) \quad . \quad (5-60)$$

If the cell is to be ignited, transfer is to label (H), else transfer is to label (I).

At label (H) an event is added to the Event List, which will ignite the impact cell at $SIMTIM + T_k$. At label (I), if all (N_B) brands have been tested, transfer is to label (J), else transfer is to label (D) where the terminal velocity is drawn for the next brand. At label (J) events generated by the BRANDG module are stored on the Event List and control is returned to the UFMGR.

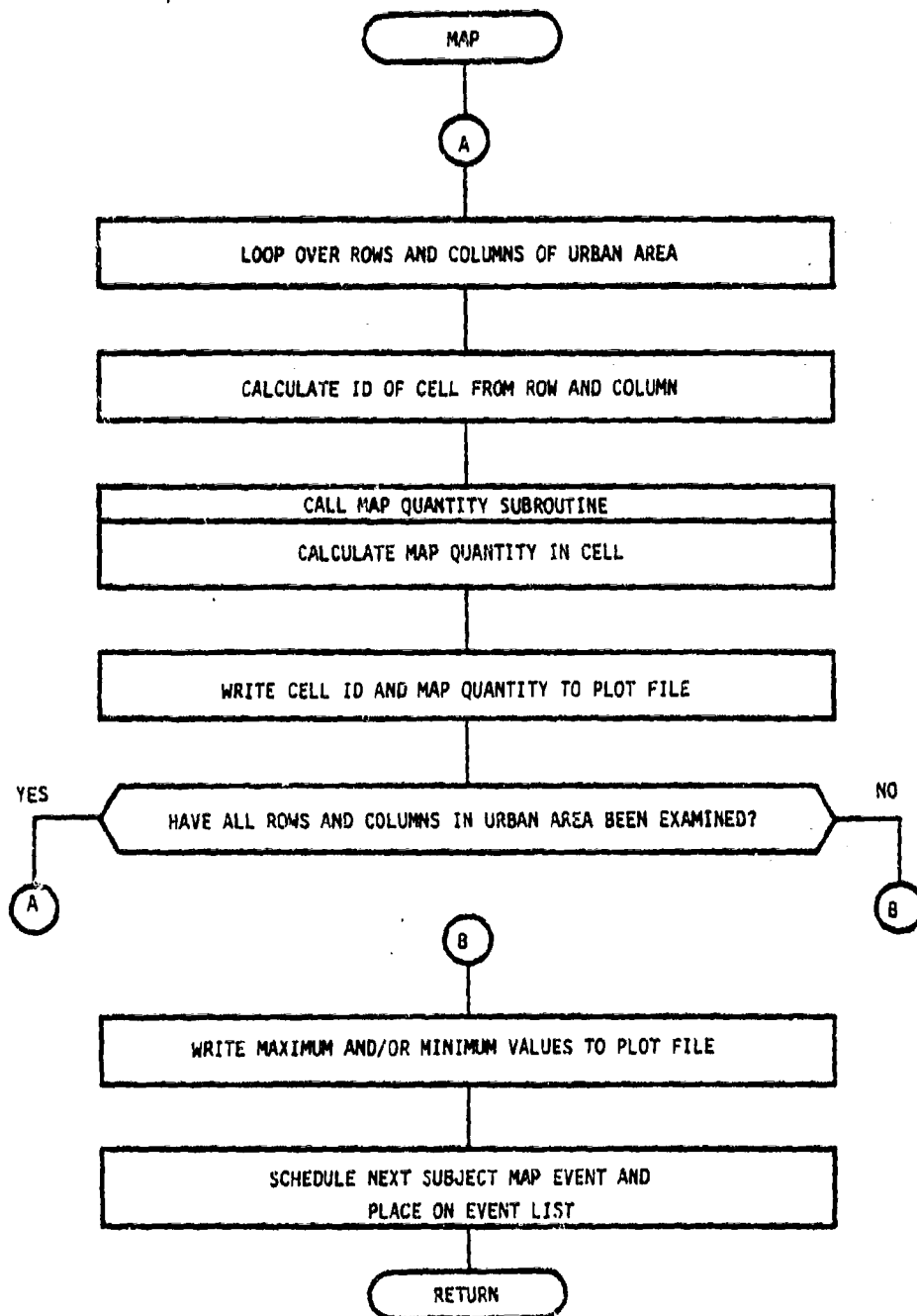


Figure 5-13. Logic flow of typical MAP module.

5.8 OUTPUT MODULES (WVMAP, CSMAP, QMAP)

The output modules present the results of the simulation in the form of maps of wind velocity (WVMAP), cell state (CSMAP), and heat production rate (QMAP) over the specified urban area. The logic flow diagrams of these modules are very similar and are, thus, represented in Figure 5-13 by a logic flow diagram typical of the three modules.

At label (A) each cell of the specified urban area (matrix) is identified by row and column. The map quantity (i.e., wind velocity, cell state, or heat production rate) is calculated for the identified cell and written to a plot file. This is continued until a value of the map quantity has been calculated and stored for every cell in the urban area.

At label (B) specified maximum and/or minimum values of the map quantity are written to the plot file. The map module then stores its next update event in the Event List. The update event is timed according to a specified schedule, which may be periodic or aperiodic.

SECTION 6

EXAMPLE MODEL RESULTS

Results from the model for eleven example cases are presented in this section. The results for each case presented consist of the following:

1. A description of the initial conditions for the fire
2. Sets of maps depicting these results:
 - a) the state of each cell in the area
 - b) heat production rate contours over the area
 - c) heat production rates of each cell in the area
 - d) wind velocity.

Map results are presented at times of 1000, 1750, 2750, 4750, 8750, 16750, and 32750 seconds after simulation initialization.

Included with the results for each case is a description of the initialization conditions and brief comments on the case results.

Initialization is an important aspect of uncontrolled urban fires in the cases of interest. For this reason, and because of its uncertainty, the model has been designed to accept arbitrary initialization processes. For the example cases presented, the initialization consisted of selecting a candidate set of cells for ignition and igniting them over a 1000 second interval with a uniform random distribution in time and a Poisson distribution of from zero to four ignitions per candidate cell for a specified expected value of ignition.

All example cases are simulated in an urban area that is 50×50 city blocks (about 56.25 km^2). Cellulosic fuels loaded at 40 kg/m^2 are uniformly distributed over the area. The model will allow different fuel types and loadings in each cell; however, for the example cases, it was desired to have the results reflect phenomenology variations instead of fuel variations.

An objective of developing the demonstration model was to demonstrate a model structure capable of integrating the range of variables and variable interactions required to describe the onset and growth of mass fires in an urban setting. Even for demonstration purposes, the model must contain physically based phenomenology models that include most of the variables and variable interactions of interest. In this sense the phenomenology models included in this demonstration urban fire model are considered to be qualitatively appropriate, although it is known that they are, in many cases, quantitatively in error.

In the interest of aiding in model development and in mitigating model maintenance problems, the model structure has been designed to readily allow the introduction of new models and/or processes and for the alteration of existing models and/or processes.

6.1 LARGE AREA FIRE WITH NO AMBIENT WIND

As shown in Figure 6-1, the central 35×35 cells of the 50×50 cell urban area are chosen as candidates for ignition, and ignited with a probability of ignition of 0.1. There is initially no ambient wind velocity; however, very strong fire-induced winds are generated, as shown in Figures 6-1(l) and 6-1(m). It is noted that the wind velocities are considered to be excessive in all of the cases presented.

Figures 6-1 through 6-1(g), together with Figures 6-1(j) and 6-1(l), show that the fire, once ignited, tends to propagate inwards, following the inward fire-generated wind flow. These figures also show that, as the fire grows inward, it generates radial "fingers" along the wind velocity stream lines. This is consistent with wildland fire experience, which reveals similar combustion patterns under high wind velocity conditions.

Figures 6-1 and 6-1(c) show a quantitative phenomenology that occurs in other example cases as well. Looking at the upper right hand corner of Figure 6-1, it can be seen that no cells are ignited above row 44. In Figure 6-1(c), it can be seen that a cell has been ignited in row 50. Because this cell is disjoint from any other ignited cell, ignition had to have occurred by branding. However, as shown by Figures 6-1(l) and 6-1(m), the winds are all directed inward toward the center of the urban area. In view of this, the only way the cell in row 50 could have been ignited by branding is for a brand to have been thrown from the lower left corner of the fire all of the way across the burning area. This is clearly erroneous and is an artifact of the simplicity of the brand transport model that is used.

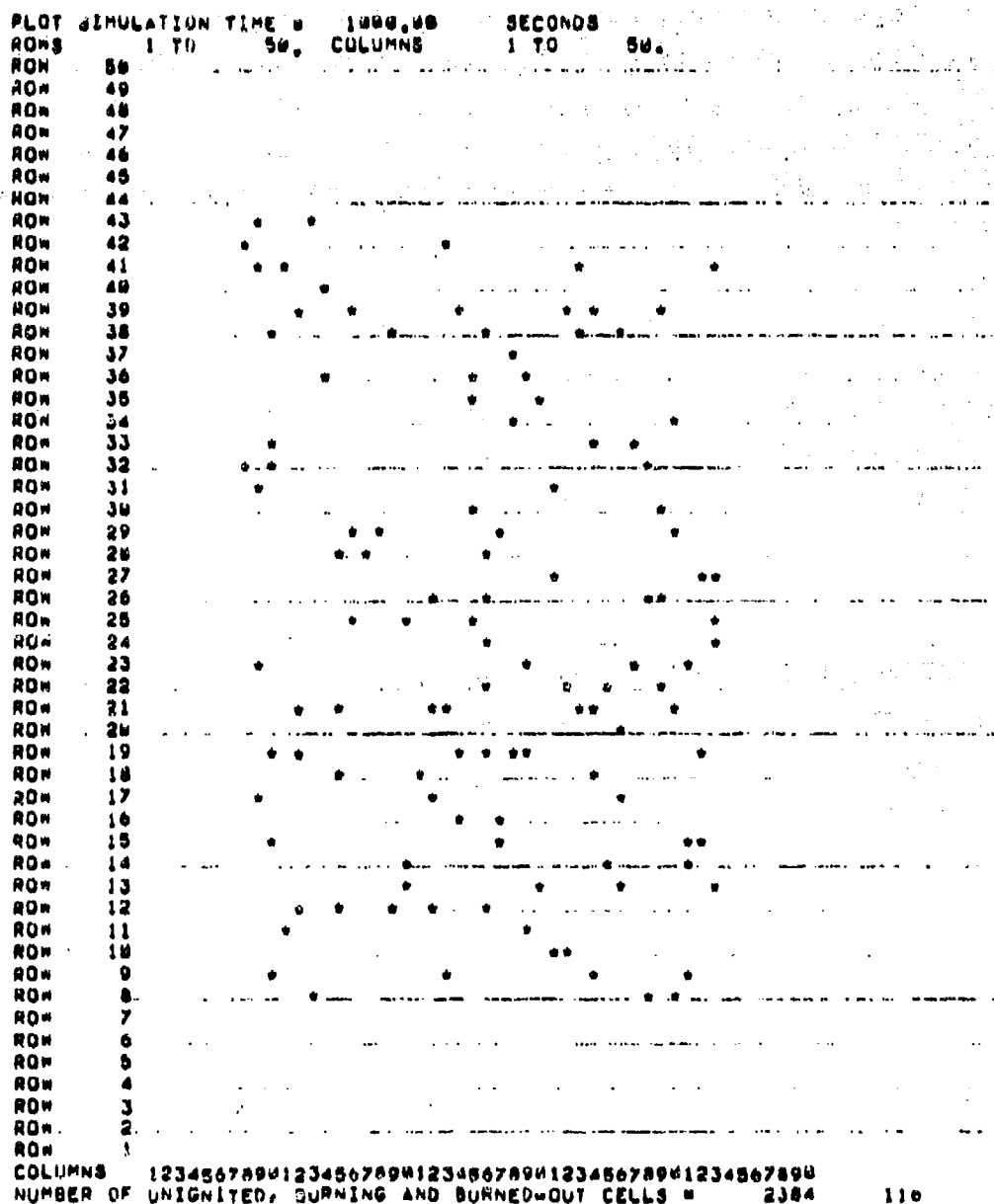


Figure 6-1. Cell state map for area fire.

PLT SIMULATION TIME 1200.00 SECONDS
 ROWS 1 TO 50, COLUMNS 1 TO 80.
 ROW 54
 ROW 49
 ROW 48

ROW 47
 ROW 46
 ROW 45
 ROW 44
 ROW 43
 ROW 42
 ROW 41
 ROW 40
 ROW 39
 ROW 38
 ROW 37
 ROW 36
 ROW 35
 ROW 34
 ROW 33
 ROW 32
 ROW 31
 ROW 30
 ROW 29
 ROW 28
 ROW 27
 ROW 26
 ROW 25
 ROW 24
 ROW 23
 ROW 22
 ROW 21
 ROW 20
 ROW 19
 ROW 18
 ROW 17
 ROW 16
 ROW 15
 ROW 14
 ROW 13
 ROW 12
 ROW 11
 ROW 10
 ROW 9
 ROW 8
 ROW 7
 ROW 6
 ROW 5
 ROW 4
 ROW 3
 ROW 2
 ROW 1
 COLUMNS 12345678901234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS 2360 132

Figure 6-1(a). Cell state map for area fire.

```

PLOT SIMULATION TIME = 1750.00 SECONDS
ROWS 1 TO 50. COLUMNS 1 TO 50.

ROW 49
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2222 278

```

Figure 6-1(b). Cell state map for area fire.

PLOT SIMULATION TIME • 2754.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 12345678901234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS • 1750 750 0

Figure 6-1(c). Cell state map for area fire.

```

PLOT SIMULATION TIME = 4750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1291 1209

```

Figure 6-1(d). Cell state map for area fire.


```

PLOT SIMULATION TIME = 0750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24

```

```

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1123 1377

```

Figure 6-1(e). Cell state map for area fire.

```

PLOT SIMULATION TIME = 16750.0 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18

ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1005 1401 14

```

Figure 6-1(f). Cell state map for area fire.

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1486 1481

PLOT SIMULATION TIME = 32750.8 SECONDS

ROWS 1 TO 54, COLUMNS 1 TO 50

```

ROW 50      ***
ROW 49      ****
ROW 48      ***
ROW 47      ****
ROW 46      *****
ROW 45      *****
ROW 44      *****
ROW 43      *****
ROW 42      *****
ROW 41      *****
ROW 40      *****
ROW 39      *****
ROW 38      *****
ROW 37      *****
ROW 36      *****
ROW 35      *****
ROW 34      *****
ROW 33      *****
ROW 32      *****
ROW 31      *****
ROW 30      *****
ROW 29      *****
ROW 28      *****
ROW 27      *****
ROW 26      *****
ROW 25      *****
ROW 24      *****
ROW 23      *****
ROW 22      *****
ROW 21      *****
ROW 20      *****
ROW 19      *****
ROW 18      *****
ROW 17      *****
ROW 16      *****
ROW 15      *****
ROW 14      *****
ROW 13      *****
ROW 12      *****

```

```

ROW 11      *****
ROW 10      *****
ROW 9        *****
ROW 8        *****
ROW 7        *****
ROW 6        *****
ROW 5        *****
ROW 4        *****
ROW 3        *****
ROW 2        *****
ROW 1        *****

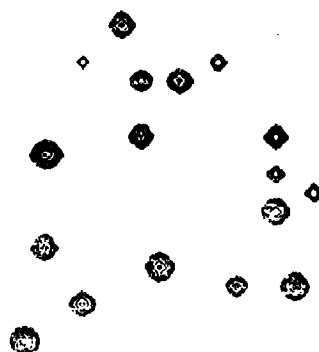
```

COLUMNS 12345678901234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 891 1487 1;

Figure 6-1(g). Cell state map for area fire.

HEPSON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY RELEASED ON TIME = 1000.00
TIME 1 TO 1000.00
WALL NOT COVERED BY
*** ONLY DATA FROM WALL AND GROUND IS PLOTTED ***
WALL SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.013)



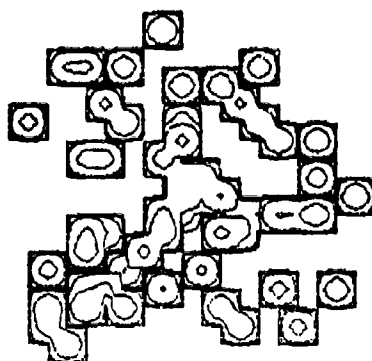
1357913579135791357913579

HEPSON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY RELEASED ON TIME = 1000.00
TIME 1 TO 1000.00
WALL NOT COVERED BY
*** ONLY DATA FROM WALL AND GROUND IS PLOTTED ***
WALL SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.013)



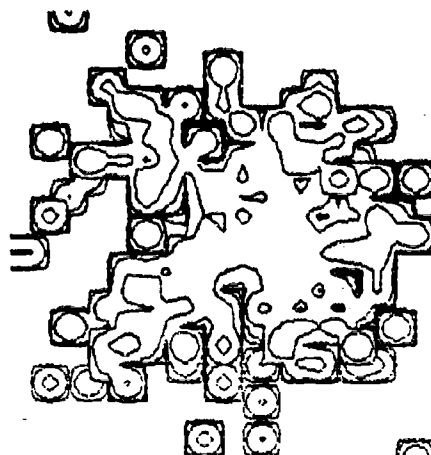
1357913579135791357913579

HEPSON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY RELEASED ON TIME = 1000.00
TIME 1 TO 1000.00
WALL NOT COVERED BY
*** ONLY DATA FROM WALL AND GROUND IS PLOTTED ***
WALL SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.013)



1357913579135791357913579

HEPSON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY RELEASED ON TIME = 1000.00
TIME 1 TO 1000.00
WALL NOT COVERED BY
*** ONLY DATA FROM WALL AND GROUND IS PLOTTED ***
WALL SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.013)



1357913579135791357913579

Figure 6-1(h). Heat production rate contour for area fire.

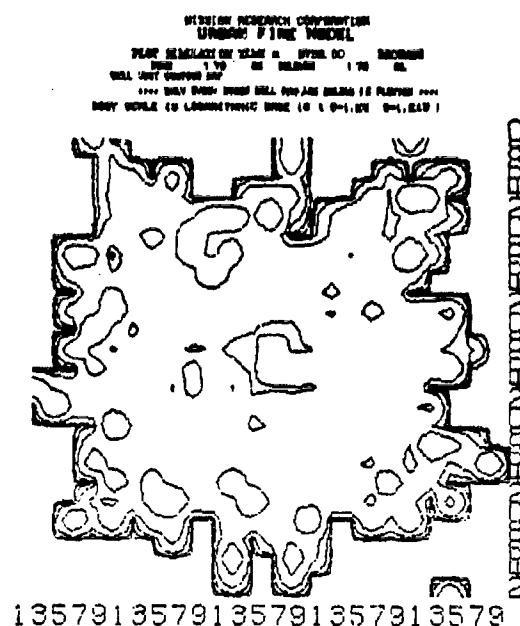
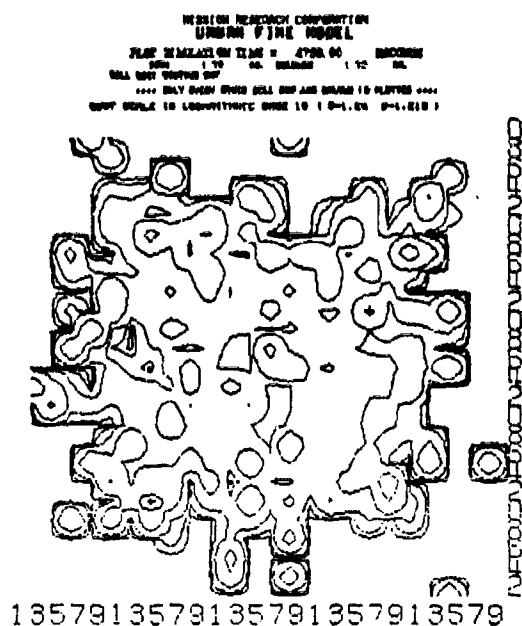
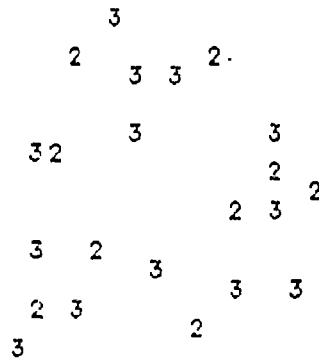


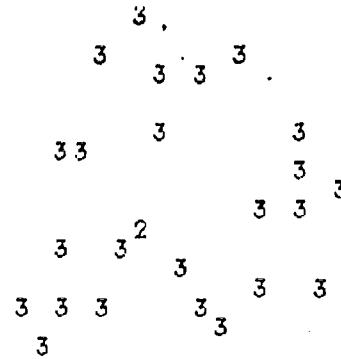
Figure 6-1(i). Heat production rate contour for area fire.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULANT ON TIME = 1000.00 SECONDS
DATA 1 TO 10 11 12 13 14 15 16 17 18 19 20
ONLY HOT: LETTERS A TO Z ARE A RANGE OF HOT VALUES
ONLY HOT: OTHER OTHER CALL FOR ARE VALUES TO PLOTTER
HOT SCALE IS LOGARITHMIC BASE 10 (0-1.00 0-1.010)



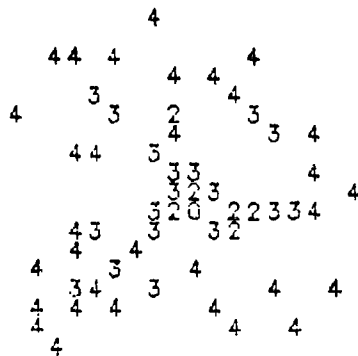
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULANT ON TIME = 1000.00 SECONDS
DATA 1 TO 10 11 12 13 14 15 16 17 18 19 20
ONLY HOT: LETTERS A TO Z ARE A RANGE OF HOT VALUES
ONLY HOT: OTHER OTHER CALL FOR ARE VALUES TO PLOTTER
HOT SCALE IS LOGARITHMIC BASE 10 (0-1.00 0-1.010)



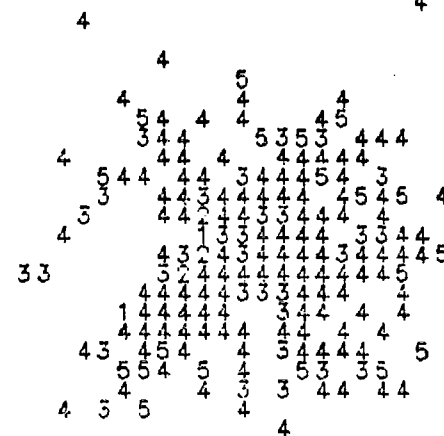
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULANT ON TIME = 1750.00 SECONDS
DATA 1 TO 10 11 12 13 14 15 16 17 18 19 20
ONLY HOT: LETTERS A TO Z ARE A RANGE OF HOT VALUES
ONLY HOT: OTHER OTHER CALL FOR ARE VALUES TO PLOTTER
HOT SCALE IS LOGARITHMIC BASE 10 (0-1.00 0-1.010)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULANT ON TIME = 1750.00 SECONDS
DATA 1 TO 10 11 12 13 14 15 16 17 18 19 20
ONLY HOT: LETTERS A TO Z ARE A RANGE OF HOT VALUES
ONLY HOT: OTHER OTHER CALL FOR ARE VALUES TO PLOTTER
HOT SCALE IS LOGARITHMIC BASE 10 (0-1.00 0-1.010)



1357913579135791357913579

Figure 6-1(j). Cell heat production rate map for area fire.

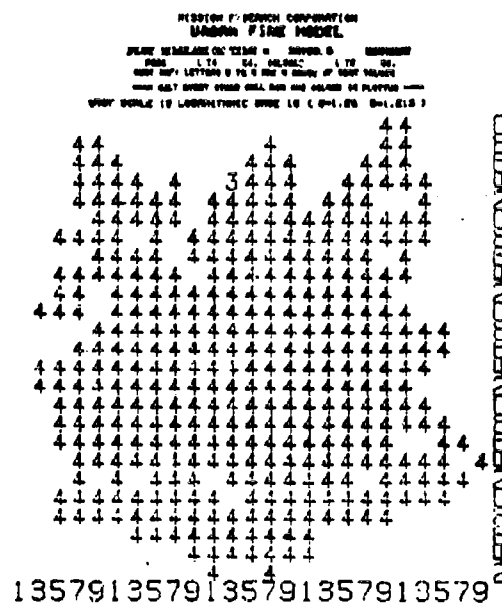
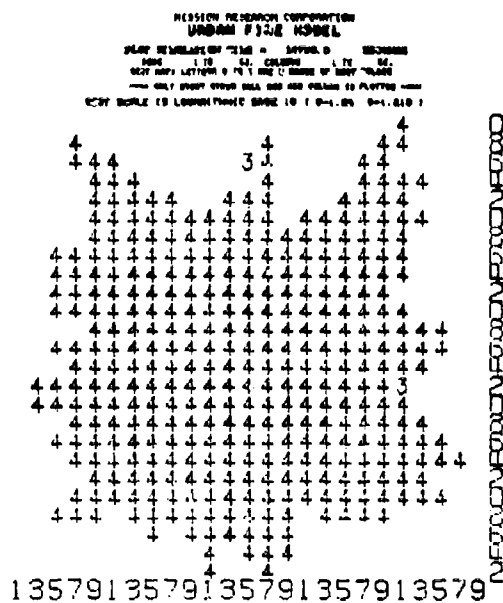
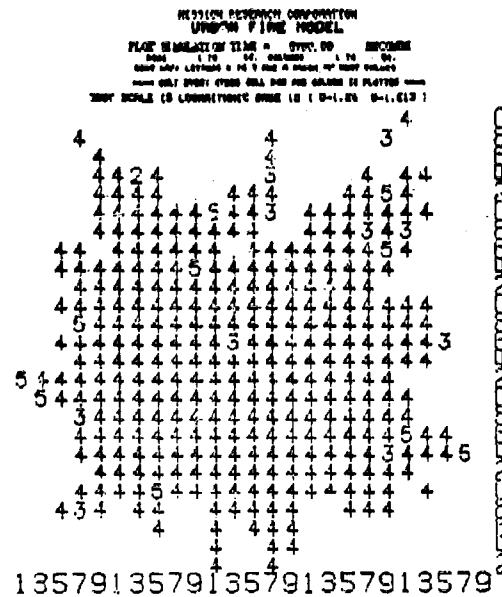
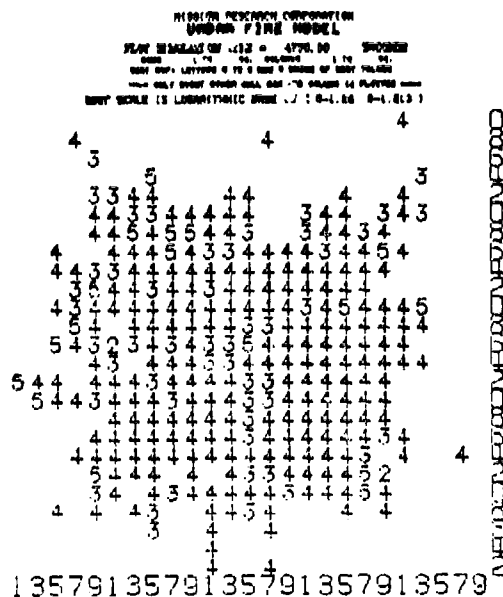


Figure 6-1(k). Cell heat production rate map for area fire.

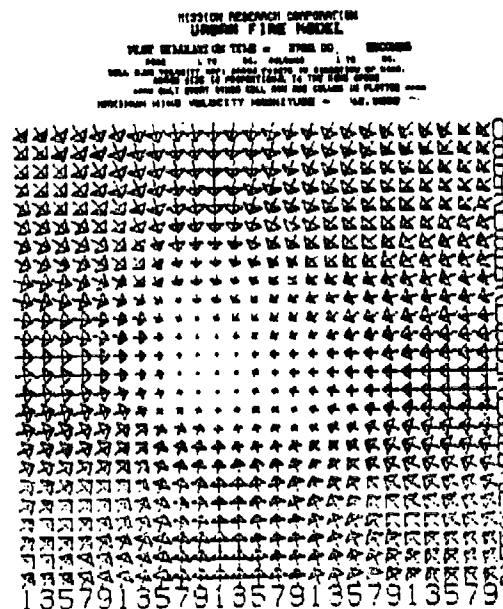
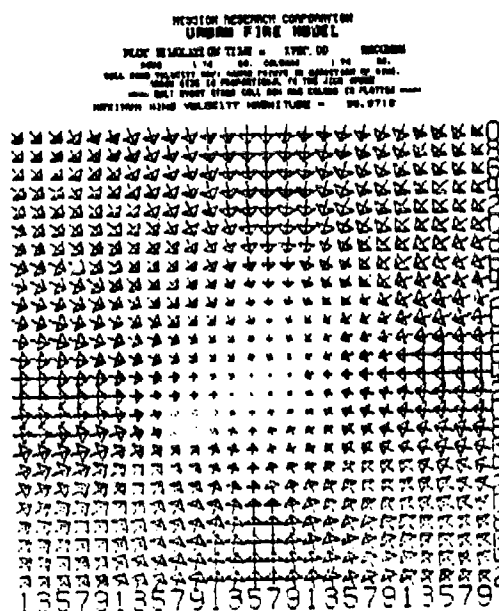
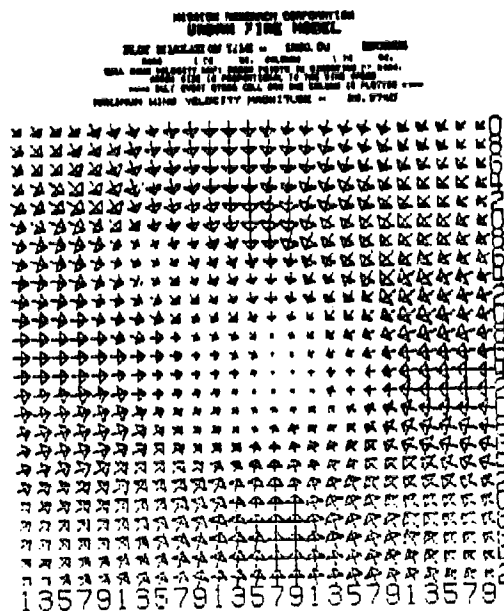
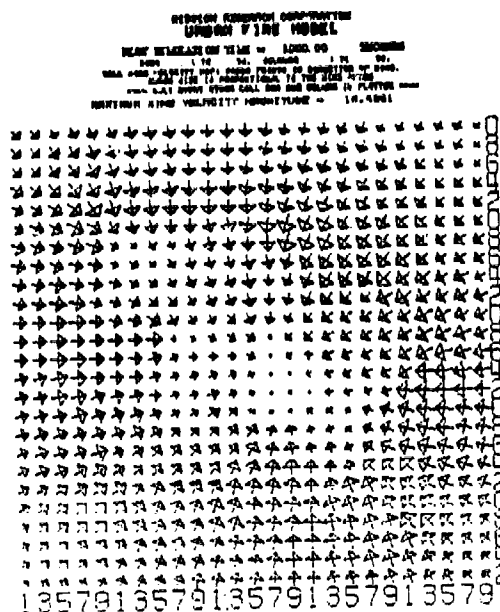
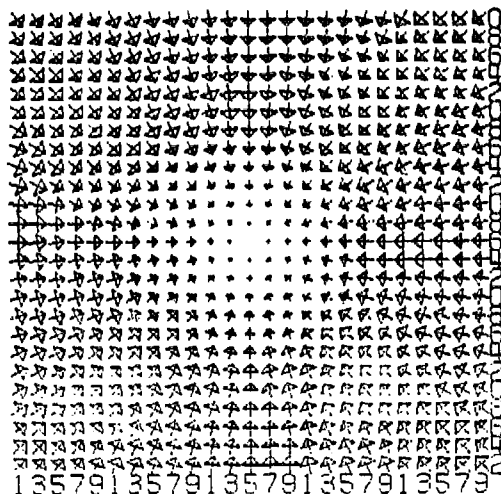
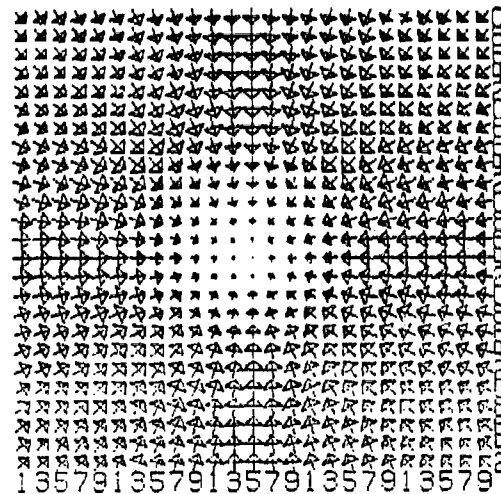


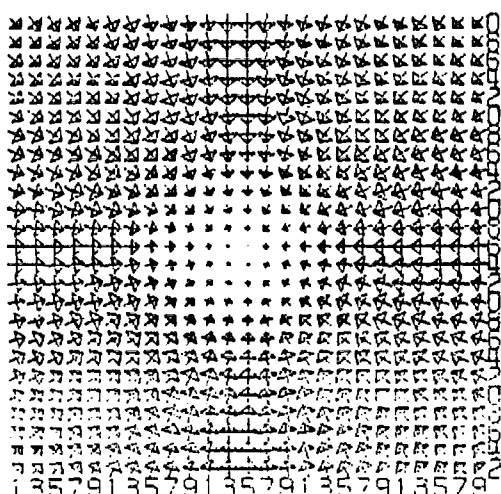
Figure 6-1(1). Cell heat production rate map for area fire.

PROXIMATE HIGH VELOCITY MAGNITUDE = 14.8510

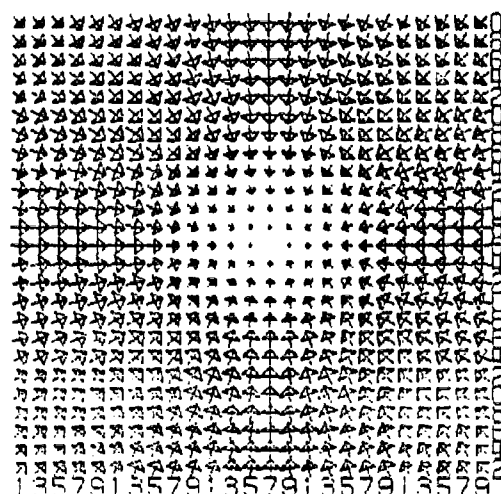


RECEIVED 1975 JUL 11 11 11 AM





WICKHAM, HARRY WILFRED, ARRESTED 12-1-1968



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6.2 LARGE AREA FIRE WITH 10 M/SEC AMBIENT WIND VELOCITY

The initial fire geometry in this case is exactly the same as in Case 6.1. The ambient wind is 10 m/sec, and directed from the lower left corner to the upper right corner. Figures 6-2 through 6-2(g) show that the fire burns very similarly to that of Case 6.1. The spread is slightly more rapid and tends to follow the wind direction more than in Case 6.1. The reason the fires are so similar is because the fire induced winds are a factor of from two to four times as large as the ambient wind. Propagation effects, which are strongly related to wind velocity, are thus dominated by the fire induced winds. Figures 6-2(l) and 6-2(m) show the interactions between the ambient and fire induced winds.

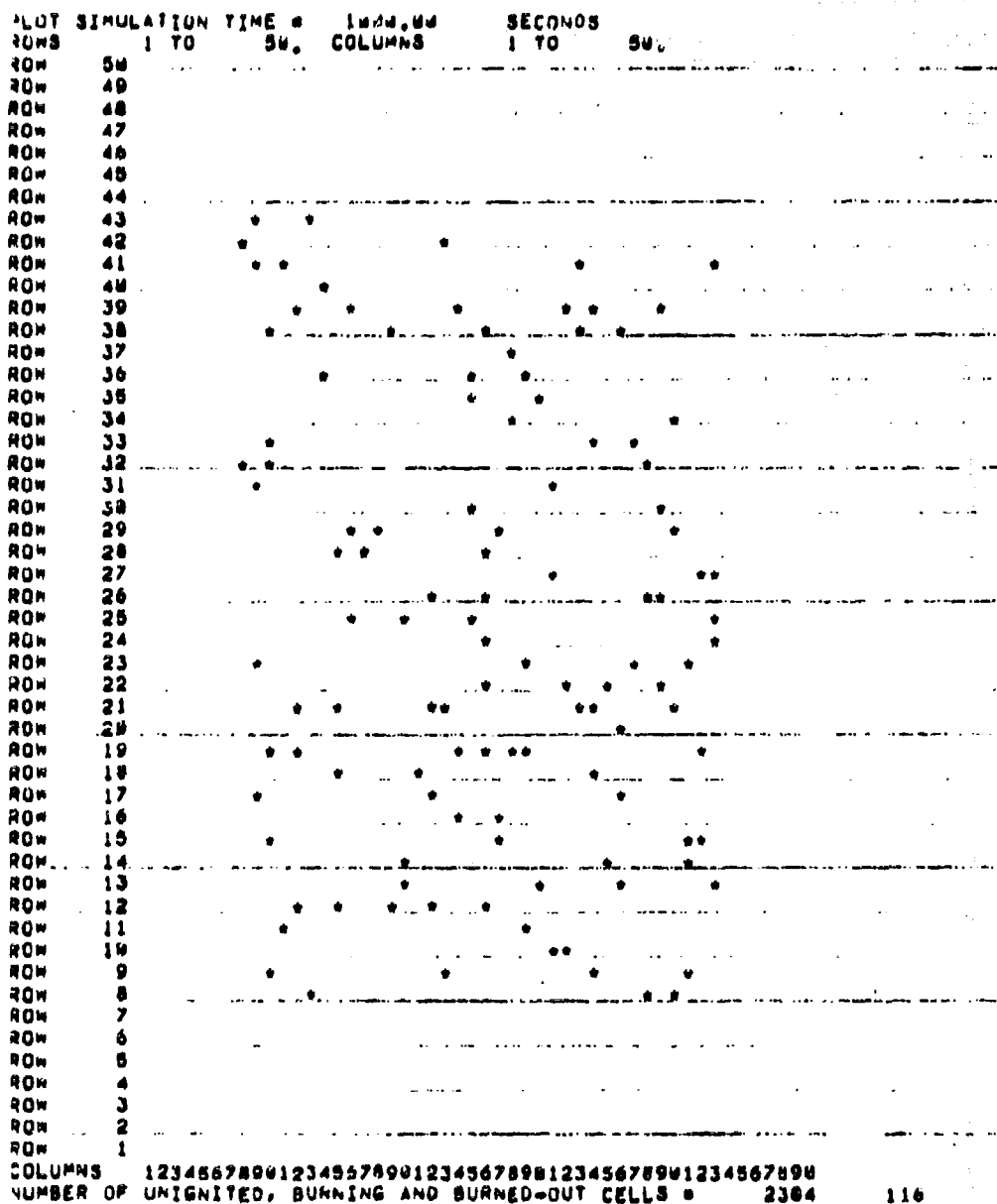
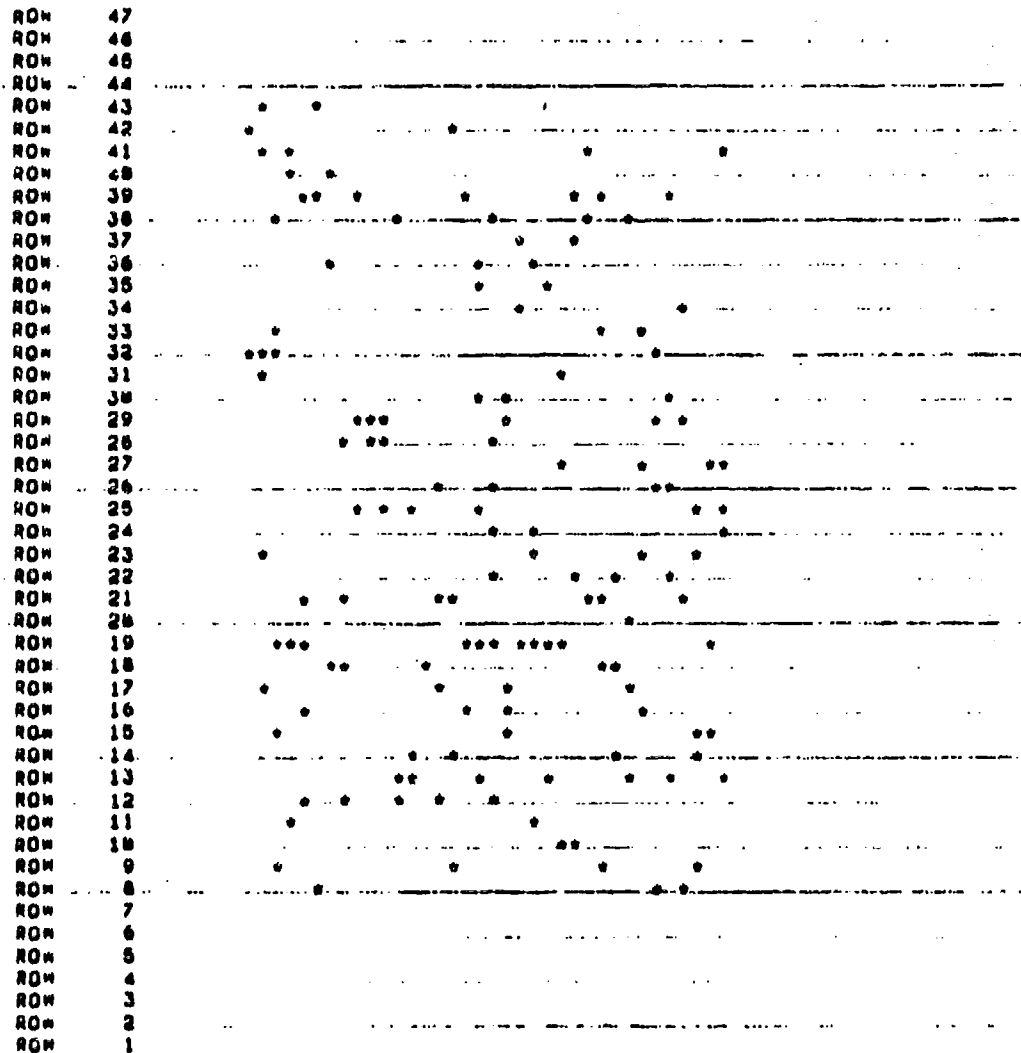


Figure 6-2. Cell state map for area fire with 10 m/s ambient wind.

PLOT SIMULATION TIME = 1260.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48



COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2389

141

Figure 6-2(a). Cell state map for area fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 1750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 80.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2233 267 0

```

Figure 6-2(b). Cell state map for area fire with .10 m/s ambient wind.

PLOT SIMULATION TIME = 2750.00 SECONDS

ROWS 1 TO 50. COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1764

740

Figure 6-2(c). Cell state map for area fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 4700.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1426 1072

```

Figure 6-2(d). Cell state map for area fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 0752.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48 *****
ROW 47 *****
ROW 46 *****
ROW 45 *****
ROW 44 *****
ROW 43 *****
ROW 42 *****
ROW 41 *****
ROW 40 *****
ROW 39 *****
ROW 38 *****
ROW 37 *****
ROW 36 *****
ROW 35 *****
ROW 34 *****
ROW 33 *****
ROW 32 *****
ROW 31 *****
ROW 30 *****
ROW 29 *****
ROW 28 *****
ROW 27 *****
ROW 26 *****
ROW 25 *****
ROW 24 *****

ROW 23 *****
ROW 22 *****
ROW 21 *****
ROW 20 *****
ROW 19 *****
ROW 18 *****
ROW 17 *****
ROW 16 *****
ROW 15 *****
ROW 14 *****
ROW 13 *****
ROW 12 *****
ROW 11 *****
ROW 10 *****
ROW 9 *****
ROW 8 *****
ROW 7 *****
ROW 6 *****
ROW 5 *****
ROW 4 *****
ROW 3 *****
ROW 2 *****
ROW 1 *****
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1246 1254

```

Figure 6-2(e). Cell state map for area fire with .10 m/s ambient wind.


```

PLU1 SIMULATION TIME = 1075.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50 *****
ROW 49 *****
ROW 48 *****
ROW 47 *****
ROW 46 *****
ROW 45 *****
ROW 44 *****
ROW 43 *****
ROW 42 *****
ROW 41 *****
ROW 40 *****
ROW 39 *****
ROW 38 *****
ROW 37 *****
ROW 36 *****
ROW 35 *****
ROW 34 *****
ROW 33 *****
ROW 32 *****
ROW 31 *****
ROW 30 *****
ROW 29 *****
ROW 28 *****
ROW 27 *****
ROW 26 *****
ROW 25 *****
ROW 24 *****
ROW 23 *****
ROW 22 *****
ROW 21 *****
ROW 20 *****
ROW 19 *****
ROW 18 *****

ROW 17 *****
ROW 16 *****
ROW 15 *****
ROW 14 *****
ROW 13 *****
ROW 12 *****
ROW 11 *****
ROW 10 *****
ROW 9 *****
ROW 8 *****
ROW 7 *****
ROW 6 *****
ROW 5 *****
ROW 4 *****
ROW 3 *****
ROW 2 *****
ROW 1 *****

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1003 1412 9

```

Figure 6-2(f). Cell state map for area fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 3275.0 SECONDS
ROW# 1 TO 50 COLUMNS 1 TO 50
ROW 50 .....
ROW 49 .....
ROW 48 .....
ROW 47 .....
ROW 46 .....
ROW 45 .....
ROW 44 .....
ROW 43 .....
ROW 42 .....
ROW 41 .....
ROW 40 .....
ROW 39 .....
ROW 38 .....
ROW 37 .....
ROW 36 .....
ROW 35 .....
ROW 34 .....
ROW 33 .....
ROW 32 .....
ROW 31 .....
ROW 30 .....
ROW 29 .....
ROW 28 .....
ROW 27 .....
ROW 26 .....
ROW 25 .....
ROW 24 .....
ROW 23 .....
ROW 22 .....
ROW 21 .....
ROW 20 .....
ROW 19 .....
ROW 18 .....
ROW 17 .....
ROW 16 .....
ROW 15 .....
ROW 14 .....
ROW 13 .....
ROW 12 .....

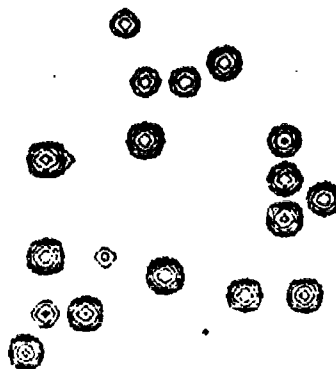
ROW 11 .....
ROW 10 .....
ROW 9 .....
ROW 8 .....
ROW 7 .....
ROW 6 .....
ROW 5 .....
ROW 4 .....
ROW 3 .....
ROW 2 .....
ROW 1 .....

COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 931 1469 110

```

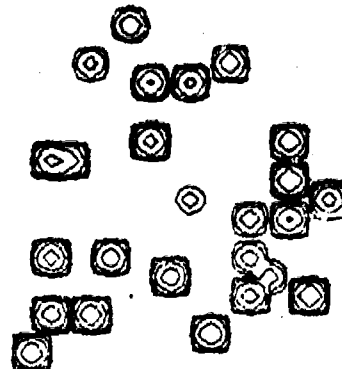
Figure 6-2(g). Cell state map for area fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL
PLAY SEQUENCE ON TIME = 0000.00 RECORD
TIME 1 TO 10.0000 1 TO 10
WIND NOT TURNED ON
*** ONLY EVERY OTHER BALL AND RELEASE IS PLOTTED ***
BURY SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



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MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL
PLAY SEQUENCE ON TIME = 0000.00 RECORD
TIME 1 TO 10.0000 1 TO 10
WIND NOT TURNED ON
*** ONLY EVERY OTHER BALL AND RELEASE IS PLOTTED ***
BURY SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



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MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL
PLAY SEQUENCE ON TIME = 0000.00 RECORD
TIME 1 TO 10.0000 1 TO 10
WIND NOT TURNED ON
*** ONLY EVERY OTHER BALL AND RELEASE IS PLOTTED ***
BURY SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



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MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL
PLAY SEQUENCE ON TIME = 0000.00 RECORD
TIME 1 TO 10.0000 1 TO 10
WIND NOT TURNED ON
*** ONLY EVERY OTHER BALL AND RELEASE IS PLOTTED ***
BURY SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



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Figure 6-2(h). Heat production rate contour for area fire with .10 m/s ambient wind.

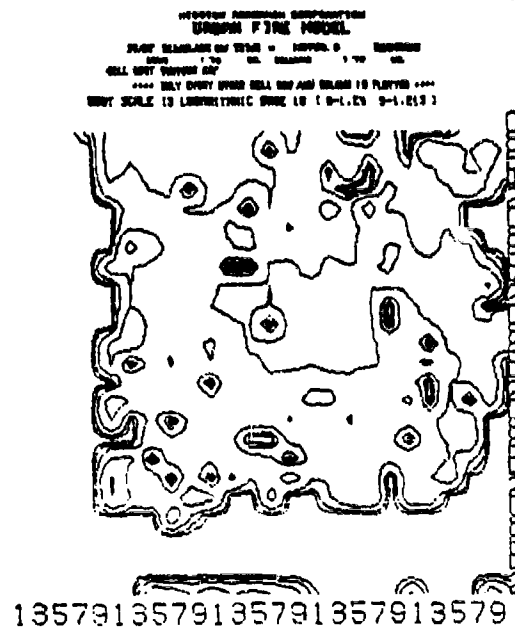
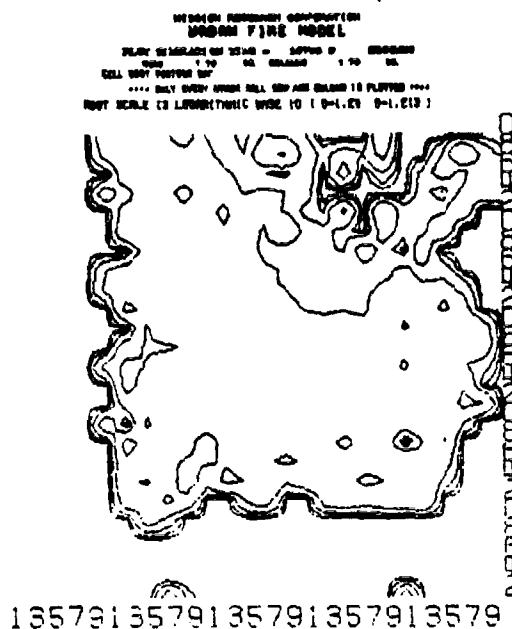
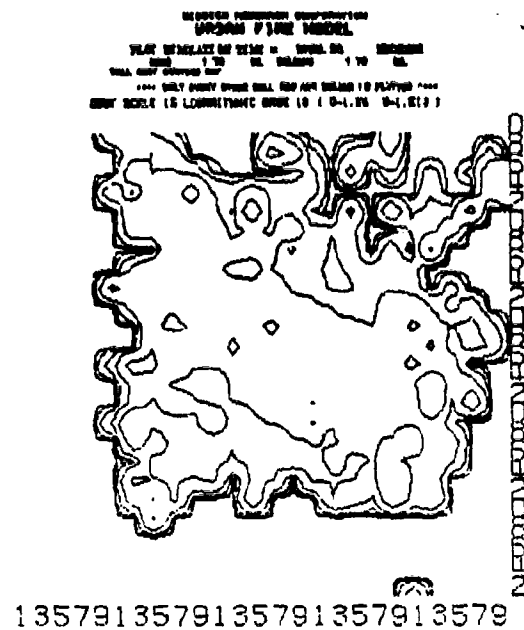
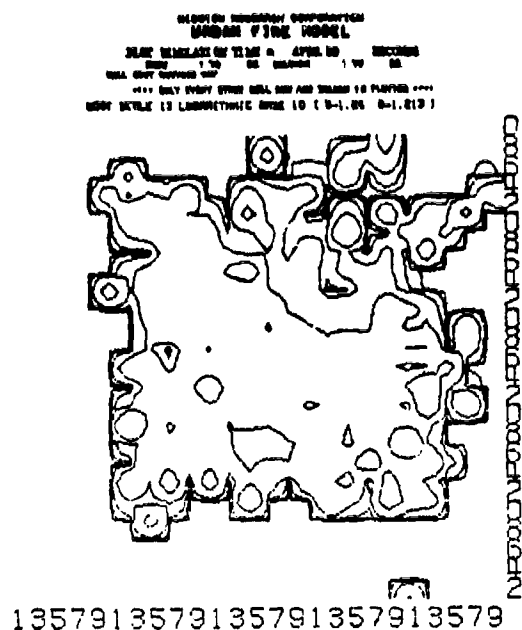
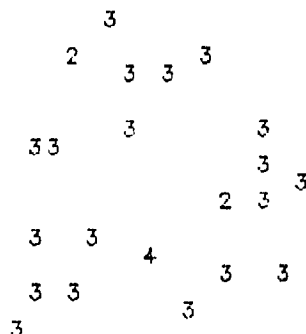


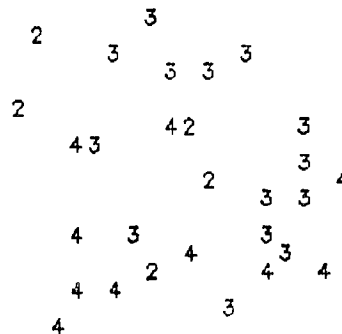
Figure 6-2(1). Heat production rate contour for area fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3000.00 SECONDS
DATA: 1 TO 99, COLUMNS 1 TO 99
NOTE: MAP: LETTERS A TO Z ARE A RANGE OF BURN VALUES
ONLY EVERY OTHER CELL AND ONE COLUMN IS PLOTTED
BURN SCALE IS LOGARITHMIC BASE 10 (0-1.25 9-1.219)



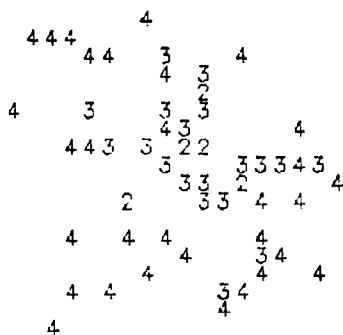
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3200.00 SECONDS
DATA: 1 TO 99, COLUMNS 1 TO 99
NOTE: MAP: LETTERS A TO Z ARE A RANGE OF BURN VALUES
ONLY EVERY OTHER CELL AND ONE COLUMN IS PLOTTED
BURN SCALE IS LOGARITHMIC BASE 10 (0-1.25 9-1.219)



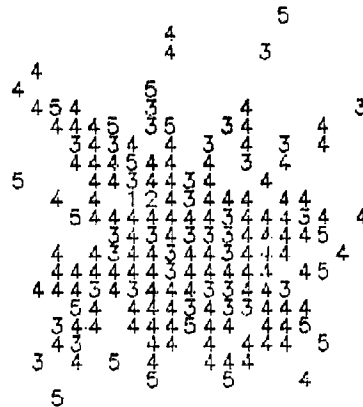
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3750.00 SECONDS
DATA: 1 TO 99, COLUMNS 1 TO 99
NOTE: MAP: LETTERS A TO Z ARE A RANGE OF BURN VALUES
ONLY EVERY OTHER CELL AND ONE COLUMN IS PLOTTED
BURN SCALE IS LOGARITHMIC BASE 10 (0-1.25 9-1.219)



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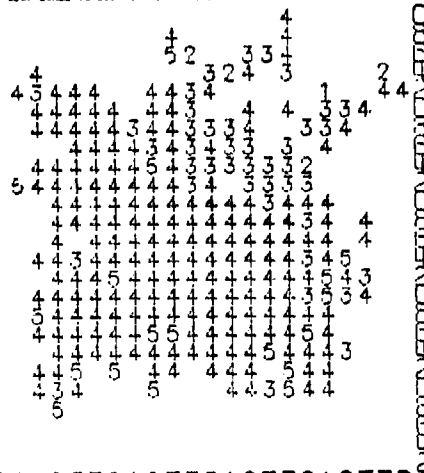
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 4250.00 SECONDS
DATA: 1 TO 99, COLUMNS 1 TO 99
NOTE: MAP: LETTERS A TO Z ARE A RANGE OF BURN VALUES
ONLY EVERY OTHER CELL AND ONE COLUMN IS PLOTTED
BURN SCALE IS LOGARITHMIC BASE 10 (0-1.25 9-1.219)



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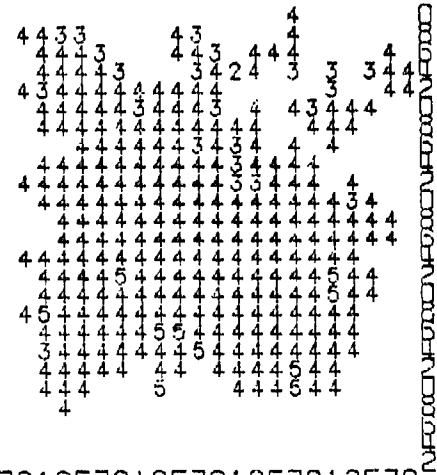
Figure 6-2(j). 11 heat production rate map for area fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 4750 00 000000
TIME 1 TO 24, COLUMN 1 TO 24,
ONLY DOTS LETTERS 0 TO 9 AND 10000 OF DOTS VALUES
ONLY DOTS OTHER CELL AND ONE VALUE IS PLATTED
DOT SCALE IS LOGARITHMIC SCALE (0-1.0E5 0-1.0E5)



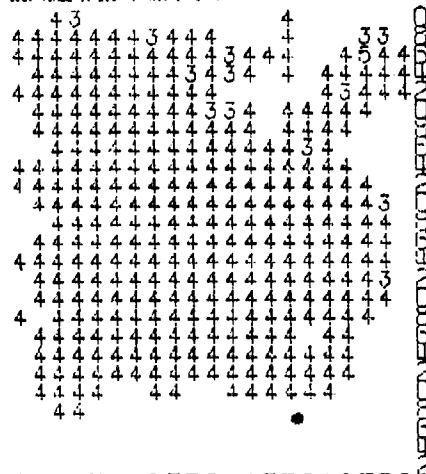
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 4750 00 000000
TIME 1 TO 24, COLUMN 1 TO 24,
ONLY DOTS LETTERS 0 TO 9 AND 10000 OF DOTS VALUES
ONLY DOTS OTHER CELL AND ONE VALUE IS PLATTED
DOT SCALE IS LOGARITHMIC SCALE (0-1.0E5 0-1.0E5)



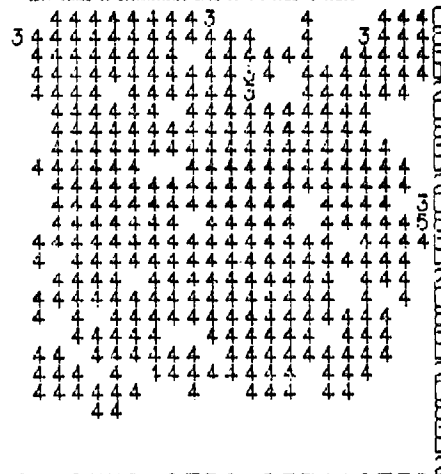
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 4750 00 000000
TIME 1 TO 24, COLUMN 1 TO 24,
ONLY DOTS LETTERS 0 TO 9 AND 10000 OF DOTS VALUES
ONLY DOTS OTHER CELL AND ONE VALUE IS PLATTED
DOT SCALE IS LOGARITHMIC SCALE (0-1.0E5 0-1.0E5)



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 4750 00 000000
TIME 1 TO 24, COLUMN 1 TO 24,
ONLY DOTS LETTERS 0 TO 9 AND 10000 OF DOTS VALUES
ONLY DOTS OTHER CELL AND ONE VALUE IS PLATTED
DOT SCALE IS LOGARITHMIC SCALE (0-1.0E5 0-1.0E5)



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Figure 6-2(k). Cell heat production rate for area fire with .10 m/s ambient wind.

[illegible][illegible][illegible]

191

6.3 LINE FIRE WITH NO AMBIENT WIND

As shown in Figure 6-3, the central 3×35 cells were ignited with a probability of ignition of 0.5. Fire induced winds are generated ranging from 7 to 18 m/s as shown in Figures 6-3(l) and 6-3(m). This is not sufficient wind speed to cause a significant amount of fire propagation. The ignited area does, however, partially fill in, due primarily to contagion. The "dumbbell" appearance shown in Figures 6-3(f) and 6-3(g) is an artifact of brands being tossed completely across the fire as described in Case 6.1.

PLOT SIMULATION TIME = 1440.00 SECONDS
 ROWS 1 TO 50, COLUMNS 1 TO 50,

ROW	50
ROW	49
ROW	48
ROW	47
ROW	46
ROW	45
ROW	44
ROW	43
ROW	42
ROW	41
ROW	40
ROW	39
ROW	38
ROW	37
ROW	36
ROW	35
ROW	34
ROW	33
ROW	32
ROW	31
ROW	30
ROW	29
ROW	28
ROW	27
ROW	26
ROW	25
ROW	24
ROW	23
ROW	22
ROW	21
ROW	20
ROW	19
ROW	18
ROW	17
ROW	16
ROW	15
ROW	14
ROW	13
ROW	12
ROW	11
ROW	10
ROW	9
ROW	8
ROW	7
ROW	6
ROW	5
ROW	4
ROW	3
ROW	2
ROW	1

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2462 38 0

Figure 6-3. Cell state map for line fire.

```

PLOT SIMULATION TIME = 1250.00 SECONDS
ROWS 1 TO 50. COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48

ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2461 39 0

```

The figure displays a 50x50 grid representing a cell state map. The rows are labeled on the left from 1 to 50, and the columns are labeled at the bottom from 1 to 50. A horizontal line of burning cells is visible across rows 26, 27, and 28. The cells in row 26 are marked with dots, while the cells in rows 27 and 28 are marked with asterisks. The rest of the grid is empty, indicating unignited cells.

Figure 6-3(a). Cell state map for line fire.

```

PLOT SIMULATION TIME = 1754.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2456 44

```

Figure 6-3(b). Cell state map for line fire.

```

PLOT SIMULATION TIME = 2750.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2449 51

```

The figure displays a 50x50 grid representing cell states during a simulation. The grid is divided into two main sections. The top section (rows 36-50) is mostly empty, indicating unignited cells. The bottom section (rows 1-35) shows a horizontal line of burning cells across row 26, extending from column 1 to column 50. The cells in row 26 are represented by a series of dots, indicating their state (unignited, burning, or burned-out). The cells in row 25 are also represented by a series of dots, indicating their state. The cells in row 24 are also represented by a series of dots, indicating their state. The cells in row 23 are also represented by a series of dots, indicating their state. The cells in row 22 are also represented by a series of dots, indicating their state. The cells in row 21 are also represented by a series of dots, indicating their state. The cells in row 20 are also represented by a series of dots, indicating their state. The cells in row 19 are also represented by a series of dots, indicating their state. The cells in row 18 are also represented by a series of dots, indicating their state. The cells in row 17 are also represented by a series of dots, indicating their state. The cells in row 16 are also represented by a series of dots, indicating their state. The cells in row 15 are also represented by a series of dots, indicating their state. The cells in row 14 are also represented by a series of dots, indicating their state. The cells in row 13 are also represented by a series of dots, indicating their state. The cells in row 12 are also represented by a series of dots, indicating their state. The cells in row 11 are also represented by a series of dots, indicating their state. The cells in row 10 are also represented by a series of dots, indicating their state. The cells in row 9 are also represented by a series of dots, indicating their state. The cells in row 8 are also represented by a series of dots, indicating their state. The cells in row 7 are also represented by a series of dots, indicating their state. The cells in row 6 are also represented by a series of dots, indicating their state. The cells in row 5 are also represented by a series of dots, indicating their state. The cells in row 4 are also represented by a series of dots, indicating their state. The cells in row 3 are also represented by a series of dots, indicating their state. The cells in row 2 are also represented by a series of dots, indicating their state. The cells in row 1 are also represented by a series of dots, indicating their state.

Figure 6-3(c). Cell state map for line fire.

```

PLOT SIMULATION TIME = 4750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

ROW 29
ROW 28
ROW 27
ROW 26 .....
ROW 25 .....
ROW 24 .....
ROW 23 .....
ROW 22 .....
ROW 21 .....
ROW 20 .....
ROW 19 .....
ROW 18 .....
ROW 17 .....
ROW 16 .....
ROW 15 .....
ROW 14 .....
ROW 13 .....
ROW 12 .....
ROW 11 .....
ROW 10 .....
ROW 9 .....
ROW 8 .....
ROW 7 .....
ROW 6 .....
ROW 5 .....
ROW 4 .....
ROW 3 .....
ROW 2 .....
ROW 1 .....

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2443 57

```

Figure 6-3(d). Cell state map for line fire.

```

PLOT SIMULATION TIME = 5752.54 SECONDS
ROWS ... 1 TO ... 50 ... COLUMNS ... 1 TO ... 80 ...
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26 .....
ROW 25 .....
ROW 24 .....

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2418 82

```

Figure 6-3(e). Cell state map for line fire.

```

PLOT SIMULATION TIME = 10750.4 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18

```

```

ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2400 100

```

Figure 6-3(f). Cell state map for line fire.

Figure 6-3(g). Cell state map for line fire.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 3400.00
TIME 1 TO 24.0000 1 TO 24.0000
CELL NOT COVERED BY
*** ONLY EVERY OTHER CELL NOT AND CELLS IS PLAYED ***
BODY STYLE (S LOGARITHMIC) BODY (S (0-1.00 0-1.00))



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 3700.00
TIME 1 TO 24.0000 1 TO 24.0000
CELL NOT COVERED BY
*** ONLY EVERY OTHER CELL NOT AND CELLS IS PLAYED ***
BODY STYLE (S LOGARITHMIC) BODY (S (0-1.00 0-1.00))



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 3800.00
TIME 1 TO 24.0000 1 TO 24.0000
CELL NOT COVERED BY
*** ONLY EVERY OTHER CELL NOT AND CELLS IS PLAYED ***
BODY STYLE (S LOGARITHMIC) BODY (S (0-1.00 0-1.00))



135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 3700.00
TIME 1 TO 24.0000 1 TO 24.0000
CELL NOT COVERED BY
*** ONLY EVERY OTHER CELL NOT AND CELLS IS PLAYED ***
BODY STYLE (S LOGARITHMIC) BODY (S (0-1.00 0-1.00))



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Figure 6-3(h). Heat production rate contour for line fire.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASED ON TIME = 47.70 SE SECONDS
RMS 1 TO 10.0000 1 TO 10
CELL SIZE 0.00000000
*** ONLY EVERY OTHER CELL SIZE AND RELEASED TO PLAYERS ***
COPY SCALE IS LOGARITHMIC SCALE IS 1 0-1.25 0-1.25 1



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASED ON TIME = 47.70 SE SECONDS
RMS 1 TO 10.0000 1 TO 10
CELL SIZE 0.00000000
*** ONLY EVERY OTHER CELL SIZE AND RELEASED TO PLAYERS ***
COPY SCALE IS LOGARITHMIC SCALE IS 1 0-1.25 0-1.25 1



135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASED ON TIME = 47.70 SE SECONDS
RMS 1 TO 10.0000 1 TO 10
CELL SIZE 0.00000000
*** ONLY EVERY OTHER CELL SIZE AND RELEASED TO PLAYERS ***
COPY SCALE IS LOGARITHMIC SCALE IS 1 0-1.25 0-1.25 1



135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASED ON TIME = 47.70 SE SECONDS
RMS 1 TO 10.0000 1 TO 10
CELL SIZE 0.00000000
*** ONLY EVERY OTHER CELL SIZE AND RELEASED TO PLAYERS ***
COPY SCALE IS LOGARITHMIC SCALE IS 1 0-1.25 0-1.25 1



135791357913579135791357913579

Figure 6-3(i). Heat production rate contour for line fire.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAN SIMULATION TIME = 1000.00 SECONDS
DATA 1 TO 99: 00000000 1 TO 99:
ONLY HOT: LETTERS 0 TO 9 ARE A PART OF HOT: VALUE
ONLY HOT: OTHER CELL ARE ARE 00000000 IN PLATES
HOT: SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

22 23 22 22
2 2 22 2

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAN SIMULATION TIME = 1700.00 SECONDS
DATA 1 TO 99: 00000000 1 TO 99:
ONLY HOT: LETTERS 0 TO 9 ARE A PART OF HOT: VALUE
ONLY HOT: OTHER CELL ARE ARE 00000000 IN PLATES
HOT: SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

43 33 33 43 3
3 3 33 4 3

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAN SIMULATION TIME = 1200.00 SECONDS
DATA 1 TO 99: 00000000 1 TO 99:
ONLY HOT: LETTERS 0 TO 9 ARE A PART OF HOT: VALUE
ONLY HOT: OTHER CELL ARE ARE 00000000 IN PLATES
HOT: SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

23 33 23 33
2 3 23 3

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAN SIMULATION TIME = 1700.00 SECONDS
DATA 1 TO 99: 00000000 1 TO 99:
ONLY HOT: LETTERS 0 TO 9 ARE A PART OF HOT: VALUE
ONLY HOT: OTHER CELL ARE ARE 00000000 IN PLATES
HOT: SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

153 33 33 43 4
4 3 33 4 4

135791357913579135791357913579

Figure 6-3(j). Cell heat production rate map for line fire.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 4790.00 SECONDS
GRID 1 TO 100, COLUMNS 1 TO 100
ONLY MAP: LETTERS A TO Z ARE A RANGE OF GRID VALUES
ONLY EVERY OTHER CELL AND COLOR IS PLOTTED
GRID SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)

4 5 4 4 4 4 4 4
4 3 4 4 4 4 4 4

1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 10790.0 SECONDS
GRID 1 TO 100, COLUMNS 1 TO 100
ONLY MAP: LETTERS A TO Z ARE A RANGE OF GRID VALUES
ONLY EVERY OTHER CELL AND COLOR IS PLOTTED
GRID SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)

4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 5 4 4 4 4 4 4 4 4 4 4 4

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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 5790.00 SECONDS
GRID 1 TO 100, COLUMNS 1 TO 100
ONLY MAP: LETTERS A TO Z ARE A RANGE OF GRID VALUES
ONLY EVERY OTHER CELL AND COLOR IS PLOTTED
GRID SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)

4 5 4 4 4 4 3 4 4 3 4 4 5
4 4 3 4 4 4 4 4 3 4 4 4 5

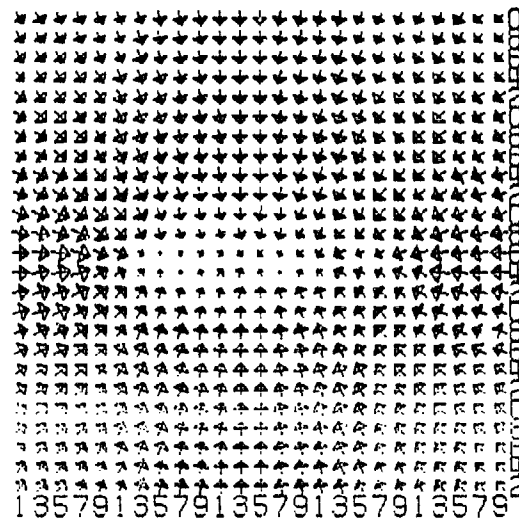
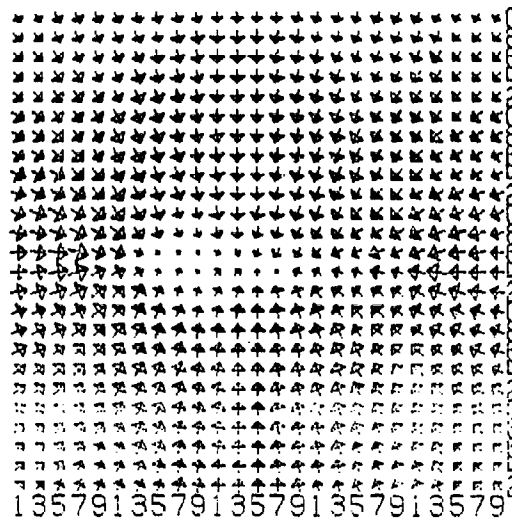
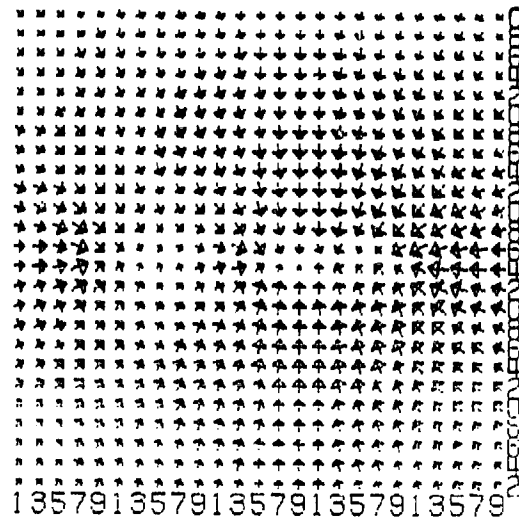
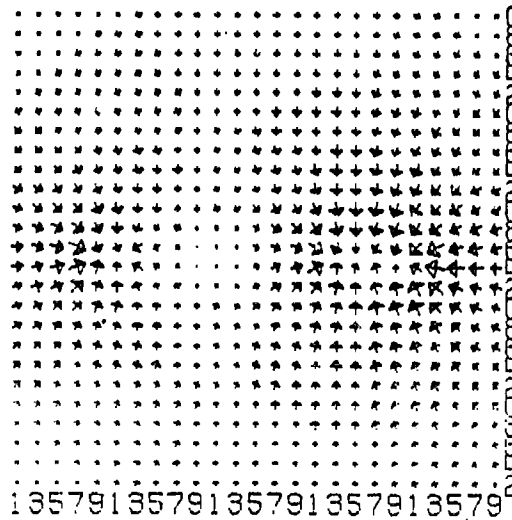
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 20790.0 SECONDS
GRID 1 TO 100, COLUMNS 1 TO 100
ONLY MAP: LETTERS A TO Z ARE A RANGE OF GRID VALUES
ONLY EVERY OTHER CELL AND COLOR IS PLOTTED
GRID SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)

4 4 4 4 4 4 4 4 4 4 4 4 4 4
4 4 4 4 4 3 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4 4 4 4 4 4

1357913579135791357913579

Figure 6-3(k). Cell heat production rate map for line fire.



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	5

[illegible][illegible]

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	8												

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6.4 LINE FIRE WITH 10 M/SEC AMBIENT WIND

The ignition geometry is the same as for case 6.3; however, the location of the candidate cells was moved to the lower left corner. This was done so that the fire would have room to propagate along the wind direction from the lower left corner to the upper right corner. Figures 6-4 to 6-4(g) show that the fire propagates much more rapidly than in Case 6.3 and that the propagation is along the wind stream lines. Comparison of the wind maps for Cases 6.3 and 6.4 shows that the ratio of the fire induced to the ambient winds is such that the 10 m/s ambient winds would be expected to cause the fire to burn significantly differently than in the case with no ambient wind.


```

PLOT SIMULATION TIME = 1000.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

```

```

COLUMNS 1234567890123456789012345678991234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2485 15

```

Figure 6-4. Cell state map for line fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 1200.00 SECONDS
ROWS 1 TO 50. COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48

ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2403 17

```

Figure 6-4(a). Cell state map for line fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 1750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2477 23 0

```

Figure 6-4(b). Cell state map for line fire with .10 m/s ambient wind.

PLOT SIMULATION TIME = 2750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2400 34

Figure 6-4(c). Cell state map for line fire with .10 m/s ambient wind.

NUMBER OF UNIGNITED, BURNING AND BURIED-OUT CELLS • 2400 3-

PLOT SIMULATION TIME • 4785.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURIED-OUT CELLS • 2422 78

Figure 6-4(d). Cell state map for line fire with .10 m/s ambient wind.

```

PLOT SIMULATION TIME = 875.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2304 130

```

Figure 6-4(e). Cell state map for line fire with .10 m/s ambient wind.

PLOT SIMULATION TIME • 10750.0 SECONDS
 ROWS 1 TO 50, COLUMNS 1 TO 50

ROW 50
 ROW 49
 ROW 48
 ROW 47
 ROW 46
 ROW 45
 ROW 44
 ROW 43
 ROW 42
 ROW 41
 ROW 40
 ROW 39
 ROW 38
 ROW 37
 ROW 36
 ROW 35
 ROW 34
 ROW 33
 ROW 32
 ROW 31
 ROW 30
 ROW 29
 ROW 28
 ROW 27
 ROW 26
 ROW 25
 ROW 24
 ROW 23
 ROW 22
 ROW 21
 ROW 20
 ROW 19
 ROW 18

ROW 17
 ROW 16
 ROW 15
 ROW 14
 ROW 13
 ROW 12
 ROW 11
 ROW 10
 ROW 9
 ROW 8
 ROW 7
 ROW 6
 ROW 5
 ROW 4
 ROW 3
 ROW 2
 ROW 1

COLUMNS 12345678901234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS • 2282 218 0

Figure 6-4(f). Cell state map for line fire with 10 m/s ambient wind.

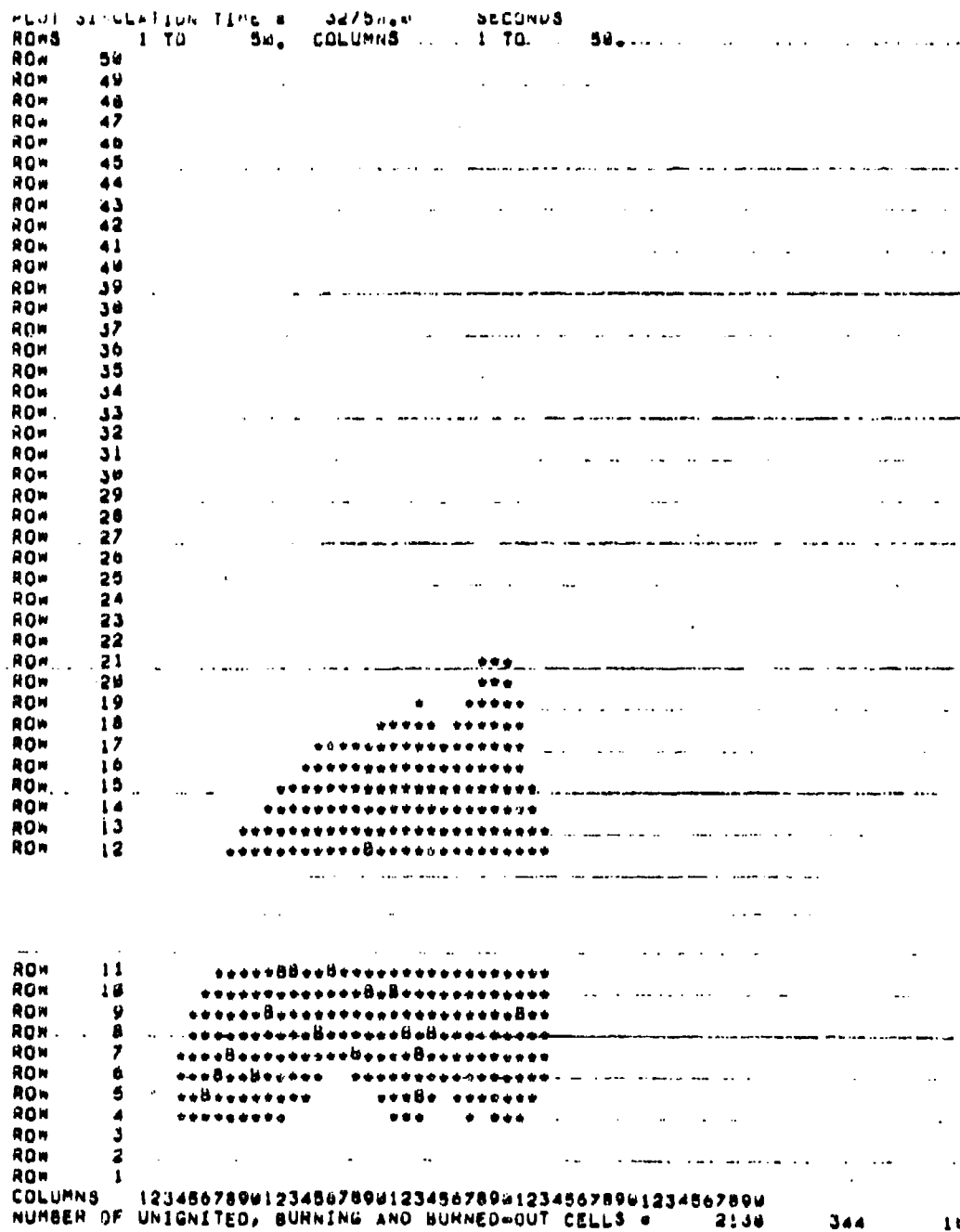


Figure 6-4(g). Cell state map for line fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 0000.00 SECONDS
STEP 1 TO 99. RELEASE 1 TO 99
CELL NOT OUTSIDE 99
*** ONLY EVERY OTHER CELL AND RELEASE IS PLAYED ***
BEST SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 0700.00 SECONDS
STEP 1 TO 99. RELEASE 1 TO 99
CELL NOT OUTSIDE 99
*** ONLY EVERY OTHER CELL AND RELEASE IS PLAYED ***
BEST SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 0000.00 SECONDS
STEP 1 TO 99. RELEASE 1 TO 99
CELL NOT OUTSIDE 99
*** ONLY EVERY OTHER CELL AND RELEASE IS PLAYED ***
BEST SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 0700.00 SECONDS
STEP 1 TO 99. RELEASE 1 TO 99
CELL NOT OUTSIDE 99
*** ONLY EVERY OTHER CELL AND RELEASE IS PLAYED ***
BEST SCALE IS LOGARITHMIC SCALE (0-1.00 0-1.00)



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Figure 6-4(h). Heat production rate contour map for line fire with .10 m/s ambient wind.

MISSION PERFORMANCE COMPARISON
 URBAN FIRE MODEL
 PLATE SIMULATION TIME = 4750.0 SECONDS
 CASE 1 TO 1000 1 TO 1000
 CASE 1000 TO 1000 1 TO 1000
 *** ONLY EVERY OTHER CELL AND SHOWN IS PLOTTED ***
 WIND SCALE IS LOGARITHMIC WIND (0-1.00 0-1.00)



1357913579135791357913579

MISSION PERFORMANCE COMPARISON
 URBAN FIRE MODEL
 PLATE SIMULATION TIME = 10750.0 SECONDS
 CASE 1 TO 1000 1 TO 1000
 CASE 1000 TO 1000 1 TO 1000
 *** ONLY EVERY OTHER CELL AND SHOWN IS PLOTTED ***
 WIND SCALE IS LOGARITHMIC WIND (0-1.00 0-1.00)



1357913579135791357913579

MISSION PERFORMANCE COMPARISON
 URBAN FIRE MODEL
 PLATE SIMULATION TIME = 4750.0 SECONDS
 CASE 1 TO 1000 1 TO 1000
 CASE 1000 TO 1000 1 TO 1000
 *** ONLY EVERY OTHER CELL AND SHOWN IS PLOTTED ***
 WIND SCALE IS LOGARITHMIC WIND (0-1.00 0-1.00)



1357913579135791357913579

MISSION PERFORMANCE COMPARISON
 URBAN FIRE MODEL
 PLATE SIMULATION TIME = 10750.0 SECONDS
 CASE 1 TO 1000 1 TO 1000
 CASE 1000 TO 1000 1 TO 1000
 *** ONLY EVERY OTHER CELL AND SHOWN IS PLOTTED ***
 WIND SCALE IS LOGARITHMIC WIND (0-1.00 0-1.00)



1357913579135791357913579

Figure 6-4(1). Heat production rate contour map for line fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASES OF TIME = 0000.00
DATE 1 78 00 000000 1 78 00
OUT PUT: LETTERS A TO Z ARE A SERIES OF TEST PLANS
ONLY EVERY OTHER CELL AND ARE CALLED IN PLATES
OUT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

2 3 3 2
3 3 2
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASES OF TIME = 1700.00
DATE 1 78 00 000000 1 78 00
OUT PUT: LETTERS A TO Z ARE A SERIES OF TEST PLANS
ONLY EVERY OTHER CELL AND ARE CALLED IN PLATES
OUT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

3 3 3 3 3 3
4 4 3
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASES OF TIME = 0000.00
DATE 1 78 00 000000 1 78 00
OUT PUT: LETTERS A TO Z ARE A SERIES OF TEST PLANS
ONLY EVERY OTHER CELL AND ARE CALLED IN PLATES
OUT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

3 2 2 3 3 3
3 3 3 3
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASES OF TIME = 0700.00
DATE 1 78 00 000000 1 78 00
OUT PUT: LETTERS A TO Z ARE A SERIES OF TEST PLANS
ONLY EVERY OTHER CELL AND ARE CALLED IN PLATES
OUT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

4 3 4 3 3 3 4 3
4 4 4 4
1357913579135791357913579

Figure 6-4(j). Cell heat production rate map for line fire with .10 m/s ambient wind.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 00:00:00
TIME 1 TO 24 HOURS
SHOT MAP: LETTERS A TO Z ARE A SCALE OF SHOT VALUES
NOTE: ONLY SHOT VALUES ARE SHOWN IN PLAYERS AREA
SHOT SCALE IS LOGARITHMIC SCALE (0 = 0.01, 9 = 0.10)

42 44 3
3 4 3 4 3
4 4 4 4 3
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 00:00:00
TIME 1 TO 24 HOURS
SHOT MAP: LETTERS A TO Z ARE A SCALE OF SHOT VALUES
NOTE: ONLY SHOT VALUES ARE SHOWN IN PLAYERS AREA
SHOT SCALE IS LOGARITHMIC SCALE (0 = 0.01, 9 = 0.10)

4 4 3
3 4 4 4 3
4 4 4 4 3
4 4 4 4 3
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 00:00:00
TIME 1 TO 24 HOURS
SHOT MAP: LETTERS A TO Z ARE A SCALE OF SHOT VALUES
NOTE: ONLY SHOT VALUES ARE SHOWN IN PLAYERS AREA
SHOT SCALE IS LOGARITHMIC SCALE (0 = 0.01, 9 = 0.10)

4 4 4 4 3 4 3 3
4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY SIMULATION TIME = 00:00:00
TIME 1 TO 24 HOURS
SHOT MAP: LETTERS A TO Z ARE A SCALE OF SHOT VALUES
NOTE: ONLY SHOT VALUES ARE SHOWN IN PLAYERS AREA
SHOT SCALE IS LOGARITHMIC SCALE (0 = 0.01, 9 = 0.10)

4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
1357913579135791357913579

Figure 6-4(k). Cell heat production rate map for line fire with .10 m/s ambient wind.

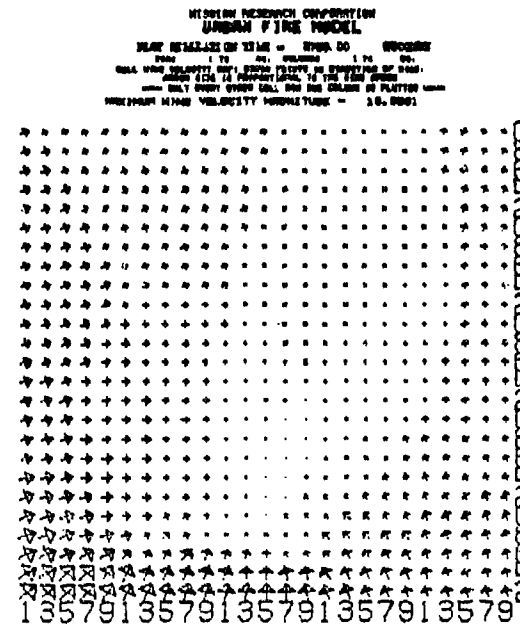
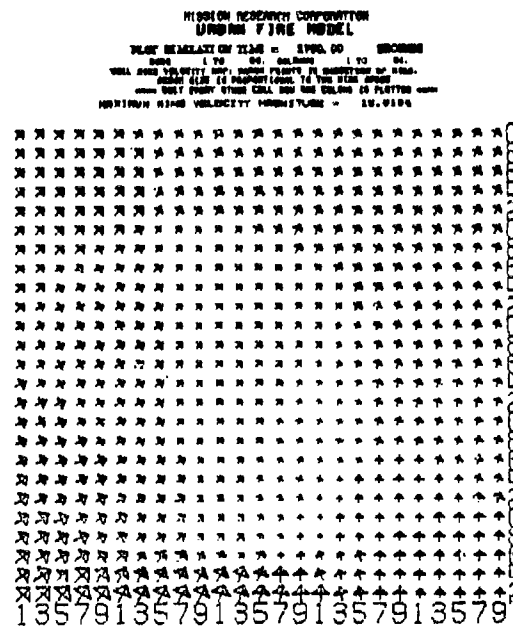
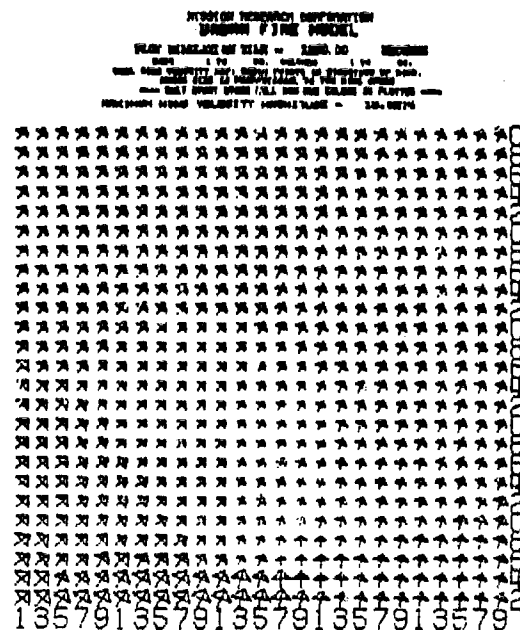
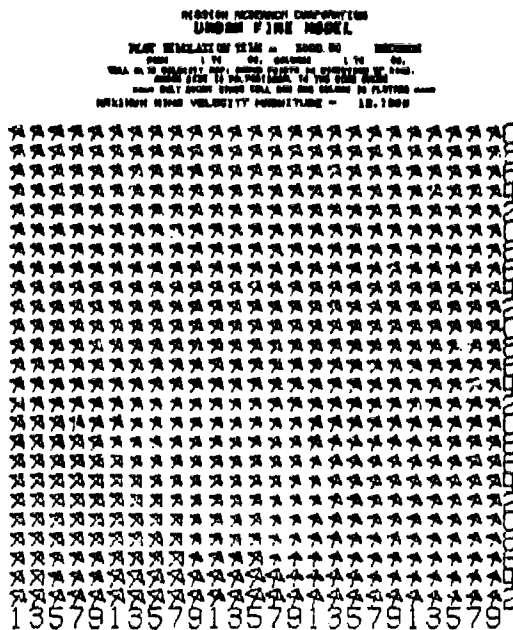


Figure 6-4(1). Wind velocity for line fire with .10 m/s ambient wind.

[illegible]

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6.5 RING FIRE WITH NO AMBIENT WIND

As shown in Figure 6-5, a four-cell wide annulus, 42 cells in diameter, was initially ignited with a probability of ignition of 0.5. There was no initial wind velocity; however, strong, inward-directed fire induced winds resulted in heavy branding and contagion in the interior of the annulus. It is clear in all of the cases that fire spread is much too rapid. However, this is graphically shown by the marked increase in the number of ignited cells in the 1000 seconds (from 1750 to 2750 seconds), as shown in Figures 6-5(b) and 6-5(c). The "tails" shown in Figures 6-5(d) through 6-5(g) are artifacts of the erroneous branding process described in Case 6.1.

PLOT SIMULATION TIME = 1440.00 SECONDS	
ROWS	COLUMNS
1 TO 50	1 TO 50
ROW 50	
ROW 49	
ROW 48	
ROW 47	
ROW 46	
ROW 45	
ROW 44	
ROW 43	
ROW 42	
ROW 41	
ROW 40	
ROW 39	
ROW 38	
ROW 37	
ROW 36	
ROW 35	
ROW 34	
ROW 33	
ROW 32	
ROW 31	
ROW 30	
ROW 29	
ROW 28	
ROW 27	
ROW 26	
ROW 25	
ROW 24	
ROW 23	
ROW 22	
ROW 21	
ROW 20	
ROW 19	
ROW 18	
ROW 17	
ROW 16	
ROW 15	
ROW 14	
ROW 13	
ROW 12	
ROW 11	
ROW 10	
ROW 9	
ROW 8	
ROW 7	
ROW 6	
ROW 5	
ROW 4	
ROW 3	
ROW 2	
ROW 1	

COLUMNS 12345678901234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2363 137

Figure 6-5. Cell state map for ring fire.

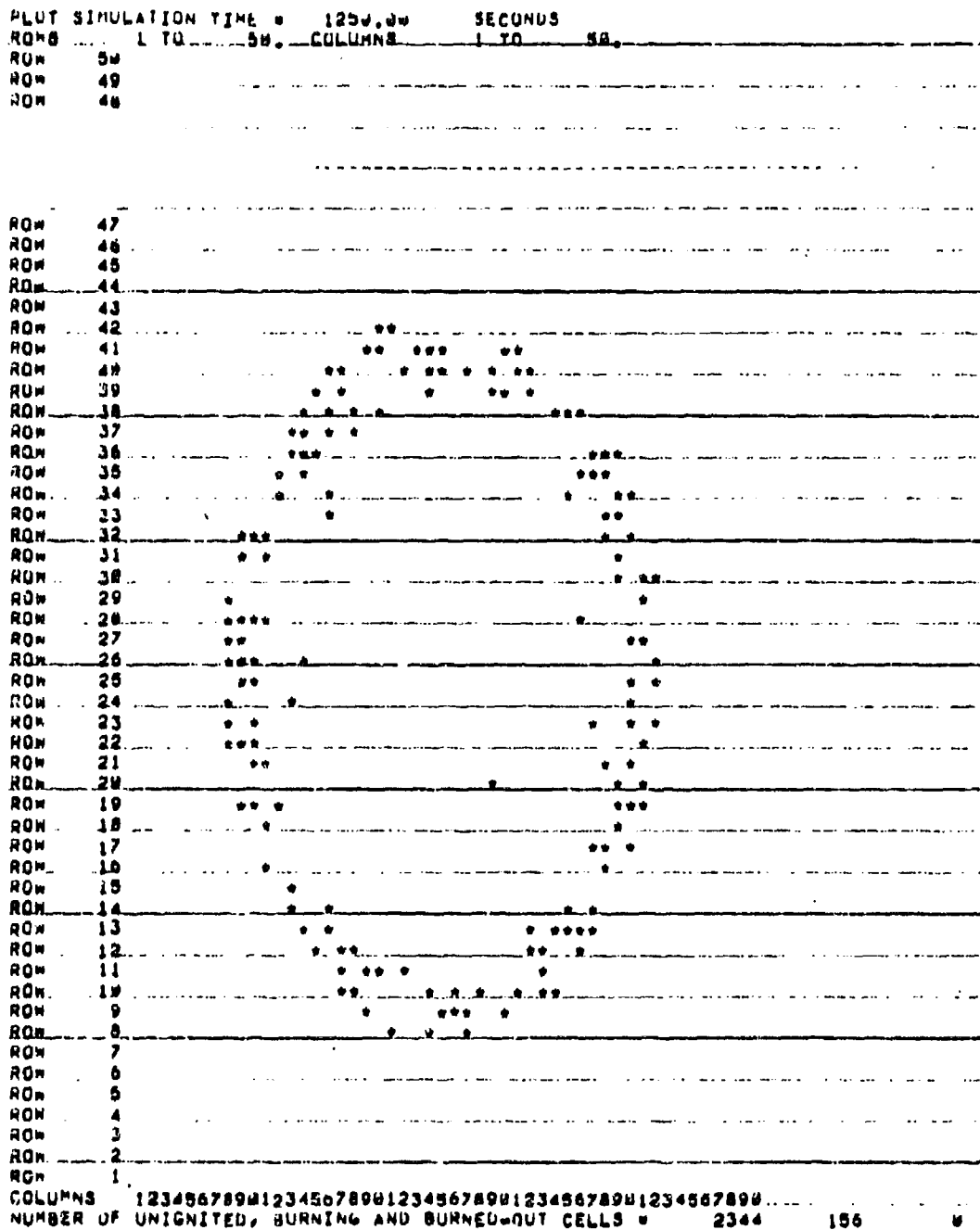


Figure 6-5(a). Cell state map for ring fire.

```

PLUT SIMULATION TIME = 1700.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2150 350 0

```

Figure 6-5(b). Cell state map for ring fire.

```

PLOT SIMULATION TIME = 2700.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

```

```

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1727 773

```

Figure 6-5(c). Cell state map for ring fire.

```

PLOT SIMULATION TIME = 4754.46 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

```

```

ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

```

```

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1598 942

```

Figure 6-5(d). Cell state map for ring fire.

```

PLOT SIMULATION TIME = 8750.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1558 942

```

Figure 6-5(e). Cell state map for ring fire.

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1558 942

PLOT SIMULATION TIME = 10750.0 SECONDS
 ROWS 1 TO 50 COLUMNS 1 TO 50

ROW	50	
ROW	49	*
ROW	48	**
ROW	47	***
ROW	46	****
ROW	45	*****
ROW	44	*****
ROW	43	*****
ROW	42	*****
ROW	41	*****
ROW	40	*****
ROW	39	*****
ROW	38	*****
ROW	37	*****
ROW	36	*****
ROW	35	*****
ROW	34	*****
ROW	33	*****
ROW	32	*****
ROW	31	*****
ROW	30	*****
ROW	29	*****
ROW	28	*****
ROW	27	*****
ROW	26	*****
ROW	25	*****
ROW	24	*****
ROW	23	*****
ROW	22	*****
ROW	21	*****
ROW	20	*****
ROW	19	*****
ROW	18	*****

ROW	17	*****
ROW	16	*****
ROW	15	*****
ROW	14	*****
ROW	13	*****
ROW	12	*****
ROW	11	*****
ROW	10	*****
ROW	9	*****
ROW	8	*****
ROW	7	*****
ROW	6	*****
ROW	5	*****
ROW	4	*****
ROW	3	*****
ROW	2	*****
ROW	1	*****

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1528 970

Figure 6-5(f). Cell state map for ring fire.

```

FUEL SIMULATION TIME = 32750.0 SECONDS
ROWS = 1 TO 50, COLUMNS = 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12

ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1490 934 75

```

Figure 6-5(g). Cell state map for ring fire.

COOPER VOLUME 1

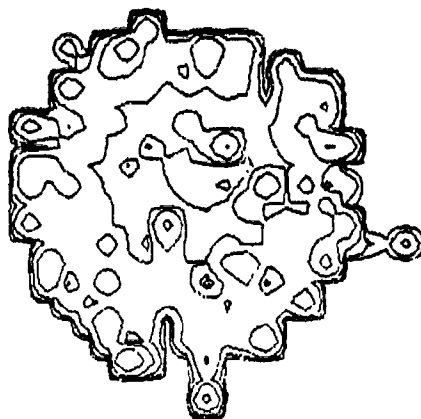
THE UNIVERSITY OF CHICAGO

THE UNIVERSITY OF CHICAGO

10

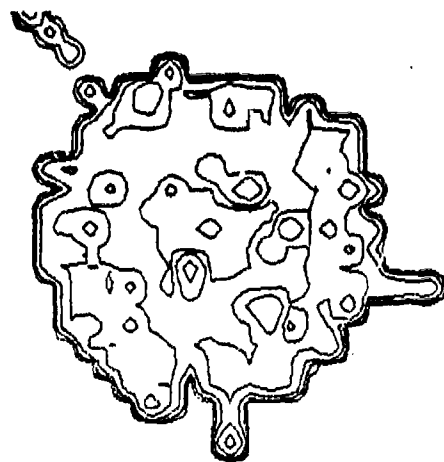
232

HEATON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY SCENARIO ON TIME = 4000.00
TIME 1 TO 20.00 20.00 1 TO 20.00
ALL BODY PARTS ARE
*** ONLY BODY PARTS ARE AND ARE RELEASED TO PLAYERS ***
BODY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)



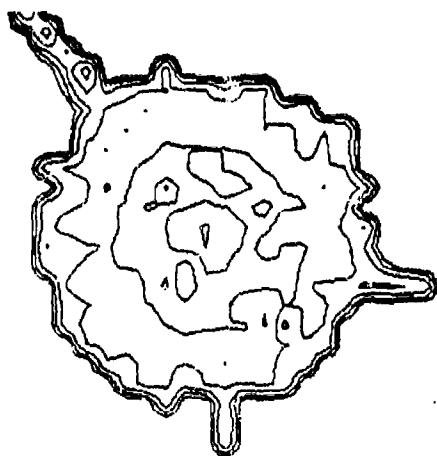
1357913579135791357913579

HEATON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY SCENARIO ON TIME = 4000.00
TIME 1 TO 20.00 20.00 1 TO 20.00
ALL BODY PARTS ARE
*** ONLY BODY PARTS ARE AND ARE RELEASED TO PLAYERS ***
BODY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)



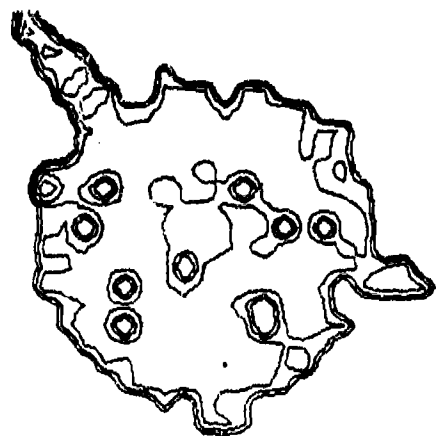
1357913579135791357913579

HEATON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY SCENARIO ON TIME = 4000.00
TIME 1 TO 20.00 20.00 1 TO 20.00
ALL BODY PARTS ARE
*** ONLY BODY PARTS ARE AND ARE RELEASED TO PLAYERS ***
BODY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)



1357913579135791357913579

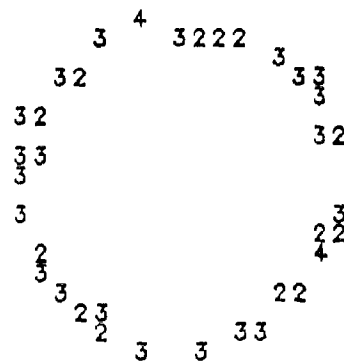
HEATON RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLAY SCENARIO ON TIME = 4000.00
TIME 1 TO 20.00 20.00 1 TO 20.00
ALL BODY PARTS ARE
*** ONLY BODY PARTS ARE AND ARE RELEASED TO PLAYERS ***
BODY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)



1357913579135791357913579

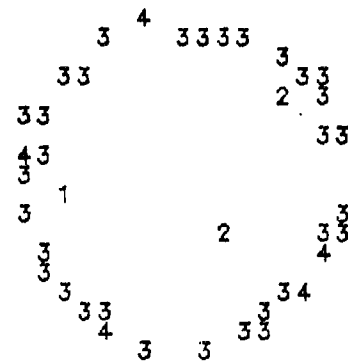
Figure 6-5(1). Heat production rate contour map for ring fire.

WILSON RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASED ON TIME = 0000.00
DATE 1 74 00 000000 1 74 00
ONLY MAP: LETTERS A TO Z ARE A PART OF THE MODEL
ONLY MAP: EVERY OTHER CELL HAS ONE VALUE IN PLAYERS
ONLY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.00)



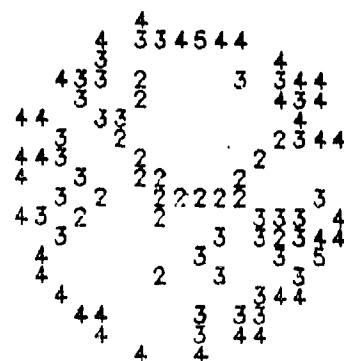
1357913579135791357913579

WILSON RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASED ON TIME = 0000.00
DATE 1 74 00 000000 1 74 00
ONLY MAP: LETTERS A TO Z ARE A PART OF THE MODEL
ONLY MAP: EVERY OTHER CELL HAS ONE VALUE IN PLAYERS
ONLY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.00)



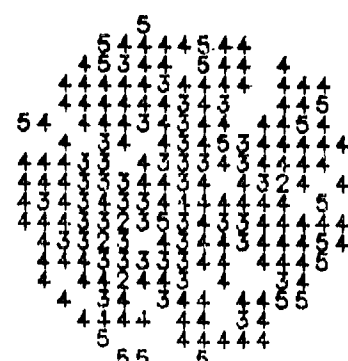
1357913579135791357913579

WILSON RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASED ON TIME = 0000.00
DATE 1 74 00 000000 1 74 00
ONLY MAP: LETTERS A TO Z ARE A PART OF THE MODEL
ONLY MAP: EVERY OTHER CELL HAS ONE VALUE IN PLAYERS
ONLY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.00)



1357913579135791357913579

WILSON RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASED ON TIME = 0000.00
DATE 1 74 00 000000 1 74 00
ONLY MAP: LETTERS A TO Z ARE A PART OF THE MODEL
ONLY MAP: EVERY OTHER CELL HAS ONE VALUE IN PLAYERS
ONLY SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.00)



1357913579135791357913579

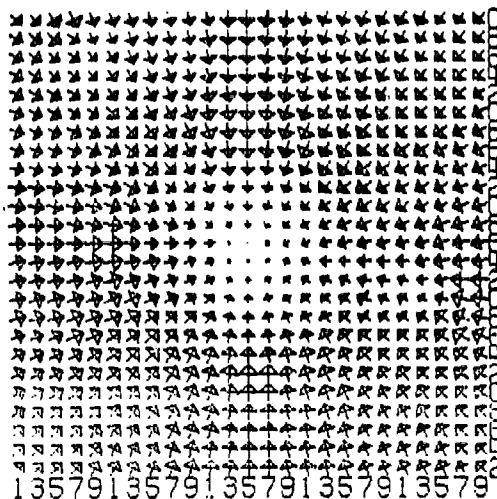
Figure 6-5(j). Cell heat production rate map for ring fire.

33 35 37 39 41 43 45 47 49 51 53 55 57 59 61 63 65 67 69 71 73 75 77 79 81 83 85 87 89 91 93 95 97 99 101 103 105 107 109 111 113 115 117 119 121 123 125 127 129 131 133 135 137 139 141 143 145 147 149 151 153 155 157 159 161 163 165 167 169 171 173 175 177 179 181 183 185 187 189 191 193 195 197 199 201 203 205 207 209 211 213 215 217 219 221 223 225 227 229 231 233 235 237 239 241 243 245 247 249 251 253 255 257 259 261 263 265 267 269 271 273 275 277 279 281 283 285 287 289 291 293 295 297 299 301 303 305 307 309 311 313 315 317 319 321 323 325 327 329 331 333 335 337 339 341 343 345 347 349 351 353 355 357 359 361 363 365 367 369 371 373 375 377 379 381 383 385 387 389 391 393 395 397 399 401 403 405 407 409 411 413 415 417 419 421 423 425 427 429 431 433 435 437 439 441 443 445 447 449 451 453 455 457 459 461 463 465 467 469 471 473 475 477 479 481 483 485 487 489 491 493 495 497 499 501 503 505 507 509 511 513 515 517 519 521 523 525 527 529 531 533 535 537 539 541 543 545 547 549 551 553 555 557 559 561 563 565 567 569 571 573 575 577 579 581 583 585 587 589 591 593 595 597 599 601 603 605 607 609 611 613 615 617 619 621 623 625 627 629 631 633 635 637 639 641 643 645 647 649 651 653 655 657 659 661 663 665 667 669 671 673 675 677 679 681 683 685 687 689 691 693 695 697 699 701 703 705 707 709 711 713 715 717 719 721 723 725 727 729 731 733 735 737 739 741 743 745 747 749 751 753 755 757 759 761 763 765 767 769 771 773 775 777 779 781 783 785 787 789 791 793 795 797 799 801 803 805 807 809 811 813 815 817 819 821 823 825 827 829 831 833 835 837 839 841 843 845 847 849 851 853 855 857 859 861 863 865 867 869 871 873 875 877 879 881 883 885 887 889 891 893 895 897 899 901 903 905 907 909 911 913 915 917 919 921 923 925 927 929 931 933 935 937 939 941 943 945 947 949 951 953 955 957 959 961 963 965 967 969 971 973 975 977 979 981 983 985 987 989 991 993 995 997 999 1001 1003 1005 1007 1009 1011 1013 1015 1017 1019 1021 1023 1025 1027 1029 1031 1033 1035 1037 1039 1041 1043 1045 1047 1049 1051 1053 1055 1057 1059 1061 1063 1065 1067 1069 1071 1073 1075 1077 1079 1081 1083 1085 1087 1089 1091 1093 1095 1097 1099 1101 1103 1105 1107 1109 1111 1113 1115 1117 1119 1121 1123 1125 1127 1129 1131 1133 1135 1137 1139 1141 1143 1145 1147 1149 1151 1153 1155 1157 1159 1161 1163 1165 1167 1169 1171 1173 1175 1177 1179 1181 1183 1185 1187 1189 1191 1193 1195 1197 1199 1201 1203 1205 1207 1209 1211 1213 1215 1217 1219 1221 1223 1225 1227 1229 1231 1233 1235 1237 1239 1241 1243 1245 1247 1249 1251 1253 1255 1257 1259 1261 1263 1265 1267 1269 1271 1273 1275 1277 1279 1281 1283 1285 1287 1289 1291 1293 1295 1297 1299 1301 1303 1305 1307 1309 1311 1313 1315 1317 1319 1321 1323 1325 1327 1329 1331 1333 1335 1337 1339 1341 1343 1345 1347 1349 1351 1353 1355 1357 1359 1361 1363 1365 1367 1369 1371 1373 1375 1377 1379 1381 1383 1385 1387 1389 1391 1393 1395 1397 1399 1401 1403 1405 1407 1409 1411 1413 1415 1417 1419 1421 1423 1425 1427 1429 1431 1433 1435 1437 1439 1441 1443 1445 1447 1449 1451 1453 1455 1457 1459 1461 1463 1465 1467 1469 1471 1473 1475 1477 1479 1481 1483 1485 1487 1489 1491 1493 1495 1497 1499 1501 1503 1505 1507 1509 1511 1513 1515 1517 1519 1521 1523 1525 1527 1529 1531 1533 1535 1537 1539 1541 1543 1545 1547 1549 1551 1553 1555 1557 1559 1561 1563 1565 1567 1569 1571 1573 1575 1577 1579 1581 1583 1585 1587 1589 1591 1593 1595 1597 1599 1601 1603 1605 1607 1609 1611 1613 1615 1617 1619 1621 1623 1625 1627 1629 1631 1633 1635 1637 1639 1641 1643 1645 1647 1649 1651 1653 1655 1657 1659 1661 1663 1665 1667 1669 1671 1673 1675 1677 1679 1681 1683 1685 1687 1689 1691 1693 1695 1697 1699 1701 1703 1705 1707 1709 1711 1713 1715 1717 1719 1721 1723 1725 1727 1729 1731 1733 1735 1737 1739 1741 1743 1745 1747 1749 1751 1753 1755 1757 1759 1761 1763 1765 1767 1769 1771 1773 1775 1777 1779 1781 1783 1785 1787 1789 1791 1793 1795 1797 1799 1801 1803 1805 1807 1809 1811 1813 1815 1817 1819 1821 1823 1825 1827 1829 1831 1833 1835 1837 1839 1841 1843 1845 1847 1849 1851 1853 1855 1857 1859 1861 1863 1865 1867 1869 1871 1873 1875

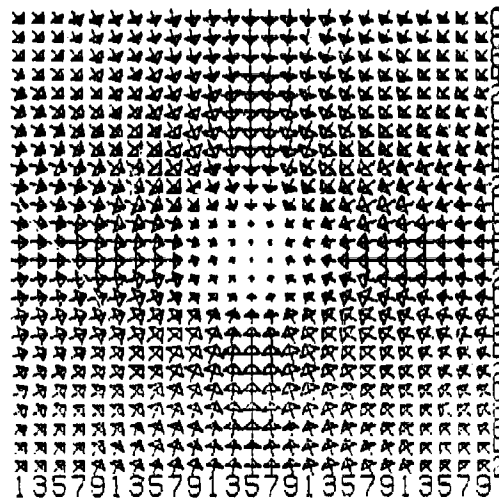
[illegible][illegible]

236

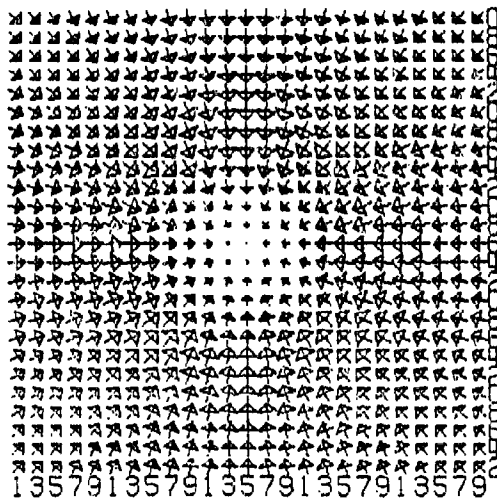
WIND SPEED AND VELOCITY MEASUREMENT = 10.0007



WIND DIRECTION VELOCITY REMARKS - 0-000000



WEEKS FROM 10 YEAR VOLUNTARY PAYMENT PLAN - 8.000000



NON HUMAN MIND VELOCITY HUMANITY - U.S. 1960

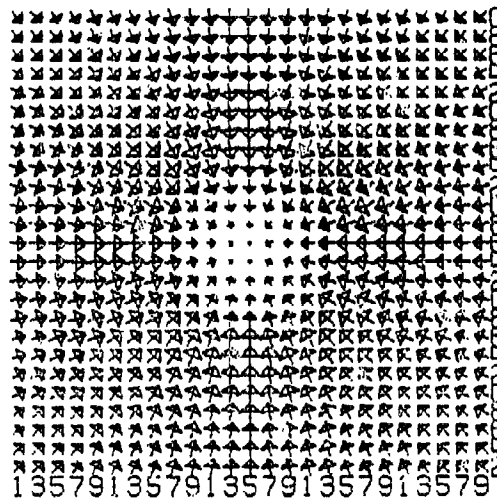


Figure 6-5(m). Wind velocity map for ring fire.

6.6 THREE SMALL FIRES WITH NO AMBIENT WIND

As shown in Figure 6-6, three centrally located 5×5 candidate sets of cells were ignited with probability of ignition of 0.5. Figures 6-6 through 6-6(g) show that none of the fires spread outwardly, although each fire filled in some. The wind velocity maps of Figure 6-6(l) and 6-6(m) show the reason for this. The fire induced wind speeds generated by these fires were high enough to cause only slight contagion and insufficient to cause branding. Since these winds were essentially directed inward toward the center of the three fires, no outward spread was possible. Only inward spread and filling in could have occurred.

```

PLOT SIMULATION TIME = 1848.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2452 48

```

Figure 6-6. Cell state map for three clamp fires.

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2452 40

PLOT SIMULATION TIME = 1250.00 SECONDS
 ROWS 1 TO 50 COLUMNS 1 TO 50

ROW	50
ROW	49
ROW	48
ROW	47
ROW	46
ROW	45
ROW	44
ROW	43
ROW	42
ROW	41
ROW	40
ROW	39
ROW	38
ROW	37
ROW	36
ROW	35
ROW	34
ROW	33
ROW	32
ROW	31
ROW	30
ROW	29
ROW	28
ROW	27
ROW	26
ROW	25
ROW	24
ROW	23
ROW	22
ROW	21
ROW	20
ROW	19
ROW	18
ROW	17
ROW	16
ROW	15
ROW	14
ROW	13
ROW	12
ROW	11
ROW	10
ROW	9
ROW	8
ROW	7
ROW	6
ROW	5
ROW	4
ROW	3
ROW	2
ROW	1

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2449 51

Figure 6-6(a). Cell state map for three clump fires.


```

PLOT SIMULATION TIME = 1754.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2448 52

```

Figure 6-6(b). Cell state map for three clump fires.

```

PLOT SIMULATION TIME = 2/50.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2446 54

```

Figure 6-6(c). Cell state map for three clump fires.

```

PLOT SIMULATION TIME = 4750.00 SECONDS
ROWS 1 TO 52, COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2441 59

```

Figure 6-6(d). Cell state map for three clump fires.

```

PLOT SIMULATION TIME = 0756.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2441 69

```

Figure 6-6(e). Cell state map for three clump fires.

```

PLCT SIMULATION TIME = 10750.0 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18

```

ROW 17
 ROW 16
 ROW 15
 ROW 14
 ROW 13
 ROW 12
 ROW 11
 ROW 10
 ROW 9
 ROW 8
 ROW 7
 ROW 6
 ROW 5
 ROW 4
 ROW 3
 ROW 2
 ROW 1

```

COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2440 60

```

Figure 6-6(f). Cell state map for three clump fires.

```

PLOT SIMULATION TIME = 32750.0 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12

ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2440 67

```

Figure 6-6(g). Cell state map for three clump fires.

MISSION RESEARCH CORPORATION
 UNKNOWN FIRE MODEL
 PLANT SIMULATION TIME = 3000.00
 TIME 1 TO 00.00000 1 TO 00.00000
 WILL NOT STOP THE RUN
 *** ONLY EVERY OTHER WILL BE PLANT IS PLANTING ***
 BEST SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.010)



1357913579135791357913579

MISSION RESEARCH CORPORATION
 UNKNOWN FIRE MODEL
 PLANT SIMULATION TIME = 3000.00
 TIME 1 TO 00.00000 1 TO 00.00000
 WILL NOT STOP THE RUN
 *** ONLY EVERY OTHER WILL BE PLANT IS PLANTING ***
 BEST SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.010)



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MISSION RESEARCH CORPORATION
 UNKNOWN FIRE MODEL
 PLANT SIMULATION TIME = 3000.00
 TIME 1 TO 00.00000 1 TO 00.00000
 WILL NOT STOP THE RUN
 *** ONLY EVERY OTHER WILL BE PLANT IS PLANTING ***
 BEST SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.010)



1357913579135791357913579

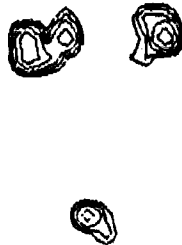
MISSION RESEARCH CORPORATION
 UNKNOWN FIRE MODEL
 PLANT SIMULATION TIME = 3000.00
 TIME 1 TO 00.00000 1 TO 00.00000
 WILL NOT STOP THE RUN
 *** ONLY EVERY OTHER WILL BE PLANT IS PLANTING ***
 BEST SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.010)



1357913579135791357913579

Figure 6-6(h). Heat production rate contour for three clump fires.

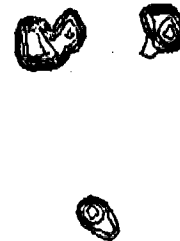
MISSION RESEARCH CORPORATION
UNBURN FINE MODEL
PLAY REPEATS ON TIME = 4700.00 RECORD
TIME 1 TO 10 10 10 10 10 10
WALL COPY OFFERS 100
*** ONLY COPY OFFERS 100 AND 100 ARE PLAYED ***
WALL COPY IS LUNARITIC 100 TO 1 0-1.00 0-1.00 1



MISSION RESEARCH CORPORATION

1357913579135791357913579

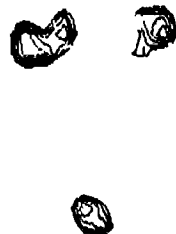
MISSION RESEARCH CORPORATION
UNBURN FINE MODEL
PLAY REPEATS ON TIME = 4700.00 RECORD
TIME 1 TO 10 10 10 10 10 10
WALL COPY OFFERS 100
*** ONLY COPY OFFERS 100 AND 100 ARE PLAYED ***
WALL COPY IS LUNARITIC 100 TO 1 0-1.00 0-1.00 1



MISSION RESEARCH CORPORATION

1357913579135791357913579

MISSION RESEARCH CORPORATION
UNBURN FINE MODEL
PLAY REPEATS ON TIME = 4700.00 RECORD
TIME 1 TO 10 10 10 10 10 10
WALL COPY OFFERS 100
*** ONLY COPY OFFERS 100 AND 100 ARE PLAYED ***
WALL COPY IS LUNARITIC 100 TO 1 0-1.00 0-1.00 1



MISSION RESEARCH CORPORATION

1357913579135791357913579

MISSION RESEARCH CORPORATION
UNBURN FINE MODEL
PLAY REPEATS ON TIME = 4700.00 RECORD
TIME 1 TO 10 10 10 10 10 10
WALL COPY OFFERS 100
*** ONLY COPY OFFERS 100 AND 100 ARE PLAYED ***
WALL COPY IS LUNARITIC 100 TO 1 0-1.00 0-1.00 1



MISSION RESEARCH CORPORATION

1357913579135791357913579

Figure 6-6(i). Heat production rate contour for three clump fires.

MISSION RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLATE REVEALATION TIME = 1000.00 SECONDS
DATE 1 TO 100.000000 1 TO 100.000000
BODY SIZE: LETTERS 1 TO 10 ARE 10 TIMES OF BODY VALUE
ONLY BODY OTHERS WILL BE AND OTHERS IN PLATES
BODY SIZE (10 LARGEST) SIZE 10 (10-1.00 10-1.00)

222 32
323 332
323 332

22

135791357913579135791357913579

MISSION RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLATE REVEALATION TIME = 1000.00 SECONDS
DATE 1 TO 100.000000 1 TO 100.000000
BODY SIZE: LETTERS 1 TO 10 ARE 10 TIMES OF BODY VALUE
ONLY BODY OTHERS WILL BE AND OTHERS IN PLATES
BODY SIZE (10 LARGEST) SIZE 10 (10-1.00 10-1.00)

433 333
434 334
433 333

43

135791357913579135791357913579

MISSION RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLATE REVEALATION TIME = 1000.00 SECONDS
DATE 1 TO 100.000000 1 TO 100.000000
BODY SIZE: LETTERS 1 TO 10 ARE 10 TIMES OF BODY VALUE
ONLY BODY OTHERS WILL BE AND OTHERS IN PLATES
BODY SIZE (10 LARGEST) SIZE 10 (10-1.00 10-1.00)

333 333
334 334
333 333

33

135791357913579135791357913579

MISSION RESEARCH CORPORATION
UNIFORM FIRE MODEL
PLATE REVEALATION TIME = 1000.00 SECONDS
DATE 1 TO 100.000000 1 TO 100.000000
BODY SIZE: LETTERS 1 TO 10 ARE 10 TIMES OF BODY VALUE
ONLY BODY OTHERS WILL BE AND OTHERS IN PLATES
BODY SIZE (10 LARGEST) SIZE 10 (10-1.00 10-1.00)

433 444
434 444
433 444

433

135791357913579135791357913579

Figure 6-6(j). Cell heat production rate map for three clump fires.

[illegible]

444 444
443 344

43
34

1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL

PLAT INFORMATION ON TIME IS SEVERAL SECONDS
DOES 1 TO 100.000000 1 TO 10
JUST ONE LETTERS TO 0 AND A POINT OF ONE VALUE
NAME GALT FROM: SINCE ONE, ONE COLUMN IS PLATTER NAME
BEST WORLD IS LUNARATIC NAME 0 (0-1,2 0-1,2)

4 4 4
4 4 4

44
44

1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FINE MIXED.
HEAT RELEASED IN THE A STRE. DO. SECTION
PART 1 TO 10. COLUMN 1 TO 10.
GIVE ME: LITTLE 1 TO 10 AND 10 AND 10 AND 10 AND 10
GIVE ME: ONLY EVERY OTHER ONE AND ONE AND ONE AND ONE AND ONE AND ONE
GIVE ME: IS A BOMBING STRIKE TO 10-10-10 10-10-10 10-10-10

444 444

44

1357913579135791357913579

**NESCOM RESEARCH CORPORATION
URBAN FIRE MODEL**

PLAN IN PLACE ON TAP: IS INPUT D **BACKLOG**
DAYS 1 TO 97, **COLUMNS** 1 TO 96,
NOTIFY LETTERS C TO E AND S RANGE OF SORT VALUES
SOURCE ONLY OVER OTHER CALL FOR AND COLUMN TO PLATED AREA
WHAT SYMBOL IS (SUBMITTING) FORM I O U DEL. RU DEL. FIN

$\begin{array}{ccc} & 4 & \\ 4 & 4 & 4 \\ 4 & 4 & 4 \end{array}$

44
44

1357913579135791357913579

Figure 6-6(k). Cell heat production rate map for three clump fires.

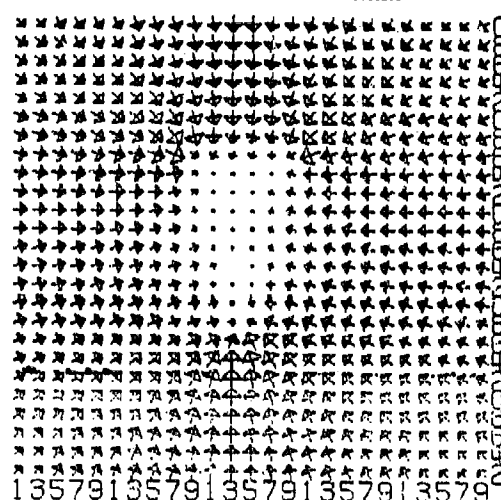
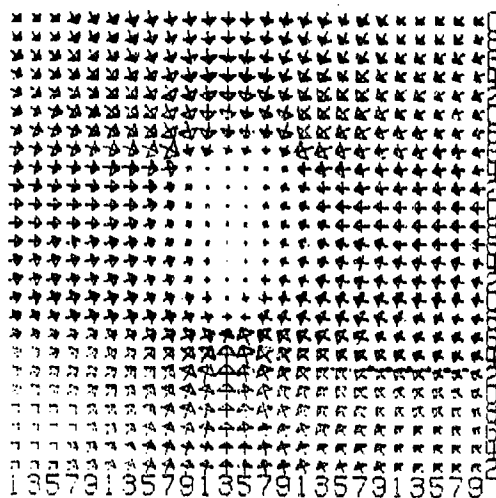
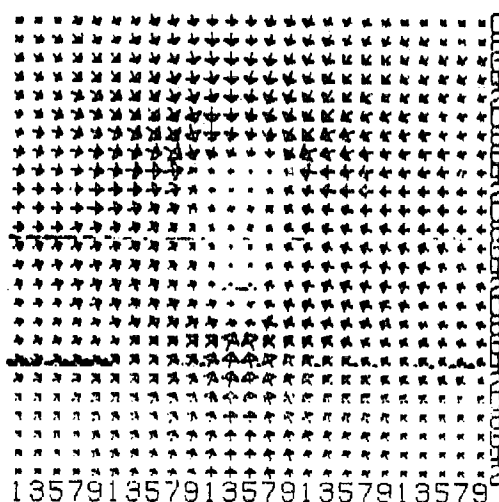
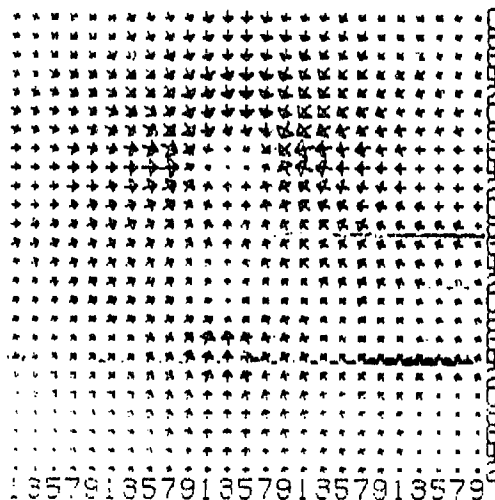


Figure 6-6(1). Wind velocity map for three clump fires.

6.7 SMALL AREA FIRE WITH AMBIENT WINDS

As shown in Figure 6-7, a 10×10 cell candidate set of cells in the lower left corner of the urban area was ignited with probability of ignition of 0.1. This location was chosen because the effects of wind velocities directed from the lower left to the upper right at speeds of 10, 20, 30, 40, and 50 m/s, were examined and are shown in Figures 6-7, 6-8, 6-9, 6-10, and 6-11, respectively.

These cases depict the sensitivity of propagation to local wind velocity. There are also the first cases in which significant collections of cells are seen to reach burnout. The effects of this are clearly shown in all of the maps at 32,750 seconds, but are best seen in the heat production rate contour maps.

```

PLOT SIMULATION TIME = 1040.00 SECONDS
ROWS 1 TO 50. COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2491 9

```

Figure 6-7. Cell state map for small area fire with ambient wind = 10 m/s.

PLOT SIMULATION TIME = 1250.0 SECONDS
 ROWS 1 TO 50. COLUMNS 1 TO 50.

ROW	47
ROW	46
ROW	45
ROW	44
ROW	43
ROW	42
ROW	41
ROW	40
ROW	39
ROW	38
ROW	37
ROW	36
ROW	35
ROW	34
ROW	33
ROW	32
ROW	31
ROW	30
ROW	29
ROW	28
ROW	27
ROW	26
ROW	25
ROW	24
ROW	23
ROW	22
ROW	21
ROW	20
ROW	19
ROW	18
ROW	17
ROW	16
ROW	15
ROW	14
ROW	13
ROW	12
ROW	11
ROW	10
ROW	9
ROW	8
ROW	7
ROW	6
ROW	5
ROW	4
ROW	3
ROW	2
ROW	1

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2451 9 0

Figure 6-7(a). Cell state map for small area fire with ambient wind
 = 10 m/s.

PLUT SIMULATION TIME = 1750.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50.

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2487 13

Figure 6-7(b). Cell state map for small area fire with ambient wind = 10 m/s.

PLOT SIMULATION TIME = 2750.00 SECONDS
 ROWS L TO 50, COLUMNS 1 TO 60

ROW	50
ROW	49
ROW	48
ROW	47
ROW	46
ROW	45
ROW	44
ROW	43
ROW	42
ROW	41
ROW	40
ROW	39
ROW	38
ROW	37
ROW	36

ROW	35
ROW	34
ROW	33
ROW	32
ROW	31
ROW	30
ROW	29
ROW	28
ROW	27
ROW	26
ROW	25
ROW	24
ROW	23
ROW	22
ROW	21
ROW	20
ROW	19
ROW	18
ROW	17
ROW	16
ROW	15
ROW	14
ROW	13
ROW	12
ROW	11
ROW	10
ROW	9
ROW	8
ROW	7
ROW	6
ROW	5
ROW	4
ROW	3
ROW	2
ROW	1

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2461 19

Figure 6-7(c). Cell state map for small area fire with ambient wind = 10 m/s.

PLOT SIMULATION TIME = 4750.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50

ROW	50
ROW	49
ROW	48
ROW	47
ROW	46
ROW	45
ROW	44
ROW	43
ROW	42
ROW	41
ROW	40
ROW	39
ROW	38
ROW	37
ROW	36
ROW	35
ROW	34
ROW	33
ROW	32
ROW	31
ROW	30

ROW	29
ROW	28
ROW	27
ROW	26
ROW	25
ROW	24
ROW	23
ROW	22
ROW	21
ROW	20
ROW	19
ROW	18
ROW	17
ROW	16
ROW	15
ROW	14
ROW	13
ROW	12
ROW	11
ROW	10
ROW	9
ROW	8
ROW	7
ROW	6
ROW	5
ROW	4
ROW	3
ROW	2
ROW	1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2459 41

Figure 6-7(d). Cell state map for small area fire with ambient wind = 10 m/s.

```

PLOT SIMULATION TIME = 8750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24

```

```

ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2438 62

```

Figure 6-7(e). Cell state map for small area fire with ambient wind = 10 m/s.

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2449 92

PLOT SIMULATION TIME = 10750.0 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50

ROW	50	
ROW	49	
ROW	48	
ROW	47	
ROW	46	
ROW	45	
ROW	44	
ROW	43	
ROW	42	
ROW	41	
ROW	40	
ROW	39	
ROW	38	
ROW	37	
ROW	36	
ROW	35	
ROW	34	
ROW	33	
ROW	32	
ROW	31	
ROW	30	
ROW	29	
ROW	28	
ROW	27	
ROW	26	
ROW	25	
ROW	24	
ROW	23	
ROW	22	
ROW	21	..
ROW	20	...
ROW	19	....
ROW	18	.....

ROW	17	....
ROW	16	.....
ROW	15	.....
ROW	14	.....
ROW	13	.....
ROW	12	.....
ROW	11	.....
ROW	10	.....
ROW	9	.....
ROW	8	....
ROW	7	...
ROW	6	..
ROW	5	
ROW	4	
ROW	3	
ROW	2	
ROW	1	

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2449 91

Figure 6-7(f). Cell state map for small area fire with ambient wind = 10 m/s.

```

PLOT SIMULATION TIME = 32756.0 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12

```

```

ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

```

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2363 143

Figure 6-7(g). Cell state map for small area fire with ambient wind = 10 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 2000.00 SECONDS
PLOT 1 TO 100.00 RELEASE 1 TO 100.00
CELL NOT CONTAINING HOT
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
HOT SCALE IS LOGARITHMIC SCALE (0-1.0E 0-1.0E 1)

MISSION RESEARCH CORPORATION

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 1700.00 SECONDS
PLOT 1 TO 100.00 RELEASE 1 TO 100.00
CELL NOT CONTAINING HOT
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
HOT SCALE IS LOGARITHMIC SCALE (0-1.0E 0-1.0E 1)

MISSION RESEARCH CORPORATION

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 2000.00 SECONDS
PLOT 1 TO 100.00 RELEASE 1 TO 100.00
CELL NOT CONTAINING HOT
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
HOT SCALE IS LOGARITHMIC SCALE (0-1.0E 0-1.0E 1)

MISSION RESEARCH CORPORATION

135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 1700.00 SECONDS
PLOT 1 TO 100.00 RELEASE 1 TO 100.00
CELL NOT CONTAINING HOT
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
HOT SCALE IS LOGARITHMIC SCALE (0-1.0E 0-1.0E 1)

MISSION RESEARCH CORPORATION

135791357913579135791357913579

Figure 6-7(h). Heat production rate contour for small area fire with ambient wind = 10 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 4790.00 SECONDS
CELL NOT OUTSIDE MAP
*** ONLY EVERY OTHER CELL NOW AND BELONG IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC SCALE 10 (0-1.25 0-1.25)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 5790.00 SECONDS
CELL NOT OUTSIDE MAP
*** ONLY EVERY OTHER CELL NOW AND BELONG IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC SCALE 10 (0-1.25 0-1.25)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1790.00 SECONDS
CELL NOT OUTSIDE MAP
*** ONLY EVERY OTHER CELL NOW AND BELONG IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC SCALE 10 (0-1.25 0-1.25)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 2790.00 SECONDS
CELL NOT OUTSIDE MAP
*** ONLY EVERY OTHER CELL NOW AND BELONG IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC SCALE 10 (0-1.25 0-1.25)



1357913579135791357913579

Figure 6-7(1). Heat production rate contour for small area fire with ambient wind = 10 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY REPEAT ON TIME = 3000.00 RECHARGE
DATA 1 TO 99. COLUMN 1 TO 99.
ONLY SPOT LETTERS 0 TO 9 ARE A PART OF SPOT VALUE
ONLY SPOT OTHER CALLS ARE ARE ARE ARE TO PLAYERS
SPOT SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

3
3
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY REPEAT ON TIME = 3700.00 RECHARGE
DATA 1 TO 99. COLUMN 1 TO 99.
ONLY SPOT LETTERS 0 TO 9 ARE A PART OF SPOT VALUE
ONLY SPOT OTHER CALLS ARE ARE ARE ARE TO PLAYERS
SPOT SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

3 4
4
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY REPEAT ON TIME = 3000.00 RECHARGE
DATA 1 TO 99. COLUMN 1 TO 99.
ONLY SPOT LETTERS 0 TO 9 ARE A PART OF SPOT VALUE
ONLY SPOT OTHER CALLS ARE ARE ARE ARE TO PLAYERS
SPOT SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

3
3
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY REPEAT ON TIME = 3700.00 RECHARGE
DATA 1 TO 99. COLUMN 1 TO 99.
ONLY SPOT LETTERS 0 TO 9 ARE A PART OF SPOT VALUE
ONLY SPOT OTHER CALLS ARE ARE ARE ARE TO PLAYERS
SPOT SCALE IS LOGARITHMIC SCALE 10 (0-1.00 0-1.010)

2 2
4 4
3 4
135791357913579135791357913579

Figure 6-7(j). Cell heat production rate map for small area fire with ambient wind = 10 m/s.

3
4 4 3
4 4 2
4 4
4

COULDS: VULDER V. COULDS V. LOREN N. NUGSEN

4
4 4
4 4 4
4 4 4 4
4 4 4 4 4

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4 3
4 4
4 4 4
4 4 4 4
4 4 4 4 4
4 4 4 4 4 4
4 4 4 4 4 4 4
4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4
4 4 4 4 4 4 4 4 4 4

[illegible][illegible]

THE UNIVERSITY OF CHICAGO

[illegible][illegible][illegible]

一	二	三	四	五	六	七	八	九	十
十一	十二	十三	十四	十五	十六	十七	十八	十九	二十
二十一	二十二	二十三	二十四	二十五	二十六	二十七	二十八	二十九	三十
三十一	三十二	三十三	三十四	三十五	三十六	三十七	三十八	三十九	四十
四十一	四十二	四十三	四十四	四十五	四十六	四十七	四十八	四十九	五十
五十一	五十二	五十三	五十四	五十五	五十六	五十七	五十八	五十九	六十
六十一	六十二	六十三	六十四	六十五	六十六	六十七	六十八	六十九	七十
七十一	七十二	七十三	七十四	七十五	七十六	七十七	七十八	七十九	八十
八十一	八十二	八十三	八十四	八十五	八十六	八十七	八十八	八十九	九十
九十一	九十二	九十三	九十四	九十五	九十六	九十七	九十八	九十九	一百

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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	8												

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	5

[illegible]

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PLOT SIMULATION TIME IN 1000.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2491

```

Figure 5-8. Cell state map for small area fire, ambient wind = 20 m/s.

PLUT SIMULATION TIME = 1250.00 SECONDS

ROWS 1 TO 50, COLUMNS 1 TO 50

ROW 50
ROW 49
ROW 48

ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2490 10

Figure 6-8(a). Cell state map for small area fire, ambient wind = 20 m/s.

PLOT SIMULATION TIME = 1752.00 SECONDS

ROWS 1 TO 52, COLUMNS 1 TO 54

ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1

COLUMNS 1234567890123456789012345678901234567890

NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2481 12

Figure 6-8(b). Cell state map for small area fire, ambient wind = 20 m/s.

```

PLOT SIMULATION TIME = 2750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2443 57

```

Figure 6-8(c). Cell state map for small area fire, ambient wind = 20 m/s.

```

PLOT SIMULATION TIME = 4752.04 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30

ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2373 127

```

Figure 6-8(d). Cell state map for small area fire, ambient wind = 20 m/s.

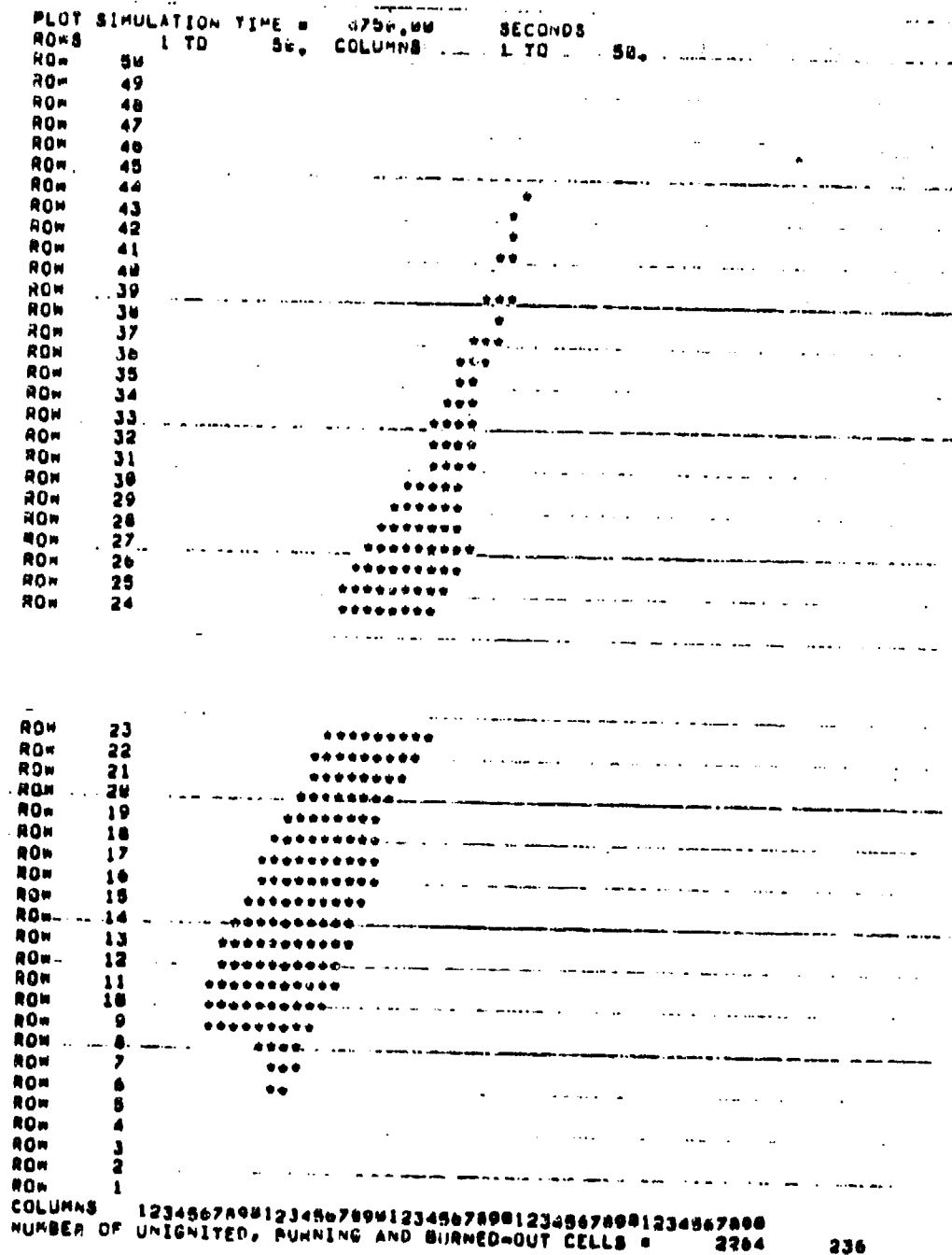


Figure 6-8(e). Cell state map for small area fire, ambient wind = 20 m/s.



Figure 6-8(f). Cell state map for small area fire, ambient wind = 20 m/s.

```

PLOT SIMULATION TIME = 32750.0 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50 .....
ROW 49 .....
ROW 48 .....
ROW 47 .....
ROW 46 .....
ROW 45 .....
ROW 44 .....
ROW 43 .....
ROW 42 .....
ROW 41 .....
ROW 40 .....
ROW 39 .....
ROW 38 .....
ROW 37 .....
ROW 36 .....
ROW 35 .....
ROW 34 .....
ROW 33 .....
ROW 32 .....
ROW 31 .....
ROW 30 .....
ROW 29 .....
ROW 28 .....
ROW 27 .....
ROW 26 .....
ROW 25 .....
ROW 24 .....
ROW 23 .....
ROW 22 .....
ROW 21 .....
ROW 20 .....
ROW 19 .....
ROW 18 .....
ROW 17 .....
ROW 16 .....
ROW 15 .....
ROW 14 .....
ROW 13 .....
ROW 12 .....

ROW 11 .....
ROW 10 .....
ROW 9 .....
ROW 8 .....
ROW 7 .....
ROW 6 .....
ROW 5 .....
ROW 4 .....
ROW 3 .....
ROW 2 .....
ROW 1 .....

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2020 300 11

```

Figure 6-8(g). Cell state map for area small fire, ambient wind = 20 m/s.

MISSION RESEARCH CORPORATION
UNDER FIRE MODEL
PLAY SIMULATION TIME = 1000.00 SECONDS
TIME 1 TO 1000.00 SECONDS 1 TO 1000.00
CELL NOT CONTROLLED
*** ONLY EVERY OTHER CELL HAS AN OUTLINE IS PLAYED ***
SHOT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

MISSION RESEARCH CORPORATION
UNDER FIRE MODEL
PLAY SIMULATION TIME = 1000.00 SECONDS
TIME 1 TO 1000.00 SECONDS 1 TO 1000.00
CELL NOT CONTROLLED
*** ONLY EVERY OTHER CELL HAS AN OUTLINE IS PLAYED ***
SHOT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

1357913579135791357913579

1357913579135791357913579

MISSION RESEARCH CORPORATION
UNDER FIRE MODEL
PLAY SIMULATION TIME = 1700.00 SECONDS
TIME 1 TO 1700.00 SECONDS 1 TO 1700.00
CELL NOT CONTROLLED
*** ONLY EVERY OTHER CELL HAS AN OUTLINE IS PLAYED ***
SHOT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

MISSION RESEARCH CORPORATION
UNDER FIRE MODEL
PLAY SIMULATION TIME = 1700.00 SECONDS
TIME 1 TO 1700.00 SECONDS 1 TO 1700.00
CELL NOT CONTROLLED
*** ONLY EVERY OTHER CELL HAS AN OUTLINE IS PLAYED ***
SHOT SCALE IS LOGARITHMIC SCALE IS (0-1.00 0-1.00)

1357913579135791357913579

1357913579135791357913579

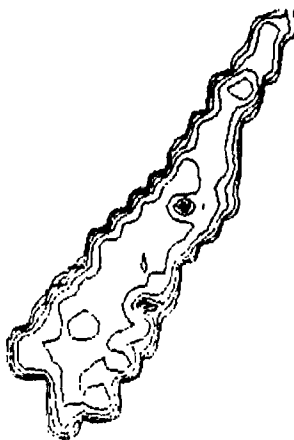
Figure 6-8(h). Heat production rate contour for small area fire,
ambient wind = 20 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 4700.00 SECONDS
RMS 1 TO 00. RELEASE 1 TO 00
CELL NOT CONTAINING 000
*** ONLY EVERY OTHER CELL NOW AND RELEASE IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC TYPE (0 (0-1.0) 0-1.010)



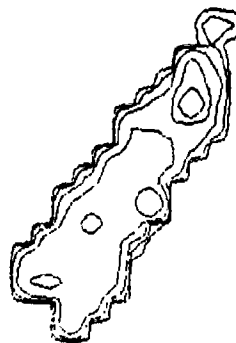
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 4700.00 SECONDS
RMS 1 TO 00. RELEASE 1 TO 00
CELL NOT CONTAINING 000
*** ONLY EVERY OTHER CELL NOW AND RELEASE IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC TYPE (0 (0-1.0) 0-1.010)



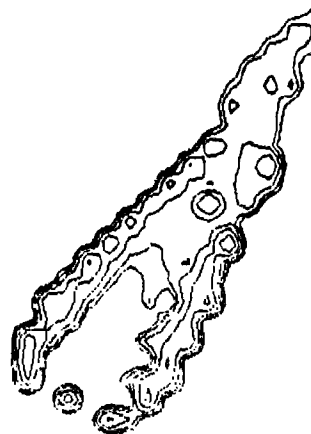
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 4700.00 SECONDS
RMS 1 TO 00. RELEASE 1 TO 00
CELL NOT CONTAINING 000
*** ONLY EVERY OTHER CELL NOW AND RELEASE IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC TYPE (0 (0-1.0) 0-1.010)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELEASE ON TIME = 4700.00 SECONDS
RMS 1 TO 00. RELEASE 1 TO 00
CELL NOT CONTAINING 000
*** ONLY EVERY OTHER CELL NOW AND RELEASE IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC TYPE (0 (0-1.0) 0-1.010)



1357913579135791357913579

Figure 6-8(1). Heat production rate contour for small area fire,
ambient wind = 20 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3000.00 SECONDS
ROWS 1 TO 90, COLUMNS 1 TO 90
ONLY MAP: LETTERS A TO Z ARE A MAP OF CITY PLACES
ONLY MAP: OTHER CELL ARE AND COLUMN IS PLATTED
ONLY SCALE IS LOGARITHMIC BASE 10 (0=1.E5 9=1.E10)

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3000.00 SECONDS
ROWS 1 TO 90, COLUMNS 1 TO 90
ONLY MAP: LETTERS A TO Z ARE A MAP OF CITY PLACES
ONLY MAP: OTHER CELL ARE AND COLUMN IS PLATTED
ONLY SCALE IS LOGARITHMIC BASE 10 (0=1.E5 9=1.E10)

4
5
135791357913579135791357913579

4
4
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3700.00 SECONDS
ROWS 1 TO 90, COLUMNS 1 TO 90
ONLY MAP: LETTERS A TO Z ARE A MAP OF CITY PLACES
ONLY MAP: OTHER CELL ARE AND COLUMN IS PLATTED
ONLY SCALE IS LOGARITHMIC BASE 10 (0=1.E5 9=1.E10)

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 3700.00 SECONDS
ROWS 1 TO 90, COLUMNS 1 TO 90
ONLY MAP: LETTERS A TO Z ARE A MAP OF CITY PLACES
ONLY MAP: OTHER CELL ARE AND COLUMN IS PLATTED
ONLY SCALE IS LOGARITHMIC BASE 10 (0=1.E5 9=1.E10)

4
4
135791357913579135791357913579

43
34
4 4
34
4
135791357913579135791357913579

Figure 6-8(j). Cell production rate map for small area fire,
ambient wind = 20 m/s.

[illegible]

COOPERATIVE MEMBERSHIP

0
1
2
3
4
5
6
7
8
9
A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z

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A fractal-like pattern of the number 4, resembling a Sierpinski triangle, with a central '5'.

ONLINE COURSE

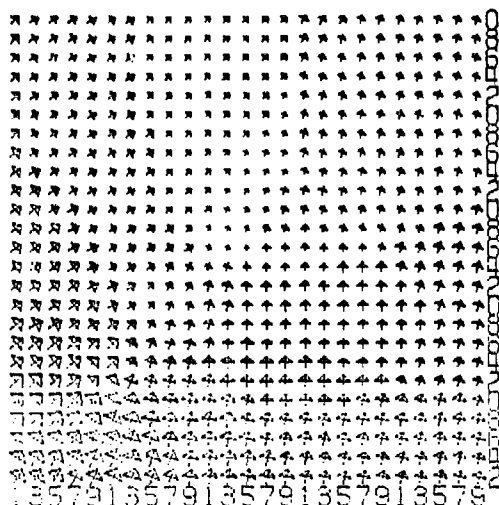
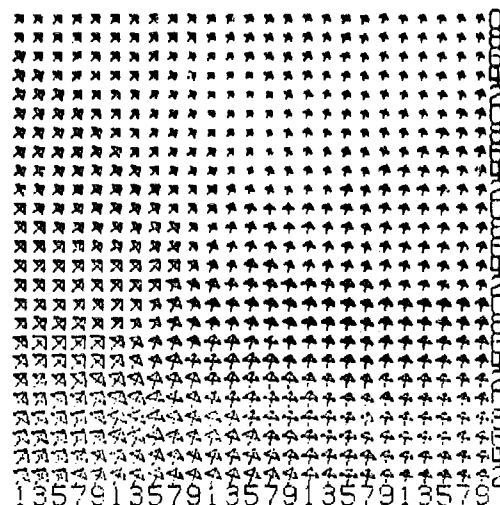
• 279

[illegible]

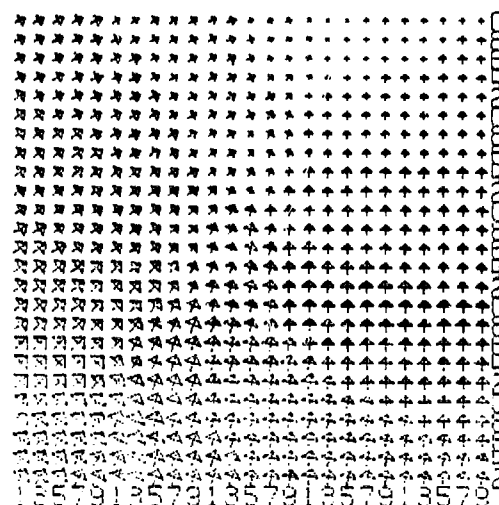
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100

280

PLANT IN RELATION TO TIME -- 4700.00 MECHANISM
 FROM 1 TO 94. CALIBRATION 1 TO 94.
 ALL HIND VELOCITY AND HIND PHOTO IN STRUCTURE OF HIND.
 FROM 010 TO 0000000000 TO TWO HIND SPIN
 -- ALL EVERY OTHER CELL AND CALIBRATION OF PLANT
 HIND HIND VELOCITY HINDTIME -- 01.0000

[illegible]

PLANT RELOCATION TIME = 2.0000 D HOURS
 0000 1 TO 00. 000000 1 TO 00.
 CELL NAME VELOCITY MAP: WINDS FROM 10 DEGREES TO 100.
 Since size is proportional to the wind speed
 each level over ground cell size and column is plotted
 MAXIMUM WIND VELOCITY MAGNITUDE = 00.1007



PLAY RELEASED ON TIME - IMPROVED MATCHING
 1 TO 00. 1 TO 00.
 WILL SHOW VELOCITY AND POSITION DATA ON SECTION OF ROAD.
 APPROX 1/2 TO 3/4 MILE TO THE ROAD OPEN
 ONLY SHOW OTHER CALL AND SHOW OTHER PLAYING
 VELOCITY AND POSITION DATA - 1/2 MILE



281

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PLOT SIMULATION TIME = 1440.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2491 9

```

Figure 6-9. Cell state map for small area fire, ambient wind = 30 m/s.

```

PLOT SIMULATION TIME = 1254.84 SECONDS
ROWS 1 TO 54, COLUMNS 1 TO 50,
ROW 54
ROW 49
ROW 48

ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2489 11

```

Figure 6-9(a). Cell state map for small area fire, ambient wind = 30 m/s.

```

PLOT SIMULATION TIME = 1750.00 SECONDS
ROWS 1 TO 54 COLUMNS 1 TO 54
ROW 53
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42

ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36
ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2479 30

```

Figure 6-9(b) Cell state map for small area fire, ambient wind = 30 m/s.

```

PLOT SIMULATION TIME = 2750.00 SECONDS
ROWS 1 TO 50 COLUMNS 1 TO 50
ROW 50
ROW 49
ROW 48
ROW 47
ROW 46
ROW 45
ROW 44
ROW 43
ROW 42
ROW 41
ROW 40
ROW 39
ROW 38
ROW 37
ROW 36

ROW 35
ROW 34
ROW 33
ROW 32
ROW 31
ROW 30
ROW 29
ROW 28
ROW 27
ROW 26
ROW 25
ROW 24
ROW 23
ROW 22
ROW 21
ROW 20
ROW 19
ROW 18
ROW 17
ROW 16
ROW 15
ROW 14
ROW 13
ROW 12
ROW 11
ROW 10
ROW 9
ROW 8
ROW 7
ROW 6
ROW 5
ROW 4
ROW 3
ROW 2
ROW 1
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2415 85

```

Figure 6-9(c). Cell state map for small area fire, ambient wind = 30 m/s

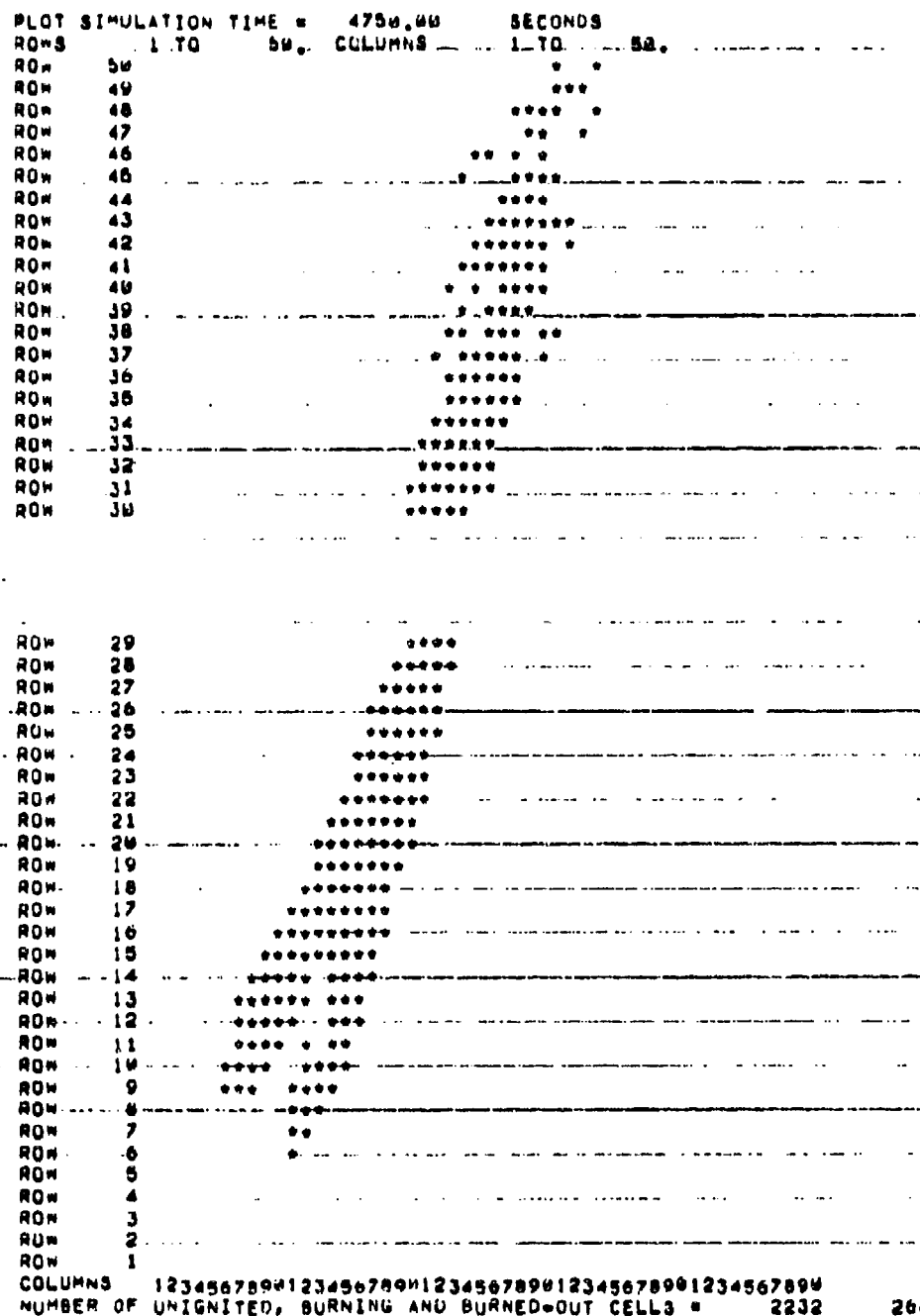


Figure 6-9(d). Cell state map for small area fire, ambient wind = 30 m/s.

```

PLOT SIMULATION TIME = 4750.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50 *****
ROW 49 *****
ROW 48 *****
ROW 47 *****
ROW 46 *****
ROW 45 *****
ROW 44 *****
ROW 43 *****
ROW 42 *****
ROW 41 *****
ROW 40 *****
ROW 39 *****
ROW 38 *****
ROW 37 *****
ROW 36 *****
ROW 35 *****
ROW 34 *****
ROW 33 *****
ROW 32 *****
ROW 31 *****
ROW 30 *****
ROW 29 *****
ROW 28 *****
ROW 27 *****
ROW 26 *****
ROW 25 *****
ROW 24 *****

ROW 23 *****
ROW 22 *****
ROW 21 *****
ROW 20 *****
ROW 19 *****
ROW 18 *****
ROW 17 *****
ROW 16 *****
ROW 15 *****
ROW 14 *****
ROW 13 *****
ROW 12 *****
ROW 11 *****
ROW 10 *****
ROW 9 *****
ROW 8 *****
ROW 7 *****
ROW 6 *****
ROW 5 *****
ROW 4 *****
ROW 3 *****
ROW 2 *****
ROW 1 *****
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2000 420

```

Figure 6-9(e). Cell state map for small area fire, ambient wind = 30 m/s.

```

PLOT SIMULATION TIME = 10754.0 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50,
ROW 50 *****
ROW 49 *****
ROW 48 *****
ROW 47 *****
ROW 46 *****
ROW 45 *****
ROW 44 *****
ROW 43 *****
ROW 42 *****
ROW 41 *****
ROW 40 *****
ROW 39 *****
ROW 38 *****
ROW 37 *****
ROW 36 *****
ROW 35 *****
ROW 34 *****
ROW 33 *****
ROW 32 *****
ROW 31 *****
ROW 30 *****
ROW 29 *****
ROW 28 *****
ROW 27 *****
ROW 26 *****
ROW 25 *****
ROW 24 *****
ROW 23 *****
ROW 22 *****
ROW 21 *****
ROW 20 *****
ROW 19 *****
ROW 18 *****

ROW 17 *****
ROW 16 *****
ROW 15 *****
ROW 14 *****
ROW 13 *****
ROW 12 *****
ROW 11 *****
ROW 10 *****
ROW 9 *****
ROW 8 *****
ROW 7 *****
ROW 6 *****
ROW 5 *****
ROW 4 *****
ROW 3 *****
ROW 2 *****
ROW 1 *****
COLUMNS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1903 561 1

```

Figure 6-9(f). Cell state map for small area fire, ambient wind = 30 m/s.


```

PLOT SIMULATION TIME = 3275.00 SECONDS
ROWS 1 TO 50, COLUMNS 1 TO 50.
ROW 50 .....
ROW 49 .....
ROW 48 .....
ROW 47 .....
ROW 46 .....
ROW 45 .....
ROW 44 .....
ROW 43 .....
ROW 42 .....
ROW 41 .....
ROW 40 .....
ROW 39 .....
ROW 38 .....
ROW 37 .....
ROW 36 .....
ROW 35 .....
ROW 34 .....
ROW 33 .....
ROW 32 .....
ROW 31 .....
ROW 30 .....
ROW 29 .....
ROW 28 .....
ROW 27 .....
ROW 26 .....
ROW 25 .....
ROW 24 .....
ROW 23 .....
ROW 22 .....
ROW 21 .....
ROW 20 .....
ROW 19 .....
ROW 18 .....
ROW 17 .....
ROW 16 .....
ROW 15 .....
ROW 14 .....
ROW 13 .....
ROW 12 .....

ROW 11 *RRRRRRRRRRRRRRR*
ROW 10 RRRRRRRRRRRRRR*
ROW 9 RRRRRRRRRRRRRR*
ROW 8 .....
ROW 7 .....
ROW 6 .....
ROW 5 .....
ROW 4 .....
ROW 3 .....
ROW 2 .....
ROW 1 .....

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1662 521 29

```

Figure 6-9(g). Cell state map for small area fire, ambient wind = 30 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PDR 1 TO 99 COLUMNS 1 TO 99
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
GUST SCALE IS LOGARITHMIC RANGE 10 (0-1.25 0-1.25)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PDR 1 TO 99 COLUMNS 1 TO 99
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
GUST SCALE IS LOGARITHMIC RANGE 10 (0-1.25 0-1.25)



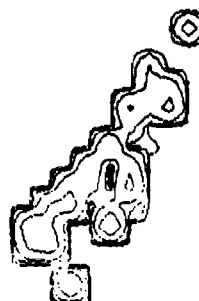
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
PDR 1 TO 99 COLUMNS 1 TO 99
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
GUST SCALE IS LOGARITHMIC RANGE 10 (0-1.25 0-1.25)



1357913579135791357913579

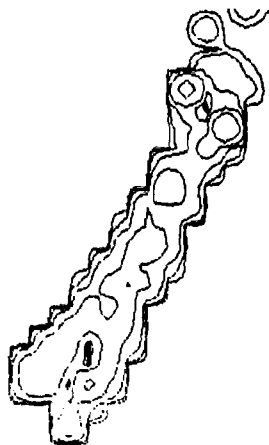
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 2750.00 SECONDS
PDR 1 TO 99 COLUMNS 1 TO 99
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL ROW AND COLUMN IS PLOTTED ***
GUST SCALE IS LOGARITHMIC RANGE 10 (0-1.25 0-1.25)



1357913579135791357913579

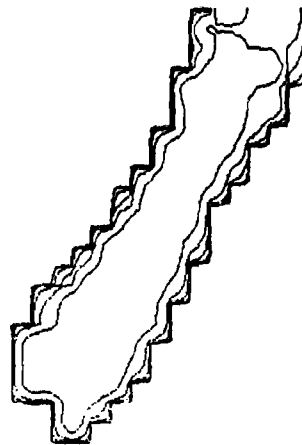
Figure 6-9(h). Heat production rate contour for small area fire,
ambient wind = 30 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
FLOW SIMULATION TIME = 4700.00 SECONDS
WIND 1 TO 20 M. S. SCALE 1 TO 20
WALL HEAT CONDUCTION ON
*** ONLY EVERY OTHER WALL HEAT AND WIND IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC WIND 10 (0-1.2% 0-1.210)



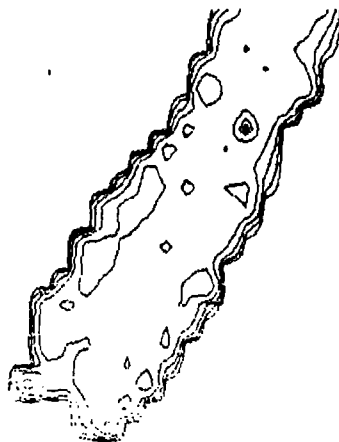
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
FLOW SIMULATION TIME = 5700.00 SECONDS
WIND 1 TO 20 M. S. SCALE 1 TO 20
WALL HEAT CONDUCTION ON
*** ONLY EVERY OTHER WALL HEAT AND WIND IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC WIND 10 (0-1.2% 0-1.210)



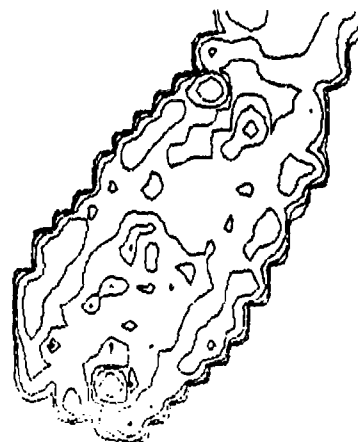
135791357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
FLOW SIMULATION TIME = 10700.0 SECONDS
WIND 1 TO 20 M. S. SCALE 1 TO 20
WALL HEAT CONDUCTION ON
*** ONLY EVERY OTHER WALL HEAT AND WIND IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC WIND 10 (0-1.2% 0-1.210)



135791357913579135791357913579

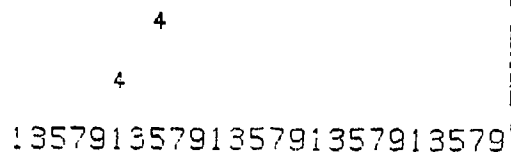
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
FLOW SIMULATION TIME = 31700.0 SECONDS
WIND 1 TO 20 M. S. SCALE 1 TO 20
WALL HEAT CONDUCTION ON
*** ONLY EVERY OTHER WALL HEAT AND WIND IS PLOTTED ***
ROOT SCALE IS LOGARITHMIC WIND 10 (0-1.2% 0-1.210)



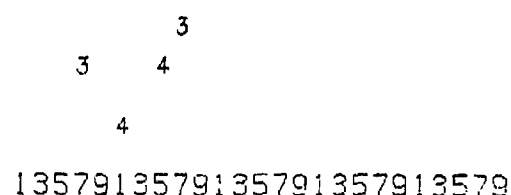
135791357913579135791357913579

Figure 6-9(1). Heat production rate contour for small area fire, ambient wind = 30 m/s.

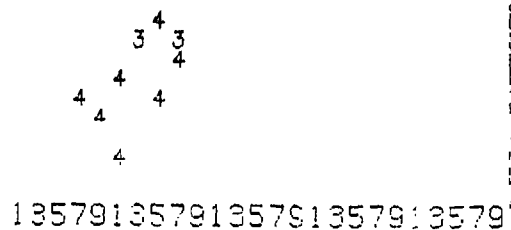
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELOCATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO Z AND 0 RANGE OF PLOT VALUES
PLOT MAP: EVERY OTHER CELL AND COLUMN IS PLOTTED
PLOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.00)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELOCATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO Z AND 0 RANGE OF PLOT VALUES
PLOT MAP: EVERY OTHER CELL AND COLUMN IS PLOTTED
PLOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.00)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELOCATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO Z AND 0 RANGE OF PLOT VALUES
PLOT MAP: EVERY OTHER CELL AND COLUMN IS PLOTTED
PLOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.00)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT RELOCATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO Z AND 0 RANGE OF PLOT VALUES
PLOT MAP: EVERY OTHER CELL AND COLUMN IS PLOTTED
PLOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.00)

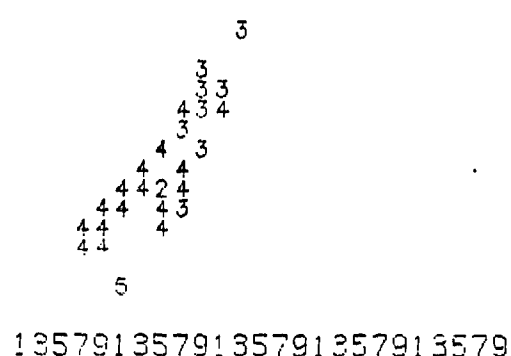


Figure 6-9(j). Cell heat production rate map for small area fire, ambient wind = 30 m/s.

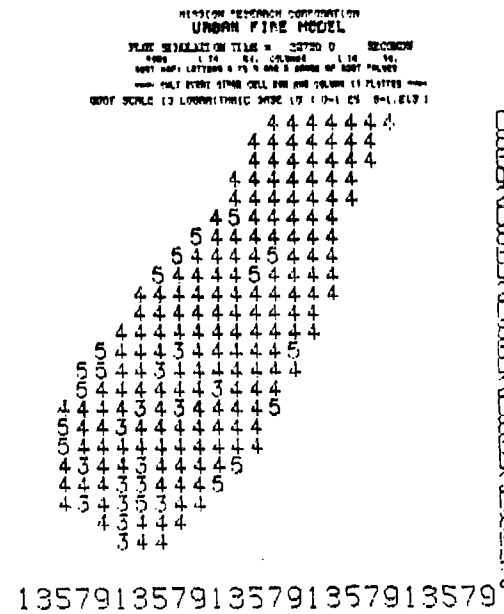
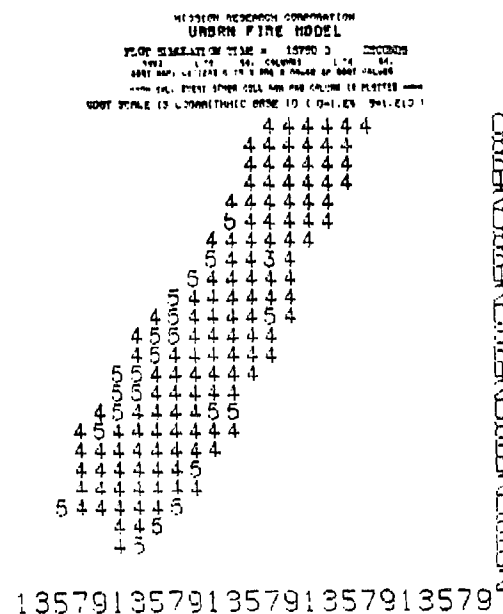
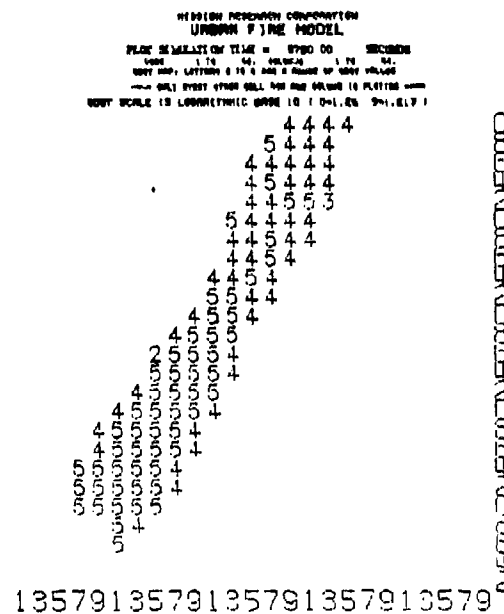
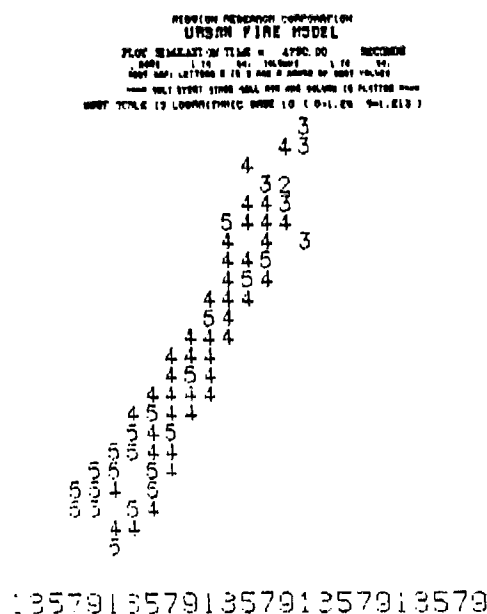


Figure 6-9(k). Cell heat production rate map for small area fire, ambient wind = 30 m/s.

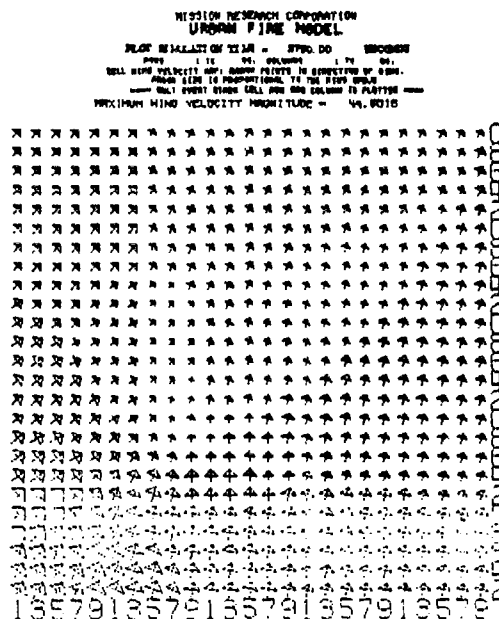
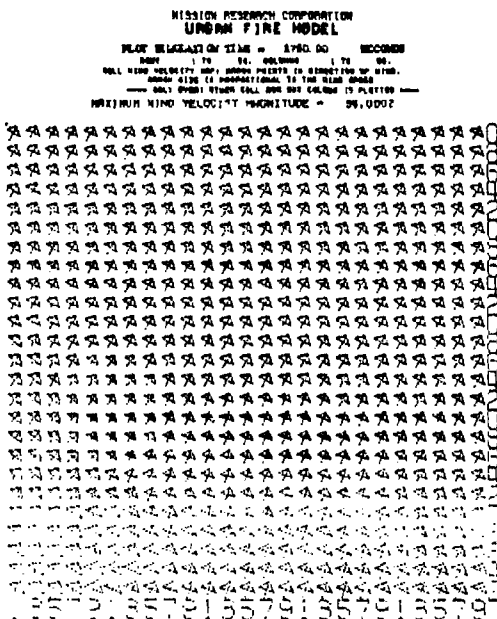
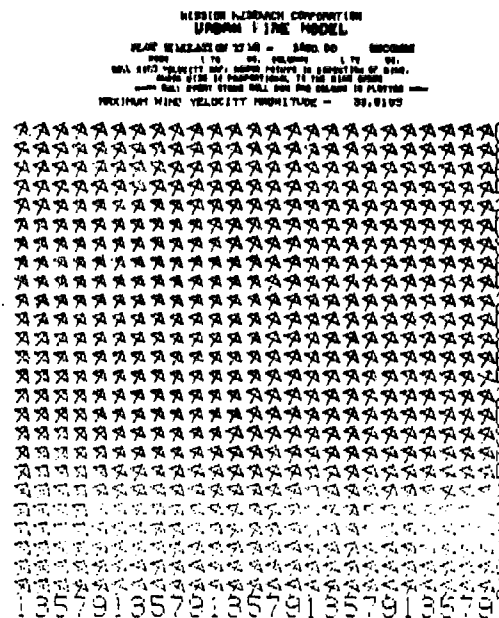
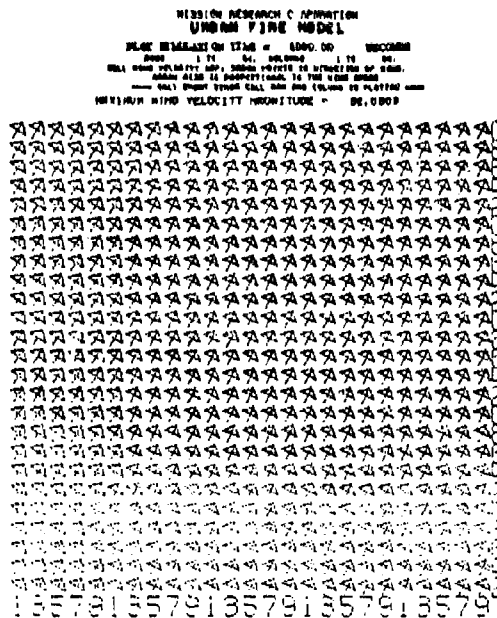


Figure 6-9(1). Wind velocity map for small area fire, ambient wind = 30 m/s.

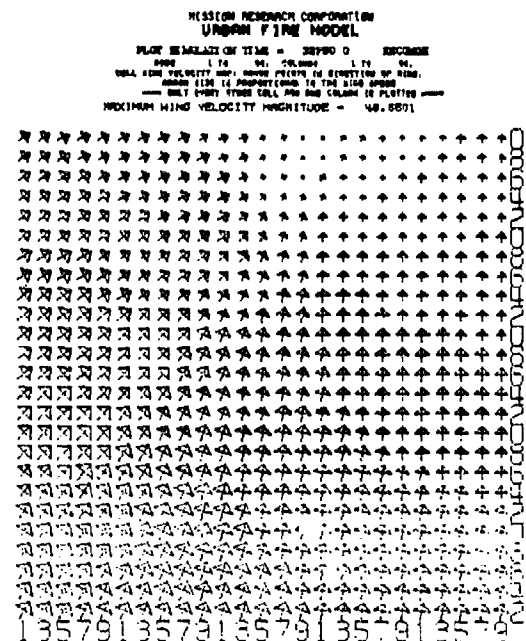
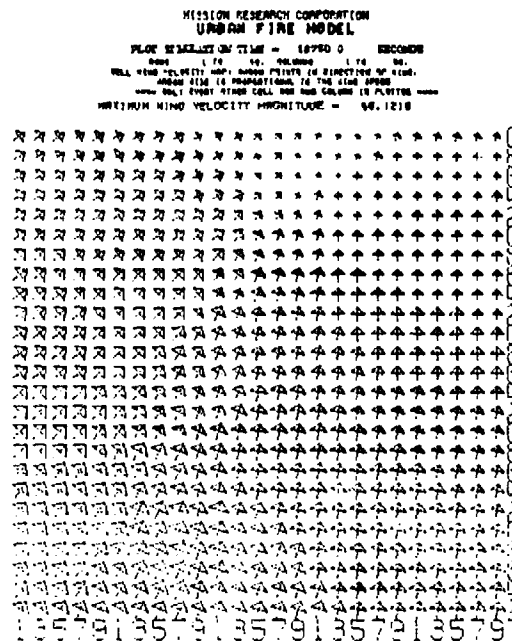
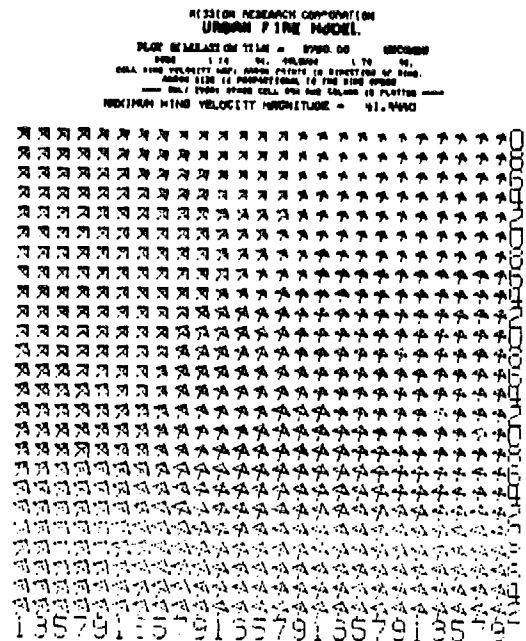
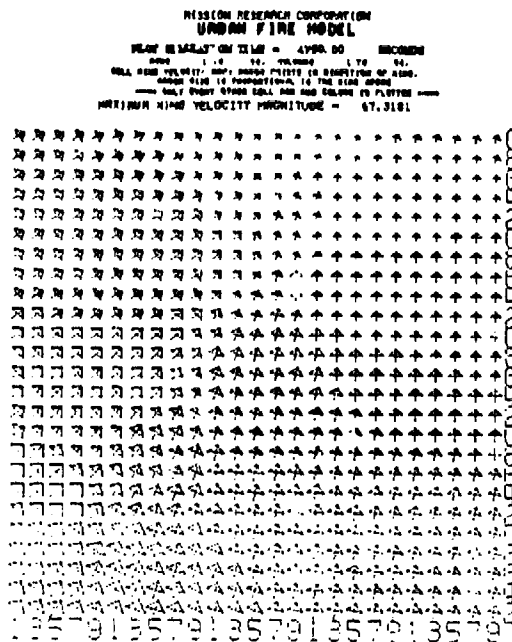


Figure 6-9(m). Wind velocity map for small area fire, ambient wind = 30 m/s.

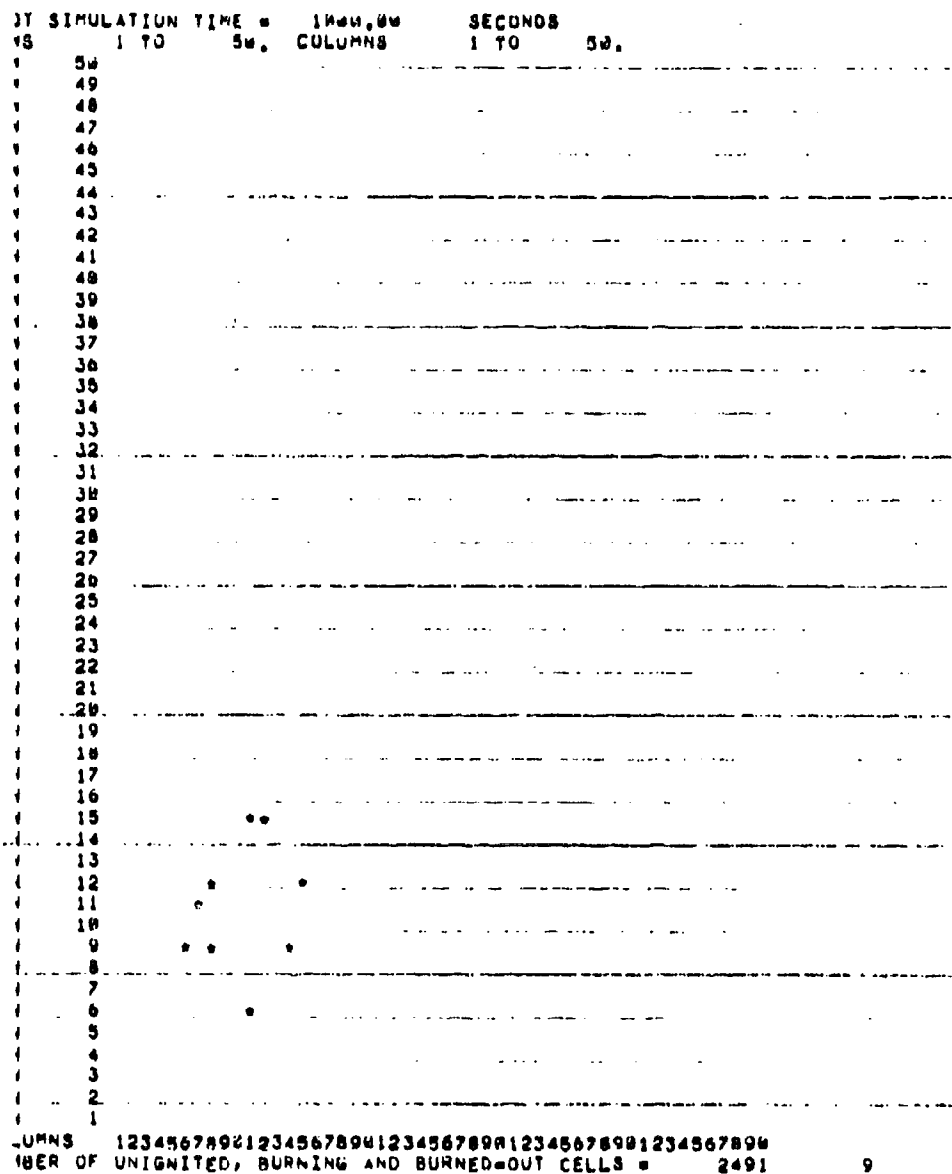


Figure 6-10. Cell state map for small area fire, ambient wind = 40 m/s.

9

IS 1 TO 50, COLUMNS 1 TO 50.

3d

1	35
1	49
1	48

1	47
1	46
1	45
1	44
1	43
1	42
1	41
1	40
1	39
1	38
1	37
1	36
1	35
1	34
1	33
1	32
1	31
1	30
1	29
1	28
1	27
1	26
1	25
1	24
1	23
1	22
1	21
1	20
1	19
1	18
1	17
1	16
1	15
1	14
1	13
1	12
1	11
1	10
1	9
1	8
1	7
1	6
1	5
1	4
1	3
1	2

UNF0 12345678901234567890123456789012345678901234567890
IBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2400

12

$$= 40 \text{ m/s.}$$

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2488 12

IT SIMULATION TIME = 1758.00 SECONDS

IS 1 TO 80, COLUMNS 1 TO 80.

50
 49
 48
 47
 46
 45
 44
 43
 42

41
 40
 39
 38
 37
 36
 35
 34
 33
 32
 31
 30
 29
 28
 27
 26
 25
 24
 23
 22
 21
 20
 19
 18
 17
 16
 15
 14
 13
 12
 11
 10
 9
 8
 7
 6
 5
 4
 3
 2
 1

COLUMNS 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2457 43

Figure 6-10(b). Cell state map for small area fire, ambient wind = 40 m/s.

49
49
48
47
46
45
44
43
42
41
40
39
38
37
36

UNMS 12345678901234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2532 168

299



Figure 6-10(d). Cell state map for small area fire, ambient wind = 40 m/s.

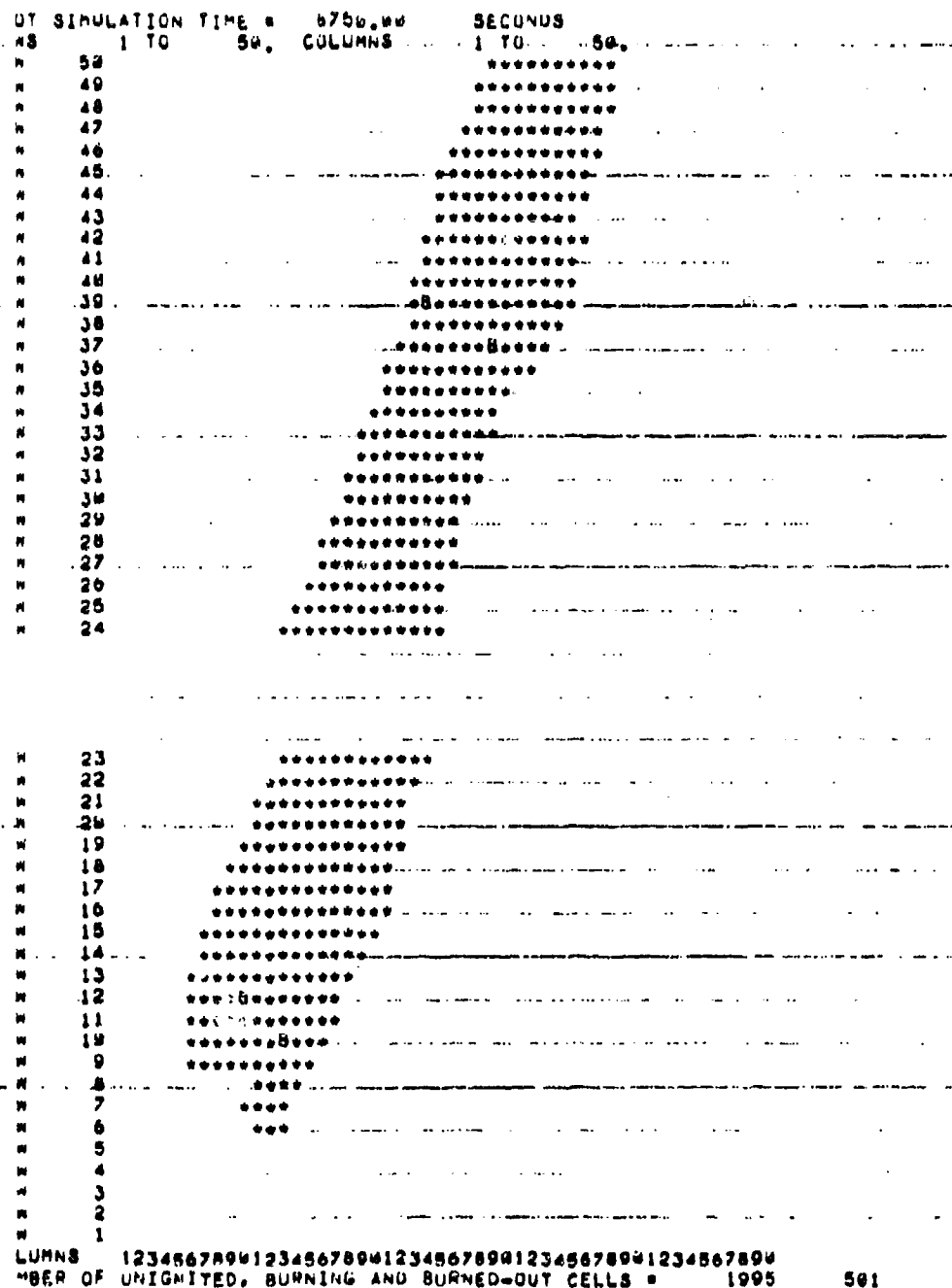


Figure 6-10(e). Cell state map for small area fire, ambient wind = 40 m/s.

DT SIMULATION TIME = 16754.0 SECONDS
 WS 1 TO 50, COLUMNS 1 TO 50.

```

    50 *****
    49 *****
    48 *****
    47 *****
    46 *****B*****
    45 *****
    44 *****
    43 *****
    42 *****
    41 *****
    40 *****
    39 *****B*****
    38 *****
    37 *****B*****
    36 *****
    35 *****
    34 *****
    33 *****
    32 *****
    31 *****
    30 *****
    29 *****
    28 *****
    27 *****
    26 *****
    25 *****
    24 *****
    23 *****B*****
    22 *****
    21 *****B*****
    20 *****B*****
    19 *****
    18 *****

    17 *****
    16 *****
    15 *****
    14 *****B*****
    13 *****
    12 *****B*****
    11 *****B*****
    10 *****B*****
    9 *****B*****
    8 *****
    7 *****
    6 *****
    5
    4
    3
    2
    1
  
```

LUMNS 1234567890123456789012345678901234567890
 MBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1772 747 21

Figure 6-10(f). Cell state map for small area fire, ambient wind
 = 40 m/s.

OT SIMULATION TIME = 32750.0 SECONDS

```

MS 1 TO 50, COLUMNS 1 TO 50.
W 50 *****
W 49 *****
W 48 *****
W 47 *****
W 46 *****
W 45 *****
W 44 *****
W 43 *****
W 42 *****
W 41 *****
W 40 *****
W 39 *****
W 38 *****
W 37 *****
W 36 *****
W 35 *****
W 34 *****
W 33 *****
W 32 *****
W 31 *****
W 30 *****
W 29 *****
W 28 *****
W 27 *****
W 26 *****
W 25 *****
W 24 *****
W 23 *****
W 22 *****
W 21 *****
W 20 *****
W 19 *****
W 18 *****
W 17 *****
W 16 *****
W 15 *****
W 14 *****
W 13 *****
W 12 *****

```

```

W 11 *****
W 10 *****
W 9 *****
W 8 *****
W 7 *****
W 6 *****
W 5 *****
W 4 *****
W 3 *****
W 2 *****
W 1 *****

```

COLUMN# 1234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1410 514 57

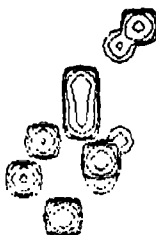
Figure 6-10(g). Cell state map for small area fire, ambient wind = 40 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
TIME 1 TO 10 SECONDS 1 TO 10
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL AND ARE COLOR IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
TIME 1 TO 10 SECONDS 1 TO 10
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL AND ARE COLOR IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



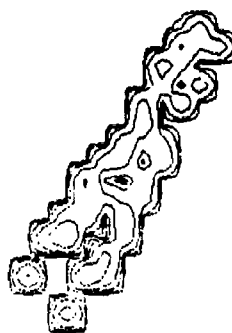
1357913579135791357913579

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
TIME 1 TO 10 SECONDS 1 TO 10
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL AND ARE COLOR IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



1357913579135791357913579

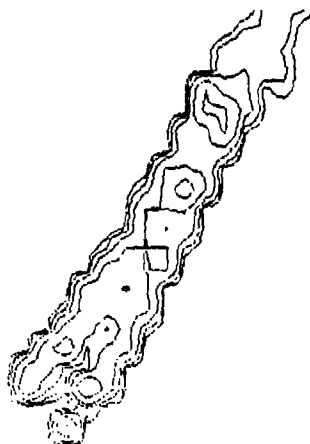
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
TIME 1 TO 10 SECONDS 1 TO 10
CELL NOT CONTAINING FIRE
*** ONLY EVERY OTHER CELL AND ARE COLOR IS PLOTTED ***
SHOT SCALE IS LOGARITHMIC (BASE 10) (0-1.00 0-1.010)



1357913579135791357913579

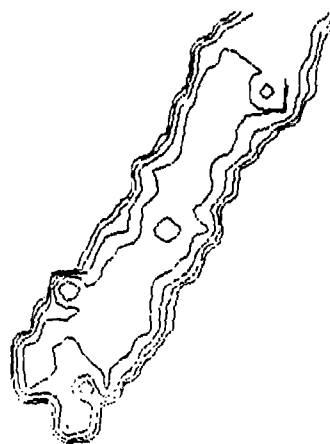
Figure 6-10(h). Heat production rate contour map for small area fire, ambient wind = 40 m/s.

HERSCHEL RESEARCH CORPORATION
URBAN FIRE MODEL
FLUX SEPARATION TIME = 1700.00
WIND 1 TO 10 M/S. RELEASE 1 TO 10
CELL SIZE CONTAINING 100
*** ONLY EVERY OTHER CELL AND AND RELEASE IS PLOTTED ***
GRID SCALE (S LOGARITHMIC GRID) (0-1.25 0-1.25)



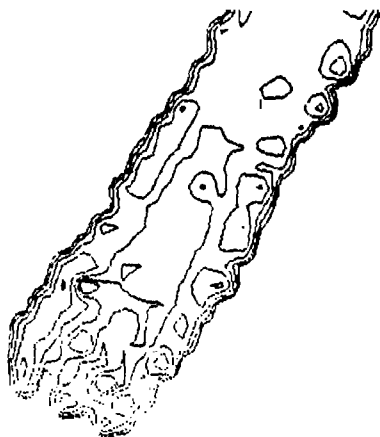
1357913579135791357913579

HERSCHEL RESEARCH CORPORATION
URBAN FIRE MODEL
FLUX SEPARATION TIME = 1700.00
WIND 1 TO 10 M/S. RELEASE 1 TO 10
CELL SIZE CONTAINING 100
*** ONLY EVERY OTHER CELL AND AND RELEASE IS PLOTTED ***
GRID SCALE (S LOGARITHMIC GRID) (0-1.25 0-1.25)



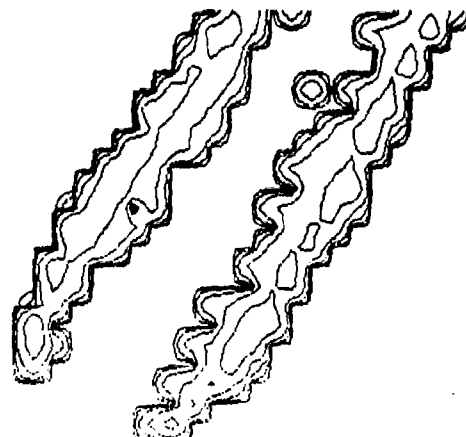
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HERSCHEL RESEARCH CORPORATION
URBAN FIRE MODEL
FLUX SEPARATION TIME = 1700.00
WIND 1 TO 10 M/S. RELEASE 1 TO 10
CELL SIZE CONTAINING 100
*** ONLY EVERY OTHER CELL AND AND RELEASE IS PLOTTED ***
GRID SCALE (S LOGARITHMIC GRID) (0-1.25 0-1.25)



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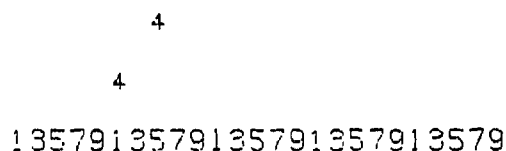
HERSCHEL RESEARCH CORPORATION
URBAN FIRE MODEL
FLUX SEPARATION TIME = 1700.00
WIND 1 TO 10 M/S. RELEASE 1 TO 10
CELL SIZE CONTAINING 100
*** ONLY EVERY OTHER CELL AND AND RELEASE IS PLOTTED ***
GRID SCALE (S LOGARITHMIC GRID) (0-1.25 0-1.25)



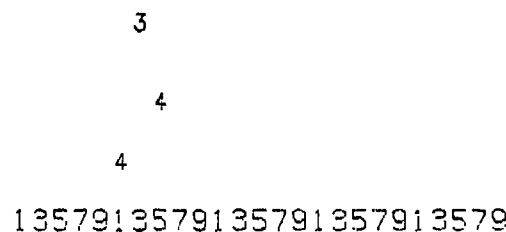
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Figure 6-10(i). Heat production rate contour map for small area fire, ambient wind = 40 m/s.

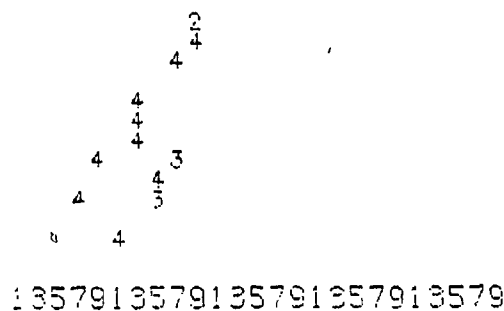
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO S AND 0 SHOWS SP. POINT VALUES
--- ONLY SPOT OTHER CELL AND AND COLUMN IS PLOTTED ---
SPOT SCALE IS LOGARITHMIC BY 10 (0-1.0E 0-1.0E 1)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO S AND 0 SHOWS SP. POINT VALUES
--- ONLY SPOT OTHER CELL AND AND COLUMN IS PLOTTED ---
SPOT SCALE IS LOGARITHMIC BY 10 (0-1.0E 0-1.0E 1)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO S AND 0 SHOWS SP. POINT VALUES
--- ONLY SPOT OTHER CELL AND AND COLUMN IS PLOTTED ---
SPOT SCALE IS LOGARITHMIC BY 10 (0-1.0E 0-1.0E 1)



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
PLOT MAP: LETTERS A TO S AND 0 SHOWS SP. POINT VALUES
--- ONLY SPOT OTHER CELL AND AND COLUMN IS PLOTTED ---
SPOT SCALE IS LOGARITHMIC BY 10 (0-1.0E 0-1.0E 1)

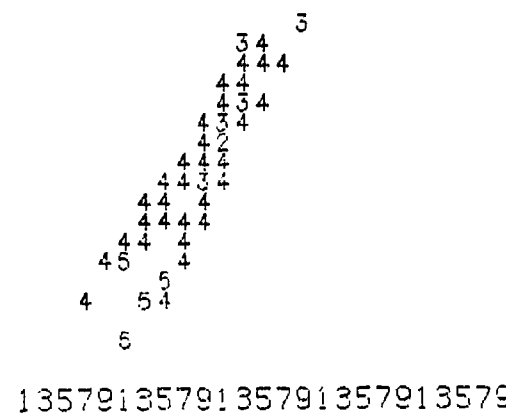


Figure 6-10(j). Cell heat production rate map for small area fire, ambient wind = 40 m/s.

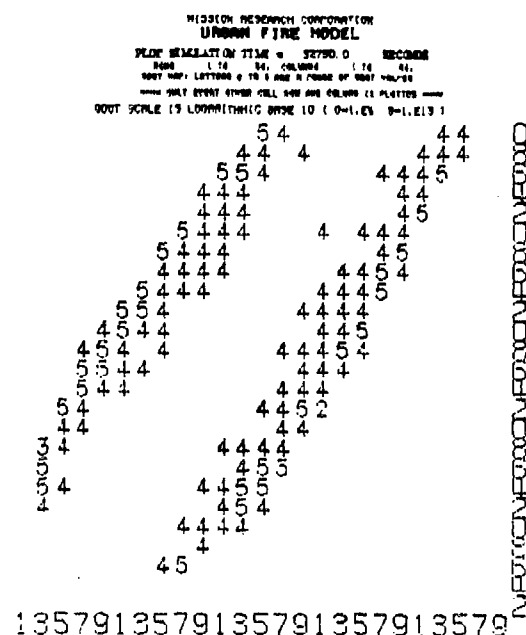
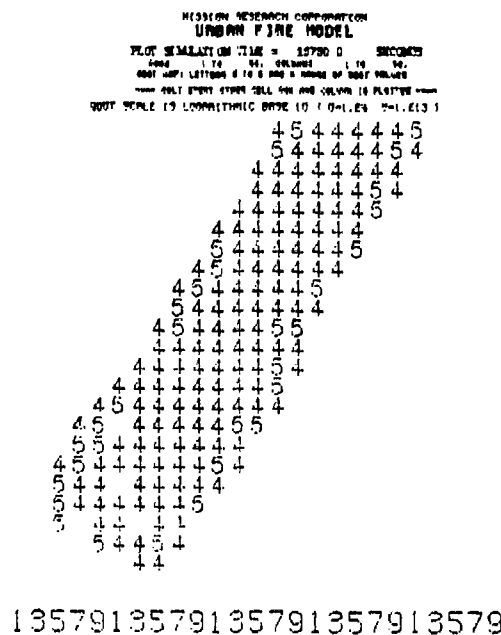
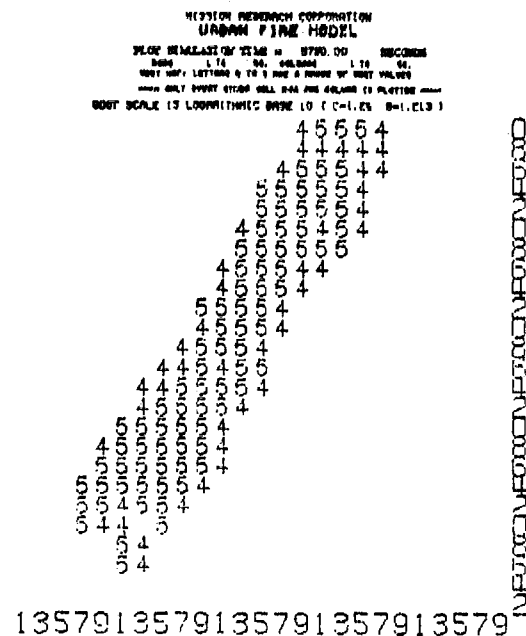
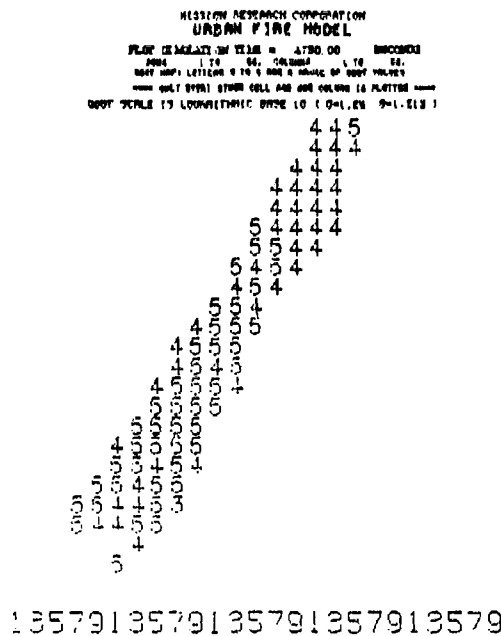
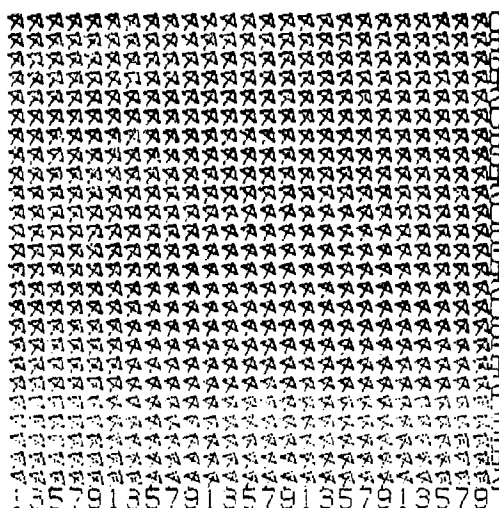
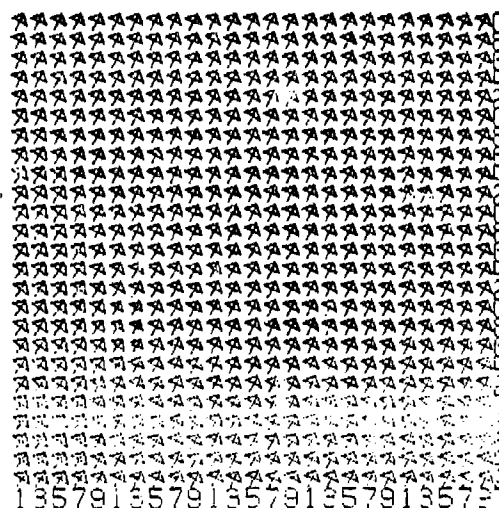
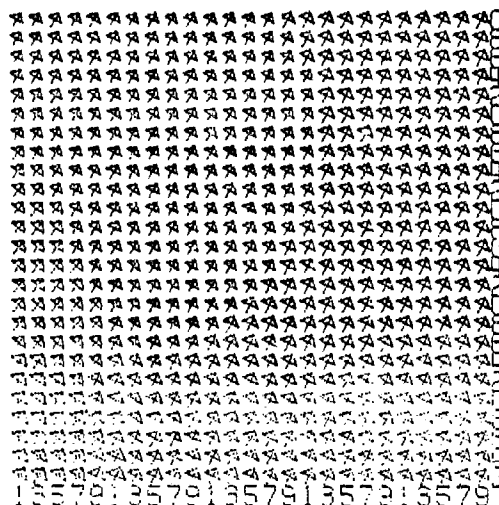


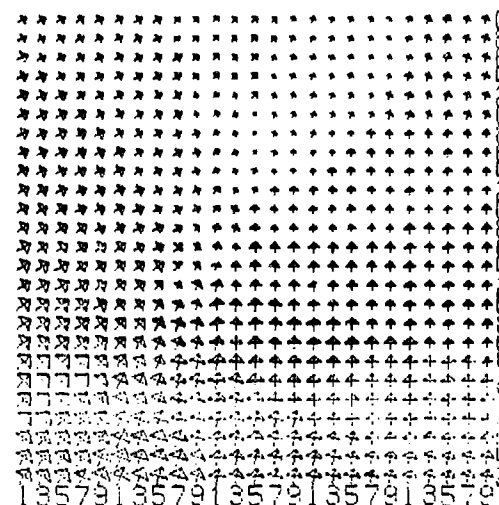
Figure 6-10(k). Cell heat production rate map for small area fire, ambient wind = 40 m/s.

[illegible][illegible]

PLAN IN MAGNETIC FIELD = 1300 DO RECORDS
 0000 1 10 00 000000 1 10 00
 ALL HIGH VELOCITY IMP: IMPACT POINTS IN SECTION OF RING
 0000 0100 10 0000000000, 10 100 0100 0000
 0000 0000 0000 0000 0000 0000 0000 0000 0000 0000
 (RING) HIGH VELOCITY MAGNITUDE = 04.7807



READ MEASUREMENTS ON THERM. IN WIND DO. RECORD IN
 FORM 1 TO 4. COLUMN 1 TO 4.
 GALL. WIND VELOCITY AT: GIVEN POINTS IN DIRECTION OF WIND.
 NUMBER 1120 IS MAXIMUM, TO THE SAME POINT.
 GALL. THERM. WIND GALL. AND GALL. IN PLATE
 MAXIMUM WIND VELOCITY MAGNITUDE = 99.721



308

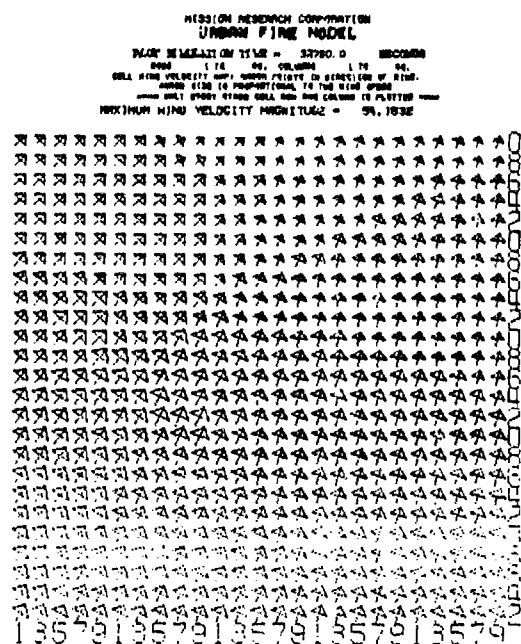
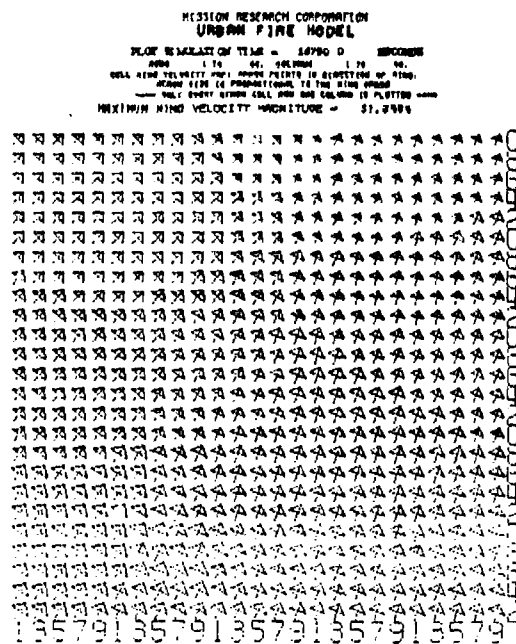
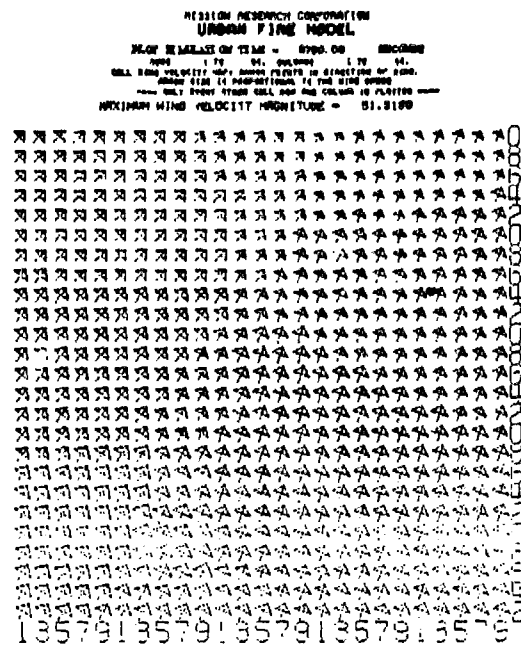
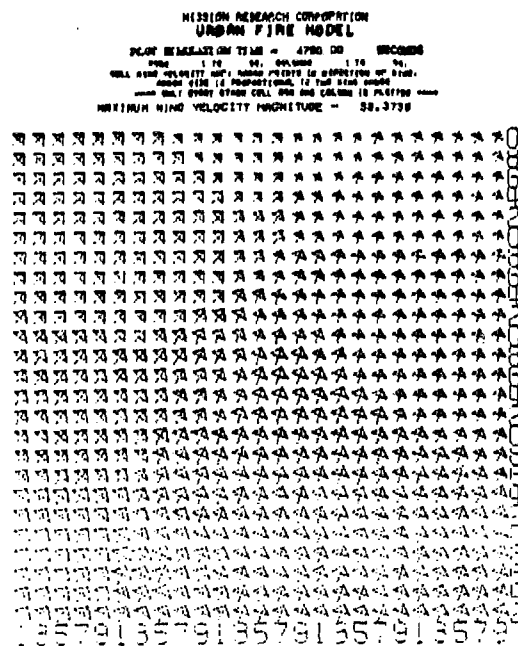


Figure 6-10(m). Wind velocity map for small area fire, ambient wind = 40 m/s.

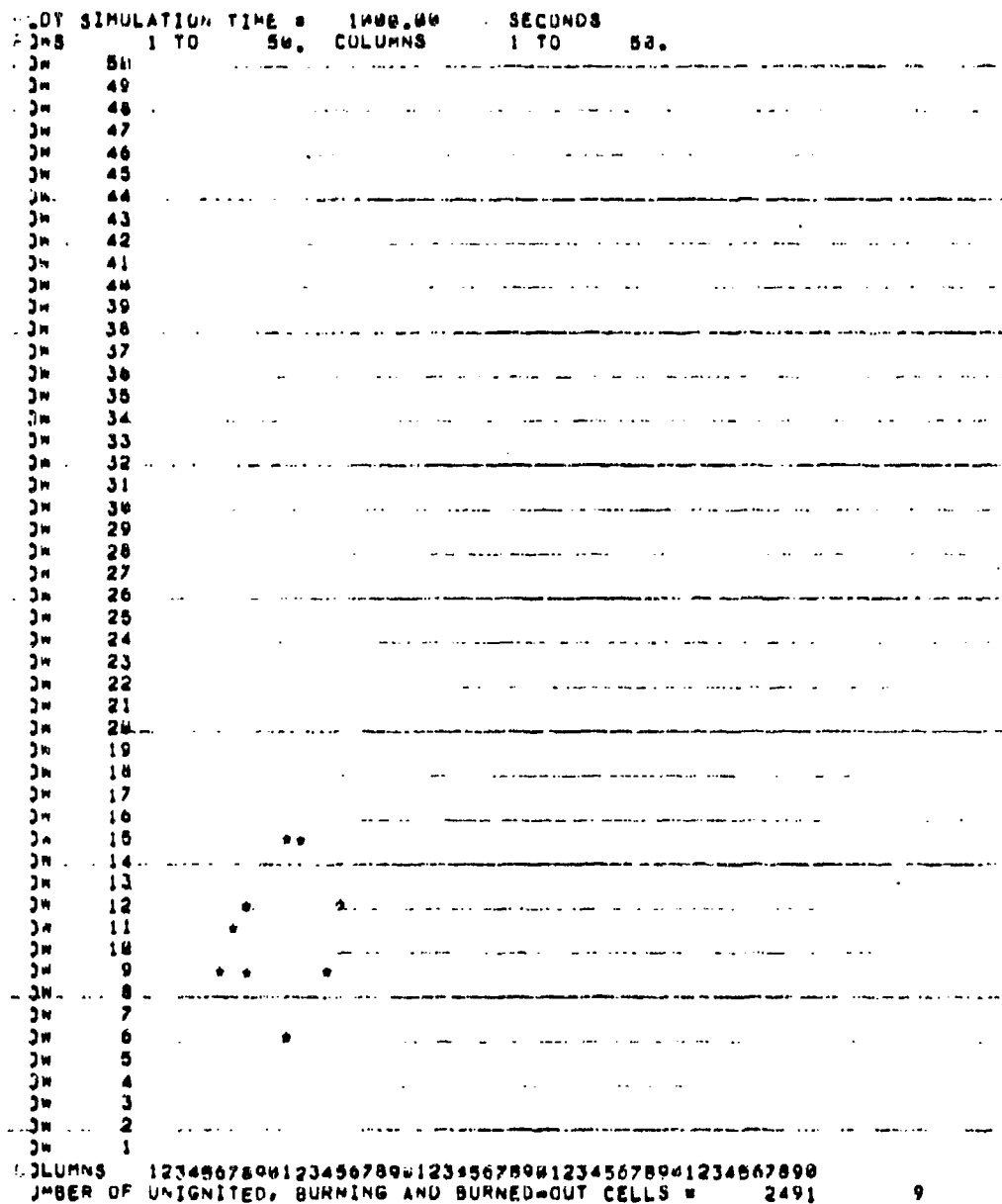


Figure 6-11. Cell state map for small area fire, ambient wind = 50 m/s.

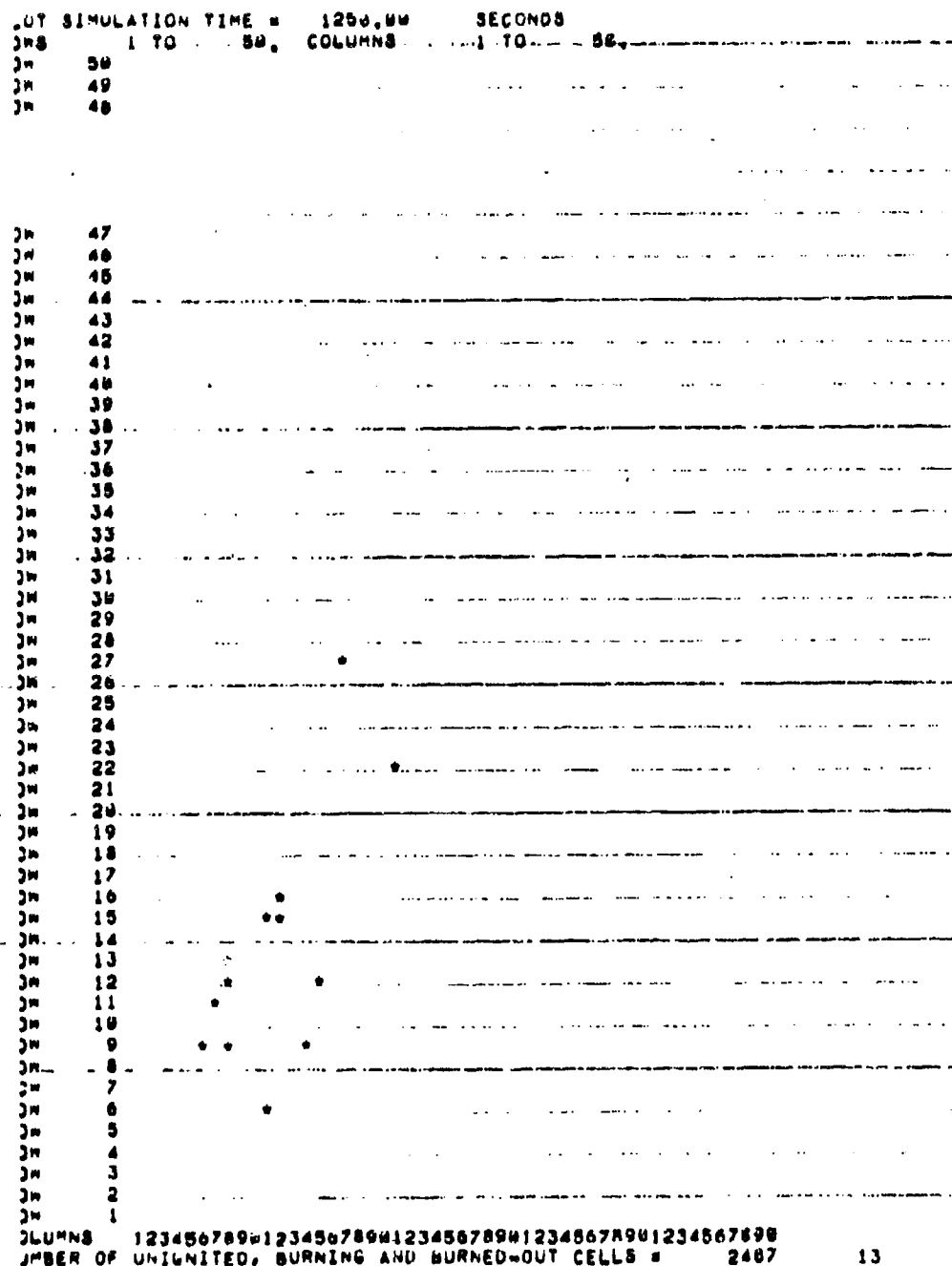


Figure 6-11(a). Cell state map for small area fire, ambient wind = 50 m/s.

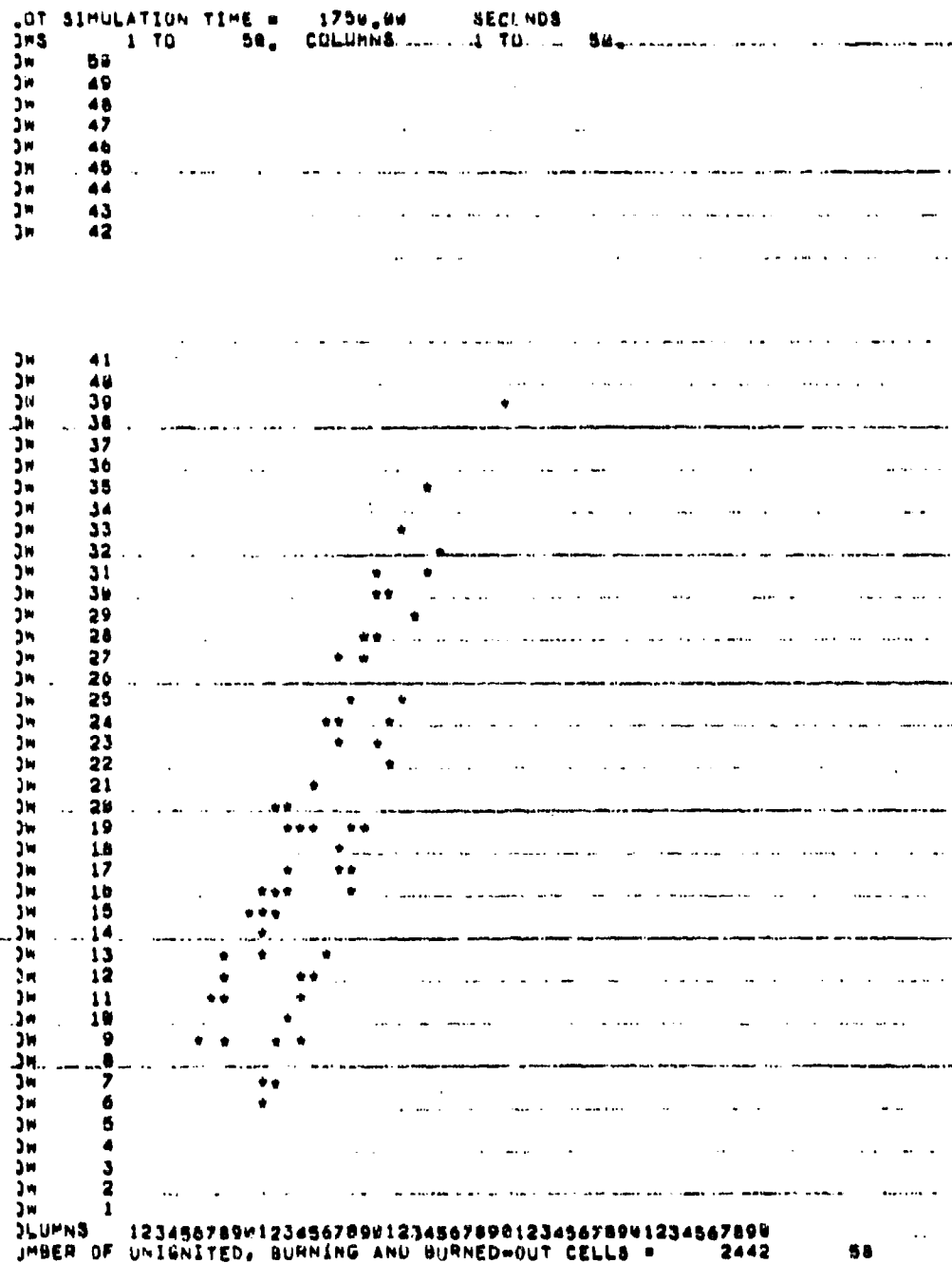


Figure 6-11(b). Cell state map for small area fire, ambient wind = 50 m/s.

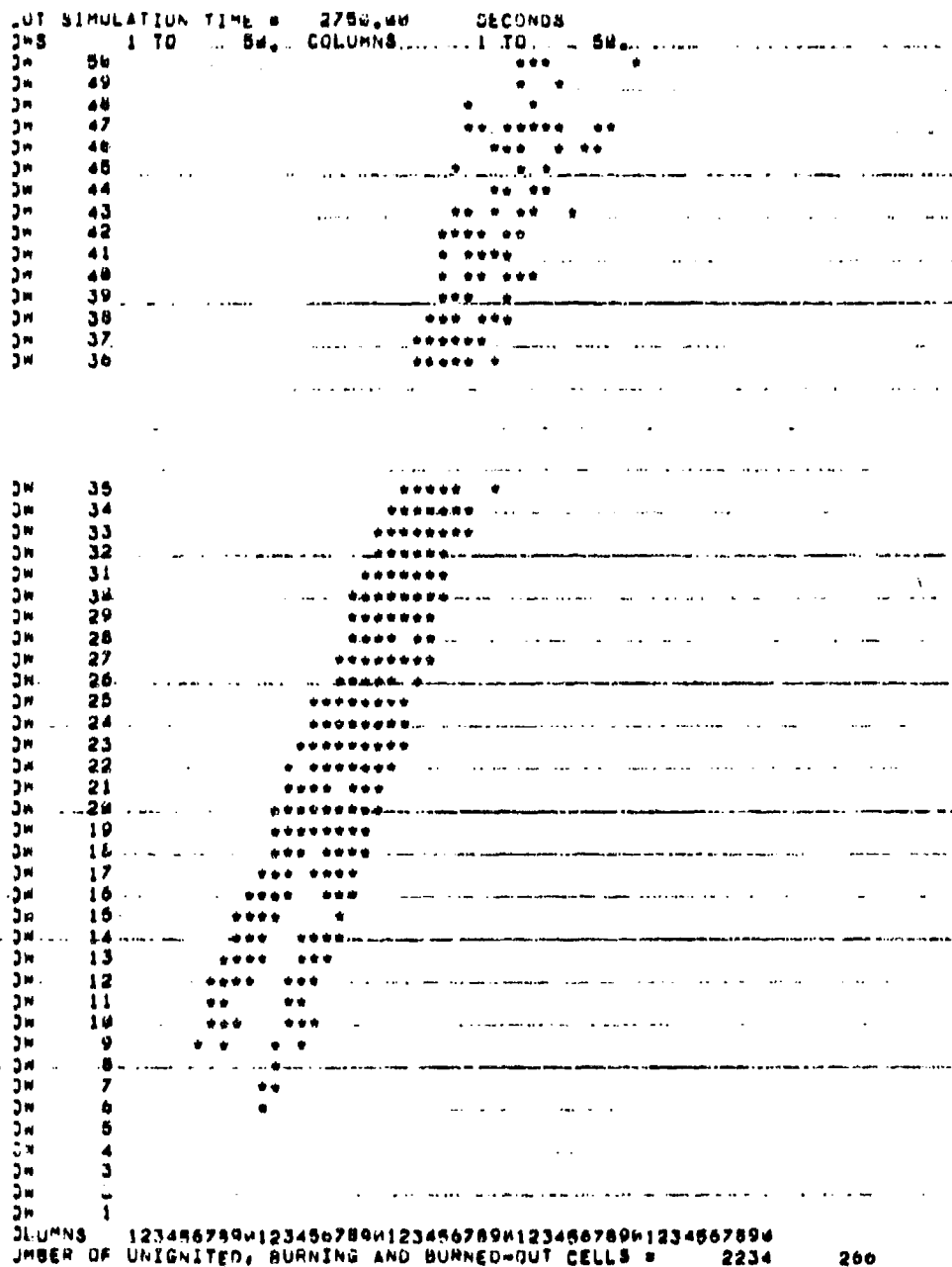


Figure 6-11(c). Cell state map for small area fire, ambient wind = 50 m/s.

```

NOT SIMULATION TIME = 4750.00 SECONDS
JMS 1 TO 50. COLUMNS 1 TO 50.
JM 50 *****
JM 49 *****
JM 48 *****
JM 47 *****
JM 46 *****
JM 45 *****
JM 44 *****
JM 43 *****
JM 42 *****
JM 41 *****
JM 40 *****
JM 39 *****
JM 38 *****
JM 37 *****
JM 36 *****
JM 35 *****
JM 34 *****
JM 33 *****
JM 32 *****
JM 31 *****
JM 30 *****

```

```

JM 29 *****
JM 28 *****
JM 27 *****
JM 26 *****
JM 25 *****
JM 24 *****
JM 23 *****
JM 22 *****
JM 21 *****
JM 20 *****
JM 19 *****
JM 18 *****
JM 17 *****
JM 16 *****
JM 15 *****
JM 14 *****
JM 13 *****
JM 12 *****
JM 11 *****
JM 10 *****
JM 9 *****
JM 8 *****
JM 7 *****
JM 6 *****
JM 5 *****
JM 4 *****
JM 3 *****
JM 2 *****
JM 1 *****

```

COLUMNS 12345678901234567890123456789012345678901234567890
 NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 2075 425

Figure 6-11(d). Cell state map for small area fire, ambient wind = 50 m/s.


```

OUT SIMULATION TIME = 1675.44 SECONDS
MS 1 TO 50, COLUMN# 1 TO 50
IN 50 *****
IN 49 *****
IN 48 *****
IN 47 *****
IN 46 *****
IN 45 *****
IN 44 *****
IN 43 *****
IN 42 *****
IN 41 *****
IN 40 *****
IN 39 *****
IN 38 *****
IN 37 *****
IN 36 *****
IN 35 *****
IN 34 *****
IN 33 *****
IN 32 *****
IN 31 *****
IN 30 *****
IN 29 *****
IN 28 *****
IN 27 *****
IN 26 *****
IN 25 *****
IN 24 *****
IN 23 *****
IN 22 *****
IN 21 *****
IN 20 *****
IN 19 *****
IN 18 *****

IN 17 *****
IN 16 *****
IN 15 *****
IN 14 *****
IN 13 *****
IN 12 *****
IN 11 *****
IN 10 *****
IN 9 *****
IN 8 *****
IN 7 *****
IN 6 *****
IN 5
IN 4
IN 3
IN 2
IN 1

COLUMNS 1234567890123456789012345678901234567890
NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1703 646 15

```

Figure 6-11(f). Cell state map for small area fire, ambient wind = 50 m/s.

```

NOT SIMULATION TIME = 32/51.0 SECONDS
INS 1 TO 50, COLUMNS 1 TO 50,
)W 50 *****B*****
)W 49 *****B*****
)W 48 *****B*****
)W 47 *****B*****
)W 46 *****B*****
)W 45 *****B*****
)W 44 *****B*****
)W 43 *****B*****
)W 42 *****B*****
)W 41 *****B*****
)W 40 *****B*****
)W 39 *****B*****
)W 38 *****B*****
)W 37 *****B*****
)W 36 *****B*****
)W 35 *****B*****
)W 34 *****B*****
)W 33 *****B*****
)W 32 *****B*****
)W 31 *****B*****
)W 30 *****B*****
)W 29 *****B*****
)W 28 *****B*****
)W 27 *****B*****
)W 26 *****B*****
)W 25 *****B*****
)W 24 *****B*****
)W 23 *****B*****
)W 22 *****B*****
)W 21 *****B*****
)W 20 *****B*****
)W 19 *****B*****
)W 18 *****B*****
)W 17 *****B*****
)W 16 *****B*****
)W 15 *****B*****
)W 14 *****B*****
)W 13 *****B*****
)W 12 *****B*****

)W 11 *****B*****
)W 10 *****B*****
)W 9 *****B*****
)W 8 *****B*****
)W 7 *****B*****
)W 6 *****B*****
)W 5 *****B*****
)W 4 *****B*****
)W 3 *****B*****
)W 2 *****B*****
)W 1 *****B*****

)LUMPS 12345678901234567890123456789012345678901234567890
)NUMBER OF UNIGNITED, BURNING AND BURNED-OUT CELLS = 1329 529 64

```

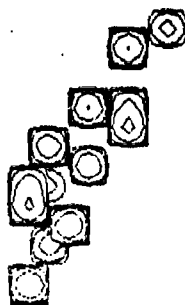
Figure 6-11(g). Cell state map for small area fire, ambient wind = 50 m/s.

MISSION RESEARCH CORPORATION
UNBURN FIRE MODEL
PLOT SIMULATION TIME = 1000.00 SECONDS
X AXIS 1 TO 50 Y AXIS 1 TO 50
CELL SIZE 10000000
*** ONLY EVERY OTHER CELL AND COLUMN IS PLOTTED ***
BODY SCALE (S LOGARITHMIC BASE 10 (0-1.25 0-1.25))



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MISSION RESEARCH CORPORATION
UNBURN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
X AXIS 1 TO 50 Y AXIS 1 TO 50
CELL SIZE 10000000
*** ONLY EVERY OTHER CELL AND COLUMN IS PLOTTED ***
BODY SCALE (S LOGARITHMIC BASE 10 (0-1.25 0-1.25))



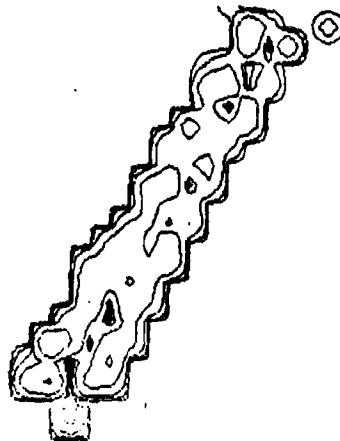
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MISSION RESEARCH CORPORATION
UNBURN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
X AXIS 1 TO 50 Y AXIS 1 TO 50
CELL SIZE 10000000
*** ONLY EVERY OTHER CELL AND COLUMN IS PLOTTED ***
BODY SCALE (S LOGARITHMIC BASE 10 (0-1.25 0-1.25))



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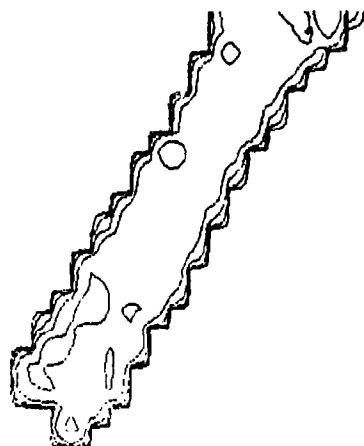
MISSION RESEARCH CORPORATION
UNBURN FIRE MODEL
PLOT SIMULATION TIME = 1750.00 SECONDS
X AXIS 1 TO 50 Y AXIS 1 TO 50
CELL SIZE 10000000
*** ONLY EVERY OTHER CELL AND COLUMN IS PLOTTED ***
BODY SCALE (S LOGARITHMIC BASE 10 (0-1.25 0-1.25))



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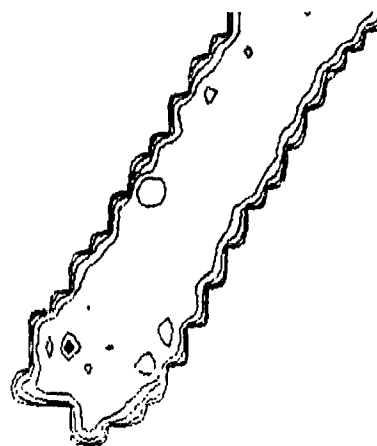
Figure 6-11(h). Heat production rate contour map for small area fire, ambient wind = 50 m/s.

MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 4700.00 SECONDS
RMS 1 TO 10 10 10 10 10 10
WILL NOT COVER MAP
*** ONLY EVERY OTHER CELL SURVIVE RELEASE IS PLAYS ***
BEST SCALE IS LOGARITHMIC (0-1.00 0-1.00)



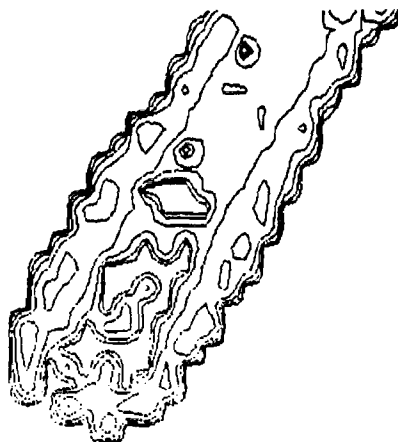
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 5700.00 SECONDS
RMS 1 TO 10 10 10 10 10 10
WILL NOT COVER MAP
*** ONLY EVERY OTHER CELL SURVIVE RELEASE IS PLAYS ***
BEST SCALE IS LOGARITHMIC (0-1.00 0-1.00)



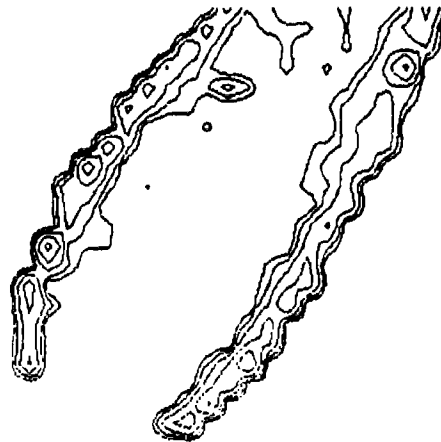
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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 6700.00 SECONDS
RMS 1 TO 10 10 10 10 10 10
WILL NOT COVER MAP
*** ONLY EVERY OTHER CELL SURVIVE RELEASE IS PLAYS ***
BEST SCALE IS LOGARITHMIC (0-1.00 0-1.00)



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MISSION RESEARCH CORPORATION
URBAN FIRE MODEL
PLAY RELEASE ON TIME = 7700.00 SECONDS
RMS 1 TO 10 10 10 10 10 10
WILL NOT COVER MAP
*** ONLY EVERY OTHER CELL SURVIVE RELEASE IS PLAYS ***
BEST SCALE IS LOGARITHMIC (0-1.00 0-1.00)



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Figure 6-11(i). Heat production rate contour map for small area fire, ambient wind = 50 m/s.

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320

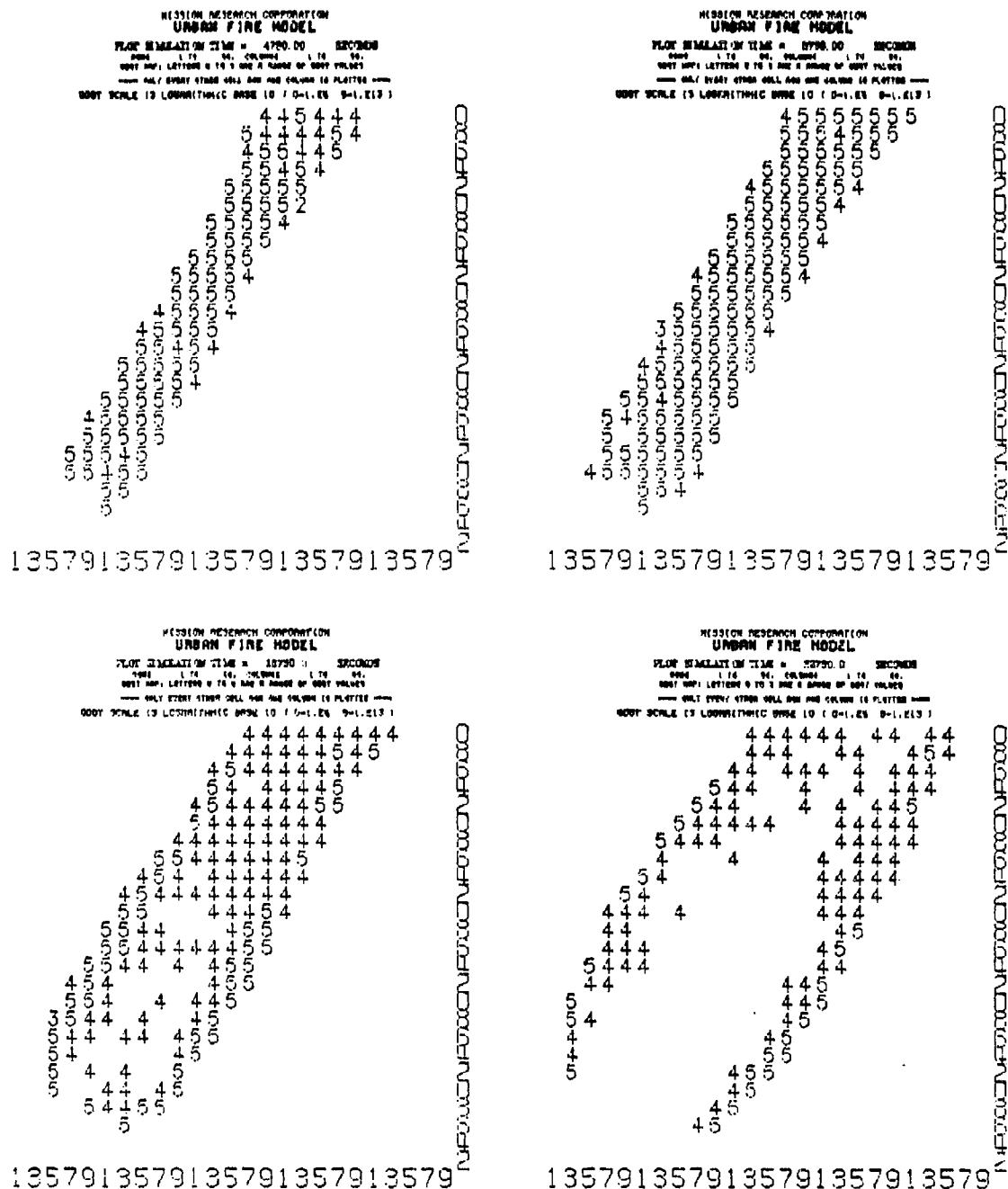
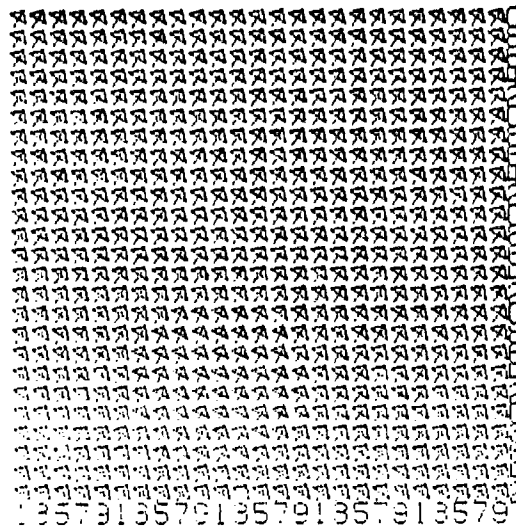


Figure 6-11(k). Cell heat production rate map for small area fire, ambient wind = 50 m/s.

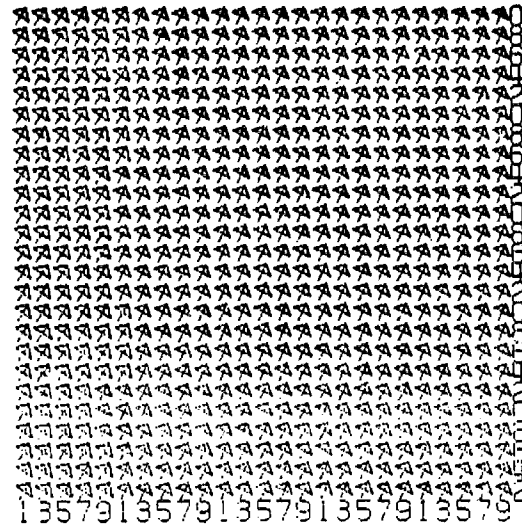
MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL

PLATE RELOCATION TIME = 1000.00 SECONDS
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
MAXIMUM WIND VELOCITY MAGNITUDE = 51.0000



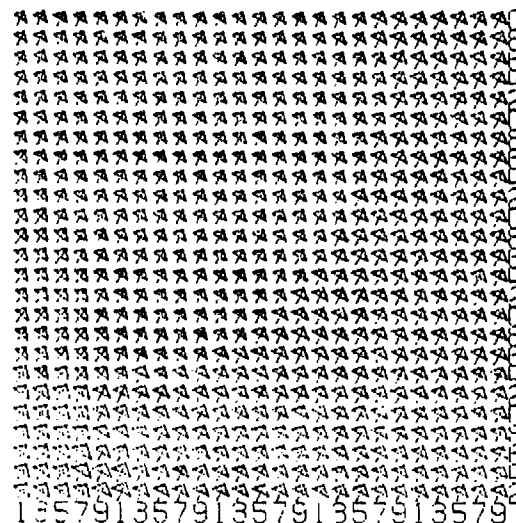
MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL

PLATE RELOCATION TIME = 1000.00 SECONDS
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
MAXIMUM WIND VELOCITY MAGNITUDE = 63.0071



MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL

PLATE RELOCATION TIME = 1700.00 SECONDS
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
MAXIMUM WIND VELOCITY MAGNITUDE = 56.1878



MISSION RESEARCH CORPORATION
UPDOWN FIRE MODEL

PLATE RELOCATION TIME = 1700.00 SECONDS
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
WIND VELOCITY MAP, WIND DIRECTION IN DEGREES OF TRUE.
WIND SPEED IN METERS PER SECOND, TO THE RIGHT OF TRUE.
MAXIMUM WIND VELOCITY MAGNITUDE = 72.0578

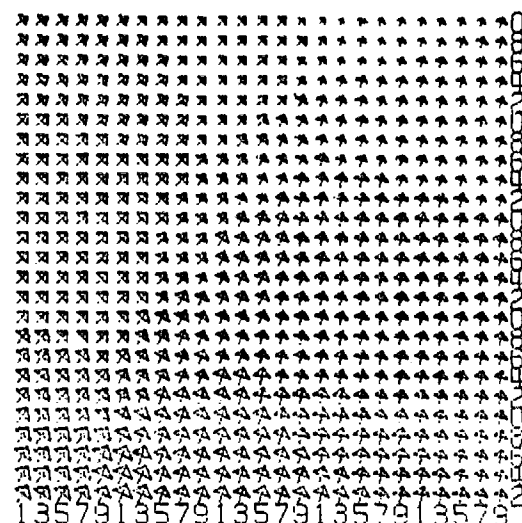
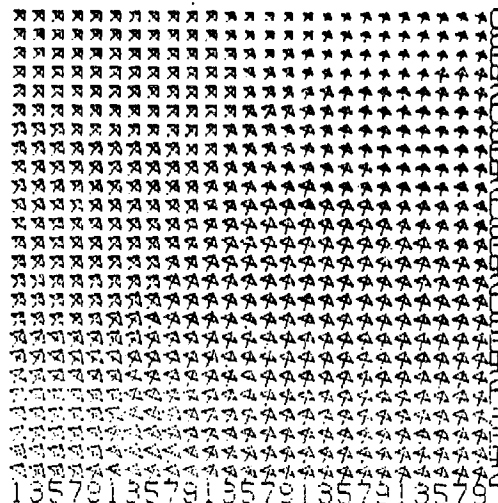


Figure 6-11(1). Wind velocity map for small area fire, ambient wind = 50 m/s.

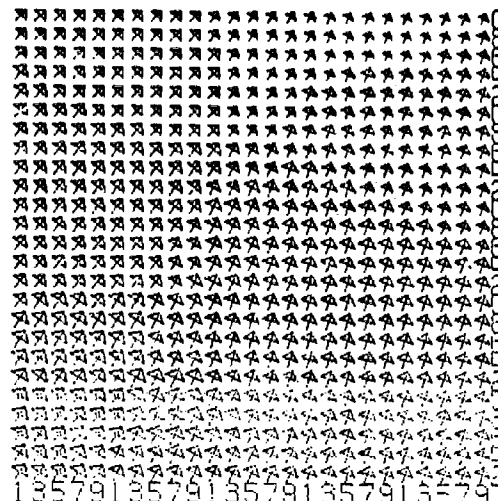
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL

PLATE RELEASED ON TIME = 4900.00 SCENE
FROM 1 TO 91, 00.0000 1 TO 91.
CALL FIRE VELOCITY MAP, SHOWS PLOTS IN DIRECTION OF WIND.
WIND VELOCITY IS PROPORTIONAL TO THE WIND SPEED.
ONLY FIRST STAGE CALL AND ONE CALL TO PLATE
MAXIMUM WIND VELOCITY MAGNITUDE = 84.8279



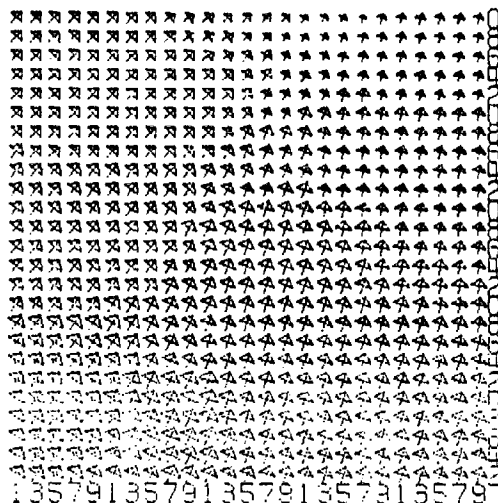
MISSION RESEARCH CORPORATION
URBAN FIRE MODEL

PLATE RELEASED ON TIME = 5100.00 SCENE
FROM 1 TO 91, 00.0000 1 TO 91.
CALL FIRE VELOCITY MAP, SHOWS PLOTS IN DIRECTION OF WIND.
WIND VELOCITY IS PROPORTIONAL TO THE WIND SPEED.
ONLY FIRST STAGE CALL AND ONE CALL TO PLATE
MAXIMUM WIND VELOCITY MAGNITUDE = 85.8304



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL

PLATE RELEASED ON TIME = 5300.00 SCENE
FROM 1 TO 91, 00.0000 1 TO 91.
CALL FIRE VELOCITY MAP, SHOWS PLOTS IN DIRECTION OF WIND.
WIND VELOCITY IS PROPORTIONAL TO THE WIND SPEED.
ONLY FIRST STAGE CALL AND ONE CALL TO PLATE
MAXIMUM WIND VELOCITY MAGNITUDE = 87.0462



MISSION RESEARCH CORPORATION
URBAN FIRE MODEL

PLATE RELEASED ON TIME = 5500.00 SCENE
FROM 1 TO 91, 00.0000 1 TO 91.
CALL FIRE VELOCITY MAP, SHOWS PLOTS IN DIRECTION OF WIND.
WIND VELOCITY IS PROPORTIONAL TO THE WIND SPEED.
ONLY FIRST STAGE CALL AND ONE CALL TO PLATE
MAXIMUM WIND VELOCITY MAGNITUDE = 88.0612

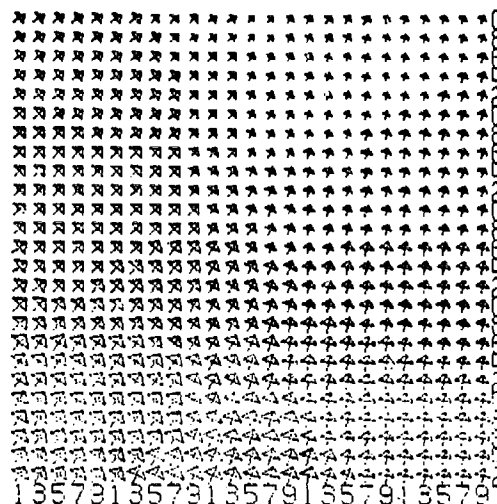


Figure 6-11(m). Wind velocity map for small area fire, ambient wind = 50 m/s.

REFERENCES

1. Martin, Stanley B., The Role of Fire in Nuclear Warfare, DNA 2692F, URS Research Company, San Mateo, CA, August 1974.
2. Small, R.D., and H.L. Brode, Physics of Large Urban Fires, PSR Report 1010, Pacific Sierra Research Corporation, 1980.
3. Alger, R.S., and S.B. Martin, Blast/Fire Interactions, Asilomar Conference, March 1979, SRI International, September 1979.
4. Alger, R.S., and S.B. Martin, Blast/Fire Interactions, Asilomar Conference, May 1980, SRI International, February 1981.
5. Weisbecker, L.W., and H. Lee, Evaluation of Systems of Fire Development, Stanford Research Institute, August 1970.
6. Rodden, Robert M., F.I. John, and R. Laurino, Exploratory Analysis of Fire Storms, Stanford Research Institute, May 1965.
7. Lonnmassen, T.E., R.K. Miller, R.G. Kirkpatrick, and J.A. Keller, A 'Firestorm' Existence and Buildup Hypothesis, Dikewood Corporation, September 1968.
8. Baldwin, R., and M.A. North, The Firestorm--Its Size and Importance, Fire Research Note 645, Fire Research Station, Joint Fire Research Organization, United Kingdom, February 1967.
9. Countryman, Clive M., Project Flambeau, Final Report, Volume 1, Pacific SW Forest and Range Experiment Station, Berkeley, CA, Office of Civil Defense.
10. Countryman, Clive M., Mass Fires and Fire Behavior, U.S. Department of Agriculture, U.S. Forest Service Research Paper PSW-19, 1964.
11. Gaskin, A.S. (ed), Operation Euroka, Supplementary Papers, Department of Supply, Australian Defence Scientific Service, Defence Standards Laboratories (DSL), Maribyrnong, Victoria, Australia, July 1971.

See also:
Operation Euroka, An Australian Mass Fire Experiment, DSL Report 386, Commonwealth of Australia, September 1970.
12. Neilsen, Hugo J., Fire Storm Analysis, ITT Research Institute, January 1970.

13. Nielsen, H.J. and L.N. Tao, "The Fire Plume Above a Large Free-Burning Fire," Tenth Symposium (International) on Combustion, Combustion Institute, p. 965, 1965.
14. Gostintsev, Yu.A. and L.A. Sukhanov, "Convective Column Above a Linear Fire in Homogeneous Isothermal Atmosphere," Combustion, Explosion, and Shock Waves, 13, p. 570, 1977.
15. Gostintsev, Yu.A., and L.A. Sukhanov, "Interaction of Convective Columns Above Linear Sources of Heat," Combustion, Explosion, and Shock Waves, 14, p. 60, 1978.
16. Gostintsev, Yu.A. and L.A. Sukhanov, "Convective Column Above a Linear Fire in a Polytropic Atmosphere," Combustion, Explosion, and Shock Waves, 14, p. 271, 1978.
17. Gostintsev, Yu.A. and L.A. Sukhanov, "Interaction Between a Convective Column and a Wind Above a Linear Fire in a Polytropic Atmosphere," Combustion, Explosion, and Shock Waves, 14, p. 452, 1978.
18. Rothmal, Richard C., A Mathematical Model for Predicting Fire Spread in Wildland Fuels, U.S. Department of Agriculture, U.S. Forest Service, Research Paper INT-115, January 1972.
19. Sanderlin, J.C., and J.M. Sunderson, Wildland Fire Modeling for Planning Support, Volume III--A Prototype Segmented Perimeter Wildland Fire Propagation Model, MRC-R-470, Mission Research Corporation, August 1976.
20. Faus, W.R., "Analysis of Fire Spread in Light Forest Fuels," J. Agr. Res., Vol. 72, No. 3, pp 93-121, 1946.
21. Tarifa, C.S., and A.M. Tanalko, "Flame Propagation Along the Interface Between a Gas and a Reacting Medium," Eleventh International Symposium on Combustion, Berkeley, CA, 1967.
22. Frandsen, W.H., "Fire Spread Through Porous Fuels from the Conservation of Energy," Combustion and Flame, Vol. 16, pp 9-16, 1971.
23. Sanderlin, J.C., and J.M. Sunderson, Wildland Fire Modeling for Planning Support. Volume IV--Rate of Spread Model Assessment, MRC-R-470, Mission Research Corporation, August 1976.
24. McCaffrey, B.J., Meeting of Eastern Section of the Combustion Institute, November 1978.

25. Cox, G., and R. Chitty, "A Study of the Deterministic Properties of Unbounded Fire Plumes," Combustion and Flame, 39, pp. 191-209, 1980.
26. Scorer, R.S., Environmental Aerodynamics, Ellis Horwood Ltd. (John Wiley & Sons), New York, p. 276, 1978.
27. Morton, B.R., G. Taylor, and J.S. Turner, "Turbulent Gravitational Convection from Maintained and Instantaneous Sources," Proc. Roy. Soc., A24, pp 1-23, 1956.
28. Tarifa, Carlos S., P. Perez del Notario, and F. Garcia Moreno, "On the Flight Paths and Lifetimes of Burning Particles of Wood," Tenth Symposium (International) on Combustion, Combustion Institute, Pittsburgh, PA, 1965.

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