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A PARAMETRIC STUDY OF PROBABILISTIC FIRE SPREAD EFFECTS

Leo A. Schmidt, Jr.

September 1979

Prepared for

Federal Emergency Management Agency

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INSTITUTE FOR DEFENSE ANALYSES

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simplifying the IITRI model.

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A PARAMETRIC STUDY OF PROBABILISTIC FIRE SPREAD EFFECTS

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for
Federal Emergency Management Agency
Washington, D.C. 20301

September 1979

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ABSTRACT

One of the basic mechanisms governing the magnitude of fire damage in an urban area resulting from a nuclear attack is the fire spread between individual structures. This paper investigates the effects of various methodological assumptions, using the basic physical models of fire spread by radiation and firebrands contained in the IITRI model. As an introduction to probabilistic effects, various regimes of solutions to fire spread by radiation in individual tracts are obtained by simplifying the IITRI model.

The spread of fire down rows of buildings and in rectangular grids, when each structure has a constant probability of igniting adjacent structures, is followed through a Monte Carlo simulation. Changes in fire spread patterns, as the probabilities are changed, are illustrated. The effects of various complicating features, such as random initial ignitions and varying ignition probabilities for each structure, are studied individually. Finally, a Monte Carlo simulation model is developed which contains almost all of the physical features of fire spread in the IITRI model. The spread of fire by firebrands across firebreaks, and the effects of ignition probabilities on the rate of fire spread are illustrated through the use of this model.

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Chapter I

INTRODUCTION

One of the most uncertain of the damaging agents from a nuclear attack on an urban area is fire. Despite the extensive research on the effects of thermal radiation from nuclear weapons on fire initiation, fire growth in buildings, and fire spread between buildings, there remains uncertainty in the extent to which fire damage will supplement blast damage, the survivability of people in fire areas, and the effectiveness of fire countermeasures. Recent studies have demonstrated the importance of interaction of blast damage and fire initiation and spread, and the need for further research to adequately understand these interactions. Moreover the circumstances under which individual fires will coalesce and give rise to mass fires adds additional problems to the prediction of fire effects.

This paper addresses the nature of fire spread between individual structures, which is the central methodological feature of many fire-spread models. It takes as given the initiation of fires, and the initial growth of fires in structures. It does not include reinforcement of fires due to mass fire effects, or blast/fire interactions although it does indicate how such effects might be added. Within this framework, this paper concentrates upon methodological implications rather than physical assumptions. The purpose of the study is to improve fire-spread models by providing a more basic understanding of the results of various methodological assumptions of fire-spread effects. In particular, it studies the implications of performing probabilistic calculations of fire-spread rather than expected value calculations.

Of the various models of fire damage phenomena, the IITRI Fire Spread Model of A.N. TAKATA [1,2,3] has probably gained the greatest acceptance. The IITRI model divides an urban area into tracts with a number of types of buildings in each tract. For each building type, fire effects within a tract are assumed to be uniform. It assesses the likelihood of primary building ignition by thermal radiation, the likelihood of fire spread to unignited buildings by radiation from burning buildings, and fire spread in and between tracts by firebrands. The IITRI model has been implemented on a computer and a few trial runs have been made. Unfortunately, not enough experience has been acquired from using the model to gain insight into the effects dominating the model.

A simplified version of the IITRI model has been developed by Miercort [4] that does not consider the ignition portion of the IITRI model, but extends it to allow for multiple weapon effects and considers buildings that have undergone blast damage. It thus is structured to allow more complex blast fire interactions. It has been computer implemented, but only a few runs with this model have been made.

In Chapter II, the behavior of the equations of the Miercort model are studied. Simplifications are developed which preserve the general nature of the solutions but which allow defining various regimes of fire spread. Criteria are developed which give the total number of buildings burned and burning times as a function of the number of initial ignitions and initial burning density.

In Chapter III probabilistic effects are introduced following a string of ignitions down a single or double row of ignitible buildings and computing the distributions of numbers of buildings burned with varying probabilities of propagation between buildings.

In Chapter IV the propagation of fires between buildings which have a fixed probability of transmitting a fire to an adjacent building and are arranged in rectangular grids is studied through a Monte Carlo simulation. The differences in behavior of the fire spread as the probability of spread is presented, and measures are developed to describe these phenomena. The overall fire spread by radiation is compared to that expected from the IITRI model.

In Chapter V the model is extended to include various effects. The effects of varying ignition patterns, random initial ignitions, transmissions of fire in one of multiple burning periods, and different spread probabilities for each building are all studied separately. Finally, a simulation model is developed which includes all these effects as well as fire spread by firebrands. This model includes almost all of the physical fire spread features contained in the IITRI model.

Chapter II

EXPECTED VALUE RADIATION TRANSPORT MODELS

This chapter will discuss an expected value representation of fire spread by radiation obtained by simplifying the Miercort representation of the IITRI model to a single type of structure, and concentrating attention upon these features of the model that influence fire spread by radiation. A pair of differential equations are obtained to describe burning rates. The regimes of the solutions of these equations are explored. The Chapter differs from others in this report in that a general familiarity will be the IITRI fire spread model is assumed.

A target area is represented as a number of tracts which presumably have fire breaks between them. The fire spread within a tract is primarily by radiation, and between tracts by firebrands. The model gives the probability of a burning building wall igniting an adjacent unburned wall as a function of the distance between the walls. The distance between adjacent walls is given as a probability density function which depends upon the density of buildings in a tract. The following paragraphs formalize these concepts.

Following the IITRI model, call the probability function PR(r) the probability that a burning building will ignite another at a distance r from it. Call FR(ξ) the probability that the nearest building within 45° from a perpendicular to a randomly chosen wall of a randomly chosen building is within a scaled distance ξ, where,

$$\xi = r\sqrt{\rho}/S,$$

with r = the actual distance,

S = the average base dimension of a building,

ρ = building density $= \frac{NS^2}{A}$, with N the number of buildings in a tract of area A.

Now call $\bar{\rho}$ the density of unburned buildings in a tract. Then the expected number of ignitions produced by a burning building, $SR(\bar{\rho})$, is given by the integral

$$SR(\bar{\rho}) = 4\frac{\sqrt{\bar{\rho}}}{S}\int_0^\infty PR(N,r) \cdot \left.\frac{dFR(\xi)}{d\xi}\right|_{\xi = \frac{r\sqrt{\bar{\rho}}}{S}} dr \quad ,$$

which sums the probability of fire spread at some distance times the probability of being at that distance. The factor 4 occurs since a building has four walls that may spread fire.

In [4], $SR(\bar{\rho})$ is computed to be

$$SR(\bar{x}) = \begin{cases} 118.4\bar{x}^{0.5} \quad , & \bar{x} < 6.1 \cdot 10^{-5} ft^{-2} \\ 6.35\bar{x}^{-0.199} \quad , & \bar{x} > 6.1 \cdot 10^{-5} ft^{-2} \quad , \end{cases}$$

where $\bar{x}$ is defined as $\sqrt{\bar{\rho}}/S$.

Now $\bar{\rho}$ is $\frac{NS^2}{A}$, so

$$\frac{\sqrt{\bar{\rho}}}{S} = \sqrt{\frac{N}{A}} = \sqrt{\bar{x}} \quad , \qquad .$$

and thus $\bar{x}$ is the number of unburned buildings per unit area.

A value of $\bar{x} = 6.1 \cdot 10^{-5} ft^{-2}$ corresponds to 2.65 unburned buildings per acre. When $\bar{x} = 9.2697 \cdot 10^{-5} ft^{-2}$ (4.027 $acre^{-1}$), $SR(\bar{x})$ is 1, which implies that each burning building ignites only one other. For larger values of SR than the critical value, just after ignition one would expect the number of burning buildings to increase, for smaller values to decrease. In the IITRI report, characteristics of various tracts in the cities of Detroit, Albuquerque, and San Jose are presented. Values of $\bar{x}$ ranged from about 4 to 10 $acre^{-1}$ for most tracts.

After ignition of a building, a certain time is required for a fire to develop to a point where other buildings may be ignited. This time delay can vary considerably with the type of building. We shall take the time delay, t_d, as a constant time, b, plus a time exponentially distributed, i.e.,

$$p(t_d) = \frac{1}{a} \exp^{-a(t-b)} .$$

Values of b of 1/15 hour (4 minutes) and a of 1/2 hour will be used later as typical values. In the IITRI, studies [1], a Stage 1 fire is defined as a fire in a room before it builds to flashover engulfing the entire room; a Stage 2 fire is defined as a fire spreading from room to room throughout a building; and a Stage 3 fire is defined as one fully developed where other buildings can be ignited. With t in hours, the probability of staying in a time t in a Stage 1 fire is given as $\exp(-3.6t)$ and in Stage 2 as 0 for $t < 0.08$ and $\exp(-21(t-.08))$ for $t > 0.08$. In the fire model of [3], one-fourth of the fire spread by radiation was assumed to occur at exactly 1/2 hour, one-half of the spread was assumed to occur at 3/4 hour, and one-fourth of the spread at 1 hour. For spread of fire by firebrands, three-fourths are assumed to occur at exactly 1 hour and one-fourth at 1 1/2 hours. Thus, a mean time of 1/2 hour may be somewhat short and a mean time of 1 hour somewhat long.

The equations describing fire spread including time delays become stochastic non-linear differential-difference equations, quite intractable analytically. The fire computer programs of [1,2, and 3] de-emphasize the stochastic nature and obtain numerical solutions of the resulting equations. The approach we follow below is to study a somewhat idealized situation for transport by radiation where the general nature of the type of solution becomes evident.

In the spread of fire by radiation within a tract, if expected values are used and time delay effects are neglected, then a pair of differential equations can be obtained from the model of [4] to describe radiative fire spread in a tract as follows: Let F3 (following the notation of [4]) be the number of unburned buildings in a tract, and F6 the number of burning buildings. Assume all the buildings in the tract are of one type. The expected number of buildings ignited by a burning building is SR(x), where x is F3/A, with A being the tract area. Let a building spread fire during a period T3; and, as in [4], assume it is equally likely to spread a fire any time in this period. Then the rate of ignition of other buildings by a burning building is SR/T3.

The rate of decrease in number of unburned buildings with time t is given by the rate of ignitions, so

$$\frac{dF3}{dt} = -SR(F3/A)\frac{F6}{T3} \cdot$$

The change in number of burning buildings is given by the rate of ignitions minus the rate of extinguishment. Thus,

$$\frac{dF6}{dt} = \frac{F6}{T3} \; SR(F3/A) - \frac{F6}{T3} \cdot$$

Call x = F3/A. Then SR(x) is as given earlier. Let a dimensionless time τ be defined by t/T3. Let y be defined as F6/A.

Then,

$$\frac{dx}{d\tau} = -SR(x)y \ ,$$

$$\frac{dy}{d\tau} = (SR(x)-1)y \ ,$$

$$\text{with } SR(x) = \begin{cases} 0.5673x^{0.5} \ , & x < 2.657 \text{ buildings/acre} \\ 0.7579x^{0.199} \ , & x \geq 2.657 \text{ buildings/acre} \ . \end{cases}$$

The initial conditions are $x = x_0$, $y = y_0$ at $t=0$.

While these equations cannot be explicitly solved, a few comments can be made concerning their behavior. A first integral of the second equation gives

$$y = y_0 \exp\left(\int_0^\tau (SR(x)-1)\right) d\sigma \ .$$

As long as $SR(x) > 1$ ($x > x_c = 4.027$), the density of burning buildings initially increases before it eventually decreases due to a scarcity of unburned buildings. For $x_0 < 4.027$, the density of burning always decreases. For x_0 larger than this critical value, the density increases for a period and then decreases. The burning can be separated into two phases: $x > x_c$ where the fire increases, and $x < x_c$ where the fire is decreasing. Call y_c the burning density when $x = x_c$. Then the final fraction of burned buildings depends only on y_c, the density of burning buildings when the peak burning density is reached at the critical density x_c. Figure 1, obtained from numerical integration of the differential equation, shows this function.

Figure 2 shows a set of solutions for $x(\tau)$ and $y(\tau)$ with several values of initial ignition when the original density, x_0, is 6 buildings per acre. In this case the original density x_0 is greater than 6, so an initial increase in burning density occurs, followed by a dropoff when the critical density is

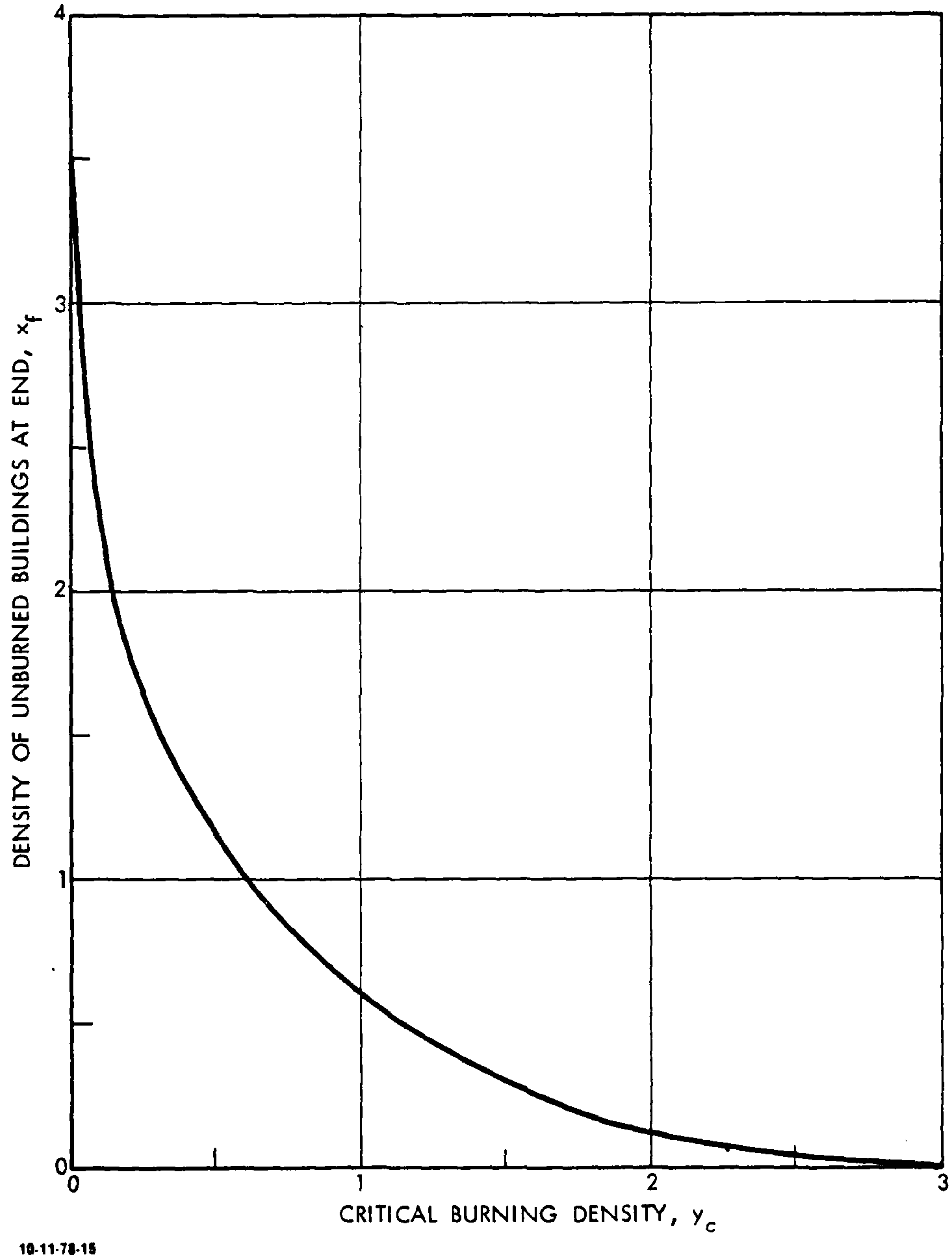

Figure 1. DENSITY OF UNBURNED BUILDINGS AT THE END OF THE FIRE AS A FUNCTION OF BURNING DENSITY WHEN THE CRITICAL UNBURNED BUILDING DENSITY IS REACHED

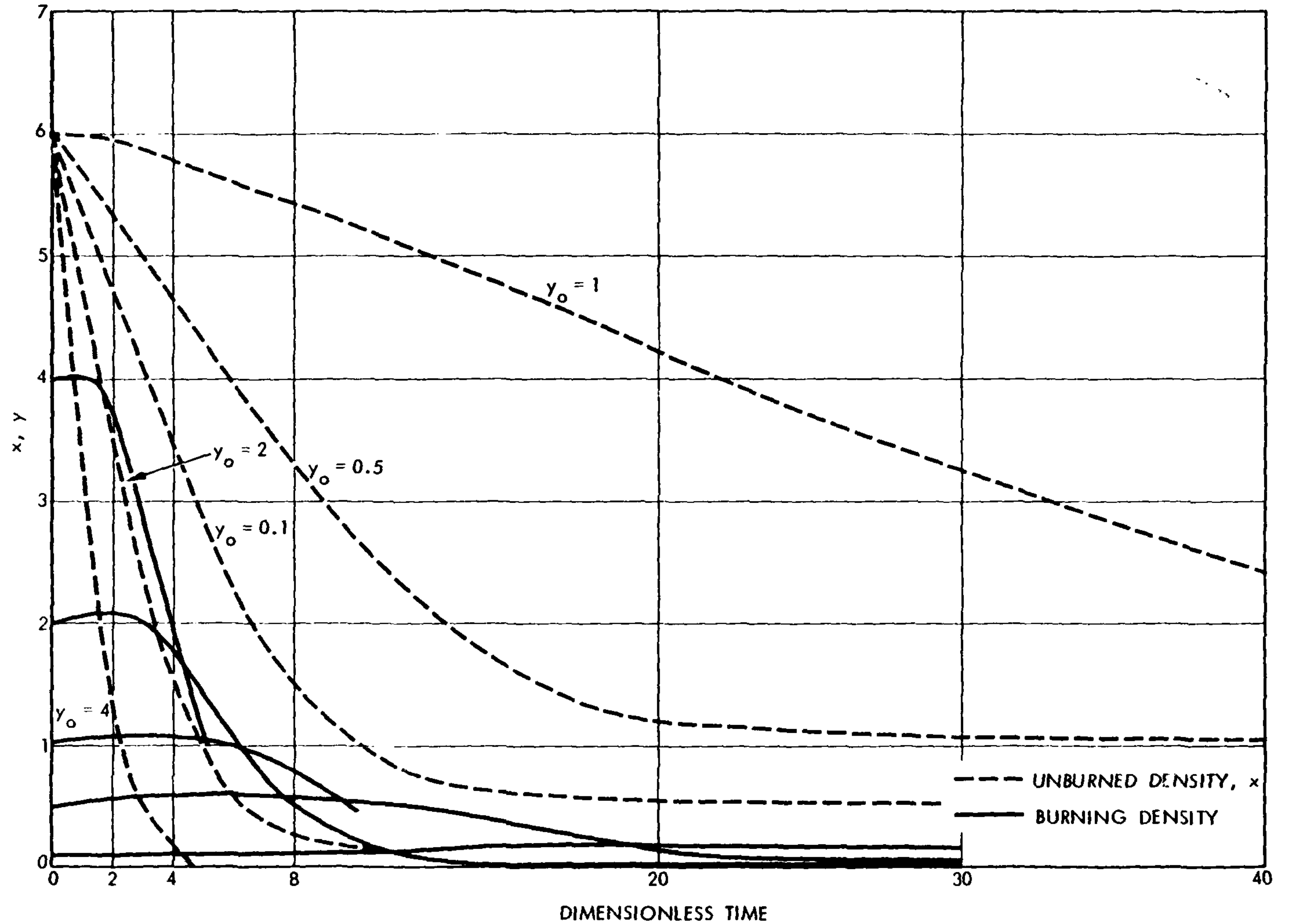

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Figure 2. UNBURNED BUILDING DENSITY X AND BURNING DENSITY AS A FUNCTION OF TIME FOR ORIGINAL BUILDING DENSITY, 6 BUILDINGS PER ACRE

reached. Two types of final burning are illustrated here: Case A--those where not all buildings are burned when the burning dies out; and Case B--where the burning density is greater then 0 when all buildings are burned. Approximate expressions for the final burning can be obtained for those two cases. For Case A, assume x is constant, or more specifically, SR(x) is constant = SR. Then we have

$$\frac{dy}{d\tau} = (SR-1)y \ ,$$

from which

$$y = \bar{y}\ \exp[(SR-1)t] \ ,$$

where $\bar{y}$ is a burning rate when the final phase is approached. Here it is seen that the fire dies exponentially, with an infinite time required for final extinction.

For Case B, assume the burning rate is a constant $\bar{y}$ during the final phase. Then

$$\frac{dx}{d\tau} = -SR(x)\bar{y} \ ,$$

$$= -ax^{b}\bar{y} \ ,$$

from which

$$x_{\bar{\tau}}^{1-b} - \bar{x}^{1-b} = -\bar{y}a\left(\tau_{\bar{\tau}} - \bar{\tau}\right)$$

where $\bar{x}$ and $\bar{\tau}$ are values of x and τ at the start of the final phase, and $x_{\bar{\tau}}$ and $\tau_{\bar{\tau}}$ are values at the end. Since b has a value of 0.2, the final decrease in unburned building density is quite rapid.

In Figure 2 where the initial density is 6 buildings/acre, it is seen that the burning rate does not increase greatly over the initial rate. The peak in burning rate at various initial building densities and initial burning rates is illustrated in Figure 3. It is seen that the contours of constant peak

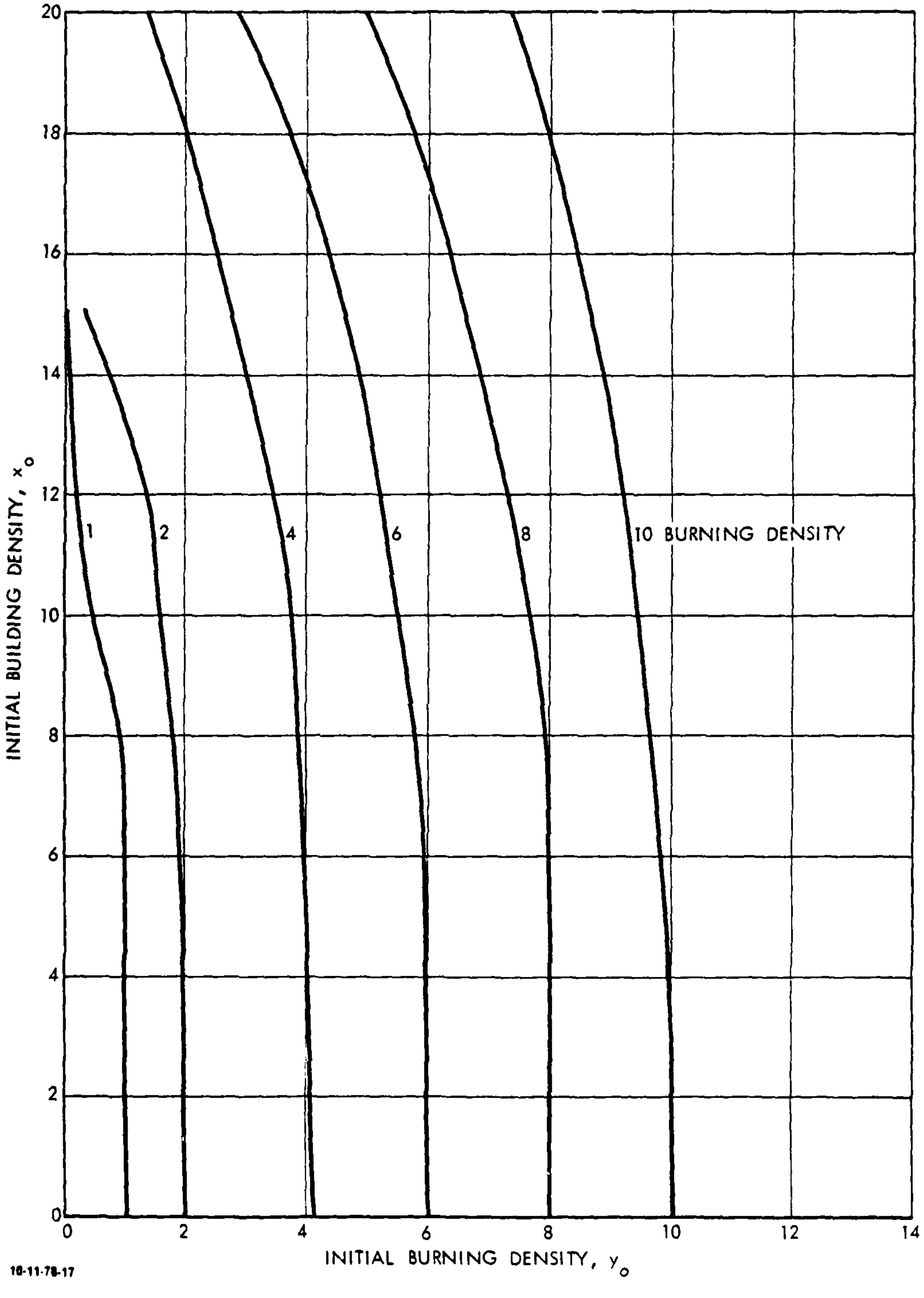

Figure 3. CONTOURS OF CONSTANT PEAK BURNING DENSITY AS A FUNCTION OF INITIAL BURNING DENSITY Y_0 AND BUILDING DENSITY X_0

burning are always quite steep, indicating that the peak rate does not grow drastically before the decrease in building density to the critical value prevents further growth in the burning rate.

Contours of constant final number of unburned buildings are shown in Figure 4. Of interest is the low final building density which is found even when the initial burning rate is rather small. This occurs, of course, since in the model the burning rate does not start to decrease until the unburned building density is 4, no matter how high the initial density.

The number of time periods required for either the fire to die out or the area to be burnt completely are shown in Figure 5. These times are given as multiples of the time T3 during which a building may spread fire. If T3 is assumed to be 3/4 hour, say, then burning times ranging from 1-1/2 to about 40 hours are illustrated here. This analysis neglected the time delay between ignition and fire spread. For the shorter time shown, this neglect would have a serious effect upon the rate of fire spread, which would be significantly slower. For the lower initial burning rates, however, the change of conditions is sufficiently slow that neglecting the time delay would not seriously affect the results.

Underlying these models is the assumption that the density of unburned buildings remains uniform in a tract as the tract burns. If, for example, a tract were ignited in one corner and a front of burning buildings progressed to the other corner, this assumption would be clearly violated; instead of a uniform density there would be a region of burnt buildings, a front of burning buildings, and a region of unburnt buildings. In this case the average distance between a burning wall and unburnt walls would not increase, as is the basic assumption in this model controlling the burning rate. Moreover, the model assumes each house may ignite four others. While this may be true for initial ignitions, for an advancing front of burning houses there are

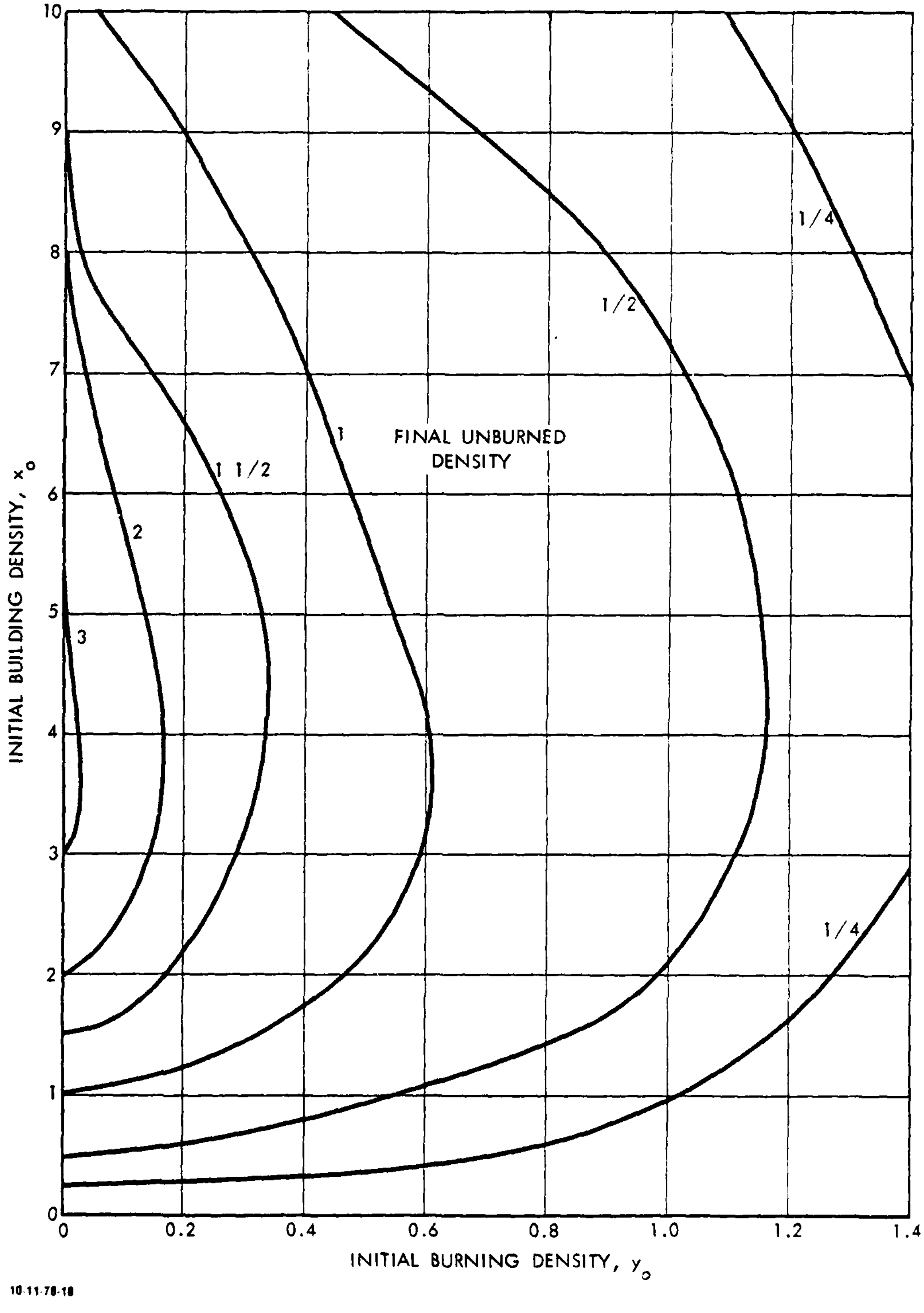

Figure 4. CONTOURS OF CONSTANT FINAL UNBURNED BUILDING DENSITY AS A FUNCTION OF INITIAL BUILDING DENSITY AND BURNING DENSITY

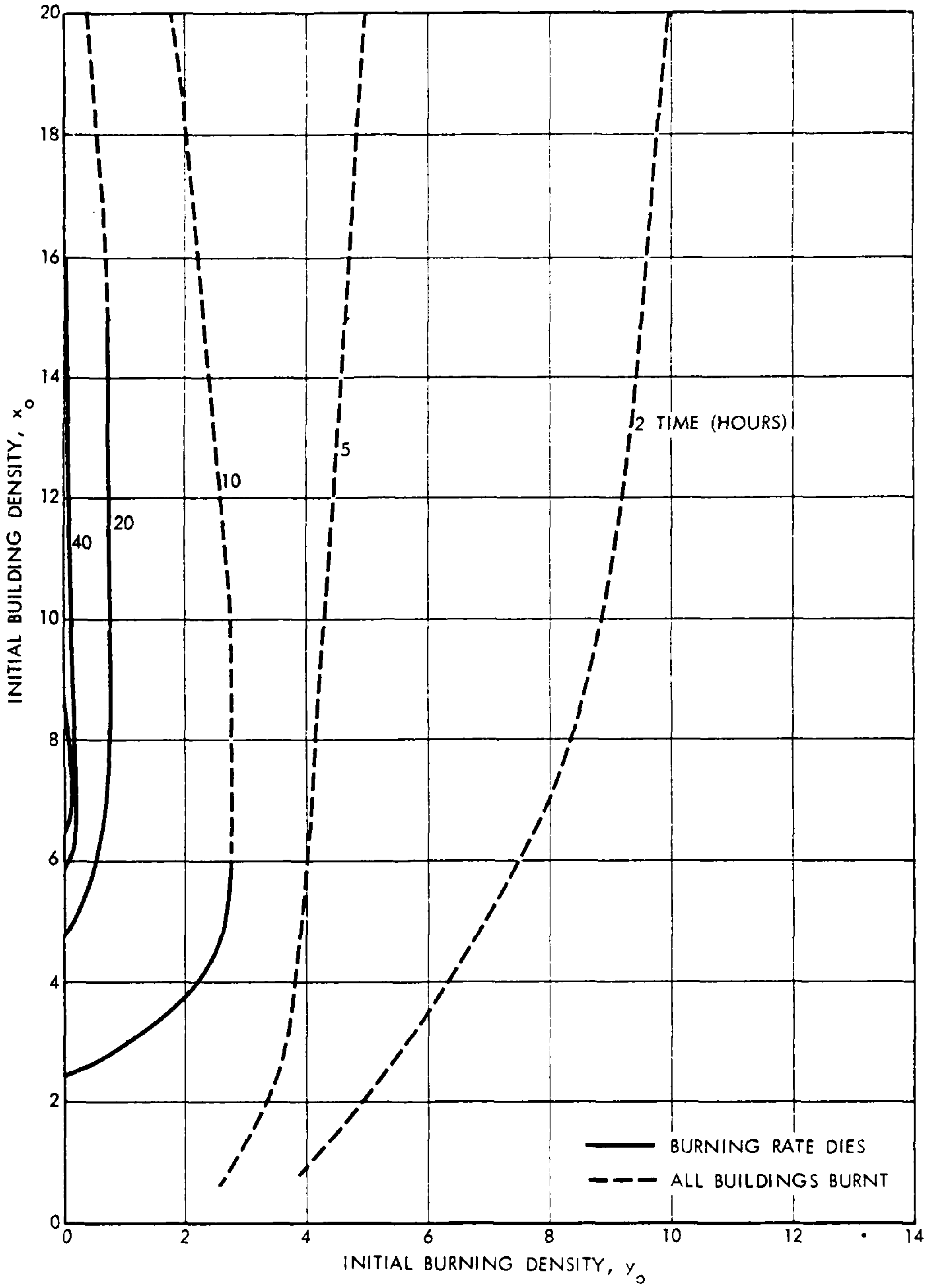

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Figure 5. CONTOURS OF CONSTANT TIME TO FIRE END AS A FUNCTION OF INITIAL BURNING RATE AND BUILDING DENSITY

burnt houses behind the front which cannot be ignited. Thus, an overestimate of propagation probabilities is obtained. On the other hand, when ignitions are random within a tract, the basic assumptions of these models may be closely approximated, since the effect of a burned building may then be to increase the average distance between walls. These questions provide one motivation for a more basic study of fire propagation within tracts.

Chapter III

ONE DIMENSIONAL PROBABILISTIC MODELS

A. SINGLE ROW OF BUILDINGS

Consider a row of buildings with a constant probability, p, of fire transfer from one building to the next. Suppose building 0 at one end of the row of buildings is ignited. It may ignite building 1; the probability of the event is p. Building 2 may be ignited only if building 1 is ignited. The probability of transmission to both building 1 and building 2 is $p \cdot p = p^2$. For building n, the probability of transmission is p^n. Table 1 gives the expected number of buildings ignited (given by $p/(1-p)$) and the 10th, 50th, and 90th percentile number of buildings ignited for various probabilities, p. Since any failure to ignite will cause a termination of the chain, rather high propagation probabilities are required before large numbers of additional buildings are ignited.

B. DOUBLE ROW OF BUILDINGS

A configuration somewhat richer in possibilities but still relatively simple to describe analytically is a double row of buildings that has a probability p_d of transmission of burning down the row, and a probability p_c of transmission across the row. An example of such an arrangement is a residential block with p_d representing the probability of transmitting from one house to the next along a street, and p_c representing the probability of transmitting across an alley to houses on the other side of the block.

Table 1. STATISTICS ON IGNITED BUILDINGS FOR VARIOUS TRANSITION PROBABILITIES

Transition Probability	Expected Number	Percentiles		
		10	50	90
0.2	0.25	0.06	0.43	1.43
0.5	1	0.15	1	3.32
0.6	1.5	0.21	1.21	4.51
0.7	2.33	0.30	1.94	6.46
0.8	4	0.47	3.11	10.32
0.9	9	1	6.57	21.85
0.95	19	2.05	13.51	44.89

Now imagine that at one end of the block either one building is ignited, or both are. Assume that an ignited building burns for one time period, at the end of which it may or may not ignite adjacent buildings. Then some measure of the distance the ignitions propagated down the block is desired. One way to study such a question is to classify the various ways in which a flame front may advance down the double row of buildings. Figure 6 illustrates such a classification of burning fronts. In this figure an indefinite number of buildings are assumed to be to the right, indicated by two sets of double dots. An unburnt building is indicated by a • , a burning building by an x, a burnt building by a z. A u indicates that a building cannot influence the propagation of the advancing front--it may be either unburnt, burning or burnt. This classification has the property that at the next period any possible transition from one of the configurations presented is also one of these configurations. For example, configuration 5 on the next step could become: (a) configuration 5 if both top and bottom adjacent unburnt structures ignite; (b) configuration 11 if the adjacent unburned structure on the

Configuration Number	Configuration	Comments
1	u x • • u x • •	
2	u x • • u z • •	Even Front
3	u z • • u x • •	
4	u z • • u z • •	
5	u x • • x • • •	
6	x • • • u x • •	
7	u x • • z • • •	Front Staggered By One Building
8	z • • • u x • •	
9	u z • • z • • •	
10	z • • • u z • •	
11	u z x • u • • •	
12	u • • • u z x •	Front Staggered By More Than One Building
13	u z z • u • • •	
14	u • • • u z z •	
• = Unburned Buildings x = Burning Buildings z = Burnt Buildings u = Any Condition		

Figure 6. CONFIGURATION OF BURNING FRONTS

top row ignites but that on the bottom row does not; (c) configuration 3 if the adjacent unburned structure on the bottom row ignites but that on the top row does not; and (4) configuration 9 if neither ignites.

The probability of each of these events can be expressed in terms of p_c and p_d as shown in Table 2. In the matrix of probabilities, and initial configurations are represented by rows, and the final configurations by columns, $\overline{p}_d$ represents $1 - p_d$, and $\overline{p}_c$ represents $1 - p_c$. Thus, for example, the probability of transition from configuration 5 to 9 is seen to be $(1-p_d)^2$. Now since any possible transition from a configuration is a configuration, and since the transition probabilities between configurations depend only upon the current configurations and not upon past history, the transitions form a Markov process with the configurations being states of the process. If $\vec{X}_0$ is a 14 component vector giving the probabilities of being in some initial set of states, and $\vec{X}_n$ gives the probabilities of being in various states after n transitions, then $\vec{X}_n = \vec{X}_0 \cdot T^n$, where T is the transition matrix shown in Table 2.

States 4, 9, 10, 13, and 14 represent absorbing states where the burning front can no longer advance; i.e., no buildings at the front are burning. As n increases, the probability of being in one of these states approaches 1. An estimate of the expected number of buildings burnt is obtained by summing the number of burning buildings for each time period as shown in Table 3.[1] This is actually a lower bound since it does not include the possibility of burning progressing to the left. For example, from state 11 (or state 12) a transition could be made to state 3 (or state 2)--now an unburned building is behind a burning building and could be ignited by it. An estimate of the

[1] The values in Table 3 were obtained by simply carrying out enough transitions so that at least 99 percent of the time all buildings are extinguished. The values thus are slightly lower than the limiting value for an infinite number of transitions.

Table 2. MATRIX OF TRANSITION PROBABILITIES FOR DOUBLE ROW OF BUILDINGS

Configurations	Initial State	Final State													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
u x · u x ·	1	p_d^2	0	0	$\bar{p}_d^2$	0	0	$p_d\bar{p}_d$	$p_d\bar{p}_d$	0	0	0	0	0	0
u x · u z ·	2	0	0	0	$\bar{p}_d$	0	0	p_d	0	0	0	0	0	0	0
u z · u x ·	3	0	0	0	$\bar{p}_d$	0	0	0	p_d	0	0	0	0	0	0
u z · u z ·	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0
u x · x · ·	5	0	0	$\bar{p}_d^2 p_c$ $+p_d p_c p_d$ $+p_d\bar{p}_c p_d$	0	$p_d^2\bar{p}_c+p_d^2 p_c$ $p_d p_c\bar{p}_d$	0	0	0	$\bar{p}_d^2\bar{p}_c$	0	$p_d\bar{p}_d\bar{p}_c$	0	0	0
x · · u x ·	6	0	$p_d^2 p_c$ $+\bar{p}_d p_c p_d$ $p_d p_c p_d$	0	0	0	$p_d^2\bar{p}_c+p_d^2 p_c$ $+p_d p_c\bar{p}_d$	0	0	0	$\bar{p}_d^2\bar{p}_c$	0	$p_d\bar{p}_d\bar{p}_c$	0	0
u x · z · ·	7	0	0	$p_c\bar{p}_d$	0	$p_d p_c$	0	0	0	$\bar{p}_d\bar{p}_c$	0	$p_d\bar{p}_c$	0	0	0
z · · u x ·	8	0	$p_c\bar{p}_d$	0	0	0	$p_d p_c$	0	0	0	$\bar{p}_d\bar{p}_c$	0	$p_d\bar{p}_c$	0	0
u z · z · ·	9	0	0	0	0	0	0	0	0	1	0	0	0	0	0
z · · u z ·	10	0	0	0	0	0	0	0	0	0	0	1	0	0	0
u z x · u · · ·	11	0	0	$\bar{p}_d p_c$	0	$p_d p_c$	0	0	0	0	0	$p_d\bar{p}_c$	0	$\bar{p}_d\bar{p}_c$	0
u · · · u z x ·	12	0	$\bar{p}_d p_c$	0	0	0	$p_d p_c$	0	0	0	0	0	$p_d\bar{p}_c$	0	$\bar{p}_d\bar{p}_c$
u z z · u · · ·	13	0	0	0	0	0	0	0	0	0	0	0	0	1	0
u · · · u z z ·	14	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Note. $\bar{p}_d = 1 - p_d$, $\bar{p}_c = 1 - p_c$.

Table 3. ESTIMATED EXPECTED NUMBER OF IGNITIONS FOR DOUBLE ROWS OF STRUCTURES

Transition Probability Along Rows, p_d	Transition Probability Across Rows, p_c					
	0	0.2	0.4	0.6	0.8	1.0
0.2	0.25 (0.25)	0.57 (0.58)	0.92 (0.92)	1.29 (1.29)	1.69 (1.69)	2.12 (2.12)
0.4	0.66 (0.66)	1.26 (1.31)	1.92 (1.97)	2.68 (2.71)	3.55 (3.55)	4.55 (4.55)
0.5	1.0 (1.0)	1.86 (2.02)	2.84 (2.98)	3.99 (4.07)	5.33 (5.35)	6.90 (6.90)
0.6	1.5 (1.50)	2.85 (3.34)	4.44 (4.80)	6.34 (6.52)	8.63 (8.68)	11.45 (11.45)
0.7	2.33 (2.33)	4.75 (6.33)	7.64 (8.63)	11.11 (11.54)	15.27 (15.37)	21.17 (21.17)
0.8	4.00 (4.00)	9.41 (15.02)	16.14 (19.16)	24.28 (25.39)	35.01 (35.26)	48.82 (48.82)
0.9	9.00 (9.00)	31.16 (63.18)	58.34 (70.16)	92.54 (96.30)	137.52 (138.24)	198.45 (198.45)
0.95	19.00 (19.00)	106.44 (231.93)	216.31 (251.04)	357.58 (367.24)	542.64 (544.36)	797.23 (797.23)

expected number of back burnings for each entry into state 11 is given by

$$B = \sum_{i=1}^{\infty} \left\{ i \left[\frac{p_c}{1-\bar{p}_c p_d} \cdot p_d^i \right] \cdot \left[(p_d p_c)^i + \sum_{n>i} (p_d p_c)^n \cdot \bar{p}_d \right] \right\} .$$

Values corrected by this estimate are shown in parenthesis in Table 3. As would be expected, when the transition probability down the row is high, but the transition probability across the row is low, a significant difference is obtained because a fire may propagate for a considerable distance along one side without jumping across to the other side. In other cases, however, the differences are relatively small.

At each stage, the probability of an advance of the burning front, i.e., the furthest distance a building is burning on either side is increased by one, can be determined by summing the probabilities of all transitions that advance the burning front. The expected distance the burning front travels is given by the sum of the expected advances for each time period. These distances are shown in Table 4. When the transition probability across rows is 0, the expected distance the front advances is the same as the expected number of buildings burnt. As the across-row transition probability approaches 1, the expected distance travelled approaches 1/2 the expected number of buildings burnt, since with each advance the building across the row will be burnt in the next period, if it is not already burnt.

Table 4 shows the strong effect a double row of structures has upon the propagation of a front. With only a single row of buildings (or, equivalently, an across-row transition probability of 0), any break in the chain of transition will cause extinguishment. With the double row there must be simultaneous failures on each side before this can occur. It is evident that this provision of alternative paths has a drastic effect

Table 4. EXPECTED DISTANCE FOR BURNING FRONT TO TRAVEL BEFORE EXTINGUISHMENT

Transition Probability Along Rows, p_d	Transition Probability Across Rows, p_c					
	0	0.2	0.4	0.6	0.8	1.0
0.2	0.25	0.30	0.36	0.42	0.49	0.56
0.4	0.67	0.84	1.03	1.24	1.49	1.77
0.5	1.00	1.29	1.61	2.00	2.44	2.96
0.6	1.50	2.01	2.60	3.31	4.17	5.22
0.7	2.33	3.33	4.52	5.94	7.63	9.63
0.8	4.00	6.39	9.89	13.00	17.35	22.63
0.9	9.00	19.44	32.37	48.56	69.87	98.73
0.95	19.00	61.50	115.06	183.93	274.09	398.12

upon the results. This leads to the important supposition that the propagation of fire by radiation within a block may be significantly affected by the detailed geometry of that block.

The previous results all assumed only one building was ignited at the end of a row. If two buildings are ignited and the transition probability is 0, then one would expect that exactly twice the number of buildings would be burnt. As p_c becomes larger, the difference decreases. Thus, for example, the expected number of buildings burnt when $p_d = 0.9$ and $p_c = 0.2$, the numbers are 31.16 for one initial ignition and 38.93 for two; at $p_c = 0.4$, the numbers are 58.34 for one initial ignition and 64.75 for two. The effect of the double ignition vanishes after a few transitions when the chance for the burning to skip across to the other row becomes significant.

Chapter IV

FIRE SPREAD IN SIMPLE RECTANGULAR GRIDS

This chapter considers fire spread in a rectangular grid covering the entire plane. No appropriate analytical description of this situation has been found; so the description presented here is primarily a heuristic analysis of the results of Monte Carlo simulations.

Consider a rectangular grid convering an entire plane where burnable structures are assumed to be at each grid intersection. If one structure is ignited, then it may ignite any of its four neighbors with a probability p.[1] After burning one period, these structures in turn may ignite any unburned neighbors, which in turn may ignite still others in the next period, and so on. On different trials a variety of burning and burnt patterns will be experienced, after traversing a variety of paths.

Although no proof has been developed, it appears likely that for transition probabilities above some critical value, the process is likely to continue indefinitely; in fact, a reasonable hypothesis is that for a transition probability greater than 0.5, the expected number of structures ignited is infinite, while at lower than 0.5 it is a finite value.

[1] In [1], the number of ignitable structure walls close to a burning wall that might be ignited by radiant transport was investigated. In most cases, only one such structure was at danger from each wall. Since most structures have four primary walls, the rectangular grid where each burning structure can ignite only its four closest neighbors seems most appropriate. If several structures in a row are burning, the radiation received by a nearby unburnt building wall is the sum of the radiation from all of the burning buildings, so its probability of ignition should be increased. The increase is neglected here, but would be an excellent item for further study.

Of course, early in the process no ignition might occur with reasonably high probability and the process could terminate; however, if the process does continue for later trials, the length of the boundary between burned and unburned points grows indefinitely and the ratio of actual new ignitions at some time period to possible new ignitions approaches a constant value. Thus the growth may be expected to continue indefinitely if the transition probability is high enough that a linear boundary may continue to travel.

As the transition probabilities change, different characteristics of the burning propagation are apparent. These are illustrated in a set of figures for various transition probabilities. Figure 7 illustrates a burning history for a transition probability of 0.3. In this figure the ignitable buildings form a 23 x 23 matrix. (The outer row is precluded from burning so in reality the matrix is 21 x 21.) Ignition of one building occurs at the center of the matrix, i.e., at row 12 and column 12. The buildings ignited are those elements of the matrix with nonzero values. The numbers represent the number of time periods from the time a building was ignited to the final time period when no more ignitions occurred. (After this last period there were no more fires in the matrix, even though on occasion fires would be burning beyond the boundary. The possibility that fires propagated outside the matrix at one point may burn back at another and ignite more structures if the matrix is ignored here.) Thus, in Figure 7 the last buildings ignited are indicated by 1, the next to the last by 2, and the first building ignited by 7. The contours are drawn at various time intervals simply to assist in visualizing the progress of the fire spread.

The propagation illustrated in Figure 7 is typical of the spread at this low transition probability, namely, a small growth followed by extinguishment. The probability that a

RESULTS AFTER 7 STEPS TRANSITION PROB. = .3000

==========RESULTS FOR TRIAL NO. ============

	J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I =	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	10	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	11	0	0	0	0	0	0	0	0	3	2	1	6	5	0	0	0	0	0	0	0	0	0	0
I =	12	0	0	0	0	0	0	0	0	4	5	6	7	0	0	0	0	0	0	0	0	0	0	0
I =	13	0	0	0	0	0	0	0	2	3	4	3	6	0	0	0	0	0	0	0	0	0	0	0
I =	14	0	0	0	0	0	0	0	1	2	3	0	5	4	3	0	0	0	0	0	0	0	0	0
I =	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.3

point will cause further ignitions depends upon the number of open branches (i.e., adjunct unburned buildings). Table 5 gives these probabilities. At the start there are four open branches, therefore, there is a 25 percent change of extinguishment. If there is one ignition, then the probability of extinguishment is 0.343 in the second period because the next point has only three open unburned braches available to it. If there are two ignitions in the first period, the probability of extinguishment is 0.118 in the second period. However, Table 5 cannot be used to compute the expected number of ignitions in the second period because it is possible that each burning structure would ignite the same unburned structure, and those would be double counted.

Table 5. PROBABILITY OF N IGNITIONS AT 0.3 TRANSITION PROBABILITY

Number of Open Branches	Number of Ignitions				
	0	1	2	3	4
4	0.24	0.41	0.26	0.08	0.008
3	0.343	0.44	0.19	0.03	0.00
2	0.49	0.42	0.09	0.00	0.00

Table 6 gives the probability of n ignitions on the first trial, the expected number of ignitions in the first period, the expected number of ignitions in the second period for n ignitions in the first period, and the expected number of buildings ignited in the second period. The expected ignitions in the second period include the double counting. For example, suppose three buildings were ignited in the first period. Without double counting each building could ignite three others for a total of nine potential burning buildings. Without double counting, at a transition probability of 0.3,

Table 6. STATISTICS FOR IGNITIONS FOR FIRST TWO BURNING PERIODS FOR VARIOUS TRANSITION PROBABILITIES

Probability of n Ignitions in First Period	Transition Probability				
	0.3	0.4	0.5	0.6	0.7
n = 0	0.24	0.13	0.06	0.03	0.01
n = 1	0.41	0.35	0.25	0.15	0.08
n = 2	0.26	0.35	0.38	0.35	0.26
n = 3	0.08	0.15	0.25	0.35	0.41
n = 4	0.01	0.03	0.06	0.13	0.24
Expected Number of Ignitions in First Period	1.2	1.6	2.0	2.4	2.8
Expected Number of Ignitions in Second Period Given n Ignitions in First Period					
n = 0	0.00	0.00	0.00	0.00	0.00
n = 1	0.9	1.2	1.5	1.3	2.1
n = 2	1.74	2.30	2.87	3.43	3.98
n = 3	2.56	3.35	4.13	3.95	5.53
n = 4	3.45	4.57	5.65	6.68	7.52
Expected Number of Ignitions in Second Period	1.05	1.84	3.17	3.69	5.29

an expected 2.7 buildings (= 9 x 0.3) would be ignited, whereas Table 6 shows the actual expected ignitions to be 2.56, about a 10 percent lowering.

For subsequent periods the number of possible configurations increases drastically, and calculations of all possible cases becomes most tedious. Table 7 presents the expected number of ignitions from n open branches assuming no double ignition possibilities. Such possibilities would serve to lower somewhat the values given. Thus, it can be seen for a transition probability of 0.3, the expected number of ignitions

Table 7. EXPECTED NUMBERS OF IGNITIONS FOR N OPEN BRANCHES

Number of Open Branches	Transition Probability				
	0.3	0.4	0.5	0.6	0.7
3	0.9	1.2	1.5	1.8	2.1
2	0.6	0.8	1.0	1.2	1.4
1	0.3	0.4	0.5	0.6	0.7

from each burning building is always under one and an extinguishment is to be expected.

For a value of transition probability of 0.5, say, the case is more complex: When three open branches are available to a burning point, the number of fires multiplies; when two are available, the fire stays constant; with one, the fire dies. The development depends upon the number of open branches and the seriousness of double ignitions. From Figure 7 the number of open branches, n, available to each burning building can be counted. They are: n = 4 is 1, n = 3 is 14, n = 2 is 5 and n = 1 is 2. Thus, in the preponderance of situations in this trial, three open branches were available. Thus one might expect a relatively slow dying out of the burning. This trial had a relatively high number of ignitions in the third period but was chosen to show some appreciable burning period. The actual number of buildings burning in this trial at successive periods was 1, 3, 3, 3, 5, 4, 3, 0. The number of possibilities for double ignitions is eight. On the average, with eight possibilities for a building to be ignited from two sources, one would expect 0 ignitions 3.92 times, ignition from one structure 3.36 times, and ignition from both buildings 0.72 times.

Figure 8 shows a burning trial with a 0.4 transition probability. The same general tendencies as with the 0.3 transition probability can be observed.

==========RESULTS FOR TRIAL NO. 6==========

RESULTS AFTER 42 STEPS TRANSITION PROB. = .4000

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	0	0	0	0	0	0	0	0	0	0	0	9	10	9	0	0	0	0	0	0	0	0	0
I = 12	0	0	0	0	0	0	0	0	0	0	0	12	11	10	0	0	0	0	0	0	0	0	0
I = 13	0	0	0	0	0	0	0	0	0	1	0	11	10	9	8	0	0	0	0	0	0	0	0
I = 14	0	0	0	0	0	0	0	0	1	2	0	4	0	8	7	0	0	0	0	0	0	0	0
I = 15	0	0	0	0	0	0	0	0	0	3	4	5	6	7	6	0	0	0	0	0	0	0	0
I = 16	0	0	0	0	0	0	0	0	0	0	0	0	0	6	3	0	0	0	0	0	0	0	0
I = 17	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4	0	0	0	0	0	0	0	0
I = 18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 8. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.4

Three cases of transitions with 0.5 probabilities are shown in Figures 9, 10, and 11. Since this 0.5 probability shows the greatest variation from trial to trial, these three cases are shown to illustrate the possibilities. In Figure 11 the method of presentation is varied, with the arrows between buildings indicating the direction of the transitions that occurred. In case of possible double igniting, both possibilities are shown, since that which actually caused the ignition is not of interest. Figures 12, 13, and 14 show trials at transition probabilities of 0.6, 0.7, and 0.8, respectively.

One means of describing the results of a trial is in terms of the number of buildings burning and number of open branches for each burning building at each burning period. These statistics are summarized for the trial presented in Figure 9 and Table 8.[1] In this table the number of predicted burnings for period n + 1 is computed on the basis of expected results at period n. To do this, the number of triple branches is multiplied by the expected number of burnings per triple branch, i.e., 1.5, double branches by 1.0, and single branches by 0.5. From this is subtracted the expected number of double ignitions for each double trial, i.e., 0.25. It can be seen that the number of ignitions on a successive trial can be predicted fairly well from the statistics on a previous trial. What cannot be easily predicted are the meanderings and starts and stops of the burning front.

Table 8 shows that the number of burnings with two open branches is comparable to that with three branches, although the ratio between the two changes drastically from trial to trial. Apparently the pattern is still not large enough to exhibit any approach to regularity in these statistics, and,

[1] In order to obtain statistics for more trials, the results in Figure 9 were extended a bit at the borders of the tableau by some hand drawing of random numbers.

==========RESULTS FOR TRIAL NO. 2============

RESULTS AFTER 33 STEPS TRANSITION PROB. = .5000

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	0	1	2	3	4	5	4	5	0	0	0	0	12	11	0	0	0	0	0	0	0	0	0
I = 3	0	0	0	4	5	6	5	6	7	0	0	0	13	14	15	0	0	0	0	0	0	0	0
I = 4	0	0	0	0	6	7	8	9	8	0	12	0	12	15	16	15	16	15	18	0	0	0	0
I = 5	0	2	1	6	7	8	9	10	9	12	13	14	11	16	17	18	17	20	19	0	15	14	0
I = 6	0	3	4	5	6	0	10	11	12	13	14	15	16	17	18	19	0	21	20	17	16	15	0
I = 7	0	0	0	0	5	0	9	0	11	12	11	14	15	14	19	20	21	22	21	18	17	14	0
I = 8	0	0	0	0	12	0	8	0	0	0	12	13	14	27	26	23	24	23	22	19	16	15	0
I = 9	0	12	13	14	13	0	7	6	0	0	0	0	13	28	27	24	25	24	21	20	0	14	0
I = 10	0	0	14	15	16	17	0	5	0	21	22	21	28	29	28	27	26	23	20	19	0	0	0
I = 11	0	12	13	12	17	18	19	0	19	20	23	22	27	30	29	26	25	22	21	20	19	0	0
I = 12	0	13	12	11	18	19	20	21	20	19	24	33	32	31	28	27	26	23	22	21	18	0	0
I = 13	0	14	15	14	13	20	21	22	23	24	25	28	29	30	29	28	25	24	23	20	17	16	0
I = 14	0	0	16	17	18	19	20	21	22	23	26	27	28	27	28	27	26	25	24	19	18	17	0
I = 15	0	0	15	16	17	18	17	20	0	0	25	24	0	26	27	26	25	18	23	20	0	0	0
I = 16	0	0	0	15	14	15	16	15	0	0	0	0	0	25	24	0	24	19	22	21	0	0	0
I = 17	0	0	0	0	13	14	15	0	0	0	0	0	23	24	23	22	21	20	19	18	17	0	0
I = 18	0	0	0	0	0	0	0	0	0	0	0	0	22	23	22	21	20	19	18	7	6	0	0
I = 19	0	0	0	0	0	0	0	0	0	0	0	18	21	20	21	0	0	18	9	8	0	0	0
I = 20	0	0	0	0	0	0	0	0	0	0	16	19	20	19	12	0	0	17	10	0	0	0	0
I = 21	0	0	0	0	0	0	0	0	0	0	17	18	19	18	13	14	13	12	11	0	0	0	0
I = 22	0	0	0	0	0	0	0	0	0	15	16	17	18	17	16	15	14	13	12	0	0	0	0
I = 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 9. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.5, SAMPLE A

RESULTS AFTER [illegible] STEPS ==========RESULTS FOR TRIAL NO. 5========== TRANSITION PROB. = .5000

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	0	0	0	0	0	0	0	11	10	0	0	0	0	0	0	0	0	0	0	0	2	1	0
I = 3	0	0	0	0	0	0	13	12	9	0	0	0	0	0	0	0	0	0	0	0	3	0	0
I = 4	0	0	0	0	0	0	14	13	12	0	0	0	0	0	0	0	0	0	0	5	4	3	0
I = 5	0	0	0	0	0	0	15	0	0	0	0	0	0	0	0	6	5	0	7	6	0	0	0
I = 6	0	0	0	0	0	0	16	15	0	0	0	0	0	5	6	7	6	9	8	7	0	0	0
I = 7	0	0	0	0	0	0	17	16	0	0	0	0	0	6	7	8	7	10	9	0	0	0	0
I = 8	0	0	0	0	0	0	18	15	16	17	16	11	4	5	8	9	10	11	10	0	0	0	0
I = 9	0	0	0	0	0	0	19	20	19	18	17	12	13	6	7	8	11	12	0	0	0	0	0
I = 10	0	0	0	0	0	0	0	21	0	0	18	13	14	15	16	0	12	13	0	11	0	0	0
I = 11	0	0	0	0	0	0	0	22	0	0	19	28	13	16	17	0	13	14	13	12	0	0	0
I = 12	0	0	0	0	0	0	0	23	22	21	20	29	28	15	18	17	16	15	14	13	0	0	0
I = 13	0	0	0	0	0	22	23	24	25	26	27	28	21	20	19	12	13	9	9	12	0	0	0
I = 14	0	0	0	0	0	0	0	0	24	25	26	23	22	0	0	0	14	13	10	11	0	0	0
I = 15	0	0	0	0	0	0	0	0	23	24	25	24	23	20	0	16	15	12	11	10	0	0	0
I = 16	0	0	0	0	0	0	0	0	0	23	16	21	22	21	20	17	16	15	12	11	0	0	0
I = 17	0	0	0	0	0	0	0	0	0	22	17	18	19	20	19	18	15	14	13	12	11	10	0
I = 18	0	0	0	0	0	0	0	0	0	21	18	17	18	19	0	17	14	13	10	0	10	9	0
I = 19	0	0	0	0	0	0	0	0	0	20	19	18	17	18	17	10	11	12	11	10	9	8	0
I = 20	0	0	0	0	0	0	0	0	0	19	18	17	16	15	16	9	8	0	2	1	8	7	0
I = 21	0	0	0	0	0	0	0	0	0	16	17	16	15	14	15	0	0	0	3	4	5	6	0
I = 22	0	0	0	0	0	0	0	0	0	0	16	15	14	13	14	0	0	0	2	0	4	5	0
I = 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 10. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.5, SAMPLE B

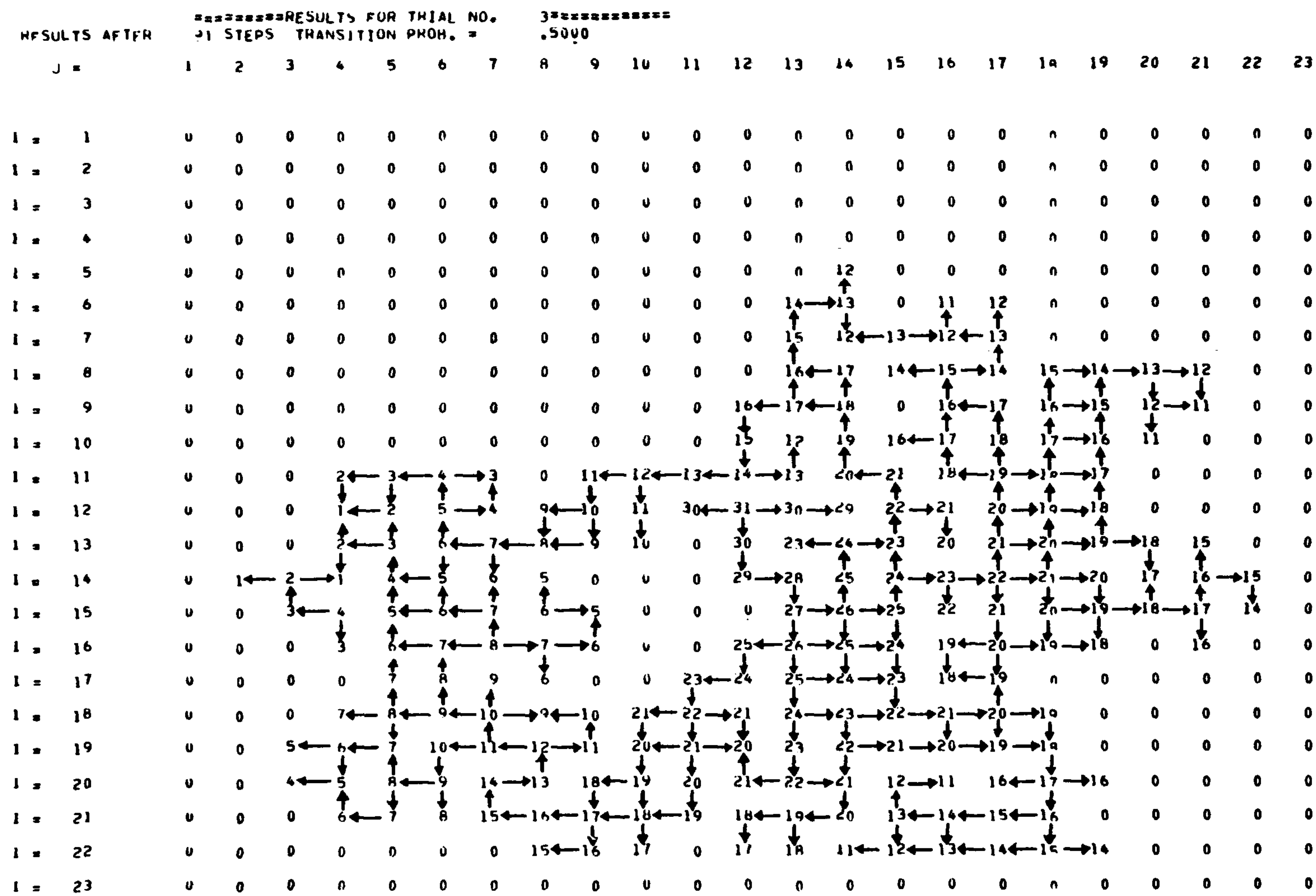

Figure 11. GRID FIRE SPREAD HISTORY SHOWING IGNITION PATHS FOR A TRANSITION PROBABILITY OF 0.5, SAMPLE C

RESULTS AFTER ========RESULTS FOR TRIAL NO. 2===========
38 STEPS TRANSITION PROB. = .6000

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	0	18	17	0	21	22	23	24	25	22	23	24	0	0	0	22	21	18	19	18	17	16	0
I = 3	0	19	0	0	0	23	24	25	26	27	24	25	26	25	0	23	22	19	20	19	16	15	0
I = 4	0	20	19	0	0	0	23	24	27	28	25	26	27	24	25	24	23	20	21	20	13	14	0
I = 5	0	21	22	23	24	0	24	25	26	29	26	27	28	27	26	25	24	23	22	21	20	13	0
I = 6	0	22	23	24	25	0	25	26	29	30	29	28	29	28	27	26	25	24	23	22	21	12	0
I = 7	0	21	22	25	26	27	28	27	30	31	30	31	30	29	28	27	26	23	22	21	20	17	0
I = 8	0	24	25	24	25	26	29	30	31	32	33	32	31	30	29	28	27	24	23	22	21	18	0
I = 9	0	25	26	25	26	27	28	29	0	33	34	29	30	29	28	27	26	25	20	21	20	19	0
I = 10	0	0	27	28	29	28	27	32	33	34	35	34	35	0	27	26	25	24	19	20	17	18	0
I = 11	0	27	28	29	30	31	32	33	34	35	36	35	36	21	26	25	24	23	14	15	16	17	0
I = 12	0	26	27	28	29	30	31	32	33	34	37	38	37	22	25	24	23	22	21	16	17	16	0
I = 13	0	25	26	27	28	29	30	31	32	35	36	37	36	23	24	23	22	21	20	19	18	17	0
I = 14	0	24	25	24	23	28	29	30	31	34	35	36	35	16	21	22	21	20	19	18	17	16	0
I = 15	0	23	24	23	22	19	28	0	32	33	34	35	8	17	20	21	20	17	18	17	16	13	0
I = 16	0	0	0	22	21	20	19	16	0	32	33	34	9	18	19	18	19	18	17	16	15	14	0
I = 17	0	0	0	19	20	19	18	17	16	15	14	11	10	17	18	17	18	17	16	15	14	13	0
I = 18	0	0	0	0	17	18	17	16	15	14	13	12	11	12	13	14	17	16	15	14	13	10	0
I = 19	0	11	12	13	16	17	12	13	14	11	12	11	12	13	14	15	16	15	14	13	12	11	0
I = 20	0	12	13	14	15	0	11	12	9	10	11	10	9	12	13	14	13	14	13	12	11	10	0
I = 21	0	11	12	13	12	0	0	1	2	9	10	9	8	7	8	11	12	11	12	0	0	0	0
I = 22	0	10	11	12	11	0	0	0	3	4	5	6	7	0	9	10	9	10	11	10	0	0	0
I = 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 12. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.6

RESULTS AFTER 24 STEPS

==========RESULTS FOR TRIAL NO. 6===========
TRANSITION PROB. = .7000

	J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I =	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I =	2	0	0	5	6	7	8	9	10	11	10	11	10	9	10	9	8	7	6	5	4	3	2	0
I =	3	0	5	6	7	8	9	10	11	12	13	12	9	10	11	10	0	6	7	6	5	2	1	0
I =	4	0	6	7	8	9	8	7	12	13	14	13	12	11	12	11	10	9	8	7	4	3	4	0
I =	5	0	7	8	9	10	11	12	11	14	15	14	13	14	13	12	11	10	9	8	3	4	5	0
I =	6	0	8	9	10	11	12	13	12	15	16	17	16	15	14	13	12	11	10	9	8	7	6	0
I =	7	0	9	10	11	12	13	14	15	16	17	18	17	16	15	14	13	12	11	10	9	8	7	0
I =	8	0	10	11	12	13	14	15	16	15	18	19	18	17	16	15	12	13	12	11	10	9	8	0
I =	9	0	11	12	13	14	15	16	17	16	19	20	15	16	15	18	13	14	13	10	11	10	9	0
I =	10	0	10	11	14	15	16	17	18	19	20	21	20	21	20	19	12	15	14	13	12	11	10	0
I =	11	0	9	12	15	16	17	18	17	20	21	22	23	22	21	20	15	16	15	14	13	12	11	0
I =	12	0	12	13	14	15	16	19	20	21	22	23	24	23	18	19	18	17	16	15	14	13	12	0
I =	13	0	11	12	13	14	15	18	19	20	21	22	23	22	21	20	19	18	17	16	15	14	13	0
I =	14	0	10	11	12	13	14	17	16	19	20	21	22	21	20	19	18	17	16	15	14	13	12	0
I =	15	0	9	10	11	12	15	16	17	18	19	20	19	20	19	18	17	16	15	14	11	12	11	0
I =	16	0	8	11	12	13	14	15	16	17	18	13	18	17	18	17	16	13	12	13	12	11	0	0
I =	17	0	9	10	11	12	13	14	15	16	17	14	15	16	17	16	15	14	13	12	11	10	9	0
I =	18	0	8	9	10	11	12	13	14	15	14	13	14	15	12	13	14	13	12	11	10	9	8	0
I =	19	0	7	8	9	4	11	12	13	14	13	12	13	14	13	12	13	12	11	4	9	8	7	0
I =	20	0	6	7	6	5	4	1	12	11	12	11	10	13	12	11	10	9	8	5	8	7	6	0
I =	21	0	5	6	5	4	3	2	11	10	11	10	9	12	11	10	9	8	7	6	5	6	5	0
I =	22	0	0	0	4	3	2	1	10	9	10	9	8	9	10	9	8	7	6	5	4	5	4	0
I =	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 13. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.7

RESULTS AFTER ==========RESULTS FOR TRIAL NO. 5============
42 STEPS TRANSITION PROB. = .8000

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	0	2	3	4	5	6	7	8	9	10	9	10	9	10	9	8	7	6	5	4	3	2	0
I = 3	0	3	4	5	6	7	8	9	10	11	12	11	10	11	10	9	8	7	6	5	4	3	0
I = 4	0	4	5	6	7	8	9	10	11	12	13	12	11	12	11	10	9	8	7	6	3	4	0
I = 5	0	5	6	7	8	9	10	11	10	13	14	13	12	13	12	11	10	9	8	7	6	5	0
I = 6	0	6	7	8	9	10	11	12	13	14	15	14	13	14	13	12	11	10	9	9	7	6	0
I = 7	0	7	8	9	10	11	12	13	14	15	16	15	14	15	14	13	12	11	8	9	8	7	0
I = 8	0	6	7	8	11	12	13	14	15	16	17	16	15	16	15	14	13	12	11	10	9	8	0
I = 9	0	7	8	9	12	13	14	15	16	17	18	17	18	17	16	15	14	13	12	11	10	9	0
I = 10	0	8	9	10	11	12	13	14	17	18	19	18	19	18	17	16	15	14	13	12	11	10	0
I = 11	0	9	10	11	12	11	14	15	16	17	20	21	20	19	18	17	16	15	14	13	12	11	0
I = 12	0	10	11	12	13	14	15	16	17	18	21	22	21	20	19	18	15	14	13	12	11	10	0
I = 13	0	9	10	11	12	13	14	17	18	19	20	19	20	19	18	17	16	15	14	13	12	11	0
I = 14	0	8	9	10	13	14	15	16	17	18	19	18	19	18	17	16	15	14	13	12	11	10	0
I = 15	0	7	8	9	12	13	14	15	16	17	16	17	18	17	14	15	14	13	12	11	10	0	0
I = 16	0	8	9	10	11	12	13	14	15	16	15	16	17	16	15	14	13	12	11	10	9	6	0
I = 17	0	7	8	9	10	11	12	13	14	15	14	13	16	15	14	13	12	11	10	9	8	7	0
I = 18	0	6	7	8	9	10	11	12	13	14	13	14	15	14	13	12	11	10	9	8	7	6	0
I = 19	0	5	6	7	8	9	10	11	12	13	12	13	14	13	12	11	10	9	8	7	6	5	0
I = 20	0	2	5	6	7	8	9	10	11	12	11	12	13	12	11	10	9	8	7	6	5	4	0
I = 21	0	3	4	5	6	7	8	9	10	11	10	11	12	11	10	9	8	7	6	5	4	3	0
I = 22	0	2	1	4	5	6	7	8	9	10	9	10	11	10	9	8	7	6	5	4	3	2	0
I = 23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

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Figure 14. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.8

Table 8. STATISTICS FROM A TRIAL WITH 0.5 PROBABILITY

Period Number	Number of Ignition Branches					Number of Double Trials	Actual Burnings	Predicted Burnings	Predicted Burnings at Period i/ Actual Burnings at i-1
	4	3	2	1	0				
33	1						1		
32		1					1	2.0	2.0
31		1					1	1.5	1.5
30		2					2	1.5	1.5
29		3	1			1	3	3.0	1.5
28		5	2			4	7	5.25	1.78
27		3	4	2		4	9	8.5	1.21
26		5	2	1		2	8	8.5	0.94
25		4	2	2		2	8	9.5	1.19
24		6	4	1		5	11	8.5	1.06
23		5	6	1		4	12	12.25	1.11
22		5	6	1		5	12	12.25	1.06
21		8	6	1		6	15	17.0	1.42
20		6	10	2		8	18	18.0	1.20
19		5	9	2	1	6	17	16.0	0.89
18		8	9			6	17	16.0	0.94
17		9	7	2		8	18	19.5	1.15
16		7	10			5	17	19.5	1.08
15		13	4	2		7	19	19.25	1.13
14		12	7	2		11	21	22.75	1.20
13		9	9	1		7	19	22.75	1.08

as can be seen from Table 8, the growth or decay in a particular part of the front can significantly affect the statistics of the whole pattern. Table 9 presents statistics comparable to Table 8 but for the 0.3 probability case of Figure 7. By comparison, it can be seen that the pattern dies out too rapidly for any significant development beyond the starting steps.

A steady growth of the number of burnings is apparent from Table 8. There appears to be a slight bias for the predicted burnings to be larger than the actual burnings, although the overall ratio of predicted to actual burnings for all trials is only 1.03. The final column in Table 8 shows the ratio of burnings predicted for the next period to the actual burnings for the current period. As can be seen in all but three periods, a growth in the pattern is predicted, but it is a variable rate of growth. The actual growth, of course, is subject to the drawing of random numbers, and the variation in the growth pattern due to these random trials is difficult to estimate. If there were no double ignition trials, then the variance of a binomial distribution would represent the variation expected. With double ignition trials, a slightly lower variance occurs due to the different statistics of these trials. The standard deviation of the number of burning buildings in period 13, computed on the basis of buildings burning at trial 14, is 1.6. The difference between predicted and actual successes near the end of the periods presented is compatible with these values. Moreover, this standard deviation is small enough and the predicted growth is large enough that, in only a few cases, would decrease in growth be expected. This is observed in the table. Thus, while the eventual extinguishment of the pattern is possible, an early extinguishment of the pattern with 0.5 ignition probability would appear to be quite unlikely.

Table 10 presents statistics comparable to Table 8, but for a transition probability of 0.7 where the fire is expected

Table 9. STATISTICS FROM A TRIAL WITH 0.3 PROBABILITY

Period Number	Ignition Branches 4	3	2	1	0	Number of Double Trials	Actual Burnings	Predicted Burnings
7	1						1	
6		3				2	3	1.2
5		3				0	3	2.7
4		3				1	3	2.7
3		3	1	1		2	5	2.69
2		2	2			2	4	3.42
1			2	1		1	3	2.82

to spread indefinitely. It should be mentioned that the ratio of predicted to actual burnings should approach 1 as the pattern becomes larger, even though the growth continues indefinitely. In a gross sense, the rate of growth should depend upon the radius of curvature of a circle enclosing the entire pattern. As this radius becomes larger, any local portion of the pattern appears to be advancing along a plane front where no overall growth in the number of burning structures would be expected as long as the geometry of the front remains approximately constant.

Substantial numbers of unburned buildings completely surrounded by burned buildings are seen in the 0.5 probability trials. There are 21 in Figure 9, 10 in Figure 10, and 12 in Figure 11. In some patterns where there is an apparent strong growth of the burning pattern in one direction to the edge of the tableau, one could expect an eventual turning back and encircling of other unburned areas. The resultant effect on the density of unburned areas is difficult to hypothesize. As growth continues, the gross features of the patterns may or may not continue, so the size and density of unburned areas may or may not be comparable. A considerably more complete computer program is needed to execute the simulation and

Table 10. STATISTICS FROM A TRIAL WITH 0.7 PROBABILITY

Period Number	Number of Ignition Branches					Number of Double Trials	Actual Burnings	Predicted Burnings	Predicted Burnings at Period i/ Actual Burnings at i-1
	4	3	2	1	0				
24	1						1		
23		4				4	4	2.80	2.80
22	2	4				3	6	6.44	1.61
21	5	4				6	9	8.33	1.39
20	6	6	1			9	13	13.16	1.46
19	3	9	1			8	13	17.29	1.33
18	9	6				9	15	15.68	1.21
17	9	8	1			14	18	22.89	1.53
16	6	15		1		15	22	23.94	1.33
15	7	18	1	1		20	27	26.25	1.19
14	8	21	1			25	30	30.80	1.14
13	12	22	2			30	36	34.65	1.16
12	10	27	2	1		30	40	42.70	1.19
11	12	25	4	1		37	42	45.50	1.13
10	11	26	5			38	42	44.87	1.07

to address such questions, which may be of considerable academic interest but little practical interest.

In Figure 14, with a transition probability of 0.8, a considerable different type of growth is seen. Here the burning front is almost in the form of a diamond-shaped pattern moving regularly out from the center of ignition. The pattern is approaching the perfectly diamond-shaped pattern one would have with transition probability of 1. It can be seen that even though there are occasional failures of ignition along the advance, the mechanics of the problem allow the front to reestablish itself and progress.

At a transition probability of 0.7, shown in Figure 13, the same basic trend occurs but the linear front reestablishment mechanism is not as strong. Table 10 summarizes some of the statistics from this trial. For a transition probability of 1, there would be four 3-branch buildings at the corners of the diamond, and all others would be 2-branch buildings. As can be seen, the ratio of 2 to 3-branch buildings is about 2 to 1. This in effect indicates that whatever growth along a linear front appears to dominate, it is frequently interrupted by non-ignitions and a subsequent fairly slow process of reestablishment. A perusal of the 0.5 transition probability trial shows some tendency for a diagonal front to persist if it becomes established, but it has little tendency to reestablish itself.

In order to compare the present results with variations to be presented in the next chapter, a measure of how many buildings are burned is desired. Due to the finite size of the tableau, no measure of total numbers burned is possible. The measure chosen is the fraction of times a building is burned when it is at a given distance from the center of ignition; i.e., the total number of steps from the center, where a step can be either horizontal or vertical. These are presented in Figure 15 for transition probabilities from 0.3 to 0.65. The results in Figure 15 are values averaged over 100 trials. Since even at 100 trials some variability in averaged results is evident, the values presented contain some additional smoothing, hopefully unbiased, of the summary results. For values of transition probability below 0.5, the finite edge effects are low, but for values appreciably above 0.5, doubling back of the pattern may serve to increase the fractions appreciably. The critical transition in the character of the fire spread at 0.5 is evident from this figure. Below this value the burning rapidly quenches, but above, it soon extends indefinitely. At values of 0.6 and above, values less than 100 percent are mostly from occasional early extinguishment of the burning and encircled regions of unburned buildings.

These results present a problem in reconciliation with the simplified IITRI model. The critical transition probability of 0.5 applies to the transfer of fire by radiation from one side of a building to another. However, this would have to be multiplied by 4 to give the value of SR which controls for growth, as described in Chapter 2. Conversely, SR values of 1, the critical value in the IITRI model, are equivalent to a value of transition probability of 0.25, at which no appreciable spread is expected. The values for representative tracts (presented by IITRI in [2]) at separation distances of 30 feet or greater are almost all below 0.5. It appears that a more complex measure of separation accounting for actual locations in a block, as well as reinforcement of radiation intensities by several nearby burning buildings, may have to be considered in order to achieve higher fire spread probabilities. The infinite rectangular grid, moreover, tends to give more spread than typical city block patterns, so even higher probabilities might be needed with actual city patterns.

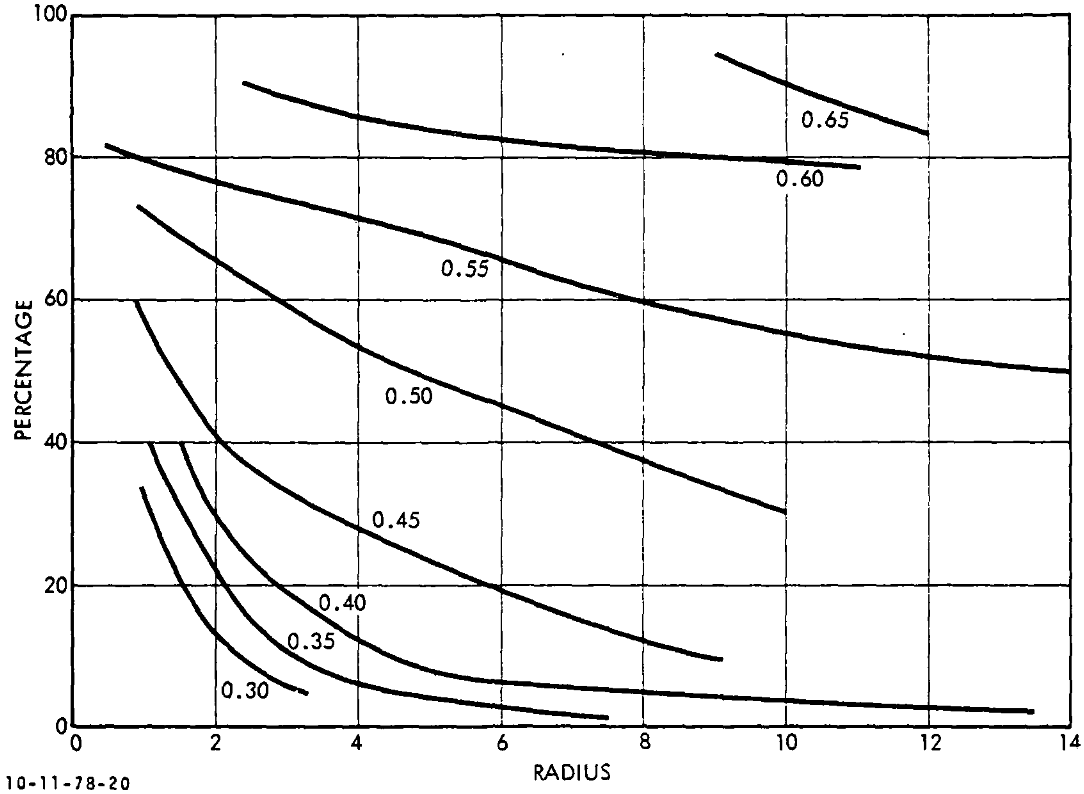


Figure 15. PERCENTAGE OF TIME WHICH BUILDINGS, AT A GIVEN RADIUS, ARE BURNED FOR VARIOUS TRANSMISSION PROBABILITIES

Chapter V

FIRE SPREAD IN GRIDS UNDER VARIOUS CONDITIONS

A. SIDE IGNITION

Figure 16 exhibits the results of a trial where the tableau size is increased to a 21 by 48 matrix and the initial ignition occurs at every element along the left hand side of the matrix. The transition probability used is 0.5 since, in this case, the entry of effects from the absorbing sides is delayed. Despite the side ignition, the results do not seem to differ significantly in a qualitative way from the single center ignition, except that the enclosed unburned areas appear somewhat larger in size. The initial uniform side ignition gives an initial uniform fire spread, however this soon approaches the irregular patterns seen with the center ignition. Figure 17 presents another trial at 0.5 probability with arrows indicating the path of fire spread.

B. MULTIPLE BURNING PERIODS

In the previous calculations it was assumed that a structure burns for only a single period after which it ignites another structure with a probability p. In this section we assume that a structure burns for n periods and, at the end of each n period, it may ignite an adjacent structure with a probability p_n. In order to find p_n equivalent to p, one wants to equate the probability of not igniting an adjacent structure at the end of one period with the probability of not igniting an adjacent structure at the end of each of n periods.

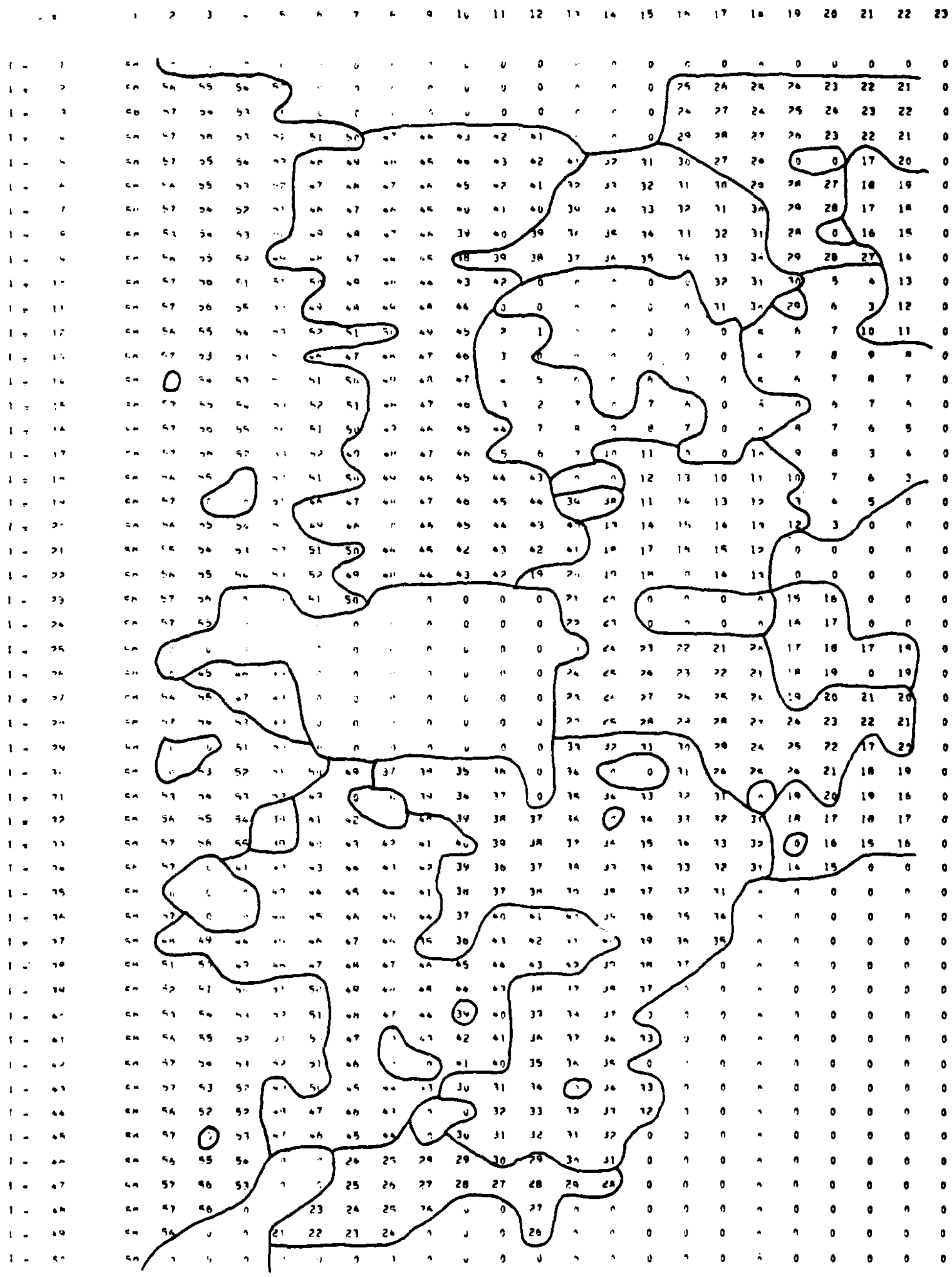


Figure 16. GRID FIRE SPREAD HISTORY FOR A TRANSITION PROBABILITY OF 0.5 WITH SIDE IGNITION, SAMPLE A

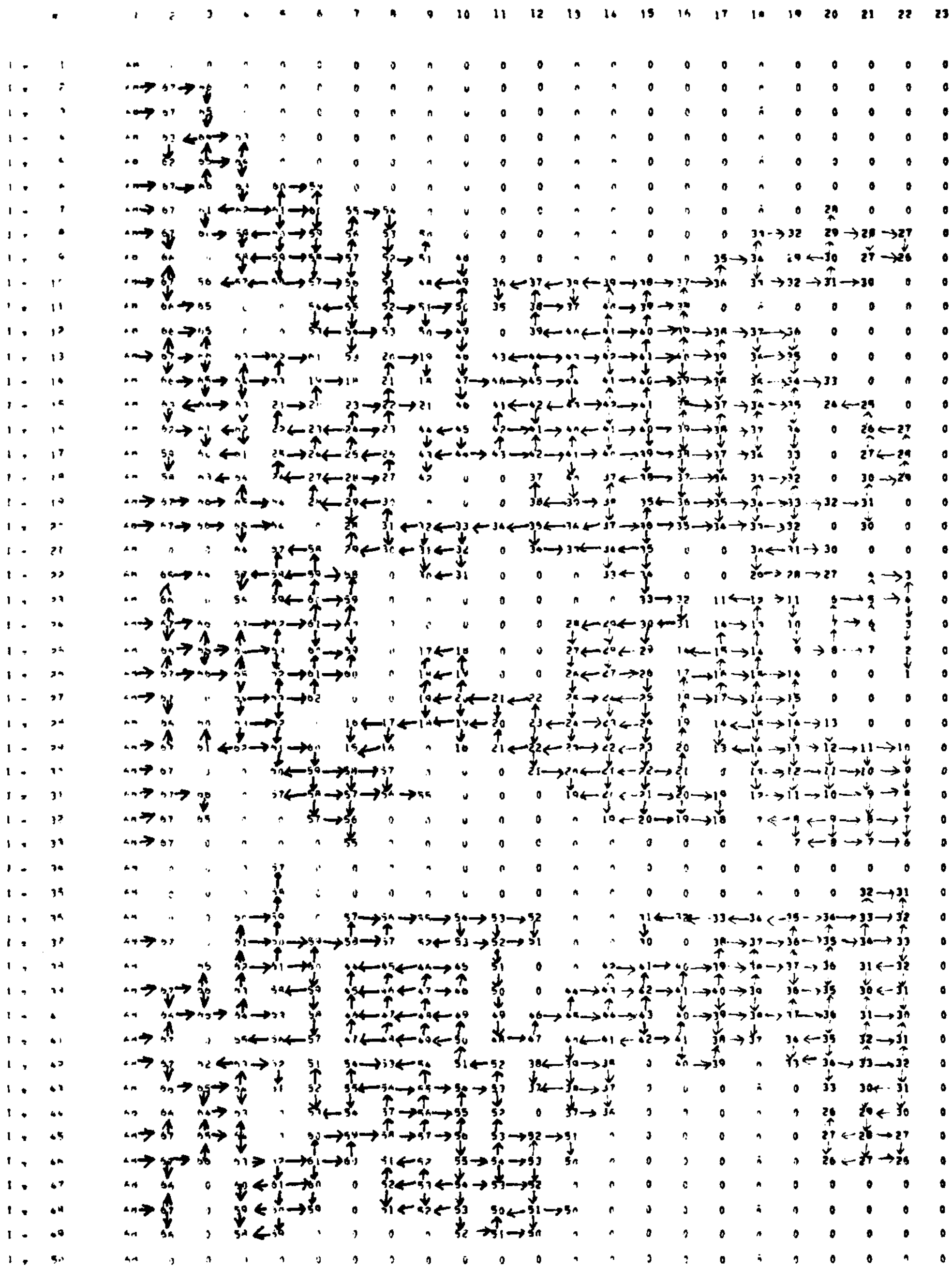


Figure 17. GRID FIRE SPREAD HISTORY SHOWING IGNITION PATHS FOR A TRANSITION PROBABILITY OF 0.5, SAMPLE B

From this one deduces

$$p_n = 1 - (1-p)^{1/n}.$$

Two 100 trial runs with a single center ignition were made with $n = 3$ and $p_n = 0.2063$ and with $n = 10$ and $p_n = 0.0670$. For each trial run the related p was 0.5. The patterns obtained appeared qualitatively similar to those with a single burning period. The fractions burned as a function of distance were computed and compared with those of Figure 15. No differences could be observed within the statistical accuracy of the results.

Another test for possible differences is the number of time periods required for extinguishing all fires. A histogram of burnout times for 1, 3, and 10 burning periods is shown in Figure 18. In this figure, the time for 3 burning periods is divided by 1.5, and for 10 burning periods by 5. Thus the periods from 40 to 45 (say) for 1 burning period correspond to the periods from 200 to 225 for 10 burning periods. The mean burnout time for 1 burning period is 26.9 periods; for 3 burning periods is 1.66 times that for 1; and for 10 burning periods is 5.02 times that for 1. The ratio of mean values for 10 periods is what would be expected because, on the average, a building will propagate burning in the middle of its period of burning, which in this case is 5 periods. Thus one would expect the transmission to be 5 times as long. For three periods, 1.65 ratio for the mean is close to 1.5, but the fact that no transmissions occur after 1.5 periods (but only after 1 or 2) might affect the mean value. With this difference in mean values in mind, the histogram in Figure 18 shows no statistically significant differences with length of burning periods.

The frequency of occurrence of burnouts in less than 10 or 15 periods shows no effect of the finite size of the computing matrix; these are trials where the burning is quenched

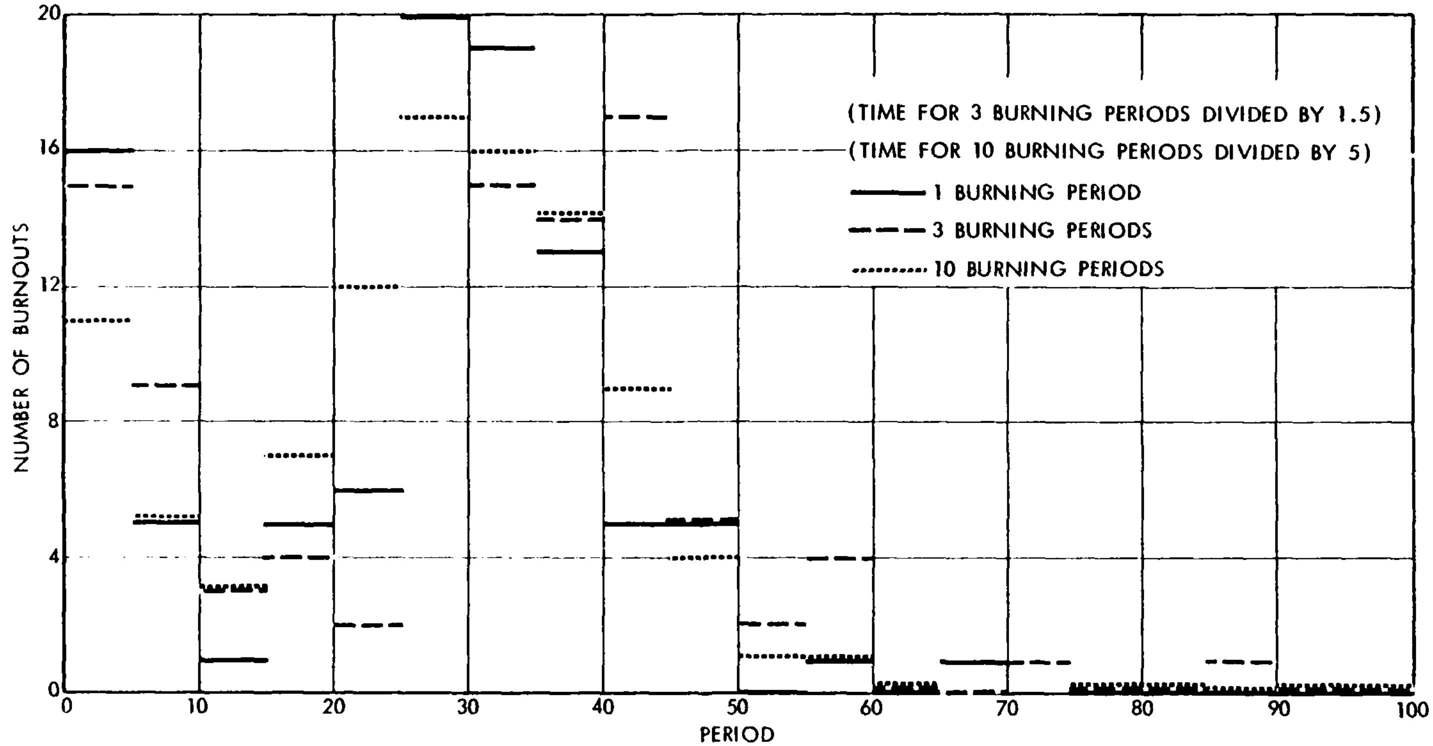


Figure 18. HISTOGRAM OF TIME TO BURNOUT FOR 100 TRIALS

before reaching the edge of the matrix. However, the later burnouts are affected by this restriction, and the mean value of number of periods only has meaning when related to the particular size of the grid used.

C. VARIABLE TRANSMISSION PROBABILITY

In this section the effect of a variable transmission probability is discussed. It is assumed that for each building, the probability of ignition is selected at random from a uniform distribution between $p - \sigma_p$ and $p + \sigma_p$. One building will be ignited in the center of the matrix and may transmit burning only at the end of a single burning period.

For a single row of buildings transmitting fire in sequence down the row (see Chapter III, A.), it can be readily shown that the expected number of buildings ignited depends only upon p and is independent of σ_p. For more complex geometries the question is solved by simulation.

In Figure 19 the results of a set of simulations are presented where the percentage of buildings burned at a given radius is plotted as a function of that radius (the same as in Figure 15). In these calculations a set of building ignition probabilities was drawn; 10 simulations were made with this set of probabilities, and then another set of ignition probabilities was drawn. The base case may be taken as the curve with $p = 0.5$ and $\sigma_p = 0.3$; i.e., a uniform distribution of probability of ignition between 0.2 and 0.8. This case was computed using 1,000 trials in the simulation--sufficient to give fairly smooth results. The results are qualitatively similar to those of constant transition probability, except that somewhat fewer buildings seem to burn. The curve labeled (0.5,0) is for 0.5 transition probability and no variation from it. This curve was taken from Figure 15 and also presents results from 1,000 trials. There is definite decrease in the

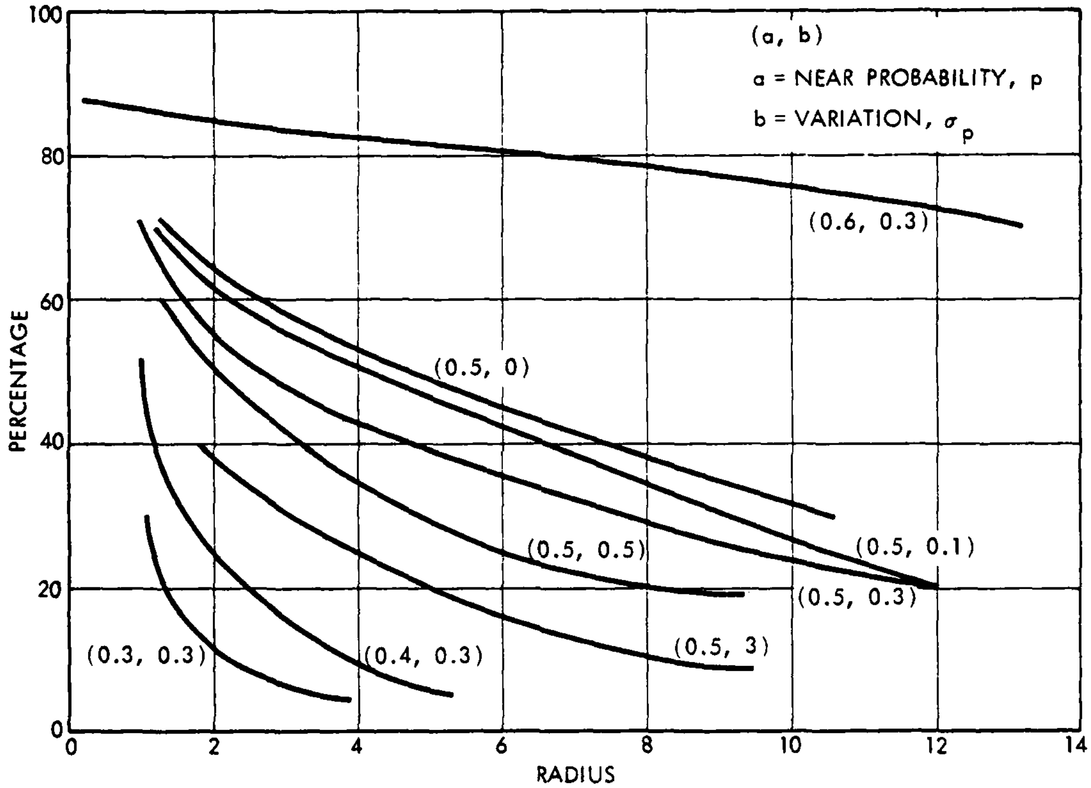


Figure 19. PERCENTAGE OF TIME WHICH BUILDINGS, AT A GIVEN RADIUS, ARE BURNED FOR VARYING TRANSMISSION PROBABILITY

amount of burning, even though the mean probability is the same. By comparison with Figure 15, the results are comparable to that which might be obtained for a constant transition probability of about 0.48.

The remainder of the curves in Figure 19 were computed with 100 trials each; this number was adequate to give reasonably steady summary statistics. The overall trends seem sufficiently reliable. The set of curves is at constant transition probability with variable σ_p. The curve labeled (.5,3) has a σ_p of 3, which in effect is a distribution where 40 percent of the buildings have 0 transition probability, 40 percent have 1 transition probability, and 20 percent are uniformly distributed between 0 and 1. A comparable constant ignition probability for this extreme case is about 0.44, a six percent dropoff. A second set of curves on this figure all have a σ_p of about 0.3. Comparison with Figure 15 indicates that this value of σ_p seems to cause about a two percent drop in effective transition probability over the entire range considered.

If fires are being propagated in a blast-damaged area, and if structures in this area have different vulnerabilities, some are more heavily damaged and, presumably, less susceptible to ignition by radiation. Thus the effect of the blast can be considered as two-fold--first to lower the mean susceptibility to fire, and second to increase the variability of the tract in fire susceptibility. It can be seen from these calculations that the primary effect is lowering the mean transmission probability. The increased variability has some, but not a great effect on fire spread.

D. RANDOM INITIAL IGNITIONS

In this section the burning resulting from several ignitions randomly occurring within a grid is studied. The question is of particular interest for fire spread probabilities below 0.5, where a single ignition can be expected to burn out only a restricted area. Various initial ignition probabilities were assumed, and by drawing random numbers, actual initial ignitions were obtained and subsequent fire spread determined. Since low fire spread probabilities were used, the results near the center of the grid are essentially free of finite edge effects. The process was repeated 100 times to collect summary statistics. Figure 20 shows the percentage of a tract burned as a function of probability of fire spread for various initial ignition probabilities.

For zero probability of fire spread, the fraction of the tract burned is given by the initial ignition probability. As the fire spread probability increases, more of the overall burning is accounted for by fire spread than by initial ignition. Finally, as the fraction burned approaches 1, greater increases in either initial ignition probability or probability of spread are needed to cause the unburned fraction to become substantially less.

Figure 21 presents the results of a trial where the ignition probability is 0.1 and the transmission probability 0.3. In Figures 22 and 23, the ignition probability is 0.2 and the transmission probability is 0.3. The circles on the figures indicate ignition points. Figure 23 shows the paths of burning. From these figures it is seen that a fairly large fraction of initial ignition propagates to the point where they intersect the propagation from other ignitions. The expected number of burnings from a single ignition, including the ignited building, on the basis of 100 trials with a single center ignition, was 5.9. Multiplying the value by the probability of ignition gives 1.18, which implies a substantial amount of overburning. Figure 20 shows that the fraction burnt was 0.56. Interference of the fires from the two ignition sources would cause the total fraction burnt to be lower, and this is why a larger total fraction was not obtained.

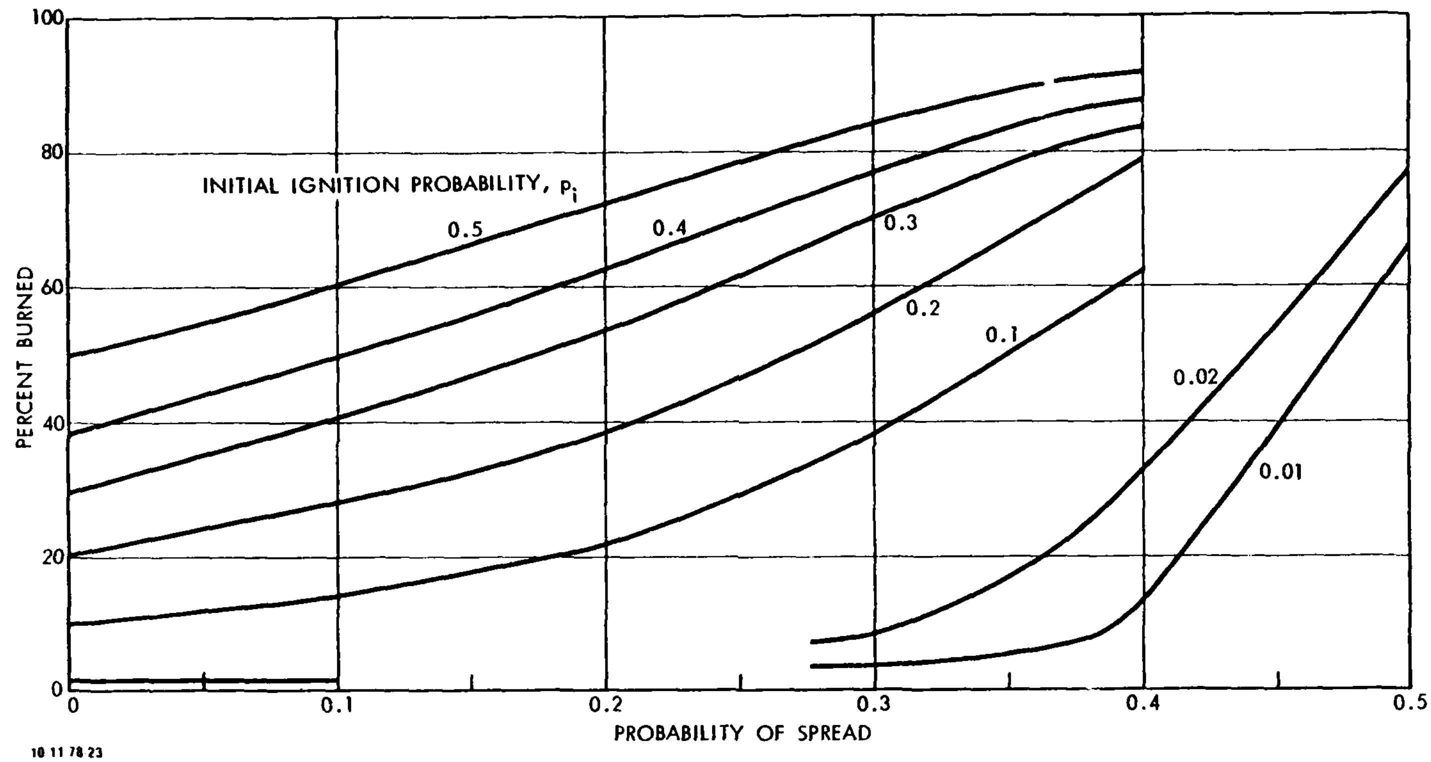


Figure 20. PERCENTAGE OF TRACT BURNED AS A FUNCTION OF PROBABILITY OF FIRE SPREAD FOR VARIOUS INITIAL IGNITION PROBABILITIES

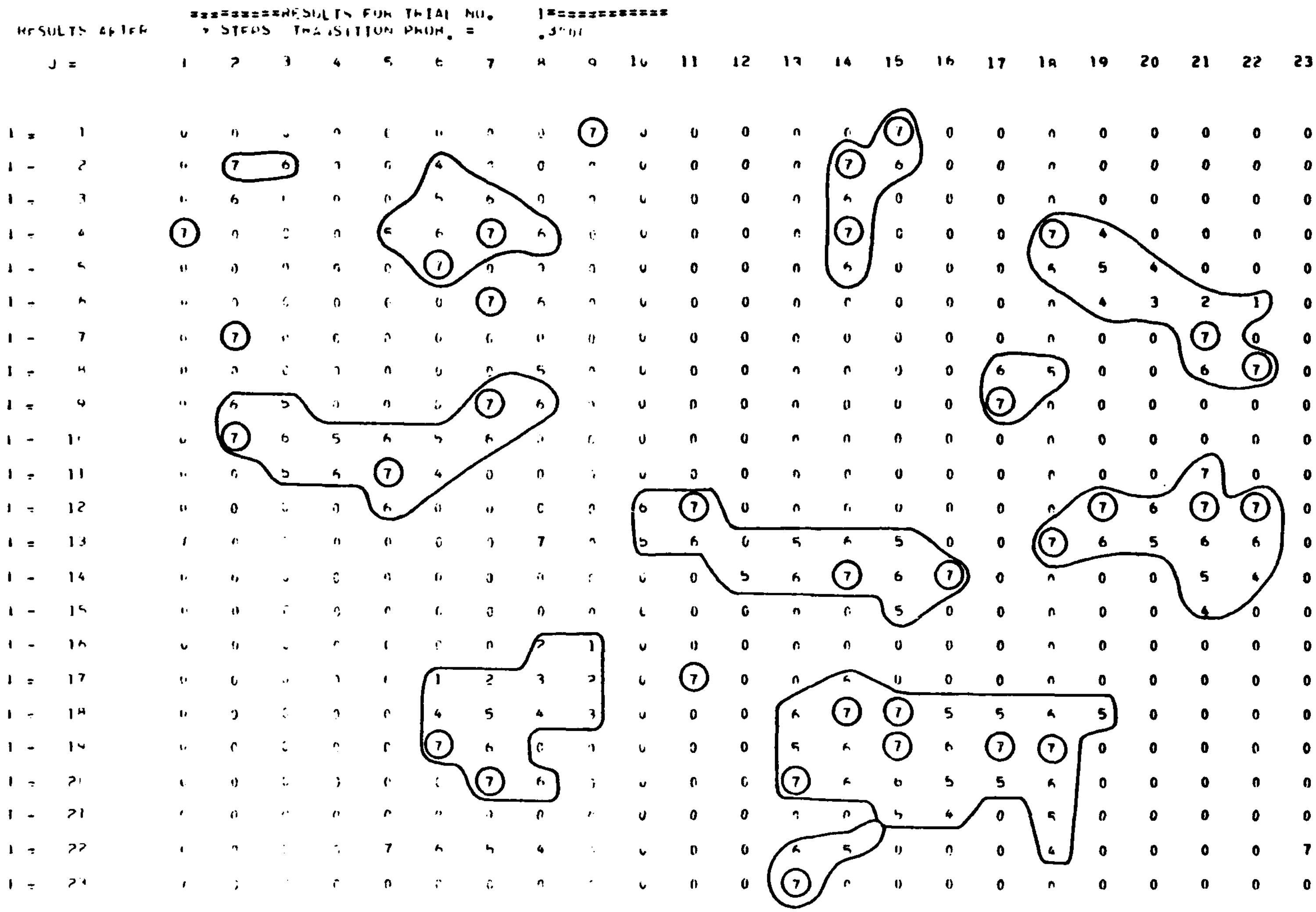


Figure 21. GRID FIRE SPREAD HISTORY FOR RANDOM INITIAL IGNITIONS AT A PROBABILITY OF 0.1 WITH A TRANSMISSION PROBABILITY OF 0.3

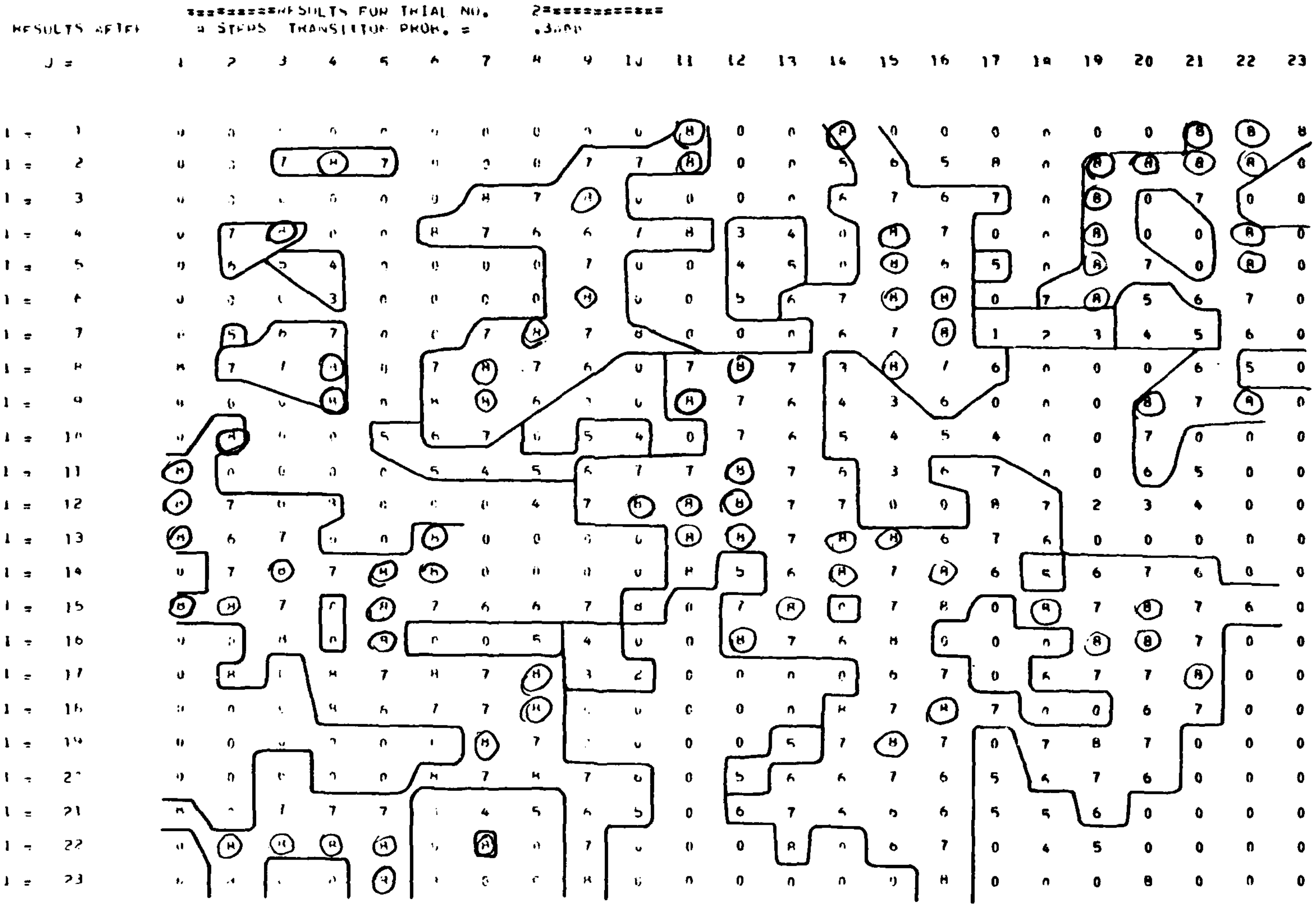


Figure 22. GRID FIRE SPREAD HISTORY FOR RANDOM INITIAL IGNITIONS AT A PROBABILITY OF 0.2 WITH A TRANSMISSION PROBABILITY OF 0.3

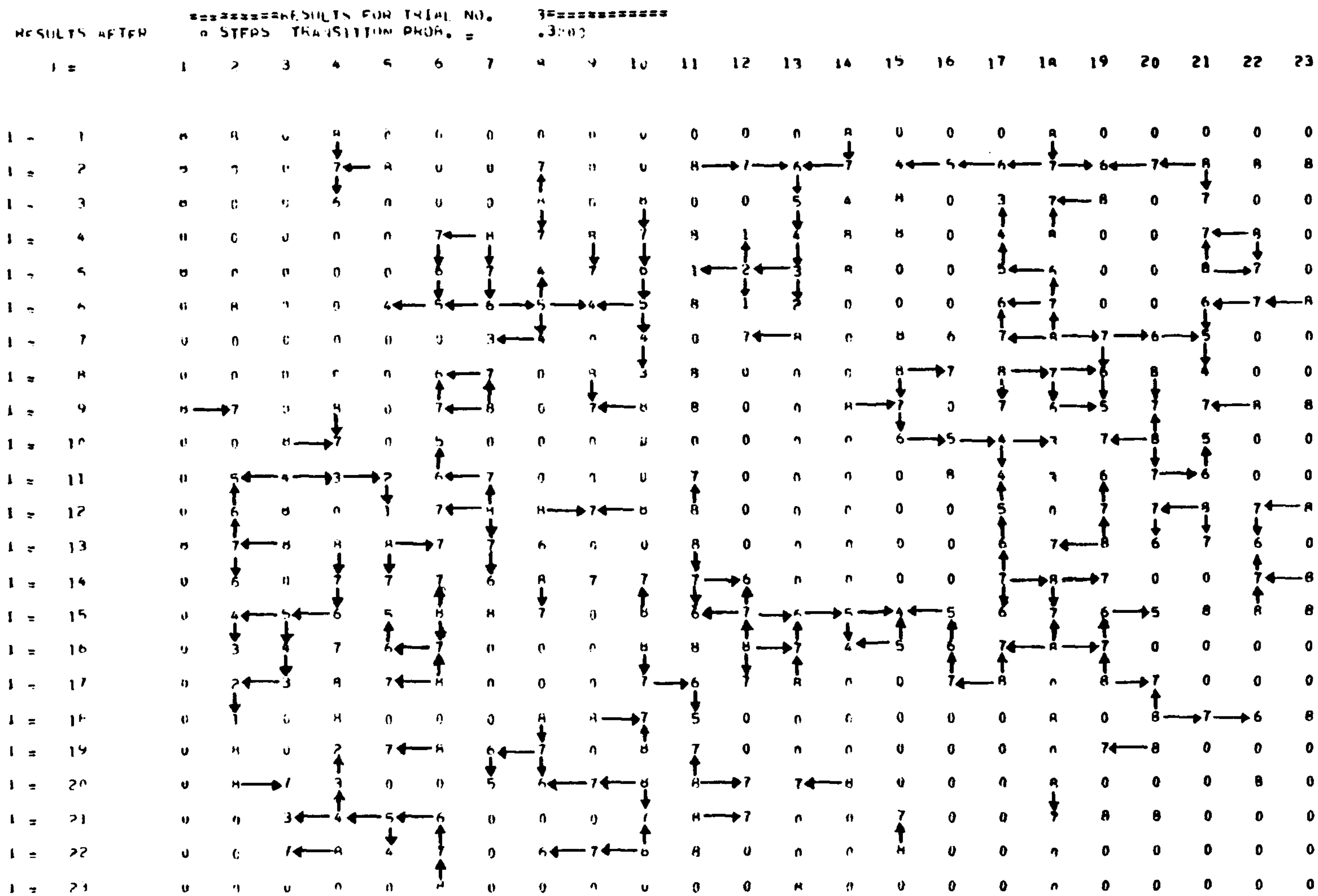


Figure 23. GRID FIRE SPREAD HISTORY SHOWING IGNITION PATHS FOR RANDOM INITIAL IGNITIONS AT A PROBABILITY OF 0.2 WITH A TRANSMISSION PROBABILITY OF 0.3

E. RADIATION AND FIREBRANDS SIMULATION MODEL

The previous section described the propagation of burning by radiation in a variety of situations that purposely were kept as simple as possible. We did this to illustrate the nature of several mechanisms that might affect burning propagation. The purpose of the full simulation is to include, in the basic probability model, several effects from the IITRI model that could significantly affect burning propagation. The basic propagation model remains the rectangular grid model. The following characteristics are included with the model: (1) propagation of fire by firebrands; (2) each building is characterized by a propagation factor and susceptibility factor for both radiation and firebrands; (3) barriers may be included; (4) random ignition occurs at the left border of the matrix; (5) the time at which a building can propagate fire is stochastic.

In the implementation of the model an array TSTATE(i,j) describes the condition of a building in the ith row and jth column. If an element of the array has a zero value, the structure is not yet ignited. When a structure is ignited, the time at which the structure can ignite other structures is drawn from a probability distribution and recorded in the array TSTATE. The simulation time is advanced in regular steps, usually 1/4 hour. When the time equals the time at which a building can propagate fire, then the immediately surrounding buildings are tested by drawn random numbers to see if they can be ignited by radiation. The basic propagation probability is multiplied by a radiation output parameter from the burning building, and a radiation susceptibility parameter from the potential host building stored in other data arrays, to obtain a modified probability. If host structures are ignited, they have numbers drawn to determine when they, in turn, can further propagate fire. After testing for radiation propagation, a test is made for firebrands. A landing location for a firebrand is drawn from a distribution function of firebrand impacts. The building is ignited based upon comparing a random number to the probability of firebrand ignition, modified by a firebrand output parameter and firebrand susceptibility parameter. By selection of radiation and firebrand output and susceptibility parameters, various geometric configurations can be simulated.

The time delay before fire spread was taken as a constant delay plus an exponentially distributed random variable. The constant time delay was 0.06 and the decay constant for the distribution 0.5. If the unit of time measurement is hours, the mean time for fire spread is 0.56 hours (or 34 minutes). If the unit of time measurement is two hours, then the mean time for fire spread is about 65 minutes. The times appear consistent with IITRI estimates.

In Figure 8 of [2], the expected number of buildings ignited per burning building is presented. The value is 0.1W where W is wind speed in miles/hour. Rather than follow individual firebrands, as in the IITRI model and [4], this simulation matches the expected number of "standard building ignitions" by firebrands, where a "standard building ignition" is one produced by a donor building with firebrand output parameter = 1, and firebrand susceptibility parameter = 1. Figure 5 of [2] presents a curve of density of firebrands, which might cause an ignition, as a function of distance. Since the firebrands are spread over a constant dispersion angle (70°), if the density at a certain distance is multiplied by the distance, and the resulting values for all distances normalized to produce an area under the curve of 1, the resulting curve gives the probability that a firebrand that will cause an ignition will produce this ignition at a certain distance. This curve is presented in Figure 24. This figure is for a wind speed W_0 of 4 mph. Following IITRI, for other wind speeds W the distance is multiplied by $\frac{W}{W_0}$. In the simulation a random number is drawn and the distance associated with the random number is determined from Figure 24.[1]

Another random number is drawn from a uniform distribution to find the angle from downwind where the firebrand lands (for simplicity in the calculations the wind is always assumed to be blowing from left to right in line with a row of buildings). The nearest building to the resulting impact location is found, assuming some given spacing between buildings in the grid, here 50 feet. A random number is drawn to determine ignition. If the building is not ignited, no more firebrand tests are mad for the donor structure in question; if the building is ignited, the process is repeated.

An illustration of simulation results is presented in Figure 25. The initial ignitions were allowed to accrue in the the leftmost four columns, with the ignition probability 0.6 in the leftmost row, decreasing linearly to zero in the fifth row. The wind speed is 4 mph, with each burning building having an expected number of firebrand ignitions of 0.1. The mean radiation transmission probability is 0.5. The output and susceptibility parameters are uniformly distributed between 0.7 and 1.3. A 250 foot firebreak is assumed in the middle of the matrix, so the susceptibility parameters for columns 9 through 12 are zero. The initial ignitions are shown in the first block of Figure 25. The succeeding blocks show ignitions at intervals of 10 time steps; here, 5/8 hour if a mean time delay of 1 hour for transmission is assumed. The numbers in the tableaus give the iteration step when the building was

[1] In the actual curve, 10 tabular values of distance are stored. An integer from 1 to 10 is drawn to select a tabular value, and another number is drawn to select an actual location in the interval. The distributions in the interval are uniform, except for the interval with the highest distance where an exponential distribution is used. Then there is a slight chance for travel to considerable distances.

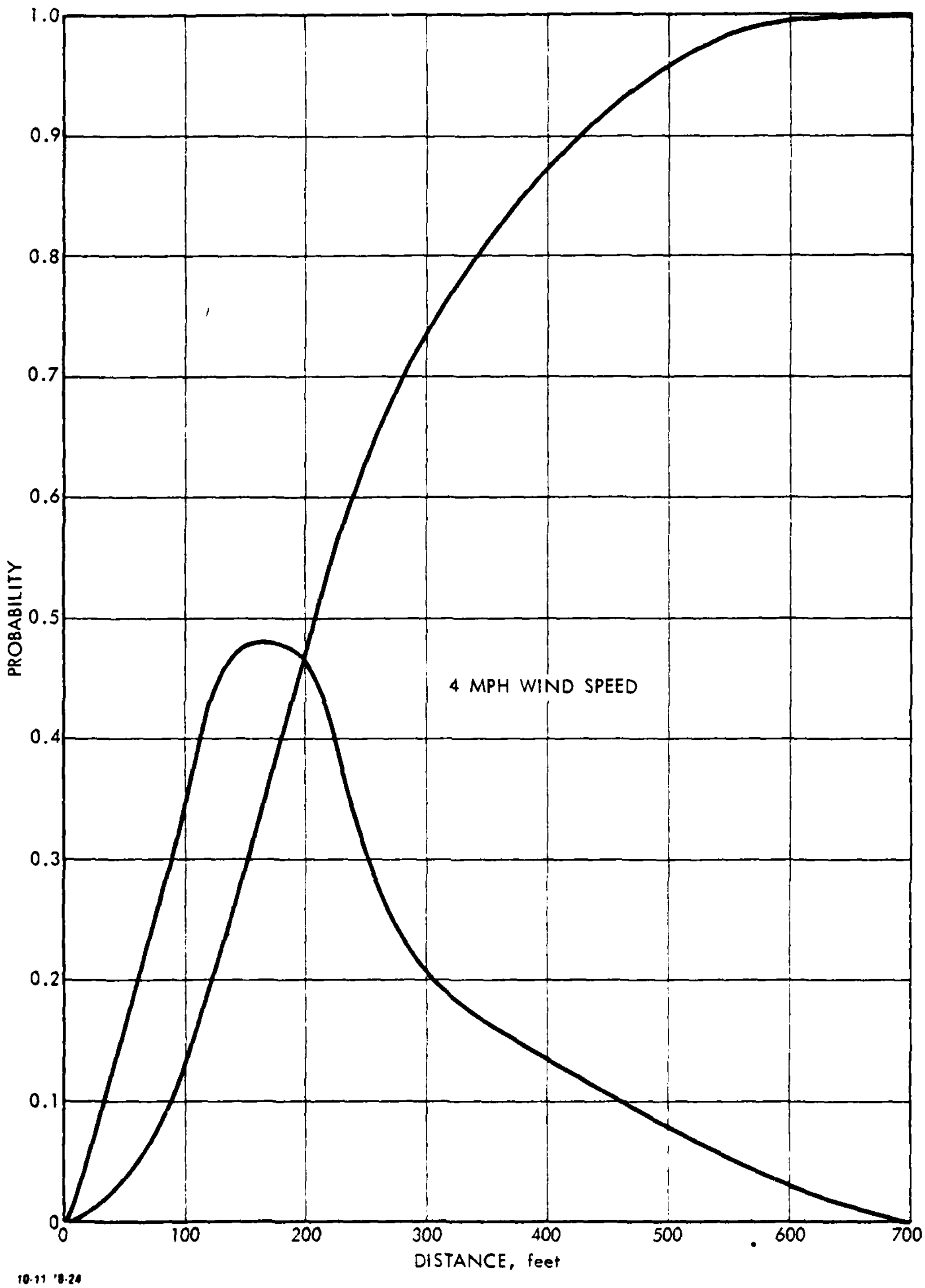


Figure 24. PROBABILITY DENSITY AND CUMULATIVE PROBABILITY FOR FIREBRANDS AS A FUNCTION OF DISTANCE

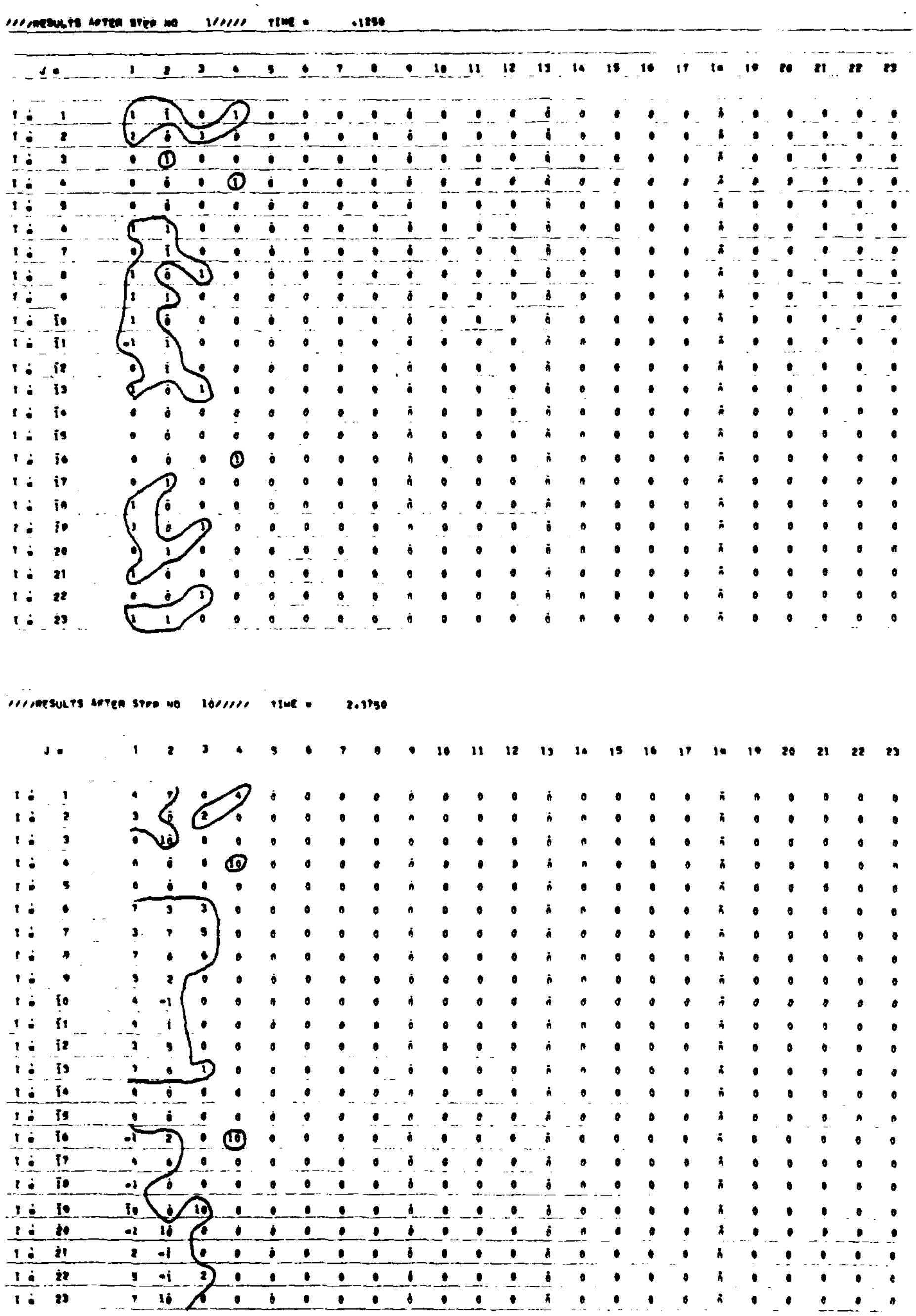


Figure 25. SAMPLE FIRE SPREAD SIMULATION RESULTS

////RESULTS AFTER STEP NO 20////// TIME = 4.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	16	17	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	13	0	12	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	4	2	3	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	0	-1	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	3	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	17	13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	13	17	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	17	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	15	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	16	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	10	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 12	13	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 13	17	16	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	10	12	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	14	16	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	3	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	10	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	12	10	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	15	10	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 30////// TIME = 7.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	26	27	4	26	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	23	0	22	17	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	14	12	13	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	3	16	14	19	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	13	-1	10	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	27	23	23	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	23	27	25	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	27	26	26	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	25	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	26	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	20	21	-1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 12	23	25	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 13	27	26	21	5	0	0	7	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 14	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	20	22	0	16	10	5	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	26	26	0	0	10	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	20	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	13	3	3	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	20	10	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	22	20	11	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	25	20	22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	27	10	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 38///// TIME = 7.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	26	27	4	26	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	23	6	22	17	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	16	12	13	4	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	3	16	14	19	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	13	-1	10	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	27	23	23	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	23	27	25	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	27	26	26	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	25	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	24	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	20	21	-1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 12	23	25	6	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 13	27	26	21	5	0	0	7	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 14	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	20	22	0	14	10	5	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	24	26	0	0	19	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	20	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	13	3	3	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	20	10	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	22	20	11	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	25	20	22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	27	10	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 40///// TIME = 9.4750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	34	37	14	34	16	0	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	33	7	32	27	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	24	22	23	14	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	13	26	24	29	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	23	16	28	22	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	37	33	33	15	5	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	33	37	35	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	37	36	36	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	35	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	34	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	39	31	10	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 12	33	35	16	13	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 13	37	36	31	15	0	0	17	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 14	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	0	0	3	0	12	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	30	32	0	24	20	15	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	34	36	0	0	29	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	30	0	0	0	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	33	13	13	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	30	20	24	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	32	30	21	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	35	30	32	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	37	20	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 56////// TIME = 12.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	44	49	26	44	26	0	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	43	17	42	37	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	56	32	33	26	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	23	36	36	39	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	33	26	38	32	11	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	47	43	43	25	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	43	47	45	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	49	46	46	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	48	42	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	44	40	0	7	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	49	41	20	22	1	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 12	43	45	26	23	5	7	9	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 13	47	46	41	25	18	5	27	26	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
I = 14	0	0	0	3	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	0	7	13	0	22	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	40	42	0	36	38	25	20	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	44	46	0	2	39	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	40	0	0	18	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	33	23	23	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	48	38	34	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	42	40	31	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	45	40	42	21	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	47	38	28	18	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 60////// TIME = 14.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	56	57	34	54	36	0	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	43	27	52	47	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	44	42	43	34	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	33	40	44	40	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	43	38	48	42	21	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	47	53	53	35	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	53	57	55	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	57	56	56	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	55	52	-1	11	3	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	56	50	19	17	1	0	12	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	49	51	30	32	11	9	14	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0
I = 12	43	55	36	33	19	17	19	24	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
I = 13	47	56	51	35	20	15	37	34	0	0	0	0	10	0	0	0	0	0	0	0	0	0	0
I = 14	0	5	16	13	0	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 15	0	4	17	23	0	32	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 16	58	52	7	44	48	35	38	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	54	56	0	12	49	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	50	0	0	28	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	63	33	33	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	50	48	44	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	52	58	41	30	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	45	54	52	31	29	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	47	44	38	28	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 76////// TIME = 17.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	66	67	66	66	66	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	63	37	62	57	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	56	52	53	66	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	63	56	56	59	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	53	46	58	52	31	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	67	63	63	65	35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	63	67	65	67	3	6	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	67	66	66	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	65	62	10	21	13	10	8	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	66	66	29	27	11	9	22	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 11	69	61	40	42	21	19	24	0	0	0	0	0	8	6	2	-1	0	0	0	0	0	0	0
I = 12	63	65	46	43	25	27	29	36	0	0	0	0	11	12	3	0	0	0	0	0	0	0	0
I = 13	67	66	61	45	30	25	47	46	0	0	0	0	26	8	2	0	0	0	0	0	0	0	0
I = 14	0	14	26	23	0	0	66	0	0	0	0	0	0	5	-1	0	0	0	0	0	0	0	0
I = 15	8	16	27	33	0	42	43	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
I = 16	68	62	17	56	58	65	48	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	66	66	3	22	59	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	68	0	2	39	42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	53	63	43	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	48	58	56	37	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	42	60	51	40	15	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	65	66	62	41	38	26	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	67	58	48	38	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 86////// TIME = 19.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	74	77	56	74	56	0	0	46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	73	67	72	67	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	66	62	63	56	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	63	60	66	69	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	63	56	60	62	41	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	77	73	73	55	45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	73	77	75	57	13	14	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	77	76	76	52	10	19	8	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	75	72	28	31	25	20	18	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	76	73	39	37	21	19	32	24	0	0	0	0	-	0	0	0	19	0	0	0	0	0	0
I = 11	79	71	58	52	31	29	34	0	0	0	0	0	18	14	12	10	0	0	0	0	0	0	0
I = 12	73	75	56	53	35	37	39	44	0	0	0	0	25	29	13	0	0	0	0	0	0	0	0
I = 13	77	76	71	55	48	35	57	56	0	0	0	0	38	19	12	6	0	0	0	0	0	0	0
I = 14	8	25	36	33	0	0	54	0	0	0	0	0	0	15	10	0	0	0	0	0	0	0	0
I = 15	0	24	37	43	0	52	53	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0
I = 16	78	72	27	66	68	55	50	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	76	76	13	32	7	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	70	0	12	46	52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	43	53	53	30	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	70	68	66	47	6	16	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	72	76	61	50	25	19	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	75	73	72	51	48	36	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	77	68	58	48	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 96////// TIME = 22.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	86	87	84	84	86	0	0	56	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	83	57	82	77	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	76	72	73	64	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	63	76	76	79	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	73	66	78	72	51	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	87	83	83	68	59	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	83	87	85	67	23	24	11	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	87	86	86	62	29	29	10	29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	85	82	30	41	33	30	28	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	86	86	69	67	31	29	42	34	0	0	0	0	0	0	0	0	29	0	0	0	0	0	0
I = 11	80	81	80	62	41	39	44	0	0	0	0	0	28	26	22	20	0	0	0	0	0	0	0
I = 12	83	85	86	63	45	47	69	54	0	0	0	0	33	37	23	6	5	0	0	0	0	0	0
I = 13	87	86	81	65	58	65	67	66	0	0	0	0	46	29	22	14	7	0	0	0	0	0	0
I = 14	0	39	46	63	0	0	64	0	0	0	0	0	0	25	20	0	0	0	0	0	0	0	0
I = 15	0	34	67	53	0	62	63	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0
I = 16	80	82	37	74	78	65	66	58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	84	86	23	42	17	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	80	0	22	58	62	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	73	63	63	60	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	40	78	76	57	16	26	15	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	62	80	71	60	35	29	17	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	85	86	82	61	58	46	0	34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	67	78	68	58	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 100////// TIME = 24.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	86	97	76	94	76	0	0	66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	83	67	92	87	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	86	82	83	74	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	73	86	84	89	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	83	76	88	82	61	51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	97	93	93	75	65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	93	97	95	77	33	34	21	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	97	96	96	72	39	39	28	39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	85	92	40	51	43	40	38	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	86	96	59	57	41	39	52	46	0	0		0	0	0	0	0	39	0	0	0	0	0	0
I = 11	89	91	78	72	51	49	54	[illegible]	[illegible]	0	0	0	38	34	32	30	6	6	-1	0	0	0	0
I = 12	83	95	76	73	55	57	59	66		0	0	0	45	42	33	16	19	0	0	0	0	0	0
I = 13	97	96	91	75	68	55	77	74	0	0	0	0	58	30	32	24	17	0	0	0	0	0	0
I = 14	0	45	56	53	0	0	[illegible]	0	0	0	0	0	0	39	30	4	0	0	0	0	0	0	0
I = 15	0	44	57	63	0	[illegible]	73	0	0	0	0	0	0	31	0	3	0	0	0	0	0	0	0
I = 16	80	92	47	86	[illegible]	75	70	68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	84	96	33	52	27	80	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	84	[illegible]	[illegible]	60	72	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	83	7		[illegible]	96	0	0	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = [illegible]	80			67	26		25	23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = [illegible]	[illegible]	[illegible]	81	78	69	39	27	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	[illegible]	96	92	71	60	56	0	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23		[illegible]	[illegible]	68	57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 118////// TIME = 27.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	104	107	84	104	86	0	0	76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	103	77	102	97	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	88	92	93	86	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	83	96	94	99	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	93	86	90	92	71	61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	107	103	103	85	75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	103	107	105	87	43	44	31	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	107	106	106	82	40	40	38	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 9	109	102	56	61	53	50	40	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 10	104	100	69	67	51	49	62	54	0	0	0	0	0	0	0	0	40	9	5	4	1	0	0
I = 11	109	101	80	82	61	59	64	0	0	0	0	0	48	44	42	40	16	14	10	7	0	0	0
I = 12	103	105	86	83	65	67	60	74	0	0	0	0	53	52	43	26	25	0	5	2	0	0	0
I = 13	107	106	101	85	79	65	87	84	0	0	0	0	68	40	42	34	27	0	0	0	0	0	0
I = 14	0	55	66	63	0	0	84	0	0	0	0	0	0	49	40	14	0	0	0	0	0	0	0
I = 15	0	54	67	73	0	82	83	0	0	0	0	0	0	41	0	13	0	0	0	0	0	0	0
I = 16	100	102	57	94	98	85	80	78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	104	106	43	62	37	90	1	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	100	0	42	78	82	5	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	83	83	83	90	34	-1	0	24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	100	98	94	77	36	46	35	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	102	100	91	80	55	40	37	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	105	108	102	81	79	66	0	54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	107	98	88	78	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 120////// TIME = 29.4750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	114	117	94	114	96	0	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	113	87	112	107	101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	104	102	103	94	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	93	100	104	109	101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	103	90	108	102	81	71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	117	113	113	95	85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	113	117	115	97	53	54	41	50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	117	116	116	92	59	59	48	59	0	0	0	0	0	0	0	0	0	0	0	1	7	0	0
I = 9	119	112	60	71	63	60	58	68	0	0	0	0	0	0	0	0	3	4	7	4	9	0	0
I = 10	114	118	79	77	61	59	72	64	0	0	0	0	0	0	0	0	59	10	15	16	11	0	0
I = 11	119	111	90	92	71	69	74	0	0	0	0	0	58	54	52	50	26	24	20	17	6	2	0
I = 12	113	115	96	93	79	77	70	84	0	0	0	0	63	62	53	36	35	0	15	12	6	5	0
I = 13	117	116	111	95	88	75	97	94	0	0	0	0	78	50	52	44	37	0	0	0	1	2	0
I = 14	0	65	76	73	0	0	94	0	0	0	0	0	0	58	50	24	0	0	0	0	0	0	0
I = 15	0	64	77	83	0	92	93	0	0	0	0	0	0	51	0	23	0	0	0	0	0	0	0
I = 16	110	112	67	104	100	95	98	80	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	114	116	53	72	47	100	11	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	110	0	92	88	92	19	19	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	103	93	93	90	44	10	6	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	110	100	104	87	46	56	45	43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 21	112	110	101	90	65	59	67	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 22	115	110	112	91	80	76	0	64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	117	100	90	80	77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)

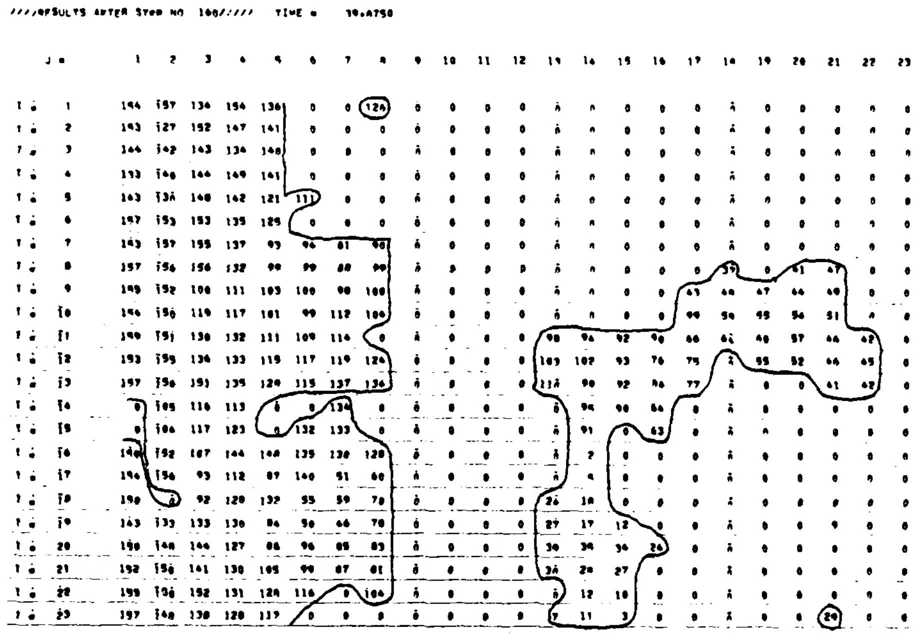
////RESULTS AFTER STEP NO 136////// TIME = 32.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	136	127	104	124	106	0	0	96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	123	97	122	117	111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	114	112	113	104	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	103	110	114	119	111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	113	100	118	112	91	81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	127	123	123	105	95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	123	127	125	107	63	64	51	60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	127	126	126	102	69	69	58	69	0	0	0	0	0	0	0	0	0	7	0	11	17	0	0
I = 9	125	122	70	81	73	70	68	70	0	0	0	0	0	0	0	0	13	14	17	14	19	0	0
I = 10	120	120	89	87	71	64	82	74	0	0	0	0	0	0	0	0	60	24	75	24	21	0	0
I = 11	129	121	100	102	81	79	84	0	0	0	0	0	68	64	62	60	36	34	30	27	16	12	0
I = 12	123	125	100	103	85	87	89	96	0	0	0	0	79	77	63	66	65	0	29	22	16	19	0
I = 13	127	126	121	105	94	85	107	104	0	0	0	0	88	60	62	56	47	0	0	0	11	12	0
I = 14	0	75	86	81	0	0	104	0	0	0	0	0	0	69	60	34	0	0	0	0	0	0	0
I = 15	0	74	87	93	0	102	103	0	0	0	0	0	0	61	0	33	0	0	0	0	0	0	0
I = 16	120	122	77	114	118	105	100	98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	124	126	63	82	57	110	21	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	120	0	62	98	102	25	29	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 19	113	103	103	100	56	20	16	48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 20	120	118	116	97	56	66	55	53	0	0	0	0	6	6	6	0	0	0	0	0	0	0	0
I = 21	122	120	111	100	79	60	57	51	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
I = 22	125	120	122	101	98	86	0	76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	127	118	108	98	87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

////RESULTS AFTER STEP NO 140////// TIME = 34.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	136	137	114	134	114	0	0	106	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	133	107	132	127	121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	124	122	123	114	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	113	126	124	129	121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	123	116	128	122	101	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	137	131	133	115	109	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	133	137	135	117	73	74	61	70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	137	136	136	112	79	79	68	79	0	0	0	0	0	0	0	0	0	17	0	21	27	0	0
I = 9	135	132	80	91	85	80	78	80	0	0	0	0	0	0	0	0	23	28	27	26	29	0	0
I = 10	136	136	99	97	81	79	92	86	0	0	0	0	0	0	0	0	79	30	45	34	31	0	0
I = 11	139	131	110	112	91	89	94	0	0	0	0	0	78	74	72	70	46	44	40	37	24	22	0
I = 12	133	135	116	113	95	97	99	104	0	0	0	0	83	87	73	96	59	0	39	32	24	29	0
I = 13	137	136	131	115	100	95	117	116	0	0	0	0	84	70	72	64	57	0	0	0	21	22	0
I = 14	0	89	96	93	0	0	114	0	0	0	0	0	0	78	70	44	0	0	0	0	0	0	0
I = 15	0	84	97	103	0	112	113	0	0	0	0	0	0	71	0	43	0	0	0	0	0	0	0
I = 16	130	132	87	124	128	115	118	108	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 17	134	136	73	92	67	120	31	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 18	130	0	72	108	112	35	39	50	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0
I = 19	123	113	113	110	66	30	26	50	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0
I = 20	130	120	124	107	66	76	65	63	0	0	0	0	10	19	10	4	0	0	0	0	0	0	0
I = 21	132	136	121	110	89	79	67	61	0	0	0	0	10	9	7	0	0	0	0	0	0	0	0
I = 22	135	136	132	111	100	96	0	86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 23	137	120	118	100	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 25. (cont'd)



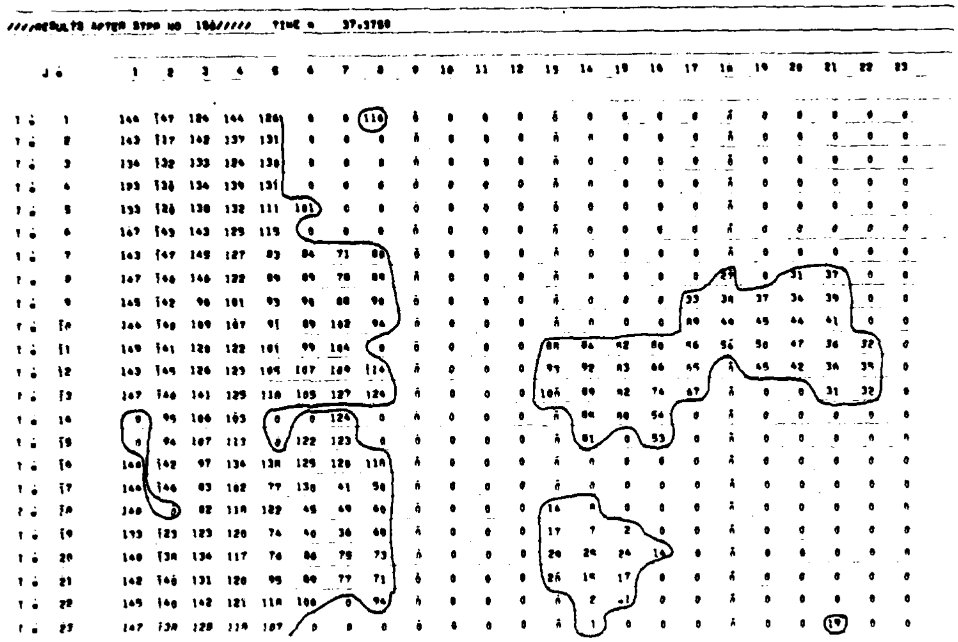


Figure 25. (cont'd)

////RESULTS AFTER STEP NO 170////// TIME = 42.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	144	167	144	164	146	0	0	134	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	143	137	162	157	151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	154	152	153	144	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	143	156	154	159	151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	153	146	158	152	131	121	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	167	163	163	145	139	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	163	167	168	147	103	104	91	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	167	144	164	142	109	109	98	109	0	0	0	0	0	0	0	0	0	47	0	51	57	0	0
I = 9	165	162	110	121	113	110	108	110	0	0	0	0	0	0	0	0	53	58	57	54	59	0	0
I = 10	144	168	129	127	111	109	122	114	0	0	0	0	0	0	0	0	109	64	65	66	61	0	0
I = 11	149	161	140	142	121	119	124	0	0	0	0	0	108	104	102	100	76	74	70	67	56	52	0
I = 12	143	165	140	143	125	127	129	134	0	0	0	0	113	112	103	88	89	0	49	62	56	55	0
I = 13	147	166	161	145	138	125	147	146	0	0	0	0	120	109	102	94	87	0	0	9	51	52	0
I = 14	7	115	126	123	0	0	164	0	0	0	0	0	0	108	100	74	0	0	0	0	0	0	0
I = 15	6	114	127	133	0	142	143	0	0	0	0	0	0	101	0	73	0	0	0	0	0	0	0
I = 16	144	162	117	156	158	165	140	138	0	0	0	0	0	12	9	0	0	0	0	0	0	0	0
I = 17	144	166	103	122	97	150	61	70	0	0	0	0	-1	19	0	0	0	0	0	0	0	0	0
I = 18	148	7	102	138	142	65	69	48	0	0	0	0	34	28	0	0	0	0	0	0	0	0	0
I = 19	143	143	143	140	96	60	56	88	0	0	0	0	37	27	22	1	-1	0	0	0	19	0	0
I = 20	140	158	154	137	96	104	95	93	0	0	0	0	44	45	44	34	0	0	0	0	0	0	0
I = 21	142	160	151	140	115	109	97	91	0	0	0	0	44	38	37	0	0	0	0	0	0	0	0
I = 22	145	148	142	141	138	126	0	114	0	0	0	0	0	22	20	1	0	0	0	0	0	0	0
I = 23	147	158	148	138	127	0	0	0	0	0	0	0	17	21	13	6	0	0	0	0	39	0	0

////RESULTS AFTER STEP NO 180////// TIME = 44.4750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	176	177	154	174	156	0	0	146	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	173	147	172	167	161	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	144	162	163	154	164	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	193	166	164	169	161	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	143	156	166	162	141	131	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	177	173	173	155	145	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	173	177	175	157	113	114	101	110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	177	176	170	152	119	119	108	119	0	0	0	0	0	0	0	0	0	57	0	61	67	0	0
I = 9	175	172	120	131	125	120	110	120	0	0	0	0	0	0	0	0	63	68	47	64	69	0	0
I = 10	176	176	139	137	121	119	132	126	0	0	0	0	0	0	0	0	119	76	75	74	71	0	0
I = 11	179	171	150	152	131	129	134	0	0	0	0	0	118	114	112	110	66	84	80	77	66	62	0
I = 12	173	175	156	153	139	137	139	144	0	0	0	0	123	122	113	96	95	0	75	72	66	65	0
I = 13	177	176	171	155	148	135	157	156	0	0	0	0	138	110	112	104	67	0	0	19	61	62	0
I = 14	17	125	136	133	0	0	154	0	0	0	0	0	0	115	110	84	0	0	0	0	0	0	0
I = 15	16	126	137	163	0	152	153	0	0	0	0	0	0	111	18	83	0	0	0	0	0	0	0
I = 16	170	172	127	164	100	155	150	140	0	0	0	0	14	22	19	0	0	0	0	0	0	0	0
I = 17	174	176	113	132	107	100	71	69	0	0	0	0	18	29	0	3	0	0	0	0	0	0	0
I = 18	170	17	112	148	152	75	79	96	0	0	0	0	44	38	0	1	0	0	2	0	0	0	0
I = 19	143	159	153	158	104	70	66	98	0	0	0	0	47	37	32	11	10	9	7	0	29	0	0
I = 20	170	160	164	147	106	116	105	103	0	0	0	0	50	54	54	44	0	0	0	0	0	0	0
I = 21	172	176	161	150	125	119	107	101	0	0	0	0	58	44	47	0	0	0	0	0	0	0	0
I = 22	175	176	172	151	140	136	0	126	0	0	0	0	0	32	30	11	0	0	0	0	0	0	0
I = 23	177	160	150	148	137	0	0	0	0	0	0	0	27	31	23	14	0	0	0	0	69	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 198///// TIME = 47.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	186	187	166	186	166	0	0	156	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	183	157	182	177	171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	176	172	173	166	176	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	163	176	174	179	171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	173	166	178	172	151	141	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	187	183	183	165	159	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	183	187	185	167	123	126	111	120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	187	186	186	162	129	129	110	129	0	0	0	0	0	0	0	0	0	67	0	71	77	0	0
I = 9	185	182	130	141	133	130	128	130	0	0	0	0	0	0	0	0	73	78	77	74	79	0	0
I = 10	184	186	149	167	131	129	142	136	0	0	0	0	0	0	0	0	120	80	85	84	81	0	0
I = 11	189	181	160	162	141	139	144	0	0	0	0	0	128	126	122	120	96	96	90	87	76	72	0
I = 12	183	185	166	163	145	147	140	154	0	0	0	0	133	132	123	106	105	0	85	82	76	75	0
I = 13	187	186	181	165	150	145	167	166	0	0	0	0	148	129	122	114	107	0	0	29	71	72	0
I = 14	27	135	146	143	0	0	164	0	0	0	0	0	0	129	120	94	0	0	0	0	0	0	0
I = 15	26	134	147	153	0	162	163	0	0	0	0	0	0	121	20	93	0	0	0	0	0	0	0
I = 16	180	182	137	174	178	165	160	158	0	0	0	0	25	37	29	0	0	0	0	0	0	0	0
I = 17	184	186	123	142	117	170	81	90	0	0	0	0	28	35	0	0	0	0	0	0	0	0	0
I = 18	180	27	122	158	142	85	89	100	0	0	0	0	56	48	0	11	0	0	12	0	0	0	0
I = 19	173	163	163	160	114	80	76	108	0	0	0	0	57	47	42	21	70	10	17	0	39	0	0
I = 20	180	178	176	157	116	126	115	113	0	0	0	0	60	65	64	54	0	0	0	-1	0	0	0
I = 21	182	180	171	160	135	129	117	111	0	0	0	0	68	58	57	0	0	6	0	3	5	0	0
I = 22	185	186	182	161	158	146	0	134	0	0	0	0	0	42	40	21	14	7	0	1	1	0	0
I = 23	187	178	160	158	147	0	0	0	0	0	0	0	37	41	33	24	0	-1	0	0	50	0	0

////RESULTS AFTER STEP NO 208///// TIME = 49.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	188	197	174	194	176	0	0	166	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	193	167	192	187	181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	188	182	183	174	180	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	173	186	184	189	181	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	183	178	188	182	161	151	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	187	193	193	175	165	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	193	197	195	177	133	134	121	130	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	197	196	196	172	139	139	128	139	0	0	0	0	0	0	0	0	0	79	0	81	87	0	0
I = 9	195	192	140	151	143	140	138	140	0	0	0	0	0	0	0	0	83	88	87	84	89	0	0
I = 10	196	198	159	157	141	139	152	144	0	0	0	0	0	0	0	0	139	90	95	94	91	0	0
I = 11	199	191	170	172	151	149	154	0	0	0	0	0	138	134	132	130	106	106	100	97	86	87	0
I = 12	193	195	176	173	155	157	159	164	0	0	0	0	143	142	133	116	115	0	99	92	86	85	0
I = 13	197	196	191	175	168	155	177	176	0	0	0	0	158	130	132	124	117	0	0	30	81	82	0
I = 14	37	145	156	153	0	0	174	0	0	0	0	0	0	135	130	104	0	0	0	0	0	0	0
I = 15	36	144	157	163	0	172	173	0	0	0	0	0	0	131	38	103	0	0	0	0	0	0	0
I = 16	190	192	167	186	188	175	170	168	0	0	0	0	39	42	39	0	0	0	0	0	0	0	0
I = 17	196	196	133	152	127	108	91	108	0	0	0	0	38	49	0	0	0	0	0	0	0	0	0
I = 18	190	37	132	168	172	95	99	110	0	0	0	0	66	58	0	21	0	0	22	0	0	0	0
I = 19	183	173	173	170	124	90	86	118	0	0	0	0	67	57	52	31	30	28	27	0	49	0	0
I = 20	190	188	186	167	128	136	125	123	0	0	0	0	79	79	76	66	0	0	0	10	7	0	2
I = 21	192	198	181	170	149	139	127	121	0	0	0	0	78	69	67	4	6	16	0	13	15	3	5
I = 22	195	198	192	171	160	150	0	146	0	0	0	0	0	52	50	31	26	17	0	11	11	0	0
I = 23	197	188	178	160	157	0	0	0	0	0	0	0	67	51	43	34	0	18	0	0	60	0	0

Figure 25. (cont'd)

////RESULTS AFTER STEP NO 210////// TIME = 52.3750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	204	207	184	204	186	0	0	178	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	203	177	202	187	191	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	186	182	193	184	188	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	183	198	194	190	191	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	193	188	190	192	171	161	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	207	203	203	185	179	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	203	207	205	187	143	144	131	140	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	207	206	206	182	140	140	130	149	0	0	0	0	0	0	0	0	0	87	0	91	97	0	0
I = 9	205	202	150	161	153	150	140	150	0	0	0	0	0	0	0	0	93	90	87	94	90	0	0
I = 10	204	200	169	167	151	149	162	154	0	0	0	0	0	0	0	0	140	100	105	104	101	0	0
I = 11	209	201	180	182	161	159	164	0	0	0	0	0	148	146	142	140	116	114	110	107	96	92	0
I = 12	203	205	186	183	165	167	169	17[illegible]	0	0	0	0	153	152	143	126	125	0	105	102	96	95	0
I = 13	207	206	201	185	178	165	107	184	0	0	0	0	168	140	142	134	127	0	0	48	91	92	0
I = 14	47	195	166	163	0	0	184	0	0	0	0	0	0	148	140	116	0	0	0	0	0	0	0
I = 15	46	196	167	173	0	182	183	0	0	0	0	0	0	141	48	113	0	0	0	0	0	0	0
I = 16	200	202	157	194	198	185	180	178	0	0	0	0	46	52	49	0	0	0	0	0	0	0	0
I = 17	204	206	143	162	137	190	101	110	0	9	0	0	48	54	0	0	0	0	0	0	0	0	0
I = 18	208	47	142	178	182	185	189	120	0	0	0	0	76	48	0	31	18	0	32	0	0	0	0
I = 19	193	183	183	180	134	180	96	129	0	0	0	0	77	67	62	41	40	36	37	9	59	0	0
I = 20	200	198	194	177	136	146	135	133	0	0	0	0	80	80	84	74	1	4	5	20	17	8	12
I = 21	207	208	191	190	159	140	137	131	0	0	0	0	88	78	77	14	16	24	18	23	25	13	15
I = 22	209	200	202	181	178	166	0	156	0	0	0	0	0	62	60	41	36	27	4	21	21	3	2
I = 23	207	198	188	178	147	0	0	0	0	0	0	0	57	61	53	44	0	28	-1	0	79	0	0

////RESULTS AFTER STEP NO 220////// TIME = 54.8750

J =	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
I = 1	216	217	194	214	196	0	0	186	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 2	213	187	212	207	201	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 3	208	202	203	194	200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 4	193	200	204	209	201	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 5	203	190	208	202	181	171	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 6	217	213	213	199	189	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 7	213	217	215	197	193	154	141	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
I = 8	217	216	216	192	159	159	148	159	0	0	0	0	0	0	0	0	0	87	0	101	107	0	0
I = 9	215	212	160	171	163	160	158	160	0	0	0	0	0	0	0	0	103	108	107	106	109	0	0
I = 10	214	210	179	177	181	159	172	164	0	0	0	0	0	0	0	0	150	110	115	116	111	0	0
I = 11	219	211	190	192	171	169	174	0	0	9	0	0	158	156	152	150	126	124	120	117	104	102	0
I = 12	213	215	194	193	179	177	179	184	0	0	0	0	169	162	153	136	135	0	115	119	108	105	0
I = 13	217	216	211	195	188	175	197	196	0	0	0	0	170	150	152	144	137	0	0	59	101	102	0
I = 14	97	169	176	173	0	0	194	0	0	0	0	0	0	155	150	124	0	0	0	0	0	0	0
I = 15	90	164	177	183	0	192	193	0	0	0	0	0	0	151	98	123	0	0	0	0	0	0	0
I = 16	210	212	167	204	208	195	190	108	0	0	0	0	54	62	59	0	0	0	0	0	0	0	0
I = 17	214	216	153	172	147	200	111	120	0	0	0	0	58	64	0	0	0	0	0	0	0	0	0
I = 18	210	57	152	188	192	115	119	130	0	0	0	0	86	78	0	61	20	0	62	0	0	0	0
I = 19	203	193	193	190	146	110	100	138	0	0	0	0	87	77	72	51	50	44	47	19	69	19	19
I = 20	210	208	204	187	196	150	145	143	0	0	0	0	99	99	94	86	11	14	15	30	27	18	22
I = 21	212	210	201	190	165	159	147	141	0	0	0	0	96	84	87	24	26	34	78	33	35	23	29
I = 22	215	218	212	191	188	176	0	164	0	0	0	0	0	72	70	91	44	39	14	31	31	13	12
I = 23	217	208	198	188	177	0	0	0	0	0	0	0	67	71	63	54	0	38	10	0	89	7	0

Figure 25. (cont'd)

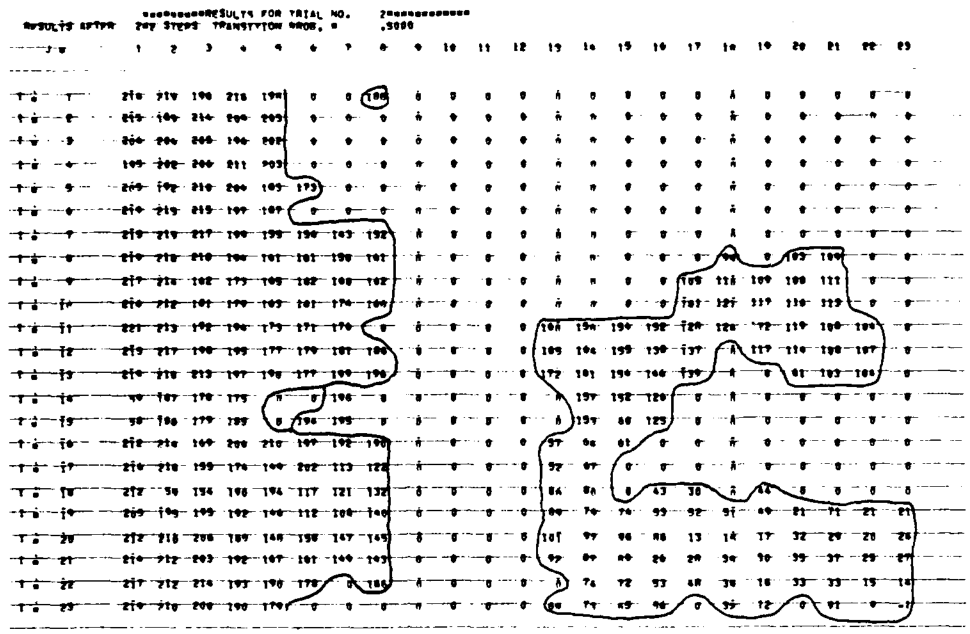


Figure 25. (concluded)

ignited with a 1/16 hour duration of each iteration step. Figure 26 shows the ignitions that were made by firebrands, by a line extending from the igniting to the ignited buildings. It can be seen that four structures were ignited by firebrands crossing the firebreak.

By estimating the location of the burning front at different times, the rate of propagation of the burning front can be calculated. The calculation is subject to some error due to the irregular nature of the front. Figure 27 presents an estimate of the rate of propagation of the front as a function of probability of fire spread. A mean burning time for the ignition distribution of 0.5 hours is used. The output and susceptibility parameters are uniformly distributed between 0.7 and 1.3. The no-firebrand-curve can be estimated fairly well. The value of the rate of propagation at a probability of spread of 1.0 is simply the reciprocal of the average time a building burns before igniting another and is probably a slightly low estimate. The rate of spread with firebrands can be estimated

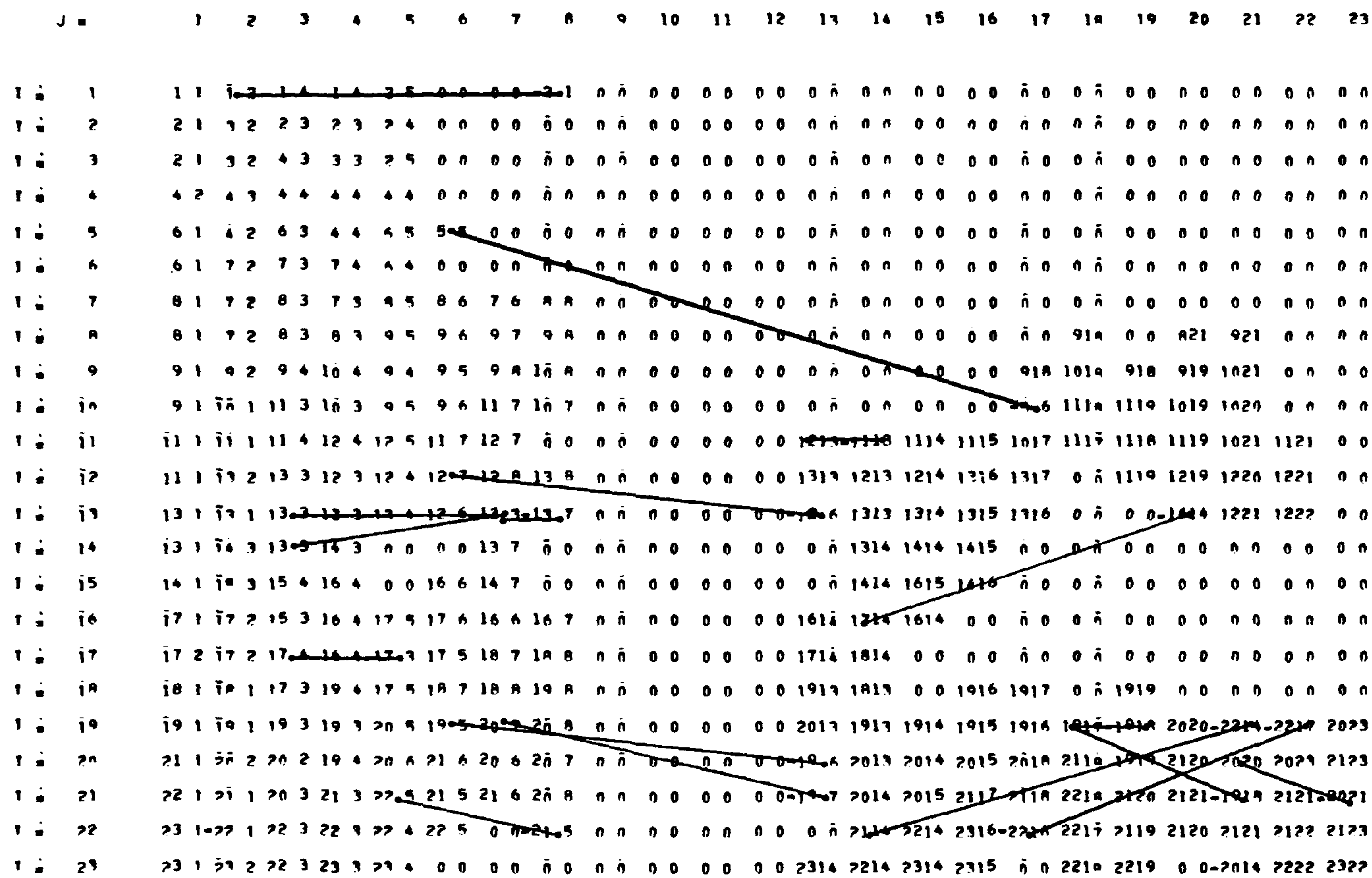


Figure 26. SAMPLE FIREBRAND PROPAGATION

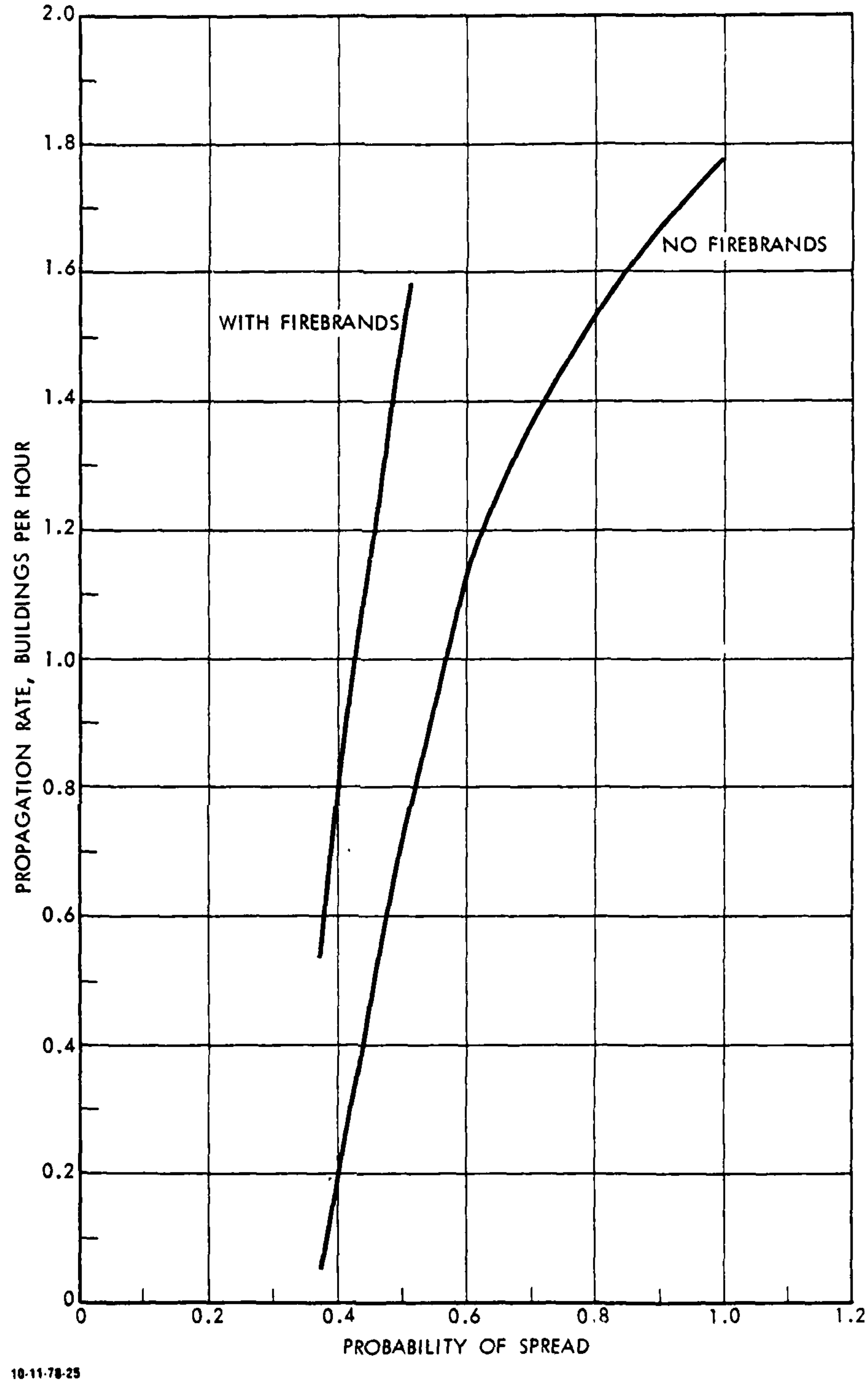


Figure 27. FIRE FRONT PROPAGATION RATE AS A FUNCTION OF TRANSMISSION PROBABILITY

at 0.4 and 0.5 probability. At 0.4 probability, the estimate is affected by the fairly high probability of a fire dying out. At 0.5 probability, the propagation is very rapid, and the effective propagation rate is affected strongly by the rate at which firebrand-ignited centers grow and coalesce. For a probability of spread of 1, the rate of front propagation may be estimated roughly as the product time delay from ignition to propagation and the average distance of firebrand propagation, a value of about nine buildings per hour, or a little less than a 1/10 mile per hour, is obtained. This rate, of course, depends upon wind speed. With wind speeds of 20 mph, a propagation rate of 1/2 mph for the burning front can be achieved.

In order to obtain a measure of the effects of firebrands and barriers on the total number of buildings burned, the percent burned in the center portion of the matrix on each side of the barrier was computed for 20 trial runs. The 5 rows on the top and bottom of the matrix and 4 rows in the end were ignored to minimize side and end effects, and the first 4 rows ignored to eliminate starting effects. Table 11 presents the percent burned in the two areas, with p_n the radiation transition probability.

For these calculations, the wind speed is 4 miles per hour and the expected number of firebrand ignitions for each building ignited is 0.1. The first two sets of cases in this table illustrate the effects of firebrands upon the percent burned. The effect appears relatively greater for the buildings in the further downwind tract, as would be expected since this tract will receive firebrands from a larger number of buildings. From Table 7, which presents expected number of ignitions from buildings with various numbers of unburned neighbors, we see that increasing the transition probability from 0.4 to 0.5 would increase the expected number of ignitions by a factor of 1.25 (assuming half the ignitions are from two-branch burnings and half are from three-branch burnings). Thus, an expected number

Table 11. EFFECT OF FIREBRANDS AND BARRIER ON PERCENT OF BUILDINGS BURNED

Conditions	Before Barrier Columns 5-8 Rows 7-17	After Barrier Columns 13-19 Rows 7-17
No Firebrands, No Barrier		
$p_n = 0.5$	73	53
$p_n = 0.4$	34	1
Firebrands, No Barrier		
$p_n = 0.5$	90	85
$p_n = 0.4$	58	48
Firebrands, Barrier		
$p_n = 0.5$	79	48
$p_n = 0.4$	52	16

of firebrand ignitions of 0.1 is equivalent (strictly in terms of expected ignitions) to increasing the radiation transition probability by 1/3. Comparing the 0.4 firebrand case with the no firebrand case (in the table) would indicate results consistent with a 0.43 transition probability.

The effect of a barrier decreased the downwind fraction burned from 85 percent to 48 percent with a 0.5 radiation transition probability, and from 52 percent to 16 percent with a 0.4 transition probability. In both cases the majority of the reduction appeared to be due to large sections simply not happening to be ignited by firebrands on individual trials. The 250 foot barrier had a significant quenching effect on fire transfer.

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Abstract

One of the basic mechanisms governing the magnitude of fire damage in an urban area resulting from a nuclear attack is the fire spread between individual structures. This paper investigates the effects of various methodological assumptions, using the basic physical models of fire spread by radiation and firebrands contained in the IITRI model. As an introduction to probabilistic effects, various regimes of solutions to fire spread by radiation in individual tracts are obtained by simplifying the IITRI model.

The spread of fire down rows of buildings and in rectangular grids, when each structure has a constant probability of igniting adjacent structures, is followed through a Monte Carlo simulation. Changes in fire spread patterns, as the probabilities are changed, are illustrated. The effects of various complicating features, such as random initial ignitions and varying ignition probabilities for each structure, are studied individually. Finally, a Monte Carlo simulation model is developed which contains almost all of the physical features of fire spread in the IITRI model. The spread of fire by firebrands across firebreaks, and the effects of ignition probabilities on the rate of fire spread are illustrated through the use of this model.

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