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ASSESSMENT OF COMBINED EFFECTS OF BLAST
AND FIRE ON PERSONNEL SURVIVABILITY

FINAL REPORT

FEMA Contract DCPA01-79-C-0265

June 1982

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ASSESSMENT OF COMBINED EFFECTS OF BLAST AND FIRE ON PERSONNEL SURVIVABILITY

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FINAL REPORT

By

A. Longinow
T. E. Waterman
A. N. Takata

for

Federal Emergency Management Agency
Washington, D.C. 20472

June 1982

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The objective of the study described was (1) to perform a preliminary analysis of hazards to sheltered personnel in a blast-fire environment produced by the detonation of a 1 MT nuclear weapon near the ground surface, and (2) to lay the basic ground work for developing a consistent, formal methodology for estimating the probability of people survival in a blast-fire environment.

(continued)

FOREWORD

This is the final report on IIT Research Institute project J6483 entitled "Assessment of Combined Effects of Blast and Fire on Personnel Survivability." This study was performed for the Federal Emergency Management Agency (FEMA) under Contract DCPA01-79-C-0265. The study was initiated on April 3, 1979, and completed December 31, 1981. Initial portions of this work were done by B. N. Norikane and N. Iwankiw.

Respectfully submitted,
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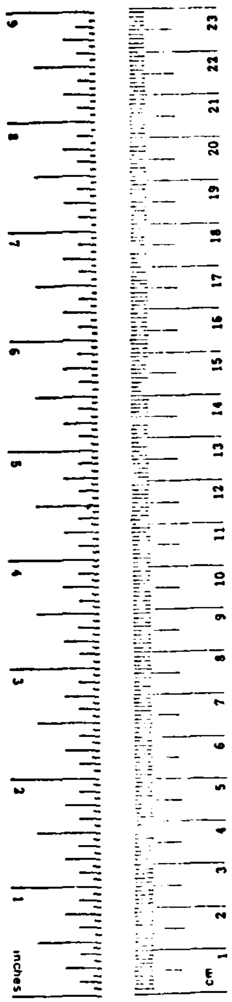
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

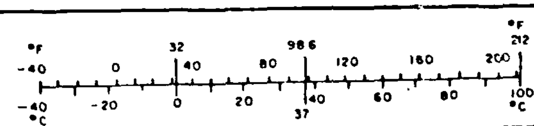
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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FEMA Contract DCPA01-79-C-0265

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SUMMARY

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ASSESSMENT OF COMBINED EFFECTS OF BLAST AND FIRE ON PERSONNEL SURVIVABILITY

The objectives of the research study described in this report were (1) to perform a preliminary analysis of hazards to sheltered personnel in a blast-fire environment produced by the detonation of a 1 MT nuclear weapon near the ground surface, and (2) to lay the groundwork for developing a consistent, formal methodology for estimating the probability of people survival in a blast-fire environment.

The study began by selecting a set of buildings to be used for constructing a variety of realistic city blocks and then portions of cities or towns. The set included four buildings; two framed single family residences, a low-rise multi-family residence, and a high-rise residential building. All are real buildings and represent a realistic sample of residential construction in terms of size, though not necessarily representative of all possible structural systems and building materials.

Each of the four buildings was analyzed to determine overpressures necessary to produce incipient collapse and breakup of the building. On the basis of the blast/structural analysis a debris catalog was assembled for each building. A debris catalog contains all of the pieces a building breaks into when subjected to incipient collapse overpressure. Each debris piece in the catalog is described in terms of the following parameters, i.e., weight, size, largest and smallest projected areas, center of gravity coordinates of the initial position at the time of separation. In addition to building parts, the debris catalog also includes a typical (basic) set of furniture items.

To expedite the determination of final debris location, a computer program was developed for debris transport analysis. This computer program has the following capabilities.

(1) Store and retrieve debris catalog data for buildings included in the analysis.

(2) For a given attack condition determine debris trajectories, final ground ranges and times of arrival for each debris piece in the catalog.

(3) Determine which debris pieces from which city blocks combine to form a debris pile in the city block of interest. Determine the special distribution of debris pieces in the block.

(4) Provide information (printout and/or contour plots) on the makeup of the debris pile for use in fire ignition and fire spread analysis.

For further study, a hypothetical city consisting of identical, two-story single-family framed residences with three types of below-grade personnel shelters was formulated and subjected to a simulated, single nuclear weapon attack. On the basis of a blast-structural analysis, zones of blast damage were identified and labeled as severe, moderate and light. Using the "debris analysis" programs, the distribution of building debris was determined. Debris piles in the severe damage area of the city were described in terms of debris weight and composition (combustible, noncombustible) as a function of ground location.

Time dependent fire effects were first determined for the entire city. The IITRI Ignition Model was updated to reflect recent analyses of blast modification of sustained ignitions (primary fires); and, combined with predictions of secondary fires to describe the initial ignition patterm over the city from a 1 MT near-surface burst. The IITRI fire spread model was applied directly to the area of light damage, and modified, and applied to the moderate damage regions. Fires in the area of severe damage were assessed, assisted by results of past debris fire experiments.

Fire spread throughout the city was assessed for a 15 percent building density assuming no concerted firefighting efforts. Individual tracts were then reevaluated to establish the impact of fire prevention and firefighting efforts on local fire progress and severity. Hazards were quantified and the probability of people survival was estimated in terms of each shelter effectiveness when located in different zones of blast damage.

The three personnel shelters included (1) a conventional would joist framed basement expediently upgraded to provide additional blast resistance, (2) a conventional residential basement with a reinforced concrete overhead slab, and (3) and expedient, would pole-type personnel shelter.

The first category shelter was found to be only marginally effective even in the zone of light blast damage. The probability of people survival in such a shelter is strongly dependent on the probability of ignition and the probability of fire suppression. Such a shelter is not recommended in fire-prone zones without substantial countermeasures. Category 2 personnel shelter is quite effective in zones of light to moderate damage and requires only limited countermeasures. In zones of severe blast damage, and due to large quantities of burning debris, the effectiveness of this shelter is substantially diminished. Significant countermeasures are required to maintain its effectiveness. The expedient, pole-type shelter proves to be the most effective of the three shelters studied. This shelter has the advantage of being sited in open areas away from potential debris zones, thus minimizing the problem of burning debris in its immediate vicinity.

With the completion of this study the groundwork has been laid for the development of a consistent, formal methodology for estimating the probability of people survival in a blast-fire environment.

1. INTRODUCTION

This research effort was performed to assess the value of existing blast/fire/people survivability data and to formulate a systematic approach for evaluating personnel survivability in a blast-fire environment. This initial study concentrated on detailed analyses of local groupings of residential structures within a city subjected to the effects of a 1 MT nuclear near-surface burst; and, the implications of the resultant blast damage and fires on people survival within three types of below grade shelters. In the study, blast was considered to cause potential shelter damage; and, to modify fire initiation, fire intensity, and fire spread within and between buildings.

Existing computer models for debris transport and fire behavior were modified as necessary to incorporate the current state of knowledge in each aspect of the study, and were supplemented with past debris fire experimental data, where no analytical models exist.

Blast damage, debris transport, fire effects and people survivability are treated in that order in the chapters to follow. While presented sequentially, each facet of the problem is examined in manner providing the data required for subsequent evaluation of blast/fire/people interaction in an attack environment.

2. BACKGROUND

The development of high-yield nuclear weapons has resulted in considerable effort toward assessing casualties and damage in populated areas exposed to nuclear weapon attacks. The effects of fire, prompt effects, and fallout have been studied. Concurrently, various passive and active defenses against these effects have also been considered. Studies of nuclear weapon effects environments have traditionally attempted to assess blast and fire effects as though each were relatively independent of the other. In fact, some damage assessment has been based on the premise that blast creates a central zone in which fire behavior is superfluous and that beyond this zone, blast can be neglected and fire damage assessed by using fire spread characterizations based on undamaged structures.

Unfortunately, this philosophy has carried over into studies of personnel survivability where again, blast and fire have been treated as only casually related phenomena whose effects can be summed to produce tallies of casualties. Perhaps this separation of effects has occurred due to the differences in the disciplines represented by those attacking each aspect of the problem. This however merely excuses but does not justify the separation. At one time, arguments could be put forth that the state of the art for assessing individual effects was so poor as to preclude useful quantitative considerations of more complex interactions. At the present time this certainly is no longer a valid reason. Enough work has been done to allow the problem to be treated in a rational manner.

Civil defense planning must ultimately rest on the cost-effectiveness of a total civil defense system. Reliable procedures for determining cost-effectiveness must treat combined weapon effects. The purpose of this chapter is to review the interaction of blast and fire as it affects people survival in a nuclear weapon effects environment as background to this study which had the following objectives.

- Assess the value of existing blast/fire/people survivability data and formulate a systematic approach for evaluating personnel survivability in blast/fire environment.
- Perform a detailed analysis of a local grouping of structures including shelters (which could be of conventional or expediently upgraded construction) and estimate people survivability when subjected to a nuclear weapon environment.

2.1 Blast-Fire Interactions; Phenomenological

Although interaction implies that two or more phenomena are operating at the same time, this discussion will broaden the definition to include conditions where blast effects have a later influence on fire behavior. Before embarking on this discussion, it should be pointed out that the degree of interaction will vary greatly depending on the general land use, structural types and occupancies being considered.

For low to moderate blast damage, phenomenological interactions between blast and fire can be conveniently categorized as the effects of blast on:

- Fire initiation
- Fire buildup and internal fire spread in damaged and undamaged buildings
- Fire intensity and external fire spread between and within damaged and undamaged buildings

As increased blast begins to destroy the identity of buildings and distribute debris over increasing areas, these categories gradually become:

- Fire initiation
- Fire buildup in debris
- Fire spread through debris
- Fire intensity
- Fire spread between debris areas

Depending on the overpressure, the mix and arrangement of buildings in any given area, both groups of descriptors may apply as certain structures remain relatively intact while others may be widely scattered.

2.1.1 Effects of Blast on Fire Initiation

Kindling materials are most susceptible to ignition by the thermal pulse from a nuclear weapon detonation. The most common of these in urban areas are room contents such as upholstered furniture, paper, and window coverings. Their ignition is usually described in terms of the total heat pulse received by the exposed material, not the fraction received prior to ignition. The minimum value of this pulse that causes ignition is called the critical ignition energy and varies with weapon yield. In studying blast-fire interaction effects on ignition, two parameters are of particular interest, these are the maximum thermal flux and the time of the thermal maximum. The latter represents for all practical purposes the time when the ignition takes place and can be used to determine the preburn time before arrival of the blast wave. Figure 1 shows the expected preburn time for materials located at regions of 4 and 6 psi overpressure for weapon yields between 1 and 100 MT. The amount of flux delivered to the material before arrival of the blast wave is also shown. This amount, as shown in Figure 1 for the 4 psi region, is at least 60 percent of the total which represents all energy of significance to ignition of the exposed material. Thus, the blast wave can be assumed to arrive after the delivery of the thermal pulse in much of the region of interest, certainly in those areas of low to moderate numbers of ignitions. This simplifies the correlations of blast effects and any possible theoretical analysis.

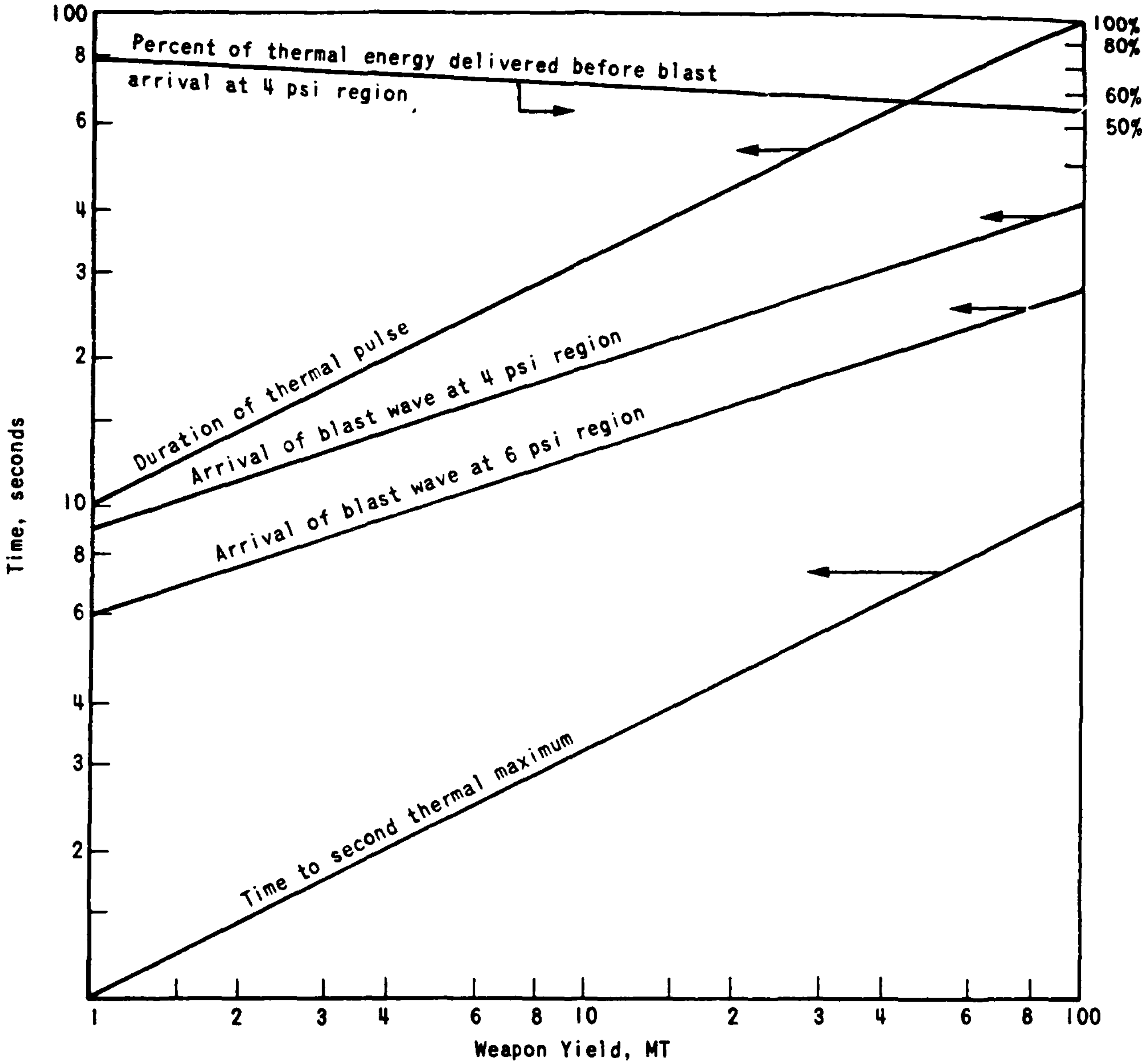

Figure 1. Times of Arrival of Thermal Energy and Blast Wave for Surface Bursts

An indication of possible blast wave velocities required to blow out the ignitions can be obtained from the studies conducted by Dahl (Ref. 1). In these studies ignited materials were suddenly subjected to airflows to determine which, for a given preburn time, have 50 percent probability of blowing out the fire. The results obtained by Dahl indicate that the magnitude of the threshold velocities increased as preburn time increased or duration of the airflow decreased.

Blast wave effects on primary ignitions were also considered for kindling fuels during full-scale tests of Operation Buster (Ref. 2). In this connection, a most interesting observation was the total consumption of some fuels by fires prior to the arrival of the blast wave. One could expect similar situations with thin window covering materials exhibiting rapid spread of flames.

More recent efforts (Ref. 3) to study blast enhancement or extinguishment of ignitions utilizing a shocktube indicated that flaming combustion was extinguished by overpressures exceeding 2.5 psi although smouldering combustion survived all overpressures capable of being produced by the facility (8 psi maximum with limited positive phase duration). In subsequent field tests, liquid fuel fires survived 5 psi overpressures from detonation of high explosives (Ref. 4).

Fires resulting from blast induced ignitions such as those from electrical short circuits, overturned appliances or ruptured gas lines are called secondary fires. The importance of secondary ignitions to the overall fire problem has been debated for the past 15 years. For example, McAuliffe and Moll (Ref. 5) have suggested a frequency of occurrence of 0.006 secondary ignitions per 1000 ft^2 of total floor area damaged by at least 2 psi blast pressure. This value has been criticized as being too high. Two factors, however, make consideration of secondary fires necessary. The first of these is that some secondary ignitions will occur in areas where natural structural array, atmospheric conditions or countermeasures have reduced primary ignitions to a negligible level. Also, since shelter structures represent a very select and critical category, their individualized occupancies must be examined for susceptibility to secondary ignitions. This will probably involve a fairly detailed evaluation of the blast response of the structures and contents. Figure 1 shows that the blast arrival from any given weapon detonation was usually too late to significantly aid in exposure of kindling to the thermal pulse of the same weapon. However, for multiple bursts, blast effects ranging from the removal of windows to the rending of entire structures will enhance the probabilities of ignition. Alternately, burst height and time between bursts could be such that dust clouds raised by the first weapon may attenuate the thermal pulse of later detonations.

2.1.2 Effects of Blast on Fire Buildup and Internal Fire Spread

For structures which have retained some semblance of their original geometry, a significant event in fire development is the occurrence of room flashover. This total involvement of a room in fire is usually coincident with the start of measurable external effects (exposure of nearby structures) as well as with the onset of rapid internal fire spread. The phenomena of flashover have been considered in several past studies (Ref. 6, 7, 8). These studies produced some interesting observations which may shed some light on possible blast wave effects.

For a flashover to occur the fire must involve room items of substance, such as upholstered furniture, beds, etc. When ignited in a manner simulating the thermal pulse, these items have shown the following fire behavior. First, the combustion continues actively in areas where mutual support leads to conservation of heat produced. This is then followed by fire penetration into the item interior with a speed governed by the general makeup of the item. Finally, upon fire penetration throughout the interior spaces of the item, it rapidly becomes totally involved in flames. Although these observations were obtained from an ignition simulating that produced by a weapon pulse, similar behavior may be expected with localized heating such as that produced by a burning window covering in contact with the item. Here, however, time of fire development of the item will also depend on the burning behavior of the window covering.

As noted, the progress of the fire within the item depends on the makeup of the item. This makeup can be altered by blast. It will also be influenced by external air currents, such as may develop between the burning items and adjacent walls or objects. Blast waves may change these air currents by either overturning or redistributing the furniture items. The effect of such changes will be primarily to delay or advance the flashover time. At this time, no information is available regarding this matter.

In addition to depositing light ignited items such as curtains on more substantial fuel sources such as beds, etc., the blast wave may tend to cluster the fuel items (Ref. 9). At overpressures where structural damage takes place, added combustibles and/or noncombustibles will be deposited over the ignited items. Little data are available pertaining to this fire situation, however, some was included in work unit 2534I mentioned previously (Ref. 3).

Following room flashover, fire spread between rooms and throughout the structure will depend on the nature of the resistance offered by structural members. This subject has been dealt with for many years in connection with providing proper fire protection for peacetime situations. Procedures have been established for measuring the fire resistance ratings of structural components. Some additional information has been obtained during IIT Research Institute (IITRI) studies (Ref. 10) which included development of techniques for interpreting the rating data in terms of fire spread.

A blast wave can modify fire spread between rooms or floors of a building in several ways. Moderate blast damage will tend to promote rapid interior fire spread by breaching barriers or by increasing fuel availability due to splintering of combustibles and removal of noncombustible cladding. Higher damage levels may result in slower fire spread due to blanketing with noncombustible debris. A small amount of quantitative data on fire spread in blast damaged structures was gathered in the field burns conducted for OCD Work Units 2534E (Ref. 11) and 2562B (Ref. 12).

2.1.3 Effects of Blast on Fire Intensity and External Fire Spread

For those situations where blast has caused structural modification conducive to an increased rate of fire spread, an increase in the level of fire exposure to nearby structures can be expected as all portions of the burning structure will tend to peak intensity at nearly the same time. Tending to counteract this will be an earlier collapse time for some structural types which will shorten the duration of high level exposure. Besides the effect it has on duration and intensity, blast damage will bare combustibles in unignited structures to the exposing fires. Blast damage will make the unignited structure more vulnerable to fires in exterior kindling fuels which otherwise might not penetrate to the interior (Ref. 10). In a similar vein, blast rearranged exterior fuels and structural debris may form bridges for fire spread where otherwise no jump would occur. An increased tendency to produce firebrands can be associated with moderate blast damage. Also, blast certainly renders unignited structures more susceptible to brands by removing barriers (windows, roofs, etc.) to brand penetration of the structural interior. Unfortunately, most understanding in this area is qualitative although small amounts of pertinent data have been gathered (Ref. 11, 12, 13, 14).

2.1.4 Effects of Blast on Debris Fire Characteristics

The importance of debris fire characteristics increases as one considers shelter spaces affording increased blast protection to the occupants. Debris fires can cause direct heat transmission through shelter walls and roof. Probably more difficult to counter is the exposure of fresh air intakes to carbon monoxide and hot fire gases. Knowledge of the duration and intensity of the debris fire is of extreme importance in assessing the total exposure and in the design of countermeasures.

In the early 1960's, no information was available on the temperature and duration of debris fires created by combined blast-fire effects. Some temperature information did exist from probings of the debris piles resulting from burned out buildings. However, these debris piles had little combustible content and should behave quite differently from blast-induced debris. In addition, no general downward heating capability was defined. One measurement of heat transmission through a shelter roof was obtained for a nonblast damaged structural burnout in 1966 (Ref. 14). Shortly thereafter, information was generated on heat transmission for several moderate area debris piles placed over a concrete slab and burned in the IITRI Fire Research Laboratory (Ref. 15). Within this study (OCD Work Unit 1134A) was one piece of field data from the burnout of a debris-loaded real structure. Although the quantity of these data were limited, they were analyzed and generalized so that approximate calculations could be made of heat flow through a concrete slab for various postulated debris fires (Ref. 16, 17).

Much more definitive data on heat and fire gases in a debris field were collected with the large-scale fire test structure built under OCD Work Unit 1135A (Ref. 18). Debris fires were burned (Ref. 19, 20, 21) representative of residential, mercantile, office, auto park, and library occupancies at moderate damage levels (contents and weak wall debris). Data on residential occupancies were extended to include very light damage (windows) to major destruction. The latter included debris representative of a row of two-story structures distributed by the 5 psi over-pressure blast wave of a 1 MT surface burst.

The large-scale experiments were augmented by development of an analytical model of heat flow through the shelter ceiling slab and conduct of a series of small segment tests. In addition, several large-scale tests employed well defined debris patterns of lumber and gypsum strips to assist in developing techniques for predicting the effects of other debris densities, depths, and compositions.

Large-scale experiments were conducted to assess the specific effects of nonuniform debris distribution and countermeasures to reduce heat penetration through the shelter envelope. Also experienced were the increased heat and gas effects of low ventilation of the fire area. Simple countermeasures were devised to counteract blast damage (cracking) of the shelter ceiling. The experiments not only define heat and gas inputs to the shelter but establish the importance of a detailed description of the nature of the debris pile (void ratio, noncombustible content, etc.) in defining its fire duration and intensity of exposure.

2.2 Blast-Fire Interactions; Operational Effects

One need only to start a chronological listing of the events of a nuclear attack to realize the many modifying effects of each event on all those that follow.

2.2.1 Building Contstruction or Upgrading Period

Among the events of importance are some which may occur years, months, or days before the attack. Of obvious inclusion is the building construction or upgrading period during which slanting or expedient upgrading techniques may be employed to harden a shelter space against blast, thermal, or fallout effects. The cost-effectiveness of slanting is, in fact, a prime informational need of the Federal Emergency Management Agency (FEMA).

Slanting for fire effects has been considered in several studies (Ref. 22,23,24) and costs of a number of such shelters are available in fair detail.

Of more immediate concern are the shelters for key workers remaining in high risk areas. Such shelters would consist of the better classes of basements, upgraded (expediently) to the extent necessary to provide protection against the direct and indirect effects of a nuclear weapon environment. The indirect effects would include postevent fires. It is a useful exercise to evaluate the effectiveness of such slanted and upgraded shelters in a combined blast-fire environment.

2.2.2 Preattack Period

In the more immediate preattack period, there are a large number of factors which will have major effects on subsequent events and levels of survival. Of prime importance is warning time. Awareness of a high probability of imminent attack can provide time for preattack countermeasures. Leadtime warning of actual attack will have a great influence on population location at the time of weapon delivery. Preattack planning and organization will have a marked effect on the efficiency with which the warning leadtime is used.

Although a systematic study has yet to be made of all possible preattack countermeasures that could be taken, a number of studies are pertinent. A great many preattack precautions for reducing the incidence and impact of fire were defined by Moll (Ref. 25). Most available data were reviewed by the Naval Radiological Defense Laboratory (NRDL) in 1965 under OCD Work Unit 2541B.

2.2.3 Attack; Immediate Effects

Obviously, the detonation of a nuclear weapon(s) creates a whole new environmental framework in which later phenomenology and operations must be assessed. Many of the changes are rather instantaneous and are called immediate or direct effects. These include blast effects and blast-fire interactions involving ignitions. Studies of the response of both structures and the population to the immediate effects (due to location) can be used to describe:

- immediate casualties
- survivors available for counteraction and rescue
- survivors requiring rescue
- number and location of firestarts
- degree of damage to structures
- amount and location of debris

In these terms, both the operational limitations and initial environmental restrictions are defined for the postattack period. Many studies and disciplines contribute to this definition.

2.2.4 Postattack Period

Study of the immediate postattack period becomes one of careful tradeoffs between fire suppression and rescue as constrained, first locally and then generally, by fire debris and fallout. As a prerequisite to study of this period, the population must be categorized as killed, injured, trapped, trapped and injured, or undamaged. The number in each catetory is determined by applying immediate effects of the attack to the population as distributed by preattack planning (or lack of same), warning time, and shelter availability.

Although blast damage and fallout contamination place important limitations on the operational aspects of the postattack period, the heart of any evaluation of this period must be a detailed time-oriented fire spread model. The magnitude of information to be handled and the degree to which it must be manipulated, immediately direct attention to a high speed computer for such a study. Mechanistic models offering a fair amount of detail on fire buildup and internal structural spread were developed for

FEMA by IITRI in the past (Ref. 26,27).* Fire defense codes (Ref. 28) were added to permit inclusions of effects of firefighting. Inputs that define surveillance requirements for fire security were developed for NFSS structures (Ref. 34) and provide further input to study of this period. Many of the constraints imposed by debris are developed in Reference 35.

It is quite obvious that debris is a major constraint to general firefighting, specific shelter protection, and rescue. Although early studies of debris were limited to descriptions of production with little analysis of transport, later studies (Ref. 20, 36, 37) provided means to estimate debris distribution in more detail.

A first attempt at the problem described is presented in the following chapters of this report.

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*IITRI has maintained its leadership role in the development of fire models through programs sponsored by the National Bureau of Standards (Ref. 29,30,31,32) and the Products Research Committee (Ref. 33). The IITRI RFIRES code is recognized as offering a practical detailed working room fire development model.

3. APPROACH TO DEBRIS CHARACTERIZATION

A fairly simple model was used to describe typical urban areas. Urban areas were modeled by blocks with only one type of structure on any block. All of the structures on any given block were assumed to be essentially identical. The blast environment was assumed to be identical for every structure on the block. Thus, analysis could be performed for one structure, and the results could be superposed to describe an entire block.

Only one blast environment was used for each structural type. The minimum, peak, free field overpressure which would produce collapse of the structure was determined using previous work and some structural analysis. The blast environment chosen was one compatible with this overpressure and a one megaton surface burst.

Every debris piece in the structure was then cataloged. That is, a postblast size and shape were determined and ten parameters were calculated and listed for each piece.

From this point, the bulk of the debris pile analysis was performed by three computer programs, TRAJCT, RANGER and BLOCK. TRAJCT determined the trajectory of a debris piece in the given environment and calculated the probable distribution of a group of similar pieces. RANGER used these distributions to determine the debris pile from a single structure. Finally BLOCK superposed the results of RANGER to describe an entire block.

3.1 Analytical Model

In addressing the primary objectives of the subject project particular attention was focused at the identification and formulation of realistic, but not unduly complex, analytical approaches. The broad scope and nature of the problem dictated the implementation of a simplified rational analysis that could adequately account for the different proposed building scenarios and the major independent variables. In this process, a number of simplifying assumptions were made that facilitated both the debris data processing and analysis. The inclusion of probability treatment of the model parameters allowed for the determination of expected value results and their dispersion. This feature, in our judgment, imparted to the study not only an economical approach but also a greater degree of credibility and usefulness than a purely deterministic solution; this is due to the fact that the blast-fire scenarios under consideration are largely hypothetical and subject to variations in weapon parameters, structural properties, and the urban environment.

It was felt that if some overall rational conclusions could be reached from this initial effort with regard to a general characterization of blast-fire interaction trends and the sensitivity of results to input variables, the research would have accomplished its purpose. In addition, the development of a generalized computer model to generate blast induced debris distributions has produced an analytical tool that can be used to evaluate other blast conditions and building configurations or to study, in more detail, selected parts of the total problem.

In the ensuing sections, the different technical aspects of the research topic will be discussed in terms of overall approach, underlying theoretical basis, initial assumptions and limitations, and the required input-output for the analysis.

3.1.1 Blast

Blast induced debris transport studies have been conducted for numerous Department of Defense Agencies with various objectives. In order to avoid redundancy, it was decided to utilize, as much as possible, a working model developed under past projects. A computerized airblast debris analysis program that was successfully used on a previous IITRI project (Ref 37) was selected.

The formulation for this model is deterministic in two dimensions and considers both drag and lift forces. Its applicability, ready availability, ease of use, and relatively quick computer turnaround influenced the decision.

The governing equations of motion for the horizontal and vertical directions of a debris piece may be written as

$$\frac{W_e}{g}\frac{dV}{dt} = F_d \tag{1}$$

and

$$\frac{W_e}{g}\frac{dU}{dt} = (F_\ell - W_e) \tag{2}$$

where

V = horizontal velocity of debris
U = vertical velocity of debris
W_e = weight of debris
F_d = horizontal drag force
F_ℓ = vertical lift force
t = time
g = gravitational constant

The aerodynamic forces are expressed as

$$F_d = \tfrac{1}{2}\rho\, C_d\, A\, (W-V)|W-V| \tag{3}$$

and

$$F_\ell = \tfrac{1}{2}\rho\, C_\ell\, A\, (W-V)|W-V| \tag{4}$$

where

W = blast wind velocity
ρ = air density
C_d = drag coefficient
C_ℓ = lift coefficient
A = maximum projected area

The blast wind velocity, W, is estimated as (Ref 38)

$$W = W_o \left(1 - \frac{t'}{t_o}\right) e^{-\frac{Kt'}{t_o}} \tag{5}$$

where

W_o = peak wind velocity

t' = time measured from shock passage

t_o = positive phase duration of dynamic pressure

K = exponential coefficient

As expressed in equations (3) and (4), the aerodynamic forces are related to the relative air velocity. These forces are a function of the size, shape and instantaneous orientation of the debris piece. These effects are accounted for by an appropriate drag or lift coefficient. The angle of attack β' will be equal to the difference of the orientation angle and the relative flow angle, α',

$$\beta' = \beta - \alpha' \tag{6}$$

however, in order to simplify the equations and the subsequent calculations the dependence of the angle of attack upon the relative flow angle was neglected. This assumption is based upon the fact that the relative air velocity will generally be horizontal (i.e., $U << (W-V)$). It is expected that the vertical velocity will always be rather small, however this assumption did not prove correct for those cases where the shape factor, S, (the ratio of minimum projected area to maximum projected area) was very small. If the relative air velocity is small, then the aerodynamic forces are small and this assumption becomes unimportant. In the final analysis the neglect of the relative flow angle in determining the angle of attack can be viewed as an uncertainty in determining the value of the aerodynamic coefficients. The value of the aerodynamic coefficient will depend upon the reference projected area of the body of interest. All coefficients were based upon the maximum projected area, A, as used in air foil theory. Drag coefficients for nonair foil shapes are usually based upon the frontal projected area.

With this convention the drag coefficient for a nearly flat plate ($S \simeq 0$) at zero angle of attack would be approximately zero. As the plate is rotated in either direction the drag coefficient should increase until it reaches a maximum value of 1.2 at an angle of attack of $\Pi/2$. Furthermore it should be noted that the frontal projected area varies like the sine of the angle of attack. Thus the following equation for the drag coefficient was evolved.

$$C_d = 1.2 \; (2 + (1-S) \, \mathrm{Sin}^2 \, \beta') \tag{7}$$

This idealization compares well with existing drag data for shapes ranging from flat plates to spheres. This form should be viewed as a rough approximation and will be adequate for the current effort.

A similar approach was applied to the determination of the lift coefficient, C_ℓ. The following approximation was formulated

$$C_\ell = (1 - S) \; \mathrm{Sin} \; (2 \; \beta') \tag{8}$$

The equation of motion for the rotary motion of the debris is

$$\frac{d\omega}{dt} = \frac{M}{I} \tag{9}$$

where

ω = roll rate or angular velocity
M = applied aerodynamic moment
I = moment of inertia

The aerodynamic moment can be related to the lifting force by assuming a point of application. Due to the absence of any details, a nominal point of application located at the quarter point was assumed, i.e.,

$$M = \frac{\delta}{4} F_\ell \tag{10}$$

where δ = the length of the debris. The length of the debris piece can be related to the size of the debris peice by assuming that

$$\delta = \sqrt{A} \tag{11}$$

Finally the moment of inertia can be approximated as:

$$I = 0.2\ \delta^2\ (S^2 + 1)\ W_e \tag{12}$$

Since the debris will exist in a wide variety of shapes the above form represents an average or nominal value. Its use should be reasonably good for most shapes. The orientation of the debris during free flight is given by the kinematic relation

$$\omega = \frac{d\beta}{dt} \tag{13}$$

The above equations, together with the initial conditions completely define the free flight motion of the debris piece.

When the debris piece strikes the ground surface, it is quite possible that it will bounce after losing some of its kinetic energy. The model's simplified treatment of the debris impact assumes that with each bounce, 75 percent of its vertical and horizontal energy will be lost, i.e., horizontal velocity is halved and vertical velocity is halved with a change of sign. The number of allowable bounces is specified as input.

The required input data for the debris blast translation model consists of the following:

1. weight of debris (lb)
2. maximum projected area (AMAX)
3. aspect ratio (AMIN/AMAX)
4. time of separation (sec)
5. initial horizontal velocity (ft/sec)
6. initial vertical velocity (ft/sec)
7. initial height above ground datum (ft)
8. initial orientation angle (rad)
9. initial roll rate (rad/sec)
10. shock velocity (ft/sec)
11. peak wind velocity (ft/sec)
12. positive phase duration (sec)
13. number of allowable bounces.

As shown above, the input must be specified in pound, ft, sec units. It was decided to ignore any initial debris collapse displacement and velocity, since their effects are expected to be negligible. The computer model assumes a drag coefficient of 1.2 and an airblast density of 0.1 lb/ft^3, which may be considered as generally representative values. The computer model does not treat the interaction of debris pieces in flight, is limited to a directional blast and neglects local effects.

The output variables which are printed every time step are:

1. time
2. horizontal velocity of debris
3. vertical velocity of debris
4. blast wind velocity
5. absolute relative velocity
6. debris horizontal distance
7. debris vertical distance
8. debris roll angle
9. debris roll rate

The output units are consistent with the input data in the pound, ft, sec system.

A simple problem was executed with this computer model to check its operation. Various diameter solid steel spheres were analyzed for trajectory response at an intial 80 ft elevation above ground under the following blast condition (1 MT):

free field pressure: 5 psi
shock velocity: 1600 ft/sec
peak airblast velocity: 240 ft/sec
positive phase duration of dynamic pressure: 3 sec

An inverse relationship between horizontal trajectory distance range and sphere diameter (or weight) was exhibited, as expected. These check results compare favorably to blast debris data published in Reference 39. This comparison is illustrated in Figure 2. The time passage until the spheres first reached

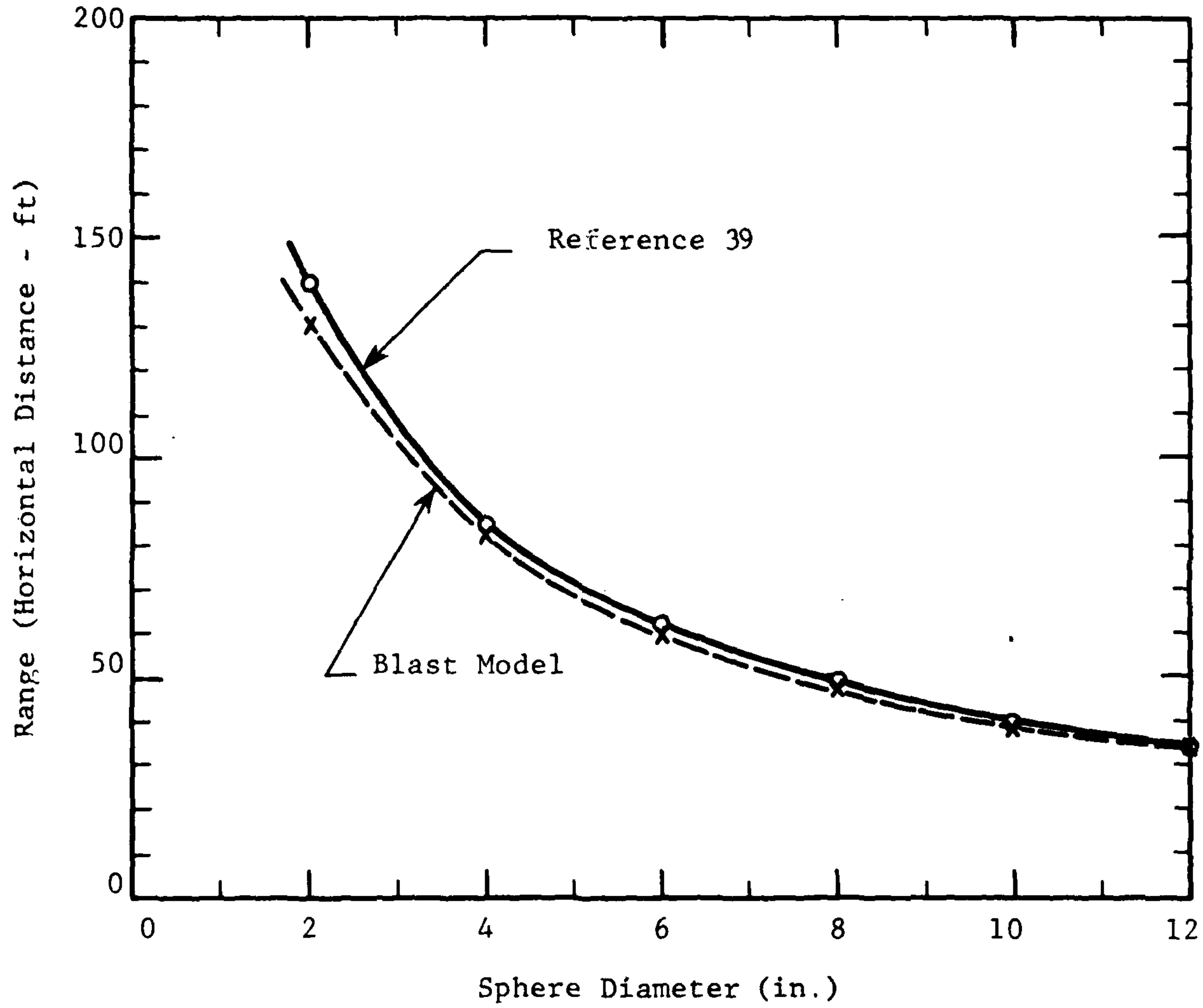


Figure 2. Sample Blast Debris Analysis Results

the ground also matched with the expected free fall time, namely $\sqrt{2(80)/32.2} = 2.23$ sec, irregardless of sphere weight. This sample problem together with the work documented in Reference 37 demonstrated the overall credibility and accuracy of the selected debris transport analysis model for the purposes of this project.

3.1.2 Probability

As discussed earlier, it was decided that a purely deterministic approach to the debris transport analysis would not only be somewhat unrealistic, but also would be beyond the scope and budget of this research effort. This conclusion was reached due to the high number of individual debris pieces possible in an urban environment along with the uncertainties associated with the blast loading, the structures, and their physical arrangement. Therefore, a statistical algorithm was developed, programmed, and added to the transport model to extrapolate the results of a limited number of debris trajectories to a more general expected final distribution. As indicated in Figure 3, the computer model is structured such that the executive program controls the input-output, the statistical computations, and the multiple subroutine's call to the deterministic blast debris analyzer described previously. This type of approach had not been attempted to date and, thus, represents a novel technique.

The input parameters for the combined probabilistic blast model are the expected values (means) and coefficient of variation (standard deviation/mean) for:

1. debris weight
2. maximum projected area
3. minimum projected area
4. initial height above ground datum
5. initial orientation angle
6. peak blast wind velocity
7. positive phase duration
8. shock velocity

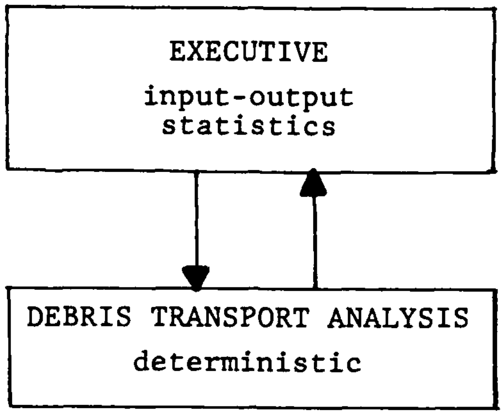


Figure 3. Probabilistic Blast Debris Analysis Computer Program Structure

All this input corresponds to the parameters required for the blast analysis described previously. In addition, the number of allowable debris bounces on the ground must be specified as well as a differential increment. The input of an expected value and a measure of dispersion characterizes the probability distributions for each of the principal debris transport variables. The differential increment is used in a numerical partial differentiation procedure to be described later.

The two major output variables of the integrated computer model are the range (horizontal distance traveled from the initial position) and time to rest of the debris fragments. The nominal value, expected value, variance and standard deviation for both are calculated as well as the fractional contributions of each input parameter to the total variance of range and time. A basic assumption made in the statistical formulation was that all the input variables are independent of each other, thereby eliminating the need for cross correlation terms. This assumption is quite realistic since there does not appear to be much interdependence between, for example, the weight of the debris and the blast wind velocity or maximum projected area, etc.

The analytical formulation of this hybrid stochastic-deterministic model will now be outlined. The expected values ($\bar{x}_i$) and coefficients of variation ($\sigma_i/\bar{x}_i$) for each input variable ($i = 1, n$) are specified. The variance of a given parameter, such as range, R, for example is computed as:

$$V(R) = \sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i}\right)^2 V(x_i) \tag{14}$$

where x_i are the independent variables

The nominal range ($\bar{R}$) and the time ($\bar{T}$) are computed from the deterministic debris trajectory analysis on the basis of the expected values of the input variables ($\bar{x}_i$). The input differential increment, Δx, is used for the numerical partial differentiation scheme. The i^{th} input parameter ($i = 1, n$) is then set to its upper (x_{iH}) and lower values (x_{iL}) by:

$$x_{iH} = (1 + \Delta x)\ \bar{x}_i \tag{15}$$

$$x_{iL} = (1 - \Delta x)\ \bar{x}_i \tag{16}$$

The deterministic trajectory solver is then called upon repeatedly to compute the upper (R_{iH} and T_{iH}) and lower (R_{iL} and T_{iL}) values of range and time corresponding to the input (x_{iH}, all others $\bar{x}_i$) and (x_{iL} all others $\bar{x}_i$), respectively. Only the i^{th} input variable is changed while the remaining parameters remain at their mean values. The first and second partial derivatives may then be obtained according to the following equations (Ref 40):

$$\frac{\partial R}{\partial x_i} = \frac{(R_{iH} - R_{iL})}{(2)(\Delta x)(\bar{x}_i)} \tag{17}$$

$$\frac{\partial T}{\partial x_i} = \frac{(T_{iH} - T_{iL})}{(2)(\Delta x)(\bar{x}_i)} \tag{18}$$

$$\frac{\partial^2 R}{\partial x_i^2} = \frac{(R_{iH} + R_{iL} - 2\bar{R})}{\{(\Delta x)(\bar{x}_i)\}^2} \tag{19}$$

$$\frac{\partial^2 T}{\partial x_i^2} = \frac{(T_{iH} + T_{iL} - 2\bar{T})}{\{(\Delta x)(\bar{x}_i)\}^2} \tag{20}$$

This process is repeated for each input variable until a full set of first and second partial derivatives of range (R) and time (T) with respect to each independent variable are known. The final step in this procedure involves the determination of the expected range (ER) and expected time (ET), their variances (VR and VT), and the fractional contributions (PR_i and PT_i) of each input parameter to the total uncertainty (variance) of the range and time. The applicable equations are:

$$ER = \bar{R} + \tfrac{1}{2} \sum_{i=1}^{n} \left(\frac{\partial^2 R}{\partial x_i^2} \right) v_i \tag{21}$$

$$ET = \bar{T} + \tfrac{1}{2} \sum_{i=1}^{n} \left(\frac{\partial^2 T}{\partial x_i^2} \right) v_i \tag{22}$$

$$VR = \sum_{i=1}^{n} \left(\frac{\partial R}{\partial x_i} \right)^2 v_i \tag{23}$$

$$VT = \sum_{i=1}^{n} \left(\frac{\partial T}{\partial x_i} \right)^2 v_i \tag{24}$$

$$PR_i = \frac{\left(\frac{\partial R}{\partial x_i} \right)^2 v_i}{VR} \tag{25}$$

$$PT_i = \frac{\left(\frac{\partial T}{\partial x_i} \right)^2 v_i}{VT} \tag{26}$$

The expected values and variances of the range and time define the relevant probability distributions for the debris. The fractional contributions to uncertainty (PR_i and PT_i) can serve to identify input variables which are the most and least critical to the analysis.

In checking the full probabilistic debris trajectory model, numerical difficulties were experienced at first. These essentially stemmed from the debris trajectory algorithm's formulation for ground capture of the debris piece and the sensitivity of the results to the specified differential increment, Δx. The model's computations of debris trajectory range and time for ground capture depended on an assumed number of bounces that the piece would experience prior to coming to full rest. Thus, certain assumptions were made with regard to the type of impact with the ground and the percentage of kinetic energy loss with each bounce. Furthermore, the final range and time values were taken at the end of the first time step after the ground surface had been penetrated by the debris piece. If a piece was just above the ground surface, it would have a slightly greater range and time then one that would just penetrate the ground surface at the end of a time step. The lack of finer resolution in these computations, while usually of neglible proportions since the integration time step is rather small, nevertheless, had an adverse effect on the statistical algorithm. Very small inconsistencies, such as those in defining a more exact range and time for debris ground penetration, contributed to the irregular nature of the numerically computed first and second derivatives and the statistical results.

The first corrective action to be implemented consisted of reducing the number of bounces to full capture of the debris piece from 5 to 1. Afterward, a linear interpolation scheme was programmed to backfigure the more accurate range and time for initial ground surface penetration. These two modifications to the trajectory analysis routine greatly improved the statistical computations. Even though very small differential increments still produced more questionable answers, increments from approximately 3 to 20 percent resulted in consistent and reasonable model output.

An attempt was made to further refine the trajectory analysis with parabolic interpolation in place of linear. This change produced results, however, that were comparable to those for the linear interpolation scheme in the range of differential increments of 3 to 20 percent but produced worse results for small increments. Thus, parabolic interpolation was discarded.

An alternative method to calculate a more accurate range and time is "recomputation" using a reduced time step. Whereas linear interpolation uses the values at both the beginning and the end of a full time step to compute the refined answer, the "recomputation" scheme uses only the available information at the beginning of the time step to determine the actual values of range and time. When the debris piece is just about to penetrate the ground surface, the actual time increment required for it to reach ground is computed by

$$\Delta t_o = \frac{-Y_o}{U} \tag{27}$$

where

Δt_o = reduced time step to reach ground
Y_o = vertical distance, above ground at previous full time step
U = vertical velocity of debris

The actual range, R, and time T, are then defined by

$$R = R_o + V\Delta t_o \tag{28}$$

and

$$T = T_o + \Delta t_o \tag{29}$$

where

R_o = range value at previous full time step

V = horizontal velocity of debris

T_o = time value at previous full time step

This recomputation method yielded comparable results to linear interpolation.

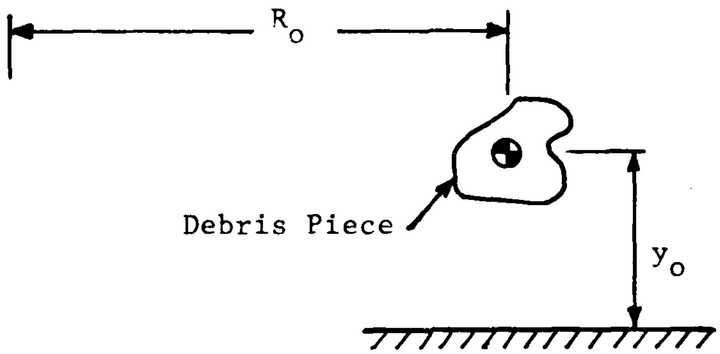


Figure 4. Debris Piece at Position R_o, Y_o

After this fine tuning of the debris model, the number of bounces that could be allowed was studied. It was found that with the aforementioned recomputation method, the assumption of five bounces likewise produced some erratic statistical results. The assumption of two bounces produced an expected range and time fairly similar to that for the five bounces with a somewhat better conditioned output. Apparently, the statistical model is quite sensitive to sudden, discontinuous energy-motion changes, such as those that occur upon impact with the ground. The one bounce immediate capture assumption produced answers that [illegible]e the most stable for various differential increments. The two bounce assumption provides a larger range and time that may be more realistic in some cases. More than two bounces does not seem to significantly change the range-time answers but does tend to prolong the computations and to confuse the statistics. Therefore, it was concluded that the finer tuned trajectory model (either the linear interpolation or recomputation) coupled with one and/or two allowable debris bounces will produce reliable and consistent debris distributions for this project. The "recomputation" method was actually used in analyzing the debris.

3.2 RANGER Theory

RANGER determines the configuration of a debris pile from one structure. The final horizontal position of each debris piece is determined by adding the blast-induced translation to the initial position of each piece. Times of arrival of every piece with similar final horizontal positions are compared to determine final vertical positions. RANGER uses the semi-stochastic output of the TRAJCT program to vary the blast translation of similar debris pieces.

The structure is divided into groups of debris pieces which have similar blast translation characteristics. An example would be sections of wall with similar postblast sizes, with the same shape, size, density and preblast height. The relevant blast translation results for the entire group would be described by the Expected Range (ER), and Expected Time (ET), and their respective standard deviations, SDR and SDT; all four are output values of TRAJCT routine and have been described earlier.

The ER of a group of debris pieces is the most likely distance to be traveled by any member of the group. The SDR measures the probable distribution of ranges seen in a large population of debris pieces with the same TRAJCT input parameters. If the blast-induced ranges have a normal distribution about the ER, then the ER and SDR can be taken as the mean range and the standard deviation of the range. While blast translations do not always fit a normal distribution, it was felt that within the accuracy of this study and for carefully selected debris groups the assumption of a normal distribution was acceptable. Selection of debris groups to fit these standards is described elsewhere.

The range, R, given each debris piece in a group is given by the equation:

$$R = ER \pm z\ (SDR) \tag{30}$$

z is a coefficient derived from a table of the standard normal distribution which contains values of A(z), where

$$A(z) = \frac{1}{2\pi} \int_0^z e^{-1/2\ x^2}\ dx \tag{31}$$

A(z) is the area under the standard normal distribution from zero to z; therefore the values of A(z) define the distribution density of a normal population about the mean. The RANGER routine uses 300 values of A(z) evaluated for z = 0.01, 0.02, 0.03, ..., 3.00. The values of A(z) were taken from Table III of John E. Freund's Mathematical Statistics (Ref 41). For a debris group of N members, an algorithm picks N/2 z's for equation (1). The z's chosen are dependent only on the size of the debris group and the shape of the distribution curve. For each z, two different ranges are calculated.

$$R1 = ER + z \times SDR \tag{32}$$

and

$$R2 = ER - z \times SDR \tag{33}$$

Each range calculated is given to a different member of the debris group. This provides for a distribution of ranges through the group with a mean value of ER and a standard deviation of approximately SDR.

RANGER uses two coordinate systems to describe debris positions. The first is a real number coordinate system defined by horizontal X and Y axes. The second is an integer system with I and J axes which are parallel to but offset from the X and Y axes. The X-Y system is measured in feet and is used to define the initial and final position of the center of gravity of a debris piece. The I-J system is used to describe the postblast debris pile. The I-J coordinates describe a grid of unit rectangles. The X and Y axes should be chosen so that the entire postblast debris pile has positive coordinates.

The horizontal blast translation of a debris piece is described by a range and an angle. In this version of the program, the angle is fixed for the entire structure. The trajectory of a debris piece was assumed to be paralled to the direction of blastwave propagation. The blast angle required for the RANGER routine is the angle in degrees from the positive X-axis to a line parallel to the blast direction.

The postblast position of the center of gravity of a debris piece is calculated by vector addition of the range to the initial X-Y position. These final X-Y coordinates are then computed into I and J coordinates using the formulas

$$ICG = X/XUNIT + 3$$

$$JCG = Y/YUNIT + 3$$

where XUNIT and YUNIT are the X and Y dimensions in feet of the I-J unit rectangle. The constant, 3, shifts the I and J axes two unit rectangles away from the X and Y axes to ensure that all debris pieces remain within the field described by the program.

To describe the debris pile, RANGER lists all of the debris pieces which either partially or fully cover each unit rectangle. The routine assumes that the debris piece comes to rest with its largest face horizontal. In this case, the piece would cover an area equal to the TRAJCT parameter, AMAX. RANGER calculates the number of unit rectangles covered by the debris piece, then assigns parts of the piece to the appropriate number of rectangles adjacent to ICG - JCG.

Once RANGER has iterated through the entire list of debris pieces, it creates a list of the debris pieces at each I-J unit. Then it sorts the list for each unit to place the debris pieces with the earliest times of arrival at the bottom of the pile. This sorted listing is the final output file of the RANGER routine.

The output file of the RANGER routine is organized by grid unit. For every unit there is a heading record which contains the I and J coordinates of the rectangle and the number of debris pieces at that location. For every debris piece at the location, there is a record containing four numbers. The first is a unique integer value to identify the debris piece. The second is a real number which tells the time-of-arrival of the debris piece at this location. The third is an integer describing the type of debris (e.g., 412 could include all wooden wall panels). The fourth number is the fraction of the entire debris piece that lies within the unit rectangle. The formating of the RANGER output file is designed primarily as an input file to the BLOCK routine.

Since the RANGER routine was written for a PDP-11/45 with a FORTRAN-IV compiler, it may require modification to run on other machines. Specifically, it uses unformatted, direct-access input and output, which may not be available on other machines. On machines with a fairly large core space available, all of these direct-access input/output statements could be easily replaced with large arrays. The rest of the program is ANSI standard FORTRAN.

3.3 BLOCK Theory

The BLOCK program generates a description of the debris pile for an entire block. It uses a RANGER output file which describes one structure to determine the pile for a given combination of structures. BLOCK uses the unit rectangles used in the RANGER program to describe the block. The output file for the program is similar in format to the RANGER output.

The current version of the program cannot be used for blocks with a mixture of different structures, unless the mixture can be described as the repetition of a single pattern. For this case, the entire pattern must be input together into the RANGER routine. For example, if every house on the block has a garage in the same relative position, then the entire house and garage structure can be included in one RANGER run, and the entire block can be described in one BLOCK run.

BLOCK uses simple superposition to determine the composite debris pile for several structures. No interaction between structures is considered. The program proceeds grid by grid; first finding all debris pieces at a grid point, then sorting them by time-of-arrival with the earliest on the bottom.

The coordinate system used for the BLOCK routine uses the same unit rectangles as the related RANGER run. The origin is chosen so that all areas of interest are in the positive quadrant. Structures contributing debris need not have positive coordinates, but only grid points in the positive quadrant will be included in the output file.

The BLOCK output file is similar to the RANGER output file. It contains a debris list for every grid rectangle covered by at least one debris piece. The first record of each list contains the I-J coordinates of the grid rectangle and the number of debris pieces there. The debris list has the same format at the RANGER output file The identification number for the debris piece names the building of origin for the debris piece and the RANGER ID for the piece. The time-of-arrival in seconds, a classification number and the fraction of the whole piece are also listed.

Like RANGER, BLOCK uses unformatted, direct-access input/output. Large arrays could be used to avoid this potential problem on other systems. The program could be fairly easily altered to handle different structures in the same block by introducing a building type parameter and assigning a RANGER output file to the new parameter.

4. DETERMINATION OF PARAMETERS FOR DEBRIS ANALYSIS

This study focused on four structural types:

1. Single family, wood-frame and brick veneer residence
2. Two-story, wood-frame residence
3. Six-story reinforced concrete building (nonarching walls)
4. Eleven-story reinforced concrete building (nonarching walls)

The architect/engineer (A/E) plans for buildings of categories 1, 3 and 4 were obtained from local sources. For category 2, the TEAPOT HOUSE from Operation UPSHOT-KNOTHOLE (Ref. 42) was chosen, since it allowed us a chance to compare our analytical results with experimental ones.

For each structure collapse conditions were postulated, then failure patterns and failure overpressures were determined. The failure patterns were used to determine the shapes of structural debris pieces. The sizes, shapes and other relevant parameters were recorded in debris catalogues. Typical furniture layouts for rooms of each structure were drawn according to the suggestions of the architects as shown in the A/E plans.

4.1 Determination of Failure Patterns

Exact determination of a failure pattern was not possible. Variations in material properties and dimensions of the structural elements, differences in quality of connections and local variations in reflected overpressures and other loads combine to make even the most intricate and sophisticated analysis subject to large uncertainties. For this reason, a simplified analysis plan was decided upon. The uncertainties were incorporated into the debris transport analysis.

Failure patterns were postulated based on simple analysis and engineering judgement. Walls, floors, roof and rafters were assumed to break at midspan or midheight. Wall members were analyzed as simply supported plates subjected to a uniform load.

All corners and edges were considered boundaries of debris pieces. All windows were neglected as debris. Large appliances and other heavy machines were also not treated, since they were heavy noncombustibles and would not affect the fire study of the debris pile. An example of a postulated failure pattern is shown in Figure 5.

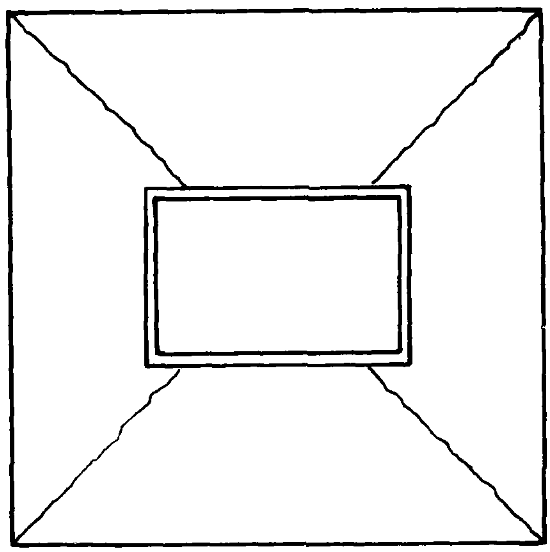


Figure 5. Failure Pattern for a Wall Panel

Since the exact dimensions of debris pieces were never certain, some measure of the uncertainty had to be included. The parameter chosen was the coefficient of variation, defined as the standard deviation of a parameter divided by mean value of the parameter. The coefficients of variation used were rough estimates of the error of a measurement. For example, the exact position of a failure line at the midsection of a wall could vary by as much as 20 percent of the section height. This would mean that the weight and maximum area of the debris piece could vary by 20 percent. If the piece was three section heights above grade, the height of the center-of-gravity could vary three and one-third percent. The minimum area, which is governed by the wall thickness, would not vary due to this uncertainty. The coefficients of variation ranged from 0.002. to 0.20.

4.2 Failure Modes of Multistory Reinforced Concrete Structures

For the taller reinforced-concrete structures, two different failure modes were considered. The first was the failure of the stiff exterior wall units leaving the frame essentially intact. The second was complete failure of the frame. To determine which mode controlled, the failure peak overpressure of the wall units was calculated using a simplified dynamic analysis. This peak overpressure was then applied to the entire structure as a dynamic load to determine the response of the frame.

4.3 Determination of Collapse Overpressure for R/C Structures

A building in the Mach region of a nuclear explosion experiences two primary loads, the diffraction load from the blast wave and the subsequent drag load. If the sides of a building remain intact, the blast wave will be most significant, and the loads can be determined from the peak overpressure. After the sides of the building collapse, blast pressures inside the building will equalize the exterior pressure and reduce the load in the building to the dynamic pressure or drag load on the open frame. Thus, the strength of the exterior walls determines the type of loading a structure undergoes.

In this analysis, the structures were assumed to react in the following manner. The free field blast wave overpressure is characterized by a step pulse with an exponential decay to zero pressure at the end of the positive phase. All the glass in the building is assumed to be broken by the initial shock. The blast-wave load is transmitted to the structural frame by the reinforced concrete wall panels. The maximum blast-wave load on the building occurs just before the collapse of these panels. After the panels collapse, the structure is essentially open and subject only to drag loads due to wind.

The 11-story R/C building had three sides with roughly 35 percent window area and one side with nearly 80 percent window area (see Figure 6a). The most severe loading condition occurs when the open side faced away from the blast. Eight inch thick precast R/C panels formed the rest of the exterior walls, (see Figure 6b). These panels were analyzed to determine their dynamic reactions up to collapse when subjected to blast.

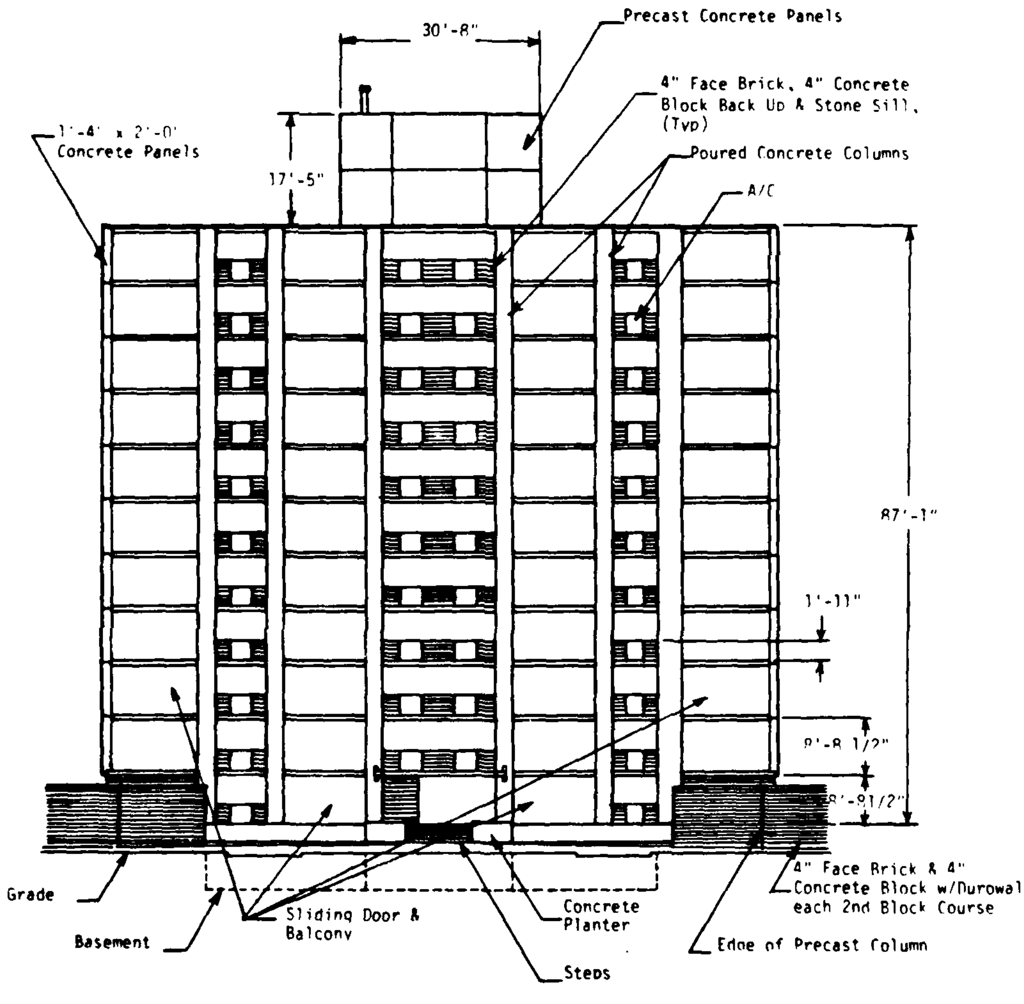


Figure 6a. Eleven-Story R/C Building

The dynamic analysis was performed according to standard procedures, such as presented in the U.S. Army Corps of Engineers Manual, EM1100-345-416, "Design of Structures to Resist the Effects of Atomic Weapons", (Ref. 43). Basically the fixed pinned slab was converted to an equivalent spring-mass system, by properly scaling the spring constant, mass and load. The scale factors are derived by equating the work done on the equivalent system to the work on the actual system. The manual provides tables of appropriate factors.

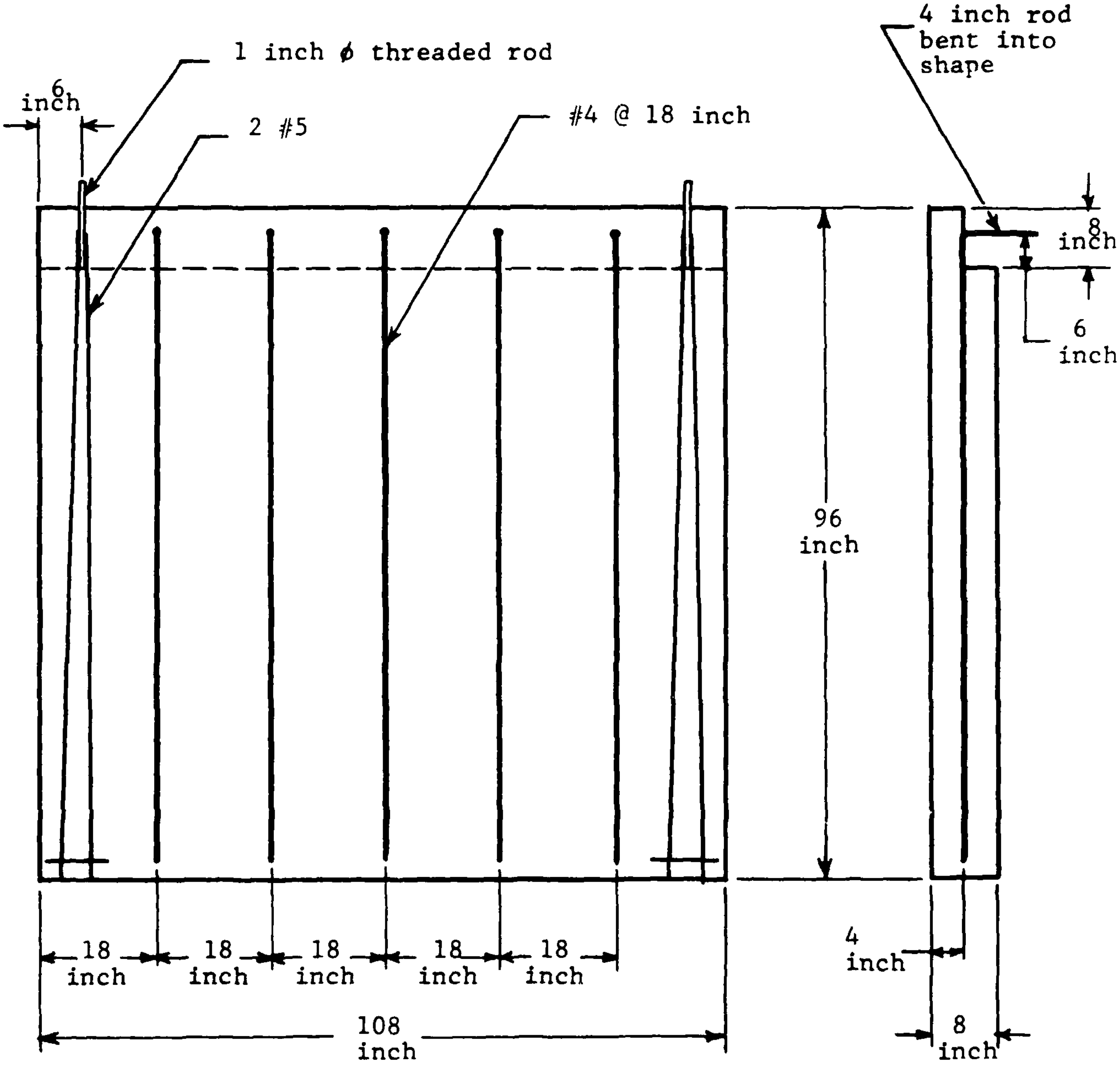


Figure 6b. Typical 11-Story R/C Building Wall Panel Design

In the analysis, the ultimate resistance of a typical panel, R_{mp}, and the fundamental period of time, T, were determined from section and material properties of the slab. The total duration of the net blast wave load, t_d, on the average panel was derived from the building geometry. The ratio of the deflection at complete failure to the ultimate elastic deflection, μ, is determined from typical values for concrete slabs.

Using these four parameters and appropriate solution techniques the maximum value of reflected overpressure and the ultimate shear in the panels was determined. From this analysis a free field overpressure of approximately 6 psi (1 MT weapon) would result in incipient collapse and breakaway of all exterior wall panels facing the blast. The horizontal force transmitted to the frame of the building at this overpressure level would have a maximum value of 52,900 lb per panel.

To check the integrity of the frame, an extremely simple model was used. A conservative modification of the portal frame analysis method was used, first to model the frame response, then to make a rough calculation of a collapse overpressure for the frame. The worst case for loading of the frame would be when all panels transmit their maxima at the same time. This would produce the largest shears and moments at the first floor. The sum of maximum horizontal forces for all the panels, 3,888,000 lb, was applied as a static load, one-half story height, 14 feet, above the first floor slab. This load was then divided between the columns, elevator shaft and exterior walls on the sides of the building. Since the precast panels on the sides of the building parallel to the blast were by far the stiffest elements resisting the load, they were apportioned, conservatively, one-third of the load. The remainder was distributed to the columns and elevator shear wall. The resulting shears and moments in the slabs and columns were less than the failure criteria for these members.

It should be noted that the above frame analysis was quite conservative since it assumed that

1. The front panels all transmitted their maximum loads simultaneously
2. This maximum load does not decay
3. The frame is rigidly fixed at the base
4. The structure does not react dynamically

In the actual conditions, less energy would be transferred to the building than the first two assumptions provide. Since the building would accelerate and the foundations would deform, less energy would be left to deform the actual structure. Thus the conclusion that the frame remains intact is justified. A brief research of relevant literature supports this conclusion. Reports of the damage done by the explosions in Hiroshima and Nagasaki indicate that the frames of reinforced concrete buildings were quite blast resistant.

After the wall panels have failed, the remaining structure would be essentially open and subject only to drag loading from the winds associated with the blast. This drag loading is characterized as a dynamic pressure on the exposed area of the frame, A. In this case the exposed area of the frame is approximately 420,000 square inches. A total lateral static load in the neighborhood of 4,000,000 lb is required to cause failure of the frame. This corresponds to a dynamic pressure of 9.5 psi. Under normal circumstances, this dynamic pressure corresponds to a peak overpressure of 30 psi.

Since the collapse overpressures of all the other structures studied was under 8 psi, it was felt that the study should concentrate on the debris generated at the 6 psi overpressure necessary to cause initial failure of the wall panels.

The six-story R/C structure studied was also of flat plate design (see Figure 7). The exterior walls were heavy masonry panels consisting of an outer layer of face brick backed by an inner layer of precast concrete block. The panels were 54 inches wide and 84 inches high. They were bordered on the sides by a window unit and a column and by concrete edge beams on top and bottom. The panels were analyzed as one way slabs, simply supported at top and bottom. The dynamic analysis method previously described was used to determine the peak overpressure required for failure of the panels.

The ultimate moment capacity of a brick wall depends upon its axial load, because the joints have limited tensile strength. Thus for a given axial load, the maximum moment can be calculated. The axial load for the exterior walls was largely dead weight. Thus the panels in the upper stories would have a reduced moment capacity. Using interaction formulas suggested in Reference 44, the static moment capacity of a 12 inch wide strip of masonry panel (brick and precast concrete block) was calculated to vary from 3250 in./lb at the upper floors to 19,500 in./lb at the lower floors. These correspond to a static pressure of 0.23 psi and 1.41 psi respectively. Dividing by a dynamic load factor of 0.45 from Figure 2.7 in Biggs (Ref. 45) and multiplying dynamic material factor of 1.25 results in pressures of 0.64 psi and 3.92 psi. The upper value was treated as the value of peak reflected pressure at failure of the lowest floor brick walls. Using Figure 3.49 of Reference 38, this reflected pressure corresponds to a peak free field overpressure of 1.95 psi, a wind velocity of 98 feet per second, and a shock velocity of 1150 feet per second. The largest load that could be transmitted to the frame by the masonry panels, about 3.5 psi, is much too small to cause failure of the frame. For free field overpressures under 10 psi, the dynamic wind loads on the open frame would be under 2 psi, and thus, not significant.

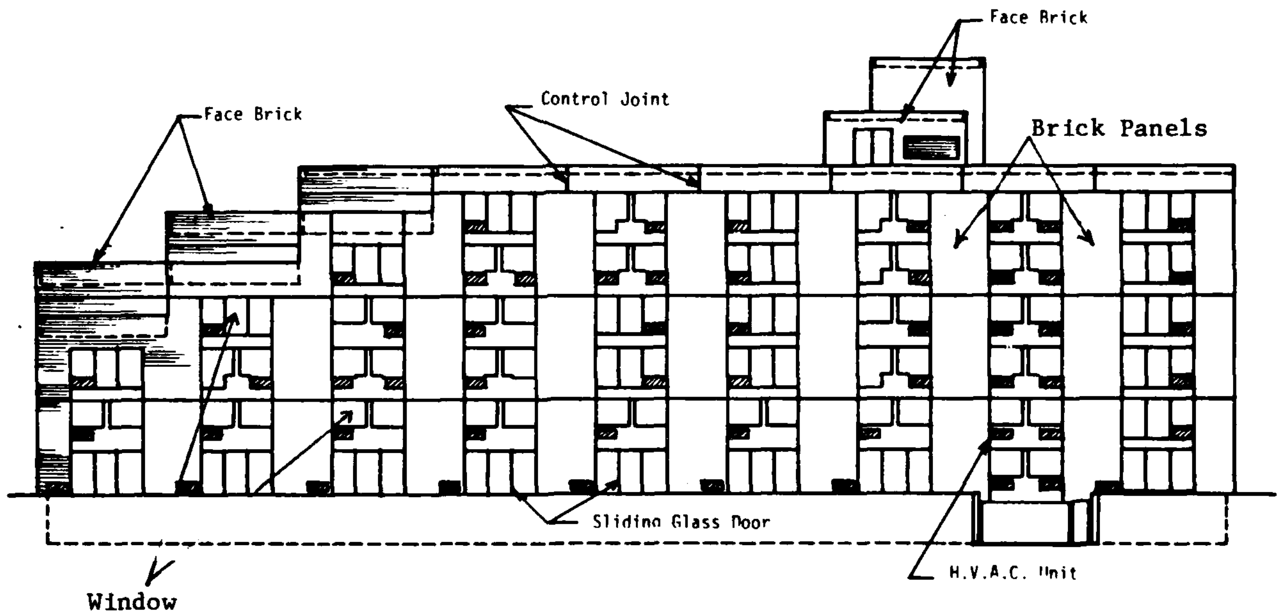


Figure 7. Six-Story R/C Building

In conclusion, the collapse of exterior wall units was chosen as the failure mode to be studied for the two R/C buildings. In this mode the frame remains essentially intact and does not contribute to the debris pile. The frame includes floor beams, floor plates, columns, elevator shaft and stairways. Everything else is assumed to become debris at the collapse overpressure.

Assuming that the blast environment was caused by a near surface burst of a one megaton nuclear weapon, the selection of a peak free field overpressure fixes all of the other blast related parameters. The relevant blast parameters for this analysis are the peak dynamic wind velocity, the velocity of the shock wave and the total duration of the positive phase of the dynamic wind pressure. For the assumed detonation conditions and peak free field overpressure of 2 psi and 6 psi, the peak wind velocities are 105 feet per second and 270 feet per second, the shock velocities are 1180 feet per second and 1300 feet per second, and the durations of the wind pressure are 5.4 seconds and 3.9 seconds. These results are included in Table 1.

TABLE 1. BLAST PARAMETERS FOR TRAJECTORY ANALYSIS

Structure	Peak Overpressure (psi)	Shock Velocity (ft/sec)	Peak Wind Velocity (ft/sec)	Duration of Wind Pressure (sec)
2-story Wood Frame (TEAPOT)	3.5	1200	175	4.5
Split-Level Brick Veneer	3.5	1200	175	4.5
6-story R/C	2.0	1180	105	5.4
11-story R/C	6.0	1300	270	3.9

4.4 Collapse Overpressure of Wood Frame Structures

The only failure mode considered for the two wood frame structures (see Figures 8a and 8b) was the failure of the entire frame. In general, different parts of the frame would fail at different values of peak overpressure. An effort was made to determine the minimum value that would cause failure of all parts.

Preliminary calculations for various members yielded extremely low values of failure overpressure. The members were treated as simply supported beams and one-way panels. The transient pressure load was approximated by a uniform static load multiplied by a dynamic load factor. Average values of timber strength were assumed. The results of these calculations are summarized in Table 2.

TABLE 2. MAXIMUM COMPUTED FAILURE OVERPRESSURES FOR WOOD FRAME HOUSES

House	Roof Rafters	Wall Studs	Floor Joists
1-story	0.7 psi	1.0 psi	2.0 psi
2-story	0.9 psi	1.2 psi	1.3 psi

When these analytic results are compared to the results of the UPSHOT-KNOTHOLE test, the overpressure values appear to be extremely conservative. In the test, two identical two-story wood frame residences were subjected to the blast from a nuclear detonation.

At one house location the peak free field overpressure was 2 psi and at the other 5 psi. The first house remained essentially intact with cracking of some structural parts. The second house was completely demolished. Since all of the structural parts analyzed, failed at or below 2 psi, unacceptably large discrepancies are apparent. These differences could result from the wide variation in timber strengths, the conservative assumption of simple supports and a conservative calculation of dynamic load factors.

1 ft = 0.3048 m

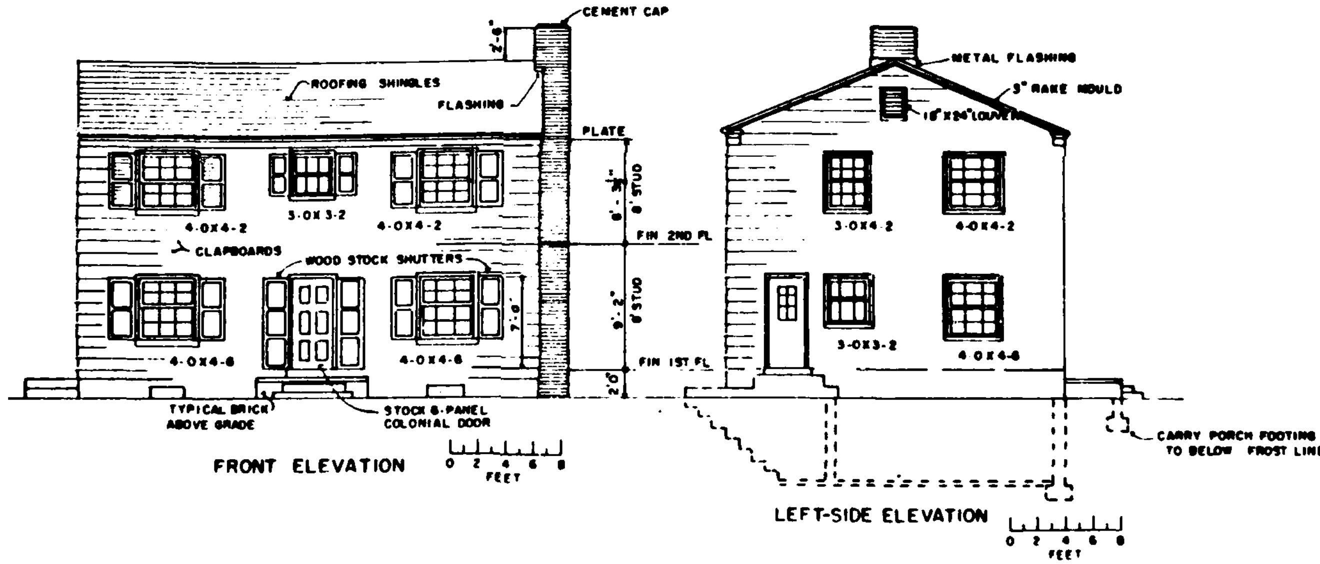
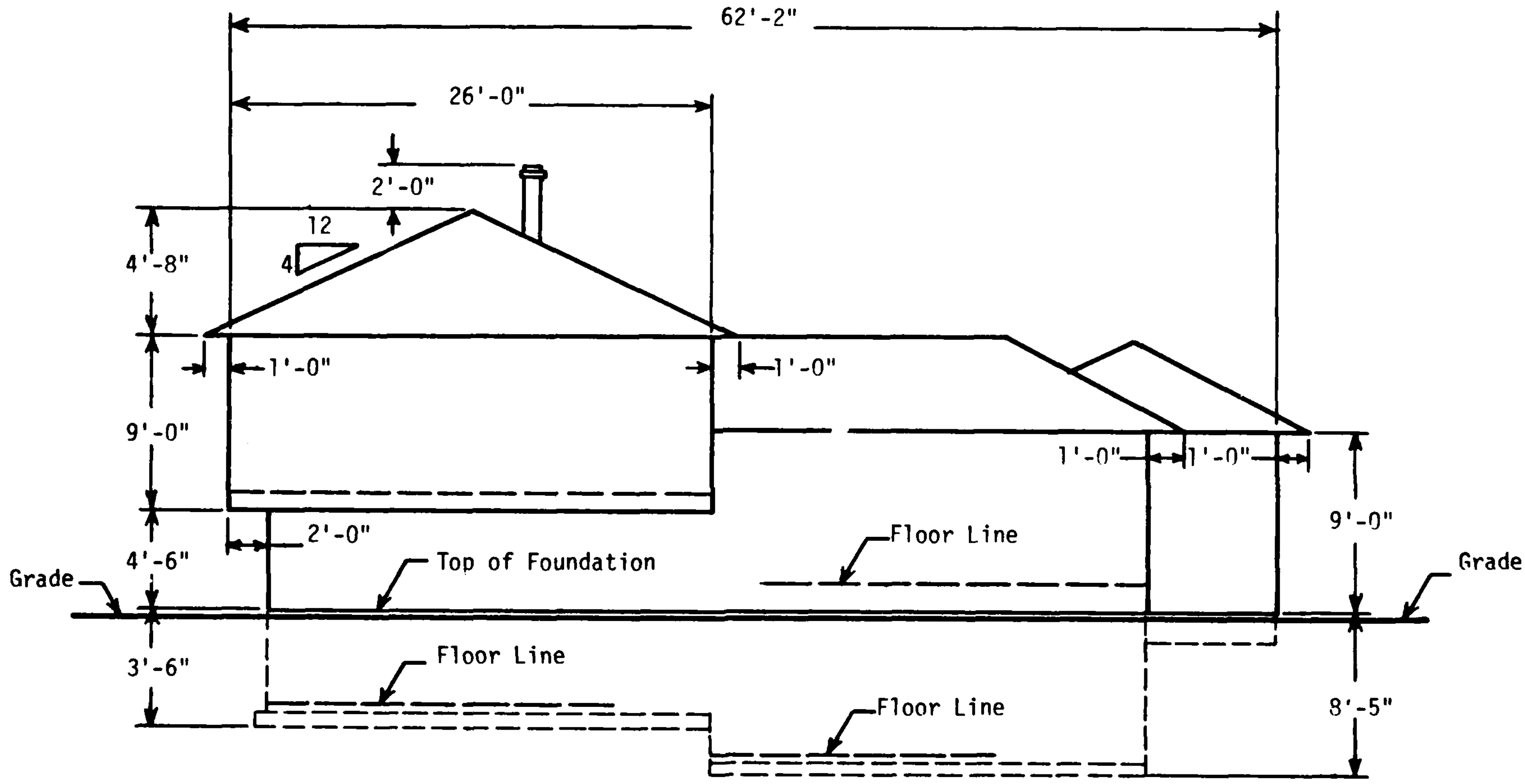


Figure 8a. Single Family Residence (TEAPOT HOUSE).



a) Left Elevation

Figure 8b. Split-Level Birch Veneer Single Family Residence.

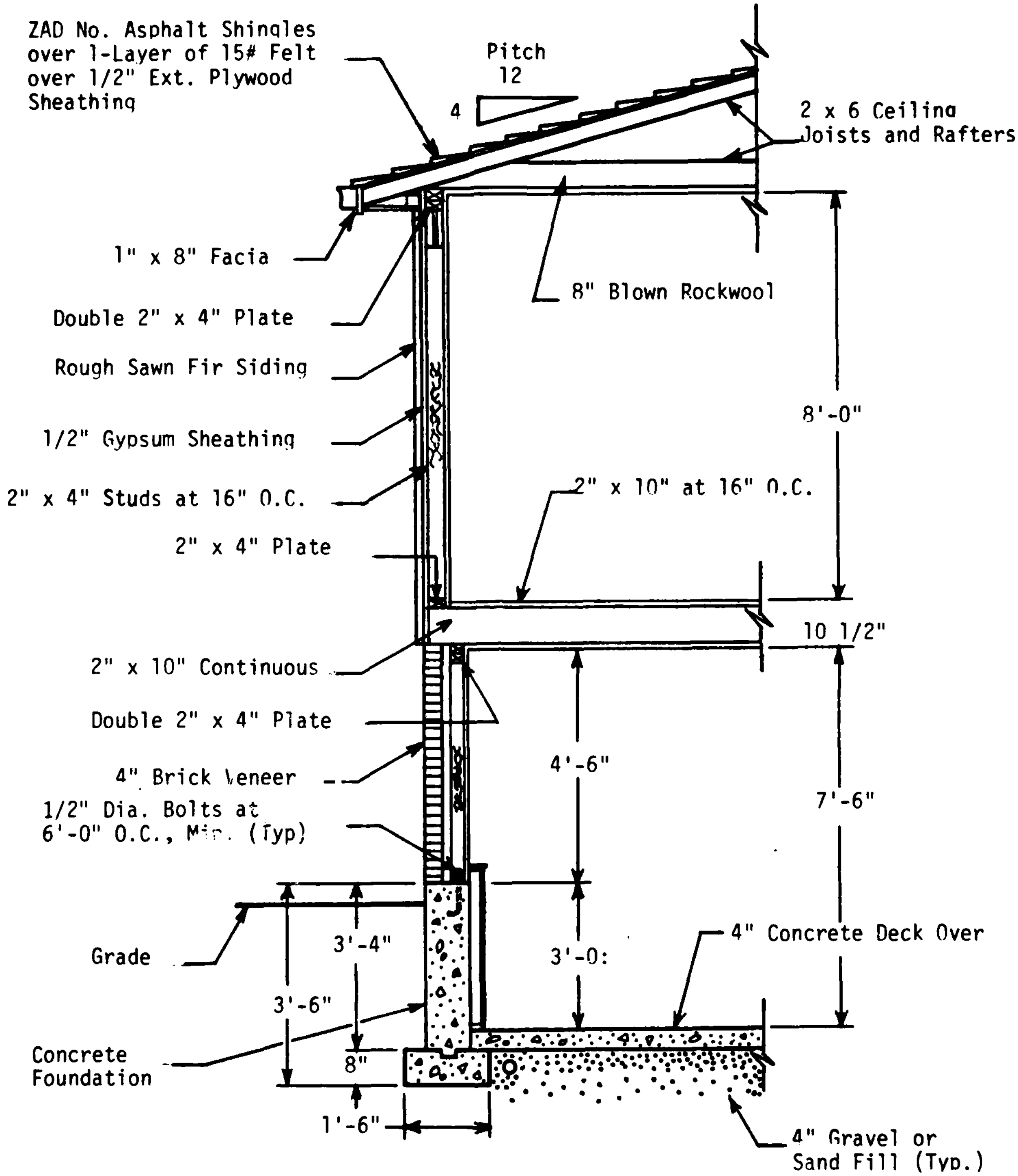


Figure 8c. Section Detail, Split-Level Residence.

After an examination of the photographs accompanying the report on UPSHOT-KNOTHOLE (Ref. 42), it was decided that the minimum collapse overpressure would lie between 2 psi and 5 psi. The average value of 3.5 psi was decided upon as a reasonable estimate of the actual collapse overpressure for both wood frame houses. The relevant blast parameters for a 1 MT surface burst at a location where the peak value of the free field overpressure is the chosen collapse overpressure were shown in Table 1.

4.5 Debris Catalogs

For each structure, debris catalogs were constructed. The catalogs consist of a list of all of the debris pieces in a structure and a parameter list for each piece. The parameter list consists of the weight, maximum projected area, miminum projected area, angle of repose and three spatial coordinates, x, y and z. The z-coordinate was the height of the center of gravity above a level ground surface. The origin of the coordinate system was located at a corner of the structure at ground level. Ground level was the average height of the surrounding ground surface.

The chosen failure pattern was used to determine the shapes of structural debris. Pieces of furniture were assumed to remain intact and were treated as single debris pieces. Interior walls were assumed to fail at mid-height and between every other stud. In the multistory R/C buildings, debris catalogs were made for a typical floor. The other floors were assumed to be identical except in altitude.

The dimensions for the structural debris were measured by scaling from the A/E plans of the structure. Dimensions for furniture items were taken from Reference 20. A portion of the postulated debris pattern for the TEAPOT HOUSE is shown in Figure 8d.

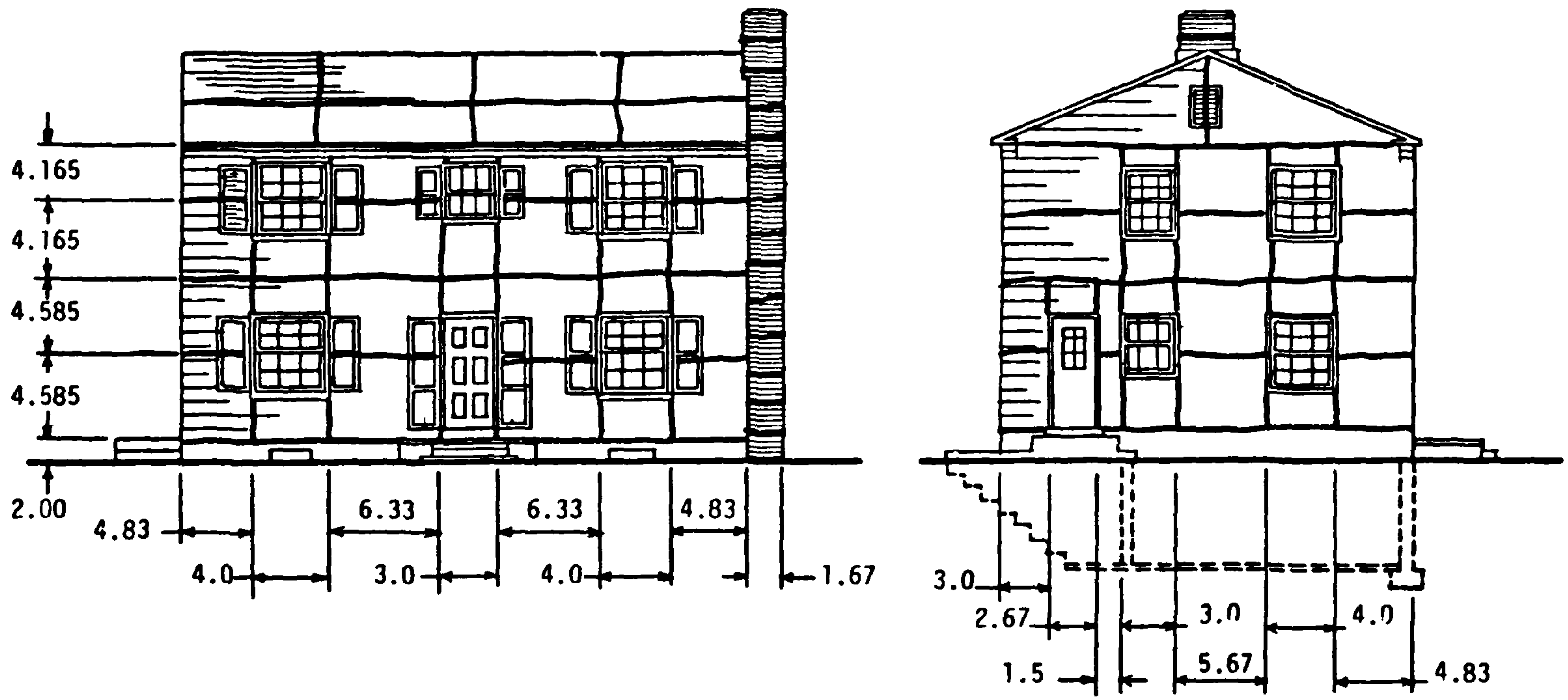


Figure 8d. Postulated Failure Pattern for TEAPOT HOUSE.

5. DEBRIS PILE ANALYSIS OF TEAPOT HOUSE

The general methodology described in Chapter 3 was applied to an analysis of TEAPOT HOUSE, the single family, wood frame house which was tested in the UPSHOT-KNOTHOLE detonation (Ref. 42). First the debris pieces were classified into groups with similar trajectory characteristics. Several runs of the FLYER program were made to refine the groups until accurate trajectory distributions were obtained for every group. Runs of the RANGER program were used to determine the debris pile for a single house. Then the BLOCK program was used for the debris pile over an entire block.

5.1 Classification of Debris

One run was made for each general debris type, e.g., wall section, door, chair, chimney, to determine the most sensitive parameters for each shape. Then debris groups were assembled that had these sensitive parameters most closely matched. No attempt was made to group different types of debris such as doors and wall sections together.

The sensitivity of trajectory to each of the parameters varied widely. In general for debris pieces initially near to the ground, height was the most important parameter. For higher initial positions weight and maximum area became most significant.

5.2 Trajectory of Typical Debris Pieces

To illustrate the performance of the computer codes several typical debris pieces were chosen:

1. a second story exterior wall section
2. a first story exterior wall section
3. a section of chimney
4. a bedroom door
5. a small table
6. an armchair

Input and output for a run of the TRAJCT code are shown in Table 3. In this table the blast parameters are listed for each run and the debris parameters for each piece. In the "Output" column PR and PT refer to the contribution of a parameter to the overall variance in range and time respectively. Under "Trajectory Results", the title "Nominal" refers to the deterministic result given the mean values of the input parameters. "Expected" refers to the most likely result as determined by the statistical algorithm in TRAJCT.

Table 3 shows the output for debris piece number 2 (front wall section 17) which is included to show an unsatisfactory parameter set. The values of nominal and effective range, 10.66 and 24.41 respectively, differ too much, and the standard deviation of the range is also comparatively large. The list of contributions shows that the only significant contributor to this variance is the height parameter and its coefficient of variation (COV). This suggests a reduction in the COV of the height. This implies limiting the heights of the debris group related to this TRAJCT run. In other runs the same COV of the height was changed to 0.05 and 0.01 with the following results:

	Coefficient of Variance of Height		
	0.10	0.05	0.01
Nominal Range	10.66	10.66	10.66
Expected Range	24.41	14.79	11.71
Standard Deviation	6.76	3.68	1.82
Nominal Time	1.38	1.38	1.38
Expected Time	2.02	1.57	1.42
Standard Deviation	0.34	0.17	0.05

The value of 0.05 variance would cover a group with a standard deviation in height of 0.45 feet which is reasonable for the first floor wall sections. Therefore the parameter set with variance in height of 0.05 was used. The other parameter sets used are given in Table 3.

TABLE 3. TRAJCT RESULTS FOR TYPICAL DEBRIS

Blast Parameters

Peak wind velocity = 175 feet per second
Duration of dynamic pressure = 4.5 seconds
Shock wave velocity = 1200 feet per second

Debris Parameters

1. Front Wall Section Number 3

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	394.53	0.05	0.15	0.35
AMAX (square feet)	26.40	0.05	0.13	0.39
AMIN (square feet)	1.68	0.01	0.00	0.00
Height (feet)	17.42	0.03	0.69	0.25
Angle (radians)	1.5708	0.05	0.29	0.01

Number of Bounces = 3

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	65.56	62.43	1.93
Time-to-rest (seconds)	1.91	1.77	0.10

2. Front Wall Section Number 17

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	434.32	0.10	0.03	0.01
AMAX (square feet)	28.99	0.10	0.02	0.00
AMIN (square feet)	1.68	0.01	0.00	0.00
Height (feet)	8.92	0.10	0.94	0.98
Angle (radians)	1.5708	0.005	0.01	0.01

Number of Bounces = 3

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	10.66	24.41	6.76
Time-to-rest (seconds)	1.38	2.02	0.34

TABLE 3. TRAJCT RESULTS FOR TYPICAL DEBRIS (continued)

3. Chimney Section Number 9

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	1195.15	0.05	0.33	0.00
AMAX (square Feet)	6.66	0.05	0.32	0.00
AMIN (square feet)	3.34	0.01	0.00	0.00
Height (feet)	11.00	0.03	0.35	1.00
Angle (radians)	1.5708	0.005	0.00	0.00

Number of Bounces = 3

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	6.42	6.59	0.53
Time-to-rest (seconds)	1.67	1.70	0.05

4. Bedroom Door Number 9

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	70.22	0.05	0.08	0.03
AMAX (square feet)	16.68	0.05	0.02	0.53
AMIN (square feet)	0.68	0.01	0.00	0.00
Height (feet)	14.84	0.03	0.90	0.43
Angle (radians)	1.5708	0.005	0.00	0.00

Number of Bounces = 3

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	95.89	98.70	3.80
Time-to-rest (seconds)	1.32	1.40	0.10

TABLE 3. TRAJCT RESULTS FOR TYPICAL DEBRIS (concluded)

5. Small Table Number 3

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	30.00	0.10	0.39	0.07
AMAX (square feet)	3.00	0.10	0.27	0.19
AMIN (square feet)	1.03	0.01	0.00	0.00
Height (feet)	3.83	0.10	0.32	0.66
Angle (radians)	6.2832	0.005	0.02	0.08

Number of Bounces = 5

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	24.76	24.75	2.35
Time-to-rest (seconds)	0.69	0.69	0.03

6. Armchair Number 2

	Input		Output	
	Mean	COV	PR	PT
Weight (lb)	150.00	0.05	0.59	0.00
AMAX (square feet)	8.25	0.05	0.37	0.25
AMIN (square feet)	7.65	0.01	0.00	0.01
Height (feet)	12.34	0.03	0.04	0.74
Angle (radians)	1.5708	0.005	0.00	0.00

Number of Bounces = 3

Trajectory Results

	Nominal	Expected	Standard Deviation
Range (feet)	55.01	55.04	2.55
Time-to-rest (seconds)	1.86	1.86	0.02

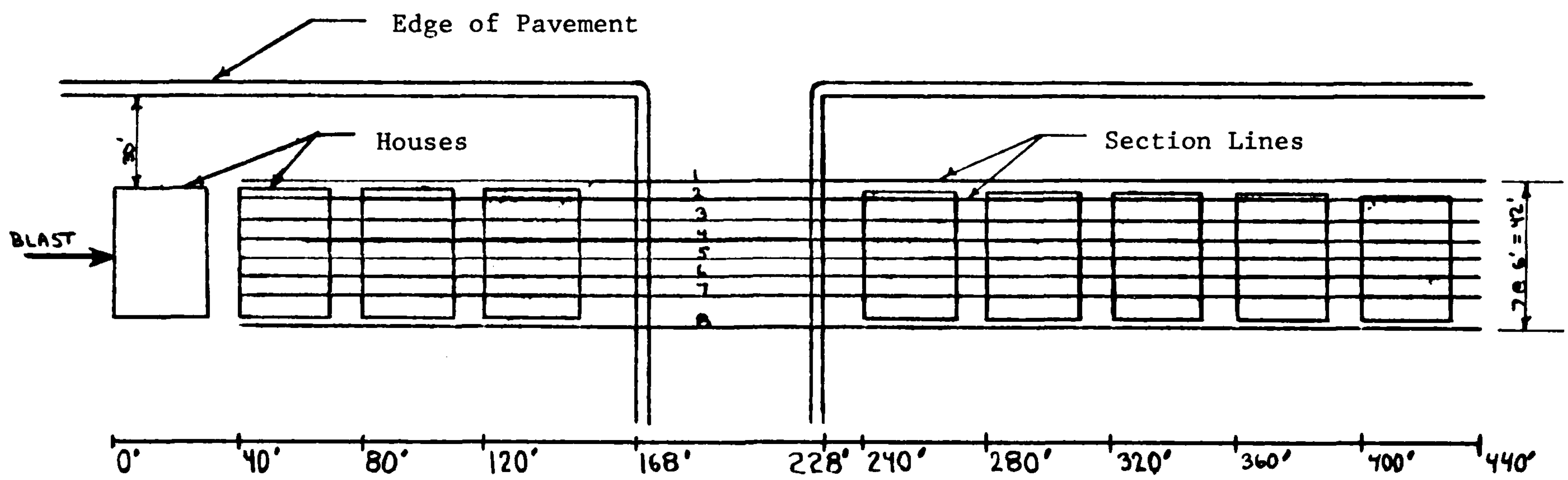
5.3 Description of Debris Pile

After parameter sets were chosen which cover all of the debris pieces, runs of the RANGER and BLOCK routines were made to describe the final debris pile. Different pile configurations are possible depending on the angle of incidence of the blast wave to the block. Two angles were chosen for this study. A blast wave propagating parallel to a row of houses was called a normal blast (Figure 9a). A second case was a blast wave propagating at a 30 degree angle to the same row of houses, (Figure 9b).

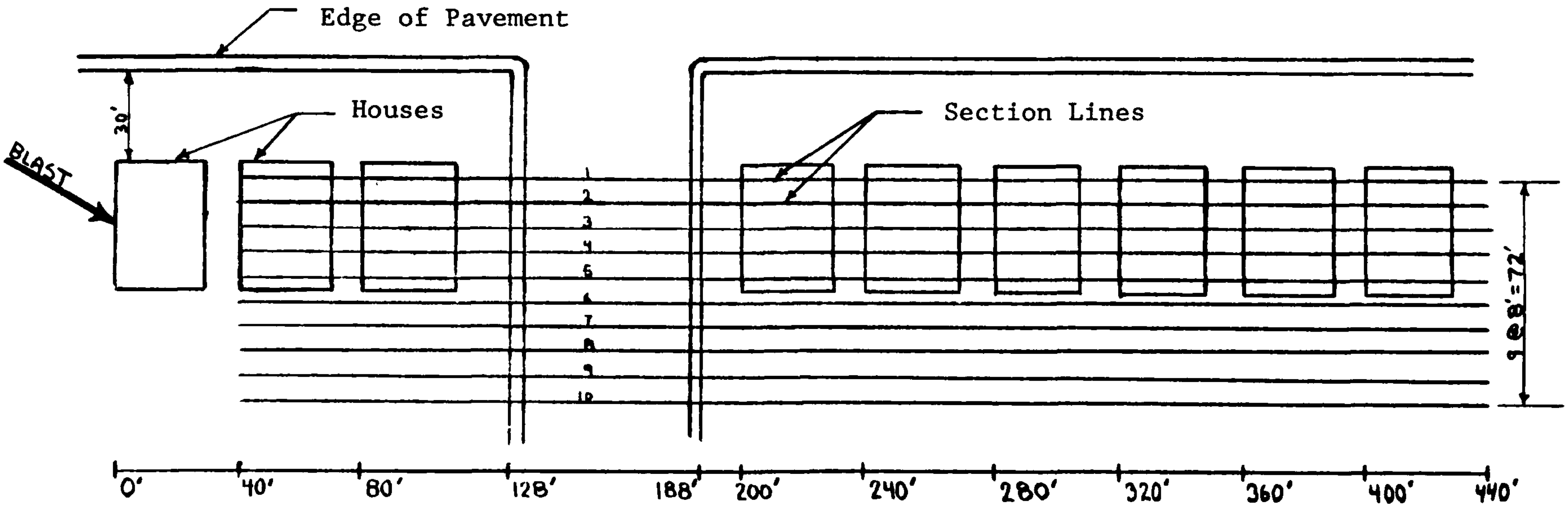
Runs of the RANGER code were made for both blast angles. This routine couples initial coordinates with trajectories to determine final resting points of each debris piece, then creates a point-by-point description of the debris pile. Tables 4 and 5 show the initial and final coordinates of the center of gravity for the examples previously listed. For both cases, unit rectangles 3 ft by 3 ft were used to define the final grid.

The BLOCK routine was run for both blast angles applied to similar blocks. The blocks used are in shown in Figure 9. The distance between rows of houses on this block, 200 feet across the backyards and 120 feet across the front street, was greater than the maximum distance any debris piece would carry in that direction. Therefore, the pile from one row of houses was isolated from that of other rows and not affected by any house outside the row. Thus only one row was considered for the model.

The results of the BLOCK runs were output files designed for use in a debris fire study. They show the number, vertical position and size of all debris pieces at every grid point. This output was used to compute the cross sections shown in Figures 10 through 17. The cross sections represent the weight of the combustible fuel along the section lines shown in Figure 9. For these sections the average weight of six adjacent units, an area three units long and two wide, was used. An entire piece was considered combustible, if any part of it was. The only non-combustible debris piece in the house were brick chimney sections.



a) Section Lines for Normal Blast



b) Section Lines for 30-Degree Blast

Figure 9. Location of Section Lines for Debris Mass Sections.

TABLE 4. FINAL COORDINATES OF TYPICAL DEBRIS - NORMAL BLAST

Debris Piece	Initial Coordinates* X	Initial Coordinates* Y	Range X	Range Y	Final Position X	Final Position Y	Grid Points Covered** (I,J)
Wall Number 3	0.	11.75	62.43	0.	62.43	11.75	(23,6),(23,7),(24,6)
Wall Number 17	0.	11.75	14.79	0.	14.79	11.75	(7,6),(7,7),(8,6)
Chimney Number 9	12.09	34.75	6.59	0.	18.68	34.75	(9,14)
Door Number 9	16.00	13.00	98.70	0.	114.70	13.00	(41,7),(41,8)
Table Number 3	22.25	13.00	24.75	0.	47.00	13.00	(18,7)
Armchair Number 2	2.50	30.50	55.04		57.54	30.50	(22,13)

*X and Y coordinates in feet

**I and J coordinates in 3 foot units

TABLE 5. FINAL COORDINATES OF TYPICAL DEBRIS - 30 DEGREE BLAST

Debris Piece	Initial Coordinates* X	Initial Coordinates* Y	Range X	Range Y	Final Position X	Final Position Y	Grid Points Covered** (I,J)
Wall Number 3	0.	11.75	54.06	31.21	54.06	42.96	(21,17),(21,18),(22,17)
Wall Number 17	0.	11.75	12.80	7.40	12.80	19.15	(7,9),(7,10),(8,9)
Chimney Number 9	12.09	34.75	5.71	3.30	17.80	38.05	(8,15)
Door Number 9	16.00	13.00	85.48	49.35	101.48	62.35	(36,23),(36,24)
Table Number 3	22.25	13.00	21.43	12.37	43.68	25.37	(17,11)
Armchair Number 2	2.50	30.50	47.67	27.52	50.17	58.02	(19,22)

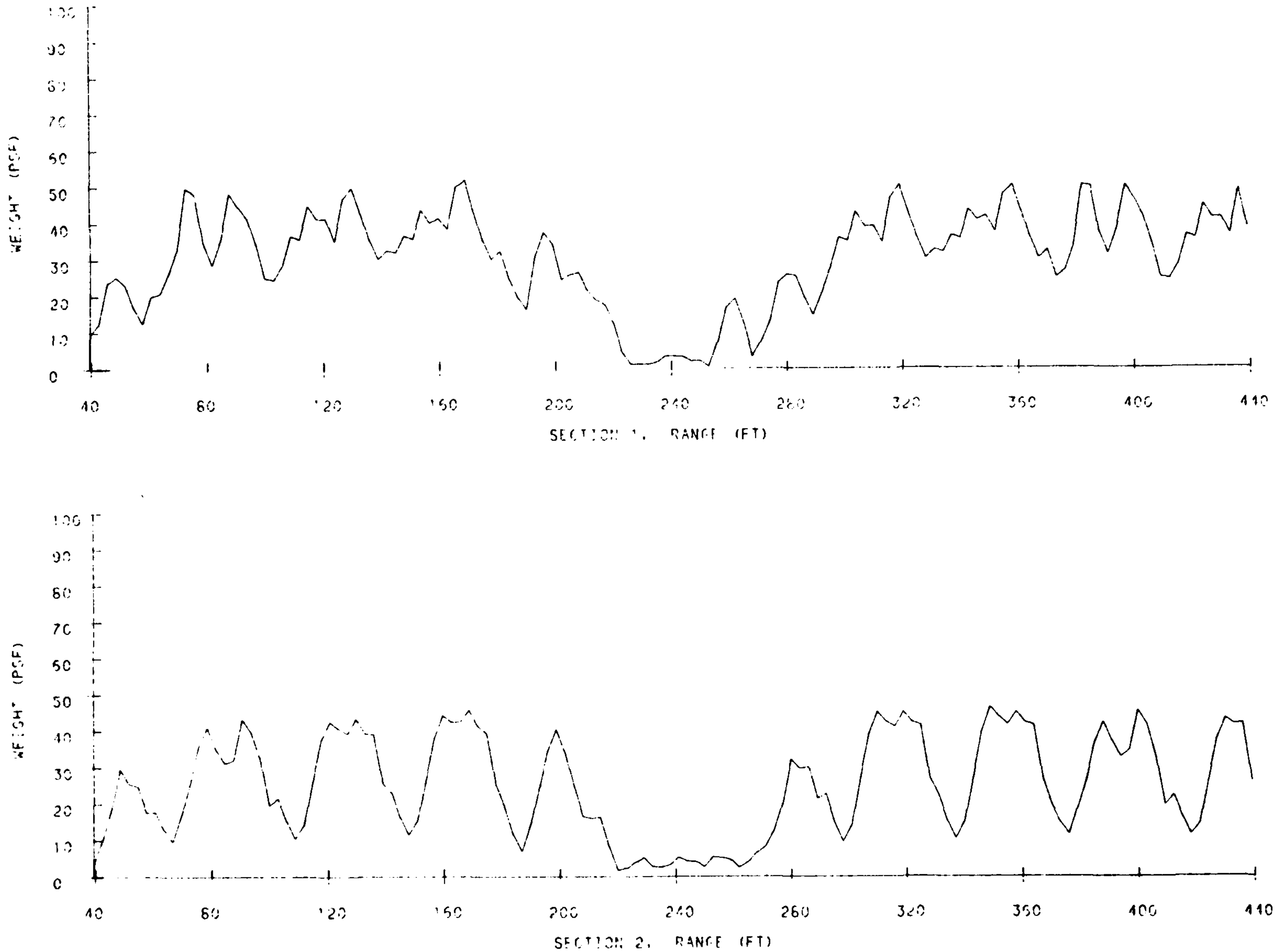


Figure 10. Distribution of Debris Mass for Normal Blast

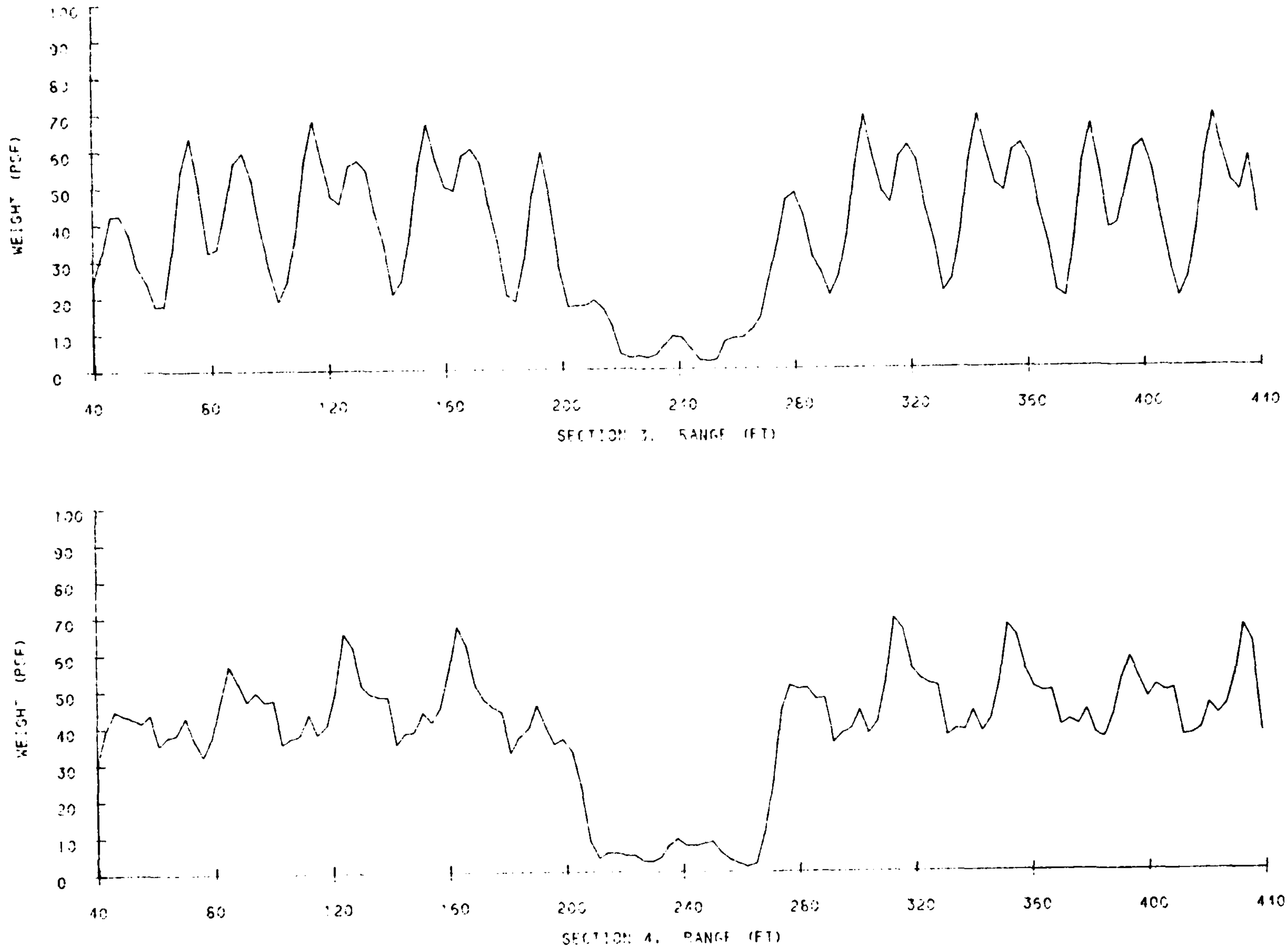


Figure 11. Distribution of Debris Mass for Normal Blast

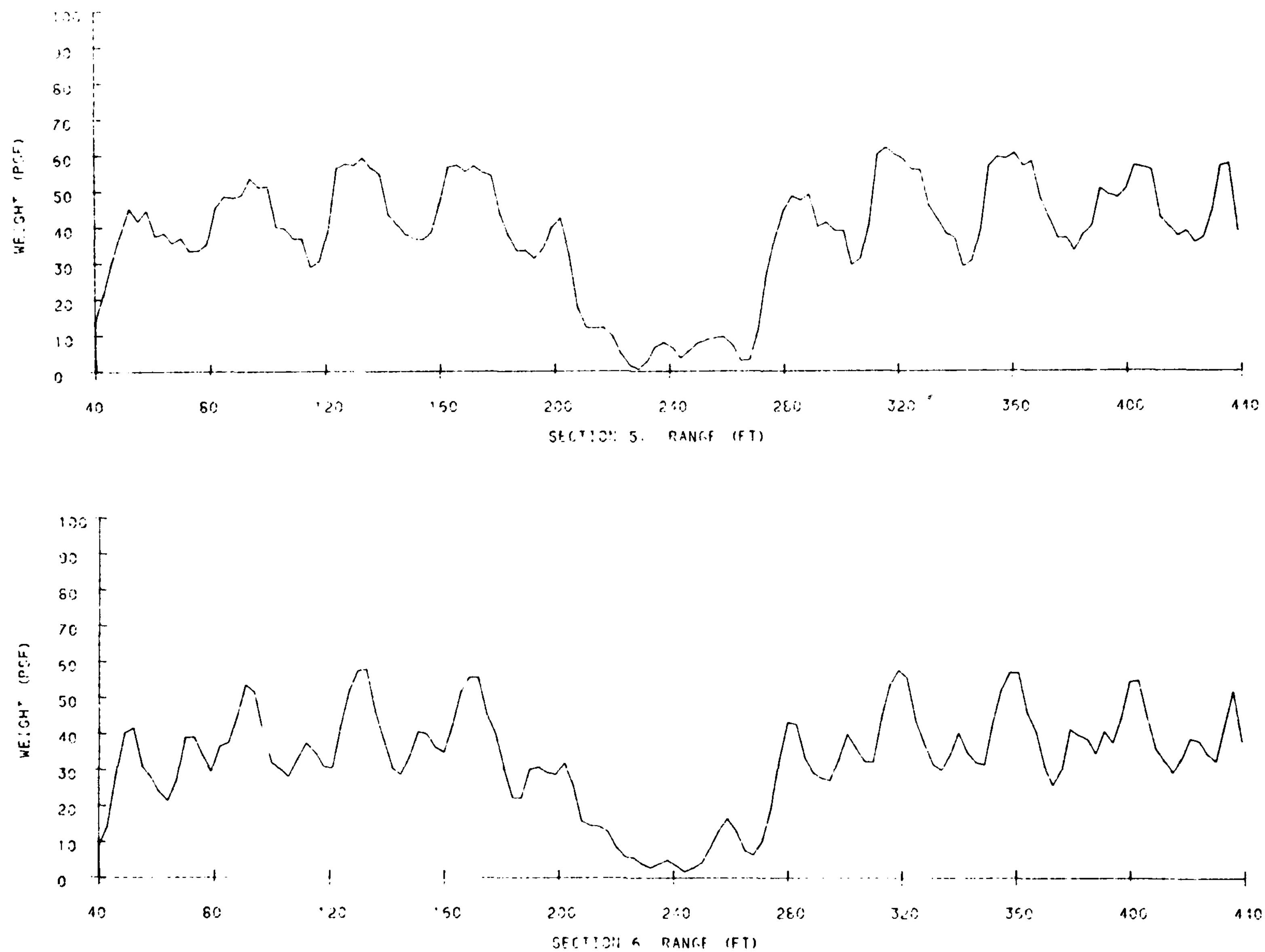


Figure 12. Distribution of Debris Mass for Normal Blast

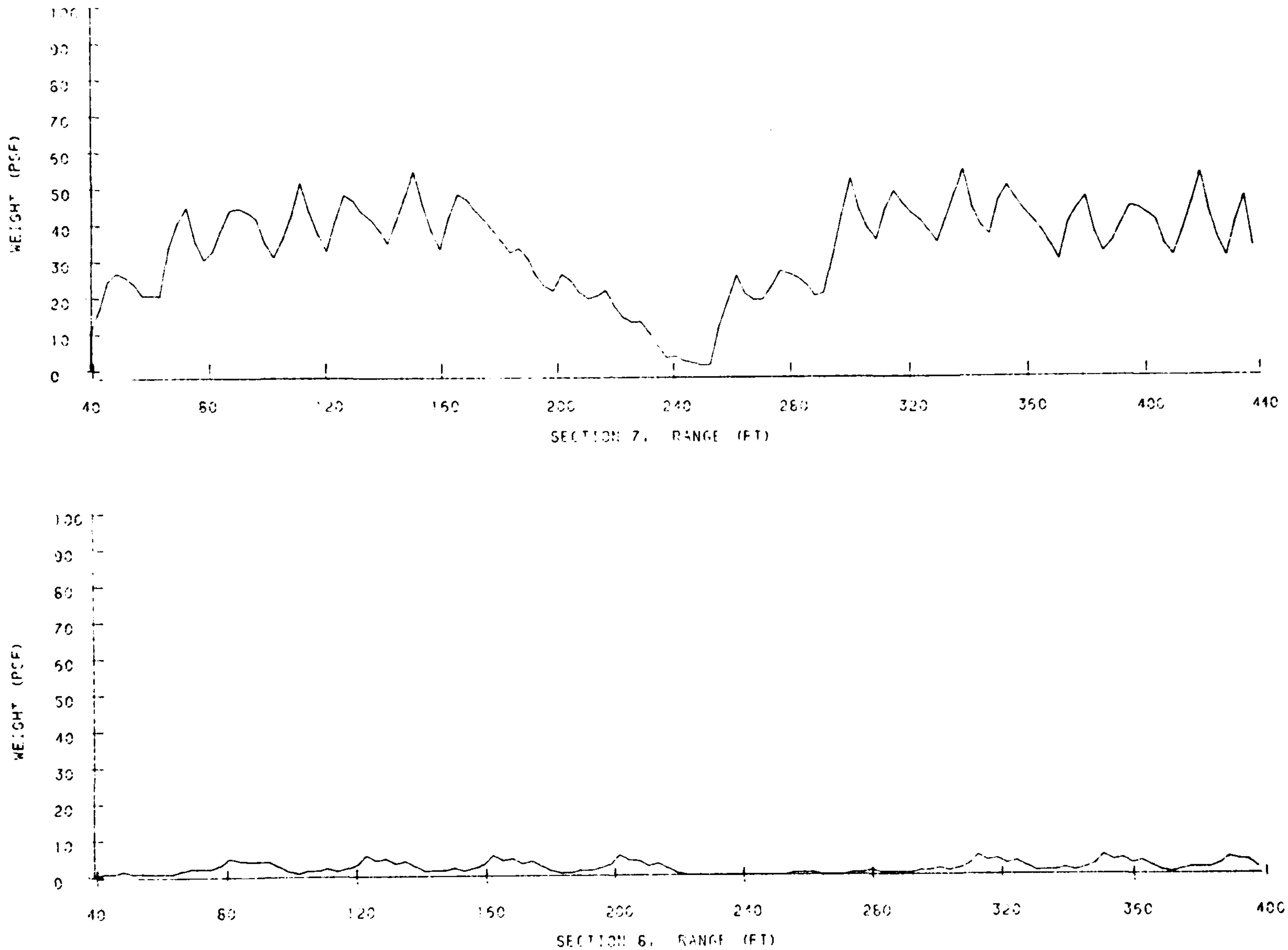


Figure 13. Distribution of Debris Mass for Normal Blast

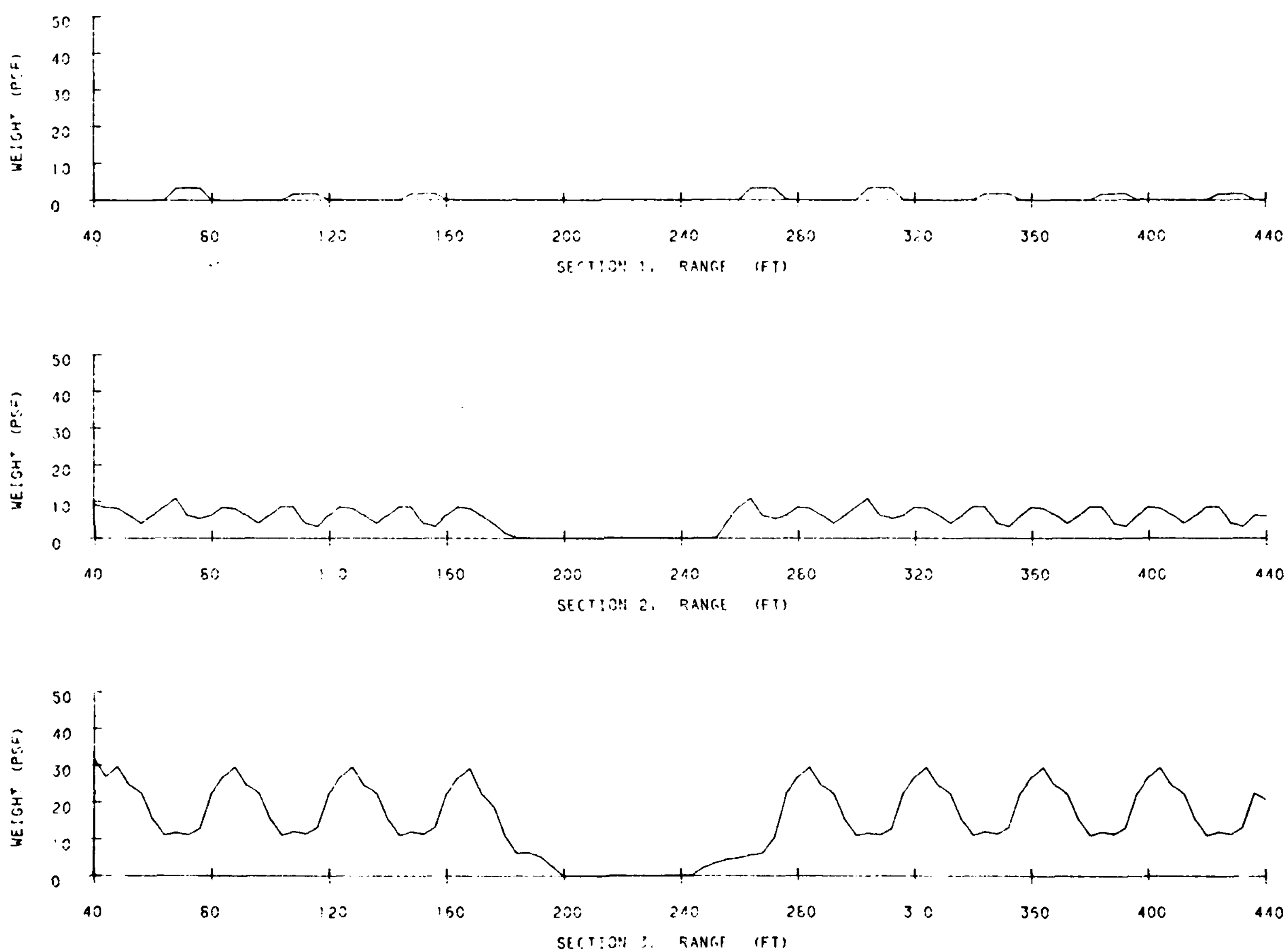


Figure 14. Distribution of Debris Mass, Blast Wave at 30 Degrees

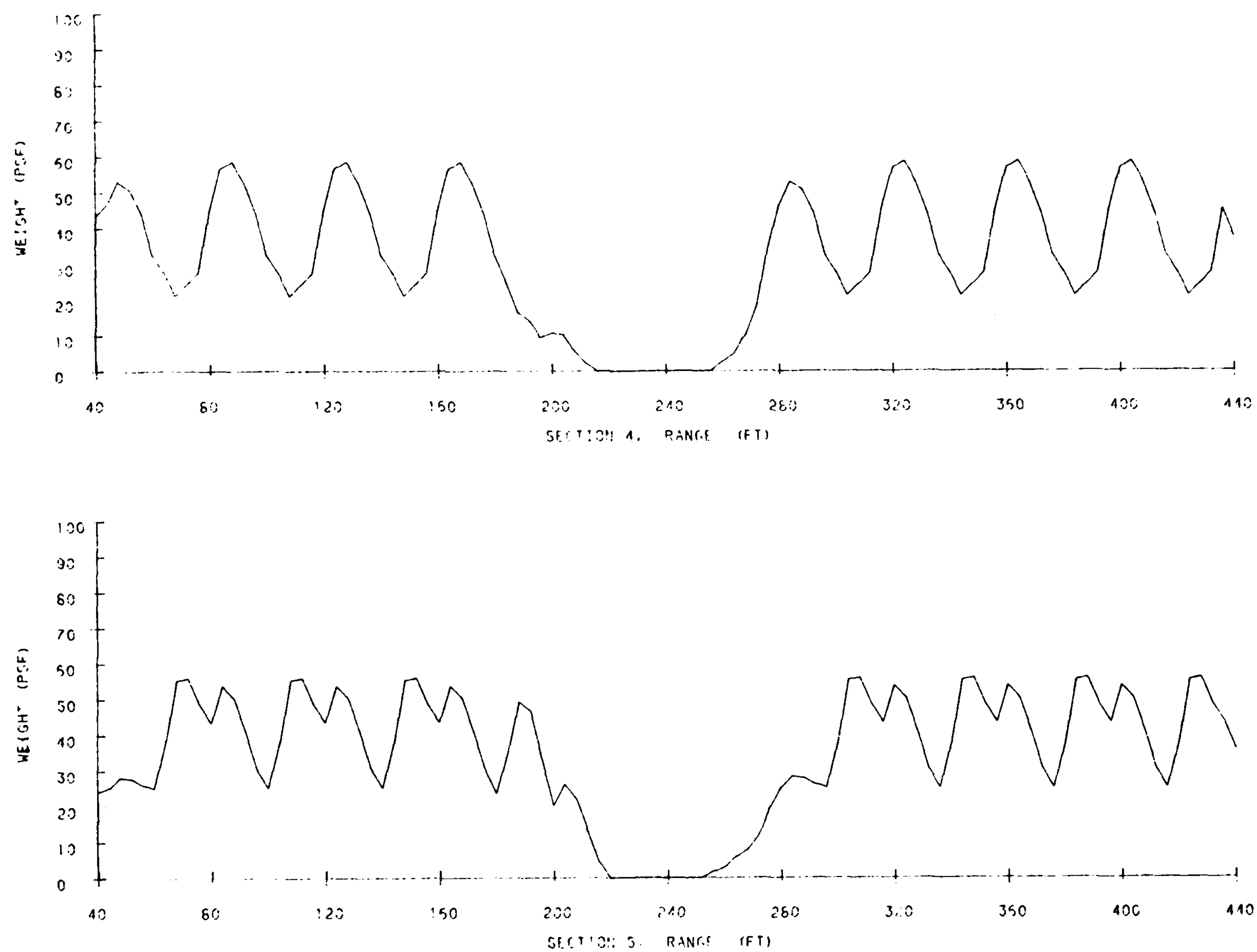


Figure 15. Distribution of Debris Mass, Blast Wave at 30 Degrees

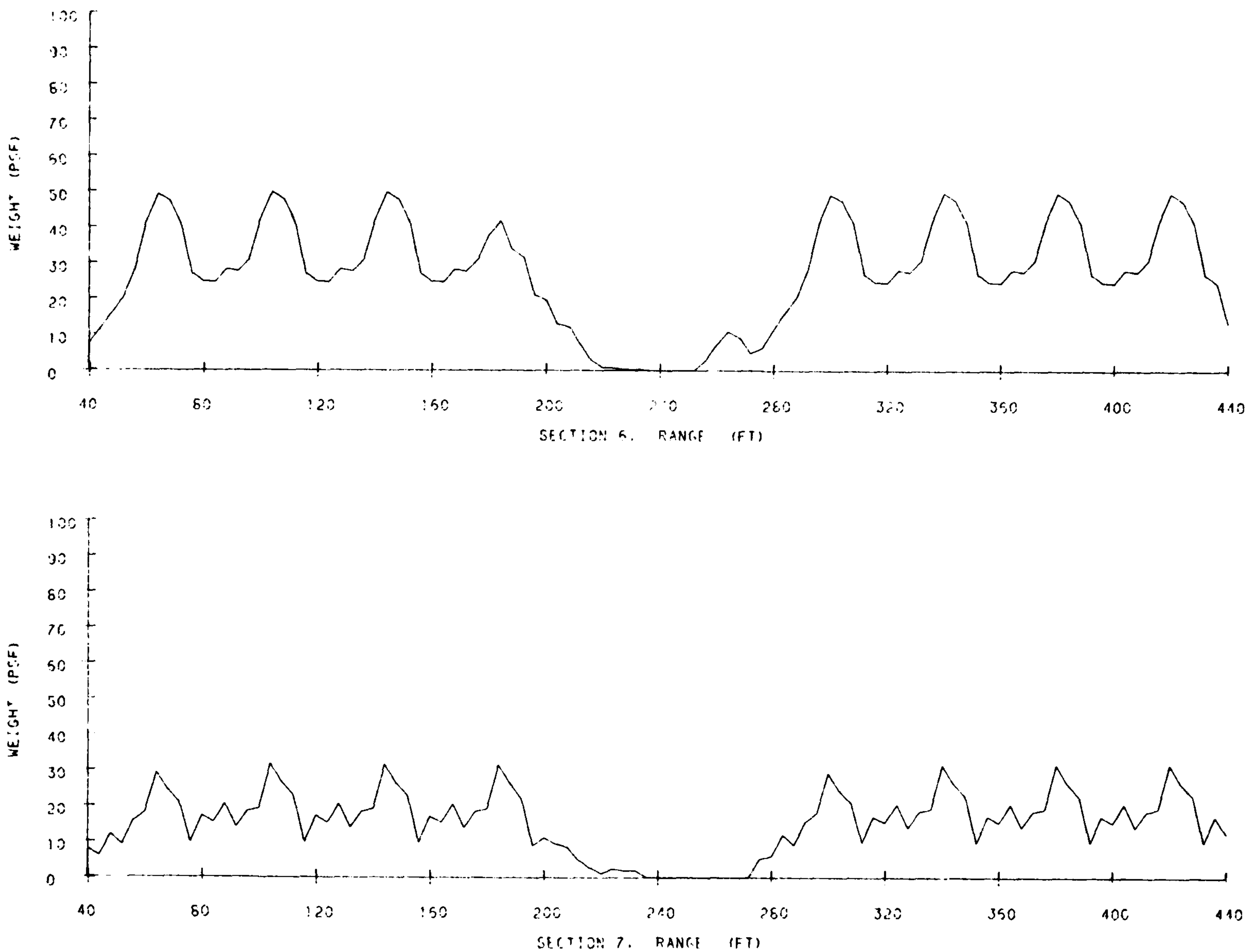


Figure 16. Distribution of Debris Mass, Blast Wave at 30 Degrees

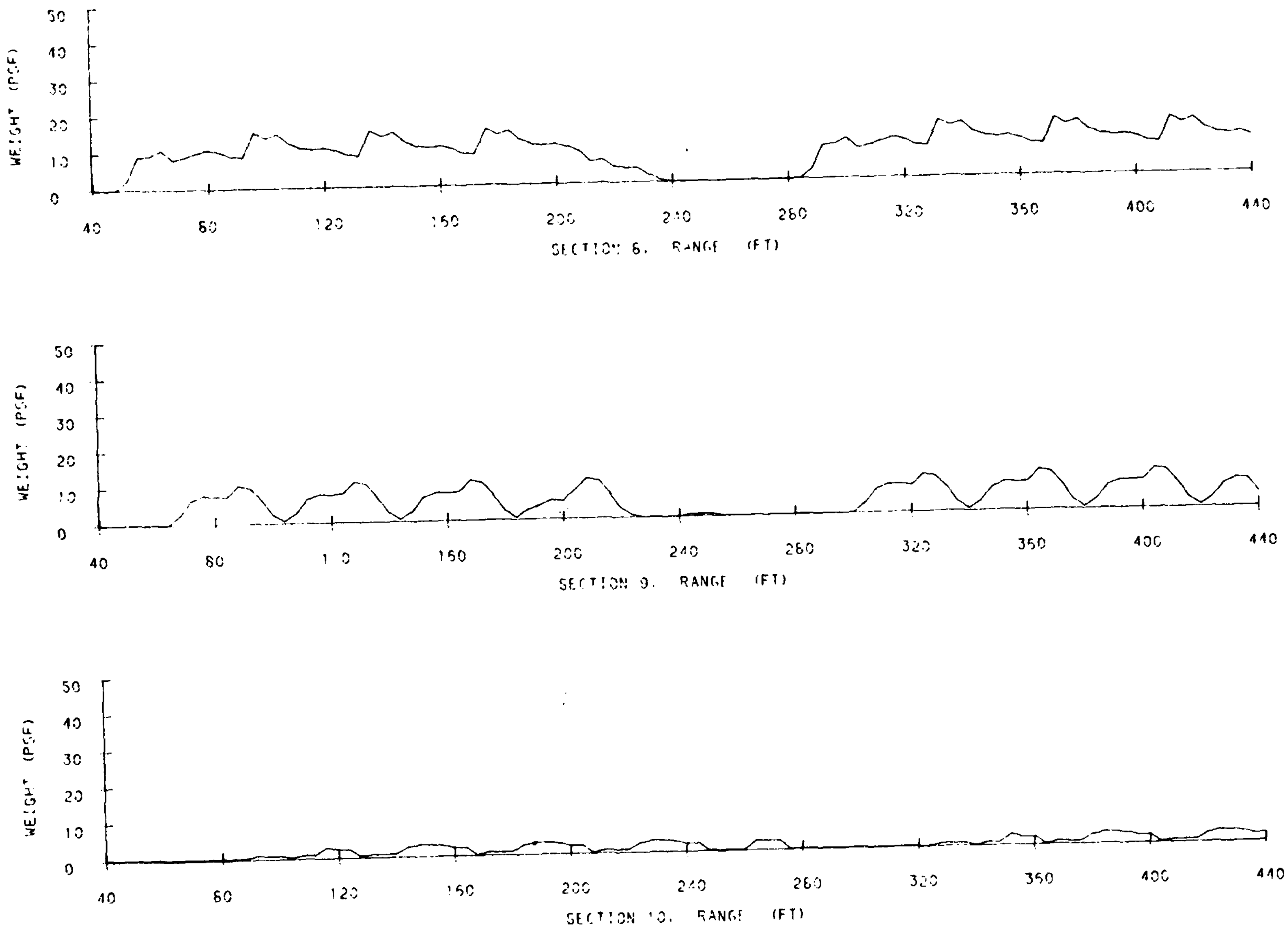


Figure 17. Distribution of Debris Mass, Blast Wave at 30 Degrees

The cross sections reveal two interesting points. First mounds of debris accumulate at intervals equal to the house intervals. These mounds form for both inclinations of the blast wave at this overpressure. At higher peak overpressures, these mounds should begin to level out. Secondly, the 30 degree blast piles separate at the crossing street creating a potential fire break. Larger angles would produce larger separations. Thus for this block configuration, at peak overpressures less than about 3 psi or for angles of blast wave incidence greater than 30 degrees, the debris piles will remain essentially isolated in one block runs.

Additional processing of the debris pile output was done for the fire study of the piles, and is summarized in Chapter 6.

6. CONSIDERATION OF FIRE EFFECTS

Whereas blast damage calculations are usually treated in a relatively uncoupled manner (i.e., gross blast field conditions applied to each structure independently), the examination of fire effects, on even a single building, must consider the impact of nearby surrounding structures; and, of the city as a whole, in relation to the local area under study. In addition, whereas blast effects can be independently studied without giving consideration to the accompanying fires, ignoring blast when estimating fire damage can produce grossly erroneous results in all areas of interest to the civil defense problem. In addition, on a relative scale, blast effects are "instantaneous" compared to the time scale for fire effects. Thus, while both blast and fire effects can be modified by preattack, passive, countermeasures, fire behavior, and effects can be significantly modified by human actions during the transattack period of fire development and spread.

The examination of fire effects requires the definition of many additional parameters beyond those required to characterize the effects of blast. Certain of these are directly related to fire phenomena; but, many are related to the compounding impacts described above. These are elucidated in succeeding sections of this chapter, followed by a brief review of selected particulars of the IITRI Fire Model (Ref. 46, 47). Gross fire spread descriptions are then presented for fire spread throughout the total city followed by estimates for more detailed fire effects in selected localized areas.

6.1 Scenario/Parameter Definition for Fire Studies

6.1.1 Burst/Atmosphere

As stated earlier in this report, the effects of a 1 MT nuclear burst are to be estimated. A near-surface burst was selected for study. To prevent certain simplifying assumptions regarding the hemogeneity of building height and spacing (described later) from unduly influencing the ignition calculations, a burst altitude of 0.5 mile aboveground was assumed. This altitude was considered sufficiently low to permit blast effects from a surface burst to be employed in the evaluation. The target city was assumed at sea level. For these conditions, a fireball radius of 2216 ft (0.42 mile) is calculated.

The two-story wood-framed house being considered here was described earlier. Blast effects calculations suggest the following damage/distance characterizations (Table 6) be employed in the fire spread/effects evaluation.

TABLE 6. DAMAGE-DISTANCE CHARACTERIZATION FOR TEAPOT HOUSE

Damage	Overpressure (psi)	Distance from Ground Zero (miles)
Severe (buildings destroyed)	>3.5	0 to 3.6
Moderate (buildings standing with major wall/roof damage)	2.0 to 3.5	3.6 to 5.3
Negligible (broken windows or none)	<2.0	>5.3

To estimate ignition frequency as a function of distance from ground zero, an atmospheric transmissivity must be chosen for the time of the assumed attack. This is usually expressed as a "visibility" and 12 mile visibility was selected. A south wind of 6 mph was assumed for evaluating firebrand travel. This visibility and wind velocity corresponds to values previously applied in the various "Five City" studies (Ref. 48, 49, 50).

6.1.2 Built-up Area

As mentioned earlier, the examination of fire effects requires that each building or local area to be studied must be considered as part of a larger total target (city) in order to assess fire spread to the local area from its surroundings. However, it was decided not to consider the specifics of any given city in this study. Instead, a hypothetical "city" was constructed entirely of the two-story wood-framed house under consideration. It was considered to extend in all directions from ground zero far beyond any blast or fire affected areas.

To more closely approximate the rates of fire spread and burning durations of a real city, the building density of the overall city was assumed to be 15 percent of the ground area. (This is three times the density of the local area for which blast affected debris was estimated in the previous chapter of the report.) For this evaluation, gross fire spread/duration was first evaluated for the total city (15% density). These results provided the overall fire environment within which a series of local areas were studied, with building density, location, and human actions varied. For calculation purposes, the city was divided into square tracts that were 0.5 mile on a side. For evaluation of local conditions, one tract location was selected at a time, and a specific building density and fire prevention and/or firefighting effort prescribed.

Parameters and techniques selected for the city and local areas are summarized below:

- all buildings are the two-story wood frame TEAPOT HOUSE
- attack occurs during daylight hours (position of window coverings)
- trees and bushes are bare (late fall, winter or early spring)
- overall city building density is 15 percent
- local tract building density is either 5 or 15 percent
- all tracts are 0.5 x 0.5 mile
- building separation (distribution) within tracts is a function of building density and building areas based on survey of residential areas in Detroit (Ref. 49)
- building separation across tract boundaries is considered to be 100 ft for 90 percent of each tract perimeter, and infinite (no firebrand crossing) along the remaining 10 percent of each tract perimeter.

Attention is directed to the latter two entries concerning building separation. These are introduced into the calculation to retain some of the variability of a real city. Such was considered necessary as the fire model circumvents certain probabilistic aspects of radiation fire spread by relating fire spread probability solely to building separation, once flame patterns are defined. The tract boundary specification is designed to allow for vacant properties, parks, rivers, and broad streets.

6.1.3 Buildings/Contents

Earlier studies involving the IITRI Fire Model developed descriptions of the position of window coverings (curtains, drapes, shades) separately for daytime and nighttime hours. Applying daytime results for Detroit (Ref. 48) to the TEAPOT HOUSE yields the following characterization (Table 7).

TABLE 7. DISTRIBUTION OF UNCOVERED WINDOW AREAS FOR TEAPOT HOUSE

Percent of Windows	Open Area (ft^2)
6.3	12.63
8.4	8.05
9.6	5.46
8.6	3.69
2.0	1.31
65.1	0.0

Window panes were assumed to transmit 70 percent of the weapon pulse.

The locations of fuels within each room were assumed to match those determined for earlier studies (Ref. 48, 49, 50). Critical ignition energies (weapon pulse) of the room items also were assumed identical to those of the earlier studies. These may be summarized:

Percent Room Items Ignited	Fluence* (cal/cm^2)
79	50
67	28
11	19
0	13

For window coverings, the energies are:

Percent Window Coverings Ignited	Fluence (cal/cm^2)
64	50
43.5	28
22.1	19
0	13

On the basis of the earlier surveys of room contents locations, the probability of burning window coverings igniting major room fuel items is assumed to be 0.40.

The TEAPOT HOUSE and contents averages 25 lb fuel/ft^2 of floor area on each story. It is assumed that 50 percent of this fuel is consumed during the active burning period** (period starting about 5 minutes after first room flashover during which a burning building gives off significant radiant energy and/or firebrands; and, is thus capable of spreading fires to surrounding, yet unignited, structures).

6.1.4 Blast/Ignition Interactions

A search of the literature produced no recent data on secondary (blast caused) ignitions. Thus, the classic study by McAuliff and Moll (Ref. 5) was reviewed for information. This study suggests a factor of 0.019 secondary ignitions per 1000 ft^2 floor area be applied to wood structures; and, that this number be halved for residential structures. The floor area of the TEAPOT HOUSE is:

Two stories x 24'8" x 33'4" = 1644 ft^2/house

*Fluence is the quantity obtained by integrating flux (cal/cm^2-sec) over time (sec).

**Also identified as "stage 3 fires" on later graphs.

Thus the suggested secondary ignition frequency is:

$$\frac{0.019/2}{1000} \times 1644 = 0.0156 \; \frac{\text{secondary ignitions}}{\text{house}}$$

McAuliff and Moll suggest that the region of secondary ignitions extend out to 2.0 psi peak overpressure for wood structures. This corresponds to 5.3 miles from ground zero for a 1 MT surface burst.

While being the cause of secondary ignitions, the blast wave from a nuclear weapon can extinguish some primary fires initiated by the thermal pulse. In 1970, Goodale (Ref. 3) reported that some flames were extinguished in the 1 to 2½ psi overpressure range; and, that all flaming, but not smoldering, combustion was suppressed by overpressures from 2½ to 8 psi. Flaming was noted to recur after delays of a few minutes up to about 1 hour. Similar results were reported in 1971 (Ref. 51) with overpressures up to 9 psi. In 1976, Wilton (Ref. 52) offered further data which suggest that the suppression of ignitions may occur at even slightly lower blast overpressure levels.

To represent the above information in a manner readily adaptable to the IITRI fire model, the following was adopted:

TABLE 8. BLAST EFFECTS ON PRIMARY IGNITIONS

Burning Window Coverings	
≥3 psi	all extinguished (≤4 miles from ground zero)
2.5 psi	50% extinguished (≈4.5 miles)
≤2 psi	none extinguished (≥5.3 miles)
Burning Major Room Items	
≥5 psi	50% extinguished (≤3 miles)
4 psi	33% extinguished (3.4 miles)
3 psi	17% extinguished (4 miles)
2 psi	none extinguished (5.3 miles)

6.2 Fire Model

As originally conceived, the IITRI Fire Model (Ref. 46 to 50) was designed to treat that area of a city having light or no blast damage for purposes of estimating fire damage as an addition to blast damage. Thus, the city was considered to have a doughnut area susceptible to fire damage with the doughnut hole already heavily damaged by blast.

With increased interest in the potential for survival in more heavily blast damaged regions, the city will now be treated as a severely blast damaged core region around ground zero, a moderately damaged ring surrounding the core, and a lightly damaged outer area gradually transitioning to the undamaged region. Thus, one further stage of refinement in prediction is to be gained. For this study, the Model has been adapted to treat both the moderate and light-to-moderate damage regions. The severely damaged region is so completely different in character (lacking discrete fuel sources and separations) that a totally different model is required. For this study, fire behavior and effects in the region of severe blast damage has been assessed through the use of hand calculation, prior experimentation, and engineering judgement.

In the following section, the IITRI Fire Model will be briefly summarized and the adaptation for its use in the region of moderate blast damage will be described. For further details on the Model, the reader is referred to the prior studies (Ref. 46 to 50).

6.2.1 Ignition Code

In its present form, the ignition code predicts the total <u>sustained</u> ignitions caused by the fireball (primary) and by blast (secondary). Various inputs are required to the code. These can be fixed or distributed (variable) values.

The code requires weapon yield, height of burst, ground altitude, atmospheric visibility, and transmissivity of window-panes as input. From these, it calculates the fireball size and radiant fluxes as a function of distance from ground zero. The code does not calculate blast overpressure versus distance; this must be input separately. Using the input given above and of building height, width, separation, position of window coverings, and season, it goes through the geometry necessary to describe the radiant intensity patterns within a room on each story of the building as affected by external shielding and the room walls. Again, most of the input may have fixed or distributed values. When the illumination of the room interior is established, the Code uses input of room dimensions, nature, and distribution of window coverings to predict the probability of either a window covering or room item ignition on the basis of its probability of being located such that it receives sufficient radiant energy. The probabilities of ignition so obtained are modified to consider only those that survive blast and involve (or spread to) major fuel items capable of causing full room involvement. These primary fire probabilities then are combined with (blast caused) secondary fire probabilities and expressed in terms of:

- probable number of buildings/tract having sustained fires
- probable number of rooms per building with sustained fires

For the TEAPOT HOUSE arranged as shown in Chapter 4 (5% building density) the Ignition Code predicts the data shown in Table 9 (1 MT near-surface burst).

TABLE 9. SUSTAINED IGNITIONS IN THE TEAPOT HOUSE

Distance from Ground Zero (miles)	Fraction of Buildings with Sustained Fires	Average Sustained Room Fires Per Building
0	0.01560	0.01560
0.5	0.01567	0.01567
1	0.24849	0.27853
1.5	0.14186	0.15393
2	0.05905	0.06038
2.5	0.02257	0.02261
3	0.01582	0.01582
3.5	0.01560	0.01560
4	0.01560	0.01560
4.5	0.05592	0.05751
5	0.04491	0.04605
5.5	0.00294	0.00300
6	0.00000	0.00000

Several interesting observations can be made regarding these results.

1. The decrease in ignition frequency at 0 and 0.5 mile compared to 1.0 mile is due to shielding of the buildings by the roof. The ignition code does not address the possibility of the blast wave opening up structures in this region so that the later portions of the fireball may ignite interior fuels.

2. For this relatively small weapon, the ratio of fluence/overpressure quickly becomes quite low as distance increases. For example, the weapon can ignite window coverings only to 5.5 miles while the blast wave extinguishes some of them out to 5.3 miles (see Table 8). Room contents are ignited by the weapon only to 3 miles; and, 50 percent of these are blast extinguished. For higher burst altitude and larger weapon sizes, fire effects are less influenced by blast as they extend to relatively greater distance.

6.2.2 Radiation Fire Spread Between Buildings

The probability of fire spread between buildings is precalculated as a function of building separation for use in the Fire Spread Code. In order to apply the model to the region of moderate blast damage, two expressions for flame area were developed. In each case, flames above the roof were considered to be one story in height (above the second story ceiling). Since the TEAPOT HOUSE is wood framed, the undamaged structures were considered to have window generated flames equal to 25 percent of the wall area at any given time. The moderately damaged structures were considered to have window (and damaged wall) flames equal to 75 percent of the wall area. The increased flame area for buildings in the region of moderate damage is probably most representative for those near the lower damage end of this region. As damage increases, the flame areas and associated radiation will also decrease (Ref. 12, 53) to a low level in the area of severe damage (Ref. 20). Wind effects on radiation levels were not considered here as they are poorly documented; and not readily entered into the firespread model. Thus, the radiation levels chosen are judged to be an "average" for all wind directions.

In addition to the flame areas described, this submodel requires criteria for spontaneous and piloted ignition, flame temperature, and flame emissivity to calculate radiant fire spread probabilities. The following were specified based on various earlier studies; and, previously used in the IITRI model:

- spontanious ignition: 0.770 cal/cm^2-sec,
- piloted ignition: 0.385 cal/cm^2-sec,
- flame temperature: equal probabilities of being 1500, 1600, 1700, 1800, or 1900°F,
- flame emissivity: 1.0

Since radiation fire spread occurs over limited distances, the effects of wind were not considered to materially affect the chances of piloted spread (sparks) in any direction; and, spontaneous or piloted ignition were considered equally probable in all directions. Using the above criteria and parameter selection, radiation fire spread probabilities were calculated as shown in Table 10.

The data shown above do not fall onto smooth curves due to the discrete nature of the variables used. The low value calculated for undamaged buildings separated by 1 ft is caused by model assumptions as to window locations.

TABLE 10. PROBABILITY OF RADIATION FIRE SPREAD BETWEEN TEAPOT HOUSES

Separation Distance, Building to Building (ft)	Probability of Radiation Fire Spread (percent)	
	Undamaged Buildings	Moderately Damaged Buildings
1	75.0	100
9	87.5	100
19	75.0	100
29	43.8	81.3
39	18.8	56.3
45	6.3	37.5
47	0.0	31.3
49	0.0	31.3
59	0.0	6.3
62	0.0	6.3
65	0.0	0.0

6.2.3 Fire Spread Code

The Fire Spread Code predicts fire spread between buildings due to either radiation or firebrands from burning buildings. It treats the total area suffering weapon ignitions and any additional area specified by the user. It is the users responsibility to select an area large enough to encompass all fire spread during the total time of interest. The choice of area must be sufficient to encompass all spread; but should be judiciously chosen since computer running time is proportional to area chosen as well as to total time history to be calculated.

The code examines fire spread at 15 minute intervals; and, events during each 15 minute period are lumped together. Fires are considered to spread from any given building only during the active burning period of that building. The active burning period of the TEAPOT HOUSE, rounded to the nearest 15 minutes, is calculated to be 45 minutes based on its fuel load.

An ignited building reaches its active burning period in 15 minutes on the average. For individual buildings, this time may vary from about 3 minutes to over 1 hour (Ref. 6). For the Code, the development of fires to the active burning period is examined each minute and accumulated for the 15 minute period (i.e., assumed to occur at the next 15 minute interval for which the total city area is examined).

Radiation levels and firebrand generation rates are not constant during the active burning period. Radiation, on the average, peaks at about the midpoint of active burning. Firebrand generation is heaviest during roof penetration, and essentially ceases once the roof has collapsed. To account for these factors during the 45 minute active burning period of the TEAPOT HOUSE, radiant and firebrand spread has been distributed based largely on experience/judgement.

TABLE 11. DISTRIBUTION OF FIRE SPREAD OCCURRENCES FOR THE TEAPOT HOUSE

Fraction of 45 min. Active Period	Fraction of Radiant Fire Spread	Fraction of Fire-brand Spread
First 15 min.	0.113	0.046
Second 15 min.	0.741	0.456
Third 15 min.	0.146	0.498
Total 45 min.	1.0	1.0

The above suggests that about 74 percent of all radiation fire spread occurs during the 15 to 30 minute period of active burning; and, that spread by firebrands occurs almost entirely (and nearly equally) during the 15 to 30 minute and 30 to 45 minute periods of active burning of any given house.

The probabilities of radiation fire spread were given in the previous section, for both the areas of undamaged and moderately damaged buildings. The method of calculating firebrand spread is summarized below.

Earlier studies (Ref. 54, 55, 56) have indicated that only the larger firebrands are capable of traveling any distance while retaining the capability to ignite common interior home furnishings. These were found to be generated as a function of roof area (primarily due to the roof sheathing); and, to be deposited downwind over a wide area as a function of wind speed and direction. Prior experiments (Ref. 56) suggest that dispersion due to variations in wind direction include an angle of 90 deg, 45 deg to either side of the nominal downwind direction. Deposition is heaviest near each burning structure, gradually decreasing to no brands about 1350 ft for the TEAPOT HOUSE in a 6 mph wind.

To ignite interior furnishings (most susceptible host materials), the brands must enter rooms through windows or other openings created by blast effects. The window area/wall area ratio for the TEAPOT HOUSE is 0.112. This number was used for regions of undamaged buildings (windows assumed broken by blast). In regions of moderate blast damage, the total opening area was assumed to be tripled (as was done for radiation fire spread described earlier), and a value of open area/wall area of 0.33 was employed.

Brand trajectories were computed under a 6 mph wind to estimate the probability of a brand entering a room (as a function of distance from a burning building). From the earlier surveys of room contents (Ref. 46, 48, 49, 50) the fraction of brands entering a room that will cause room flashover is considered to be 0.08 (ratio of horizontal surface area of easily ignited major room fuels to floor area).

Fire spread by brands is calculated within each tract of brand origin; and, to downwind and crosswind tracts based on the 90 deg dispersion angle. Included in this calculation is the separation at tract boundaries described earlier.

A major task of the Fire Spread Code is the compiling of buildings with new ignitions or new active burning periods. Thus, it handles a major "bookkeeping" job as a part of its purpose. Typically, this bookkeeping is displayed as part of the computer output in maps showing number of active fires/tract, or number of unburned buildings/tract at various time intervals. Examples of these results are included as Figures 18 to 23. Rate of heat release with time can also be displayed. As the city used here is uniform in building type and density, a line through ground zero and parallel to the nominal wind direction splits the target area into two mirror images. Only one of these (one-half the total damaged area) is shown. The asterisks (*) shown in Figures 18 to 23 depict the area of severe blast damage.

6.3 Fire Spread and Fire Development Results

As described earlier, for this study a hypothetical city was chosen, for the gross fire spread calculation, to consist solely of TEAPOT HOUSES at a building density of 15 percent of ground area and extending far beyond all weapon effects in all directions.

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=12	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=13	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=14	3.	3.	3.	2.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=15	39.	40.	39.	34.	25.	14.	3.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=16	55.	55.	55.	53.	51.	43.	34.	16.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.
J=17	18.	16.	18.	24.	35.	49.	52.	42.	25.	3.	1.	0.	0.	0.	0.	0.	0.	0.
J=18	15.	16.	16.	16.	16.	16.	33.	55.	44.	29.	3.	1.	0.	0.	0.	0.	0.	0.
J=19	******	******	******	16.	16.	16.	16.	[illegible]	51.	44.	25.	2.	0.	0.	0.	0.	0.	0.
J=20	******	******	******	******	******	16.	16.	16.	24.	56.	42.	16.	1.	0.	0.	0.	0.	0.
J=21	******	******	******	******	******	******	******	16.	16.	33.	52.	34.	2.	0.	0.	0.	0.	0.
J=22	******	******	******	******	******	******	******	16.	16.	16.	50.	43.	14.	1.	0.	0.	0.	0.
J=23	******	******	******	******	******	******	******	******	16.	16.	35.	51.	25.	2.	0.	0.	0.	0.
J=24	******	******	******	******	******	******	******	******	16.	16.	24.	54.	34.	2.	0.	0.	0.	0.
J=25	******	******	******	******	******	******	******	******	******	16.	18.	55.	39.	3.	0.	0.	0.	0.
J=26	******	******	******	******	******	******	******	******	******	16.	16.	56.	40.	3.	0.	0.	0.	0.
J=27	******	******	******	******	******	******	******	******	******	16.	18.	55.	35.	3.	0.	0.	0.	0.
J=28	******	******	******	******	******	******	******	******	16.	16.	25.	53.	34.	2.	0.	0.	0.	0.
J=29	******	******	******	******	******	******	******	******	16.	16.	35.	51.	25.	2.	0.	0.	0.	0.
J=30	******	******	******	******	******	******	******	16.	16.	16.	50.	43.	14.	1.	0.	0.	0.	0.
J=31	******	******	******	******	******	******	******	16.	16.	33.	52.	34.	2.	0.	0.	0.	0.	0.
J=32	******	******	******	******	******	16.	16.	16.	25.	56.	42.	15.	1.	0.	0.	0.	0.	0.
J=33	******	******	******	16.	16.	16.	16.	25.	52.	44.	25.	2.	0.	0.	0.	0.	0.	0.
J=34	16.	16.	16.	16.	16.	16.	33.	56.	44.	29.	3.	1.	0.	0.	0.	0.	0.	0.
J=35	18.	16.	18.	25.	35.	50.	52.	42.	25.	3.	1.	0.	0.	0.	0.	0.	0.	0.
J=36	55.	56.	55.	53.	51.	43.	34.	15.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.
J=37	39.	40.	39.	34.	25.	14.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=38	3.	3.	3.	2.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=39	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=40	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 18 Map of Target Area Showing Active (Stage 3) Fires at 1 Hour

							I											
	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=12	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=13	2.	2.	2.	2.	1.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=14	40.	42.	41.	36.	28.	16.	2.	1.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=15	237.	242.	238.	223.	189.	118.	38.	19.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=16	19.	18.	18.	20.	22.	246.	222.	128.	31.	6.	1.	0.	0.	0.	0.	0.	0.	0.
J=17	373.	385.	371.	272.	103.	26.	21.	245.	180.	37.	8.	0.	0.	0.	0.	0.	0.	0.
J=18	367.	370.	370.	385.	385.	385.	125.	18.	248.	195.	36.	6.	0.	0.	0.	0.	0.	0.
J=19	******	******	******	369.	371.	385.	385.	269.	23.	248.	180.	27.	1.	0.	0.	0.	0.	0.
J=20	******	******	******	******	******	369.	371.	385.	268.	17.	245.	125.	13.	0.	0.	0.	0.	0.
J=21	******	******	******	******	******	******	******	385.	385.	125.	20.	215.	29.	1.	0.	0.	0.	0.
J=22	******	******	******	******	******	******	******	369.	385.	384.	24.	246.	112.	9.	0.	0.	0.	0.
J=23	******	******	******	******	******	******	******	******	385.	384.	97.	21.	178.	16.	0.	0.	0.	0.
J=24	******	******	******	******	******	******	******	******	369.	385.	265.	18.	214.	21.	0.	0.	0.	0.
J=25	******	******	******	******	******	******	******	******	******	386.	369.	16.	231.	24.	0.	0.	0.	0.
J=26	******	******	******	******	******	******	******	******	******	386.	383.	16.	235.	25.	0.	0.	0.	0.
J=27	******	******	******	******	******	******	******	******	******	386.	365.	16.	229.	24.	0.	0.	0.	0.
J=28	******	******	******	******	******	******	******	******	385.	385.	237.	18.	211.	21.	0.	0.	0.	0.
J=29	******	******	******	******	******	******	******	******	385.	384.	80.	23.	172.	16.	0.	0.	0.	0.
J=30	******	******	******	******	******	******	******	385.	385.	377.	23.	239.	102.	8.	0.	0.	0.	0.
J=31	******	******	******	******	******	******	******	386.	382.	96.	21.	208.	22.	0.	0.	0.	0.	0.
J=32	******	******	******	******	******	385.	385.	382.	214.	17.	237.	112.	11.	0.	0.	0.	0.	0.
J=33	******	******	******	385.	385.	385.	379.	209.	21.	241.	167.	19.	0.	0.	0.	0.	0.	0.
J=34	385.	385.	385.	383.	379.	371.	98.	17.	241.	182.	22.	4.	0.	0.	0.	0.	0.	0.
J=35	337.	369.	332.	215.	79.	24.	21.	235.	166.	22.	6.	0.	0.	0.	0.	0.	0.	0.
J=36	18.	16.	17.	19.	23.	236.	204.	111.	18.	4.	0.	0.	0.	0.	0.	0.	0.	0.
J=37	222.	228.	223.	204.	166.	100.	20.	10.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=38	20.	21.	20.	17.	13.	7.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=39	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=40	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 19 Map of Target Area Showing Active (Stage 3) Fires at 5 Hours

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 3	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 4	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 5	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 6	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 7	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 8	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J= 9	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=10	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=11	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=12	4.	4.	4.	4.	3.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=13	62.	65.	63.	57.	45.	28.	4.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=14	152.	134.	148.	191.	230.	197.	63.	33.	4.	1.	0.	0.	0.	0.	0.	0.	0.	0.
J=15	0.	0.	0.	0.	0.	0.	168.	214.	55.	12.	1.	0.	0.	0.	0.	0.	0.	0.
J=16	0.	0.	0.	0.	0.	0.	0.	0.	219.	105.	17.	1.	0.	0.	0.	0.	0.	0.
J=17	0.	0.	0.	0.	0.	0.	0.	0.	0.	177.	119.	13.	0.	0.	0.	0.	0.	0.
J=18	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	190.	94.	4.	0.	0.	0.	0.	0.
J=19	********	********	********	0.	0.	0.	0.	0.	0.	0.	0.	231.	30.	1.	0.	0.	0.	0.
J=20	********	********	********	********	********	0.	0.	0.	0.	0.	0.	0.	157.	5.	0.	0.	0.	0.
J=21	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	228.	25.	0.	0.	0.	0.
J=22	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	0.	123.	3.	0.	0.	0.
J=23	********	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	178.	5.	0.	0.	0.
J=24	********	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	205.	6.	0.	0.	0.
J=25	********	********	********	********	********	********	********	********	********	0.	0.	0.	0.	216.	7.	0.	0.	0.
J=26	********	********	********	********	********	********	********	********	********	0.	0.	0.	0.	218.	7.	0.	0.	0.
J=27	********	********	********	********	********	********	********	********	********	0.	0.	0.	0.	214.	7.	0.	0.	0.
J=28	********	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	199.	6.	0.	0.	0.
J=29	********	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	165.	4.	0.	0.	0.
J=30	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	1.	100.	2.	0.	0.	0.
J=31	********	********	********	********	********	********	********	0.	0.	0.	0.	0.	203.	6.	0.	0.	0.	0.
J=32	********	********	********	********	********	0.	0.	0.	0.	0.	0.	0.	123.	3.	0.	0.	0.	0.
J=33	********	********	********	0.	0.	0.	0.	0.	0.	0.	0.	182.	5.	0.	0.	0.	0.	0.
J=34	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	202.	52.	1.	0.	0.	0.	0.	0.
J=35	0.	0.	0.	0.	0.	0.	0.	0.	0.	200.	69.	2.	0.	0.	0.	0.	0.	0.
J=36	0.	0.	0.	0.	0.	0.	0.	0.	173.	51.	1.	0.	0.	0.	0.	0.	0.	0.
J=37	0.	0.	0.	0.	0.	1.	187.	108.	3.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=38	182.	189.	185.	169.	137.	84.	2.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=39	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
J=40	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 20 Map of Target Area Showing Active
(Stage 3) Fires at 10 Hours

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	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 6	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 9	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=11	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=12	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=13	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=14	.993	.993	.993	.994	.996	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=15	.908	.904	.908	.920	.940	.967	.994	.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=16	.857	.855	.857	.861	.867	.899	.920	.963	.995	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=17	.953	.958	.953	.936	.908	.871	.865	.900	.940	.993	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=18	.959	.959	.959	.959	.959	.958	.913	.855	.806	.932	.993	.999	1.000	1.000	1.000	1.000	1.000	1.000
J=19	*****	*****	*****	.959	.959	.959	.958	.935	.865	.895	.940	.995	1.000	1.000	1.000	1.000	1.000	1.000
J=20	*****	*****	*****	*****	*****	.959	.959	.958	.935	.855	.906	.963	.997	1.000	1.000	1.000	1.000	1.000
J=21	*****	*****	*****	*****	*****	*****	*****	.959	.958	.913	.862	.920	.994	1.000	1.000	1.000	1.000	1.000
J=22	*****	*****	*****	*****	*****	*****	*****	.959	.959	.958	.870	.809	.967	.998	1.000	1.000	1.000	1.000
J=23	*****	*****	*****	*****	*****	*****	*****	*****	.958	.958	.908	.866	.940	.996	1.000	1.000	1.000	1.000
J=24	*****	*****	*****	*****	*****	*****	*****	*****	.959	.958	.935	.859	.920	.995	1.000	1.000	1.000	1.000
J=25	*****	*****	*****	*****	*****	*****	*****	*****	*****	.959	.952	.855	.908	.994	1.000	1.000	1.000	1.000
J=26	*****	*****	*****	*****	*****	*****	*****	*****	*****	.959	.958	.854	.904	.994	1.000	1.000	1.000	1.000
J=27	*****	*****	*****	*****	*****	*****	*****	*****	*****	.959	.952	.855	.908	.994	1.000	1.000	1.000	1.000
J=28	*****	*****	*****	*****	*****	*****	*****	*****	.958	.958	.935	.860	.920	.995	1.000	1.000	1.000	1.000
J=29	*****	*****	*****	*****	*****	*****	*****	*****	.958	.958	.906	.866	.940	.996	1.000	1.000	1.000	1.000
J=30	*****	*****	*****	*****	*****	*****	*****	.958	.959	.957	.869	.899	.967	.998	1.000	1.000	1.000	1.000
J=31	*****	*****	*****	*****	*****	*****	*****	.959	.958	.912	.862	.921	.954	1.000	1.000	1.000	1.000	1.000
J=32	*****	*****	*****	*****	*****	.958	.958	.958	.934	.854	.900	.963	.957	1.000	1.000	1.000	1.000	1.000
J=33	*****	*****	*****	.958	.958	.959	.958	.934	.848	.896	.941	.995	1.000	1.000	1.000	1.000	1.000	1.000
J=34	.959	.959	.958	.958	.958	.957	.912	.850	.806	.933	.994	.999	1.000	1.000	1.000	1.000	1.000	1.000
J=35	.951	.957	.941	.934	.906	.869	.863	.900	.940	.994	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=36	.856	.854	.856	.860	.867	.899	.921	.944	.955	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=37	.909	.905	.909	.921	.940	.967	.994	.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=38	.994	.994	.994	.995	.996	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=39	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=40	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Fig. 21 Map of Target Area Showing Fraction of Unburned Buildings at 1 Hour

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 6	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 9	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=11	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=12	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=13	.994	.994	.994	.995	.996	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=14	.872	.866	.871	.887	.913	.951	.994	.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=15	.112	.089	.109	.181	.325	.590	.879	.940	.905	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=16	.000	.000	.000	.000	.000	.065	.182	.553	.900	.980	.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=17	.000	.000	.000	.000	.000	.000	.000	.067	.349	.881	.974	.999	1.000	1.000	1.000	1.000	1.000	1.000
J=18	.000	.000	.000	.000	.000	.000	.000	.000	.052	.288	.885	.981	1.000	1.000	1.000	1.000	1.000	1.000
J=19	*****	*****	*****	.000	.000	.000	.000	.000	.000	.051	.350	.912	.997	1.000	1.000	1.000	1.000	1.000
J=20	*****	*****	*****	*****	*****	.000	.000	.000	.000	.000	.065	.562	.958	1.000	1.000	1.000	1.000	1.000
J=21	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.201	.904	.998	1.000	1.000	1.000	1.000
J=22	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.065	.608	.968	1.000	1.000	1.000	1.000
J=23	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.355	.945	1.000	1.000	1.000	1.000
J=24	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.204	.928	.999	1.000	1.000	1.000
J=25	*****	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.128	.918	.999	1.000	1.000	1.000
J=26	*****	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.167	.915	.999	1.000	1.000	1.000
J=27	*****	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.132	.919	.999	1.000	1.000	1.000
J=28	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.214	.930	.999	1.000	1.000	1.000
J=29	*****	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.374	.947	1.000	1.000	1.000	1.000
J=30	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.083	.637	.971	1.000	1.000	1.000	1.000
J=31	*****	*****	*****	*****	*****	*****	*****	.000	.000	.000	.000	.222	.925	.999	1.000	1.000	1.000	1.000
J=32	*****	*****	*****	*****	*****	.000	.000	.000	.000	.000	.092	.600	.962	1.000	1.000	1.000	1.000	1.000
J=33	*****	*****	*****	.000	.000	.000	.000	.000	.000	.069	.389	.936	.999	1.000	1.000	1.000	1.000	1.000
J=34	.000	.000	.000	.000	.000	.000	.000	.000	.070	.325	.924	.985	1.000	1.000	1.000	1.000	1.000	1.000
J=35	.000	.000	.000	.000	.000	.000	.000	.097	.390	.925	.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=36	.000	.000	.000	.000	.000	.092	.234	.603	.939	.985	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=37	.156	.128	.153	.234	.390	.642	.931	.965	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=38	.931	.927	.930	.939	.954	.974	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=39	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=40	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Fig. 22 Map of Target Area Showing Fraction of Unburned Buildings at 5 Hours

	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
J= 2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 3	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 4	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 5	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 6	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 7	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 8	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J= 9	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=10	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=11	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=12	.948	.987	.988	.989	.992	.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=13	.799	.789	.796	.817	.855	.913	.987	.994	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=14	.001	.001	.001	.002	.017	.245	.796	.894	.989	.998	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=15	.000	.000	.000	.000	.000	.000	.001	.158	.822	.961	.997	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=16	.000	.000	.000	.000	.000	.000	.000	.000	.005	.653	.948	.997	1.000	1.000	1.000	1.000	1.000	1.000
J=17	.000	.000	.000	.000	.000	.000	.000	.000	.000	.001	.575	.958	.999	1.000	1.000	1.000	1.000	1.000
J=18	.000	.100	.000	.000	.000	.000	.000	.000	.000	.000	.002	.668	.989	1.000	1.000	1.000	1.000	1.000
J=19	******	******	******	.000	.000	.000	.000	.000	.000	.000	.000	.022	.904	.998	1.000	1.000	1.000	1.000
J=20	******	******	******	******	******	.000	.000	.000	.000	.000	.000	.000	.410	.984	1.000	1.000	1.000	1.000
J=21	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.014	.920	.999	1.000	1.000	1.000
J=22	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.000	.545	.991	1.000	1.000	1.000
J=23	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.310	.984	1.000	1.000	1.000
J=24	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.177	.980	1.000	1.000	1.000
J=25	******	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.115	.978	1.000	1.000	1.000
J=26	******	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.100	.977	1.000	1.000	1.000
J=27	******	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.124	.978	1.000	1.000	1.000
J=28	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.201	.981	1.000	1.000	1.000
J=29	******	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.357	.986	1.000	1.000	1.000
J=30	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.000	.623	.992	1.000	1.000	1.000
J=31	******	******	******	******	******	******	******	.000	.000	.000	.000	.000	.175	.980	1.000	1.000	1.000	1.000
J=32	******	******	******	******	******	.000	.000	.000	.000	.000	.000	.000	.524	.990	1.000	1.000	1.000	1.000
J=33	******	******	******	.000	.000	.000	.000	.000	.000	.000	.000	.276	.983	1.000	1.000	1.000	1.000	1.000
J=34	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.178	.806	.956	1.000	1.000	1.000	1.000	1.000
J=35	.000	.000	.000	.000	.000	.000	.000	.000	.000	.188	.741	.995	1.000	1.000	1.000	1.000	1.000	1.000
J=36	.000	.000	.000	.000	.000	.000	.000	.000	.314	.810	.996	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=37	.000	.000	.000	.000	.000	.000	.247	.566	.991	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=38	.265	.234	.257	.330	.467	.683	.993	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=39	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
J=40	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

Fig. 23 Map of Target Area Showing Fraction of Unburned Buildings at 10 Hours

When the general fire spread characterization of the target area was developed, local areas were reexamined at differing building densities and with a variety of fire prevention and/or firefighting activities superimposed. In areas suffering moderate or negligible blast damage, the IITRI Fire Model was employed for the local areas as well as for the total target. Various studies were drawn on for treatment of local portions of the core area of severe blast damage (buildings demolished and scattered by blast). The following sections first describe the gross fire spread through the total target, and then successively treat local areas suffering negligible, moderate and severe blast.

6.3.1 Fire Spread In City

The TEAPOT HOUSE was considered to suffer blast damage as shown in Table 6, repeated below as Table 12.

TABLE 12. DAMAGE-DISTANCE CHARACTERIZATION FOR TEAPOT HOUSE

Damage Level	Peak Overpressure (psi)	Distance From Ground Zero (miles)
Severe (buildings destroyed)	>3.5	<3.6
Moderate (buildings standing with major wall/roof damage)	2 to 3.5	3 to 5.3
Negligible (broken windows or none)	<2	>5.3

Since the IITRI Fire Model was applied only to the regions of moderate and negligible damage, it addresses the region beyond 3.7 miles. Assuming ground zero to be at the center of one tract (0.5 x 0.5 miles), the first tract treated by the model (in the upwind, downwind or crosswind directions) is centered at 4 miles from ground zero. No fire spread of significance is considered to occur from the area of severe damage to the area of moderate damage; as, without standing buildings, the radiation levels are greatly reduced and the generation of firebrands low. This is in contrast to the high levels of radiation and high rates of firebrand generation within the moderately damaged area.

In examining the graphs to follow, it should be remembered that each tract is 0.5 x 0.5 miles; and, thus each tract center is 0.5 miles from the next (tracts are in rows parallel and perpendicular to the nominal wind directions--i.e., streets run north-south and east-west). Results for any tract are thus the average over a 0.5 mile distance from ground zero for tracts along or perpendicular to the nominal wind direction. To place the magnitude of building fires per tract in perspective, each tract with 15 percent building density, contains a total of 1193 buildings.

Figures 24, 25, and 26 describe the first 5 hours of fire development in the downwind, crosswind and upwind directions respectively. In each direction, fires develop most rapidly in the tracts centered at 5 miles from ground zero, due to the higher incidence of weapon caused ignitions at this distance. Only a slight influence of wind is seen during this first 5 hour period. Fires at 6 miles are increasing slightly faster in the downwind case. Fires at 4 miles are increasing slightly faster in the upwind case ("4 miles" is downwind of "5 miles" for the tracts upwind of ground zero). In all cases, the active fires at 5 miles decrease sharply at 5 hours since almost all buildings in the 5 mile tracts are already consumed.

Fire spread in the 6 to 10 hour time period is depicted in Figures 27, 28 and 29 for downwind, crosswind, and upwind fire spread, respectively. Here, the tracts at 6.5 miles from ground zero clearly show the effects of wind. The tracts at 4 and 4.5 miles from ground zero show less fires upwind or ground zero because there are less buildings left to burn. By 10 hours, upwind fire spread has ceased, crosswind spread is developing very slowly in the 6.5 mile tract, and downwind spread shows some fire development in the 7 mile tract. The fact that fire spread within tracts is faster that that between tracts is clearly evidenced by examining the rate of fire development at 6 miles relative to the growth at (spread to) 6.5 mile tracts. The rapid fire growth within tracts is attributable to the ease of radiation fire spread across the smaller separation distances.

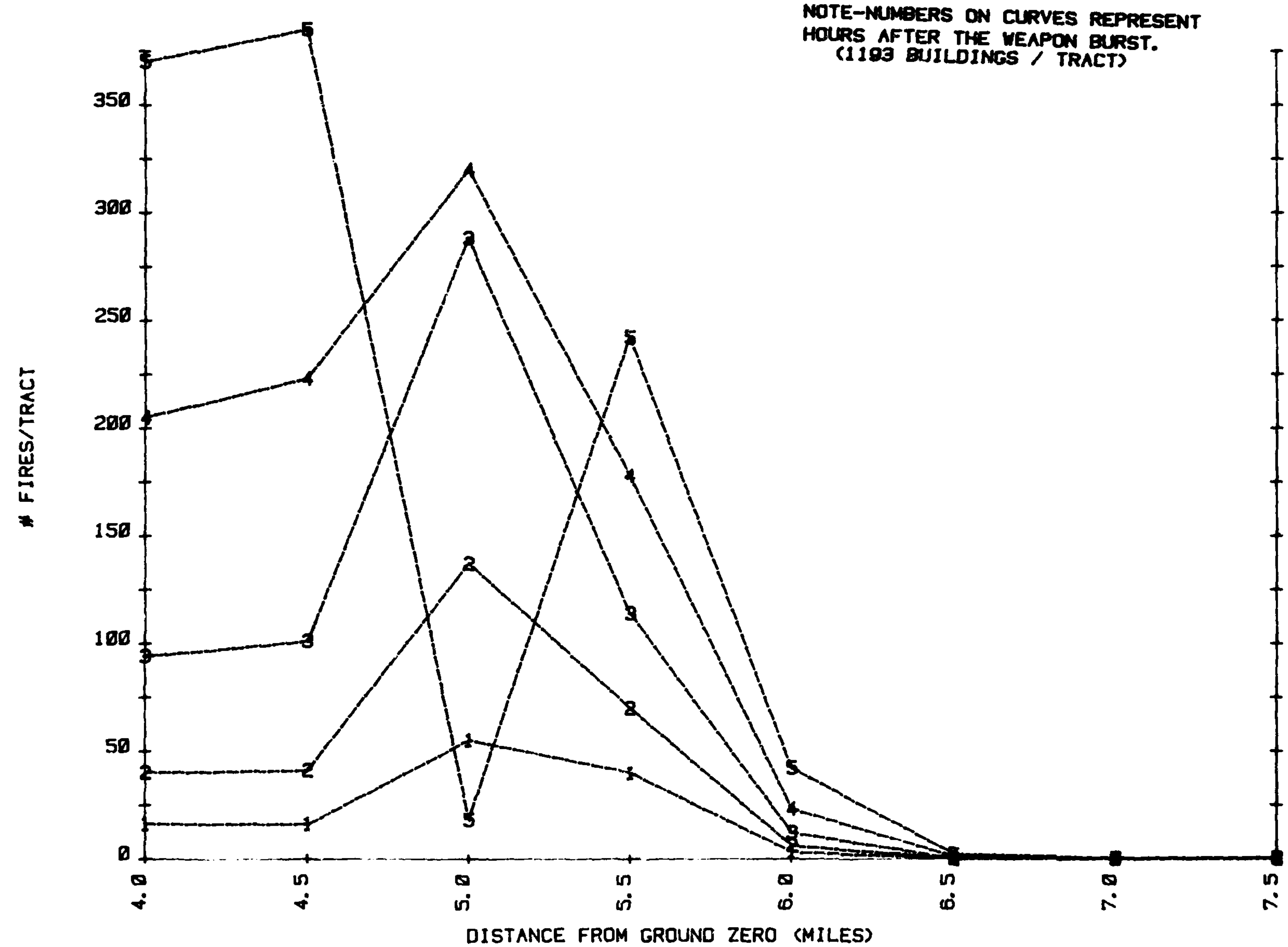


FIG. 24 FIRE SPREAD IN CITY - DOWNWIND [0-5 HRS]

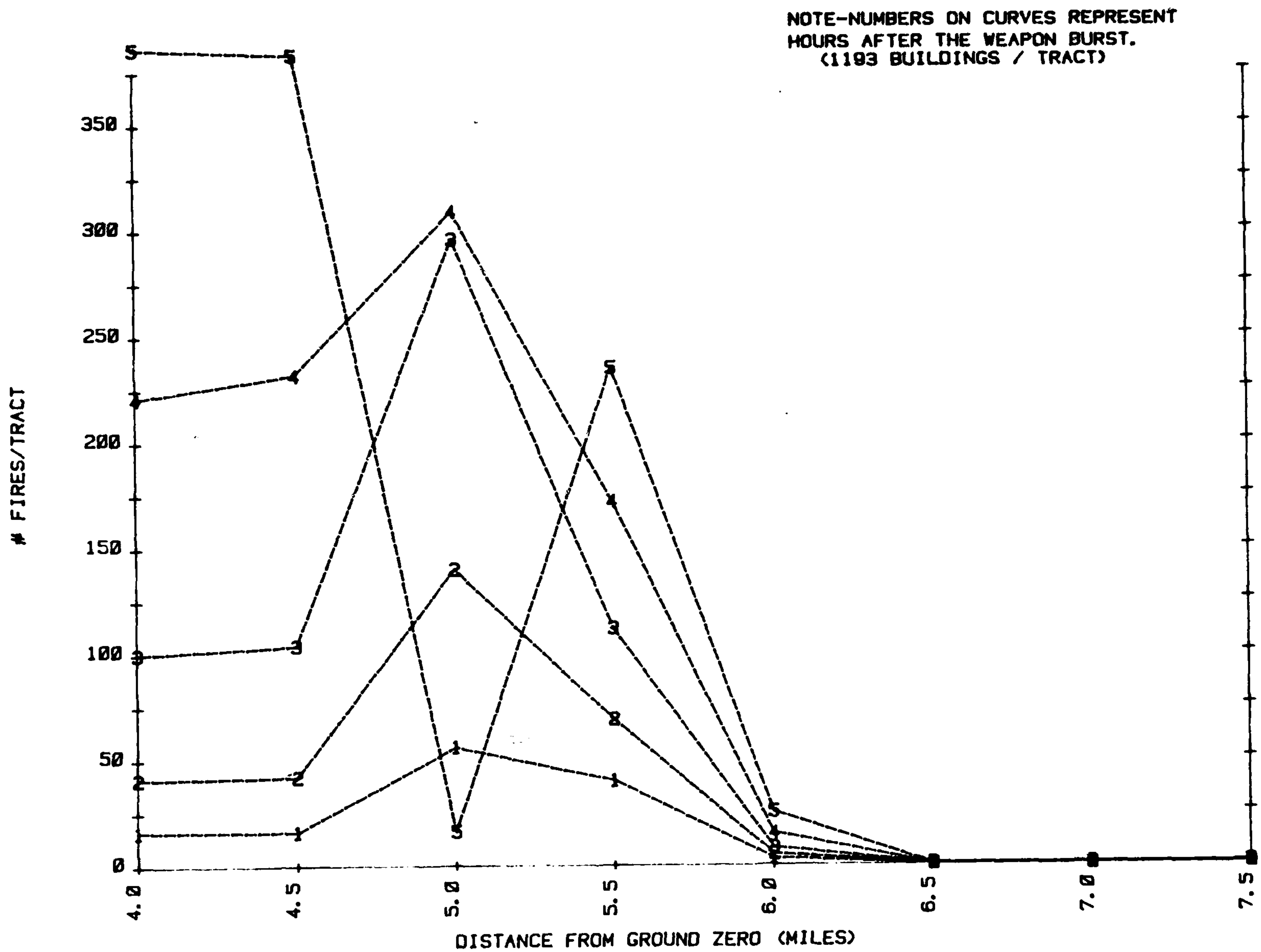


FIG. 25 FIRE SPREAD IN CITY - CROSSWIND [0-5 HRS]

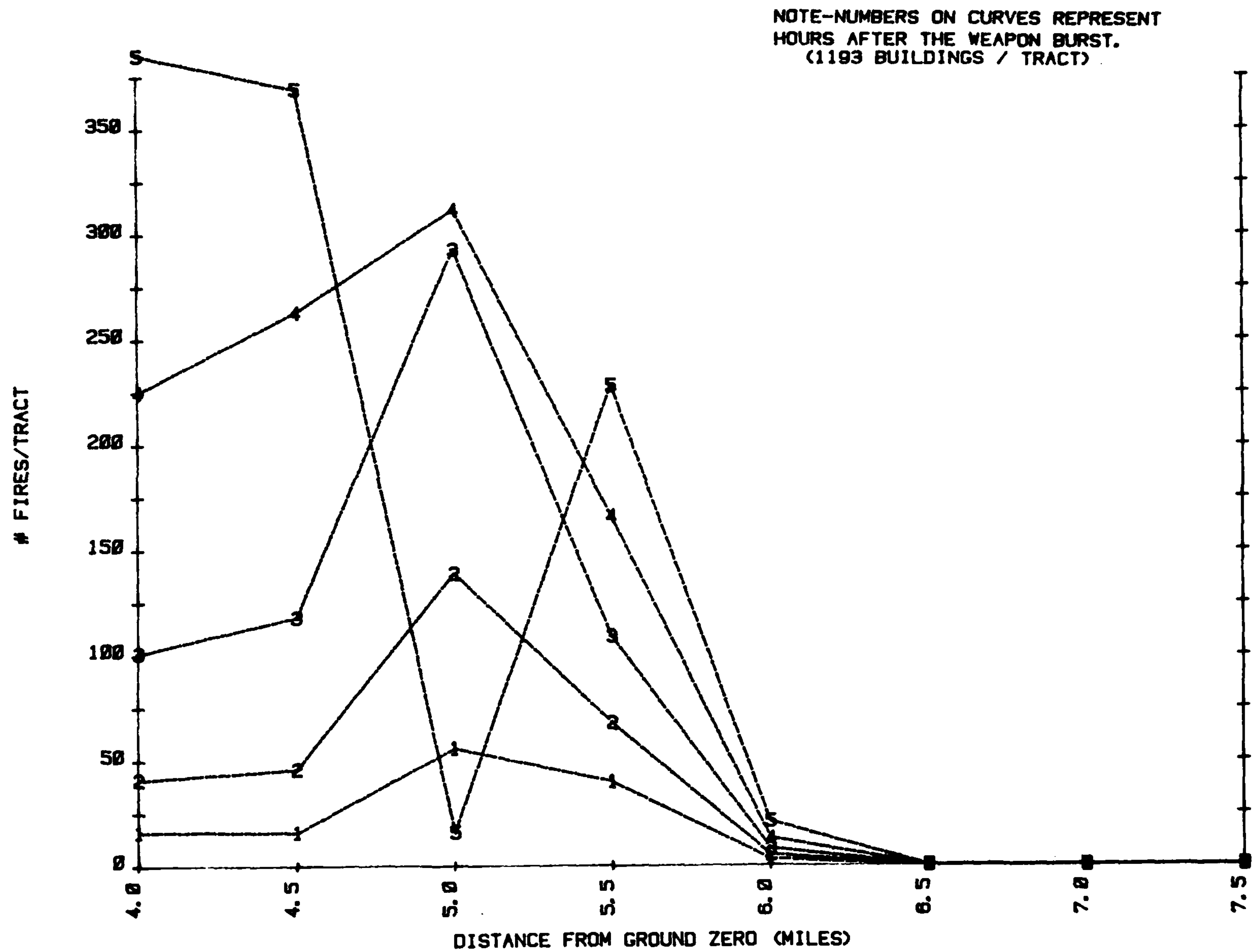


FIG. 26 FIRE SPREAD IN CITY - UPWIND [0-5 HRS]

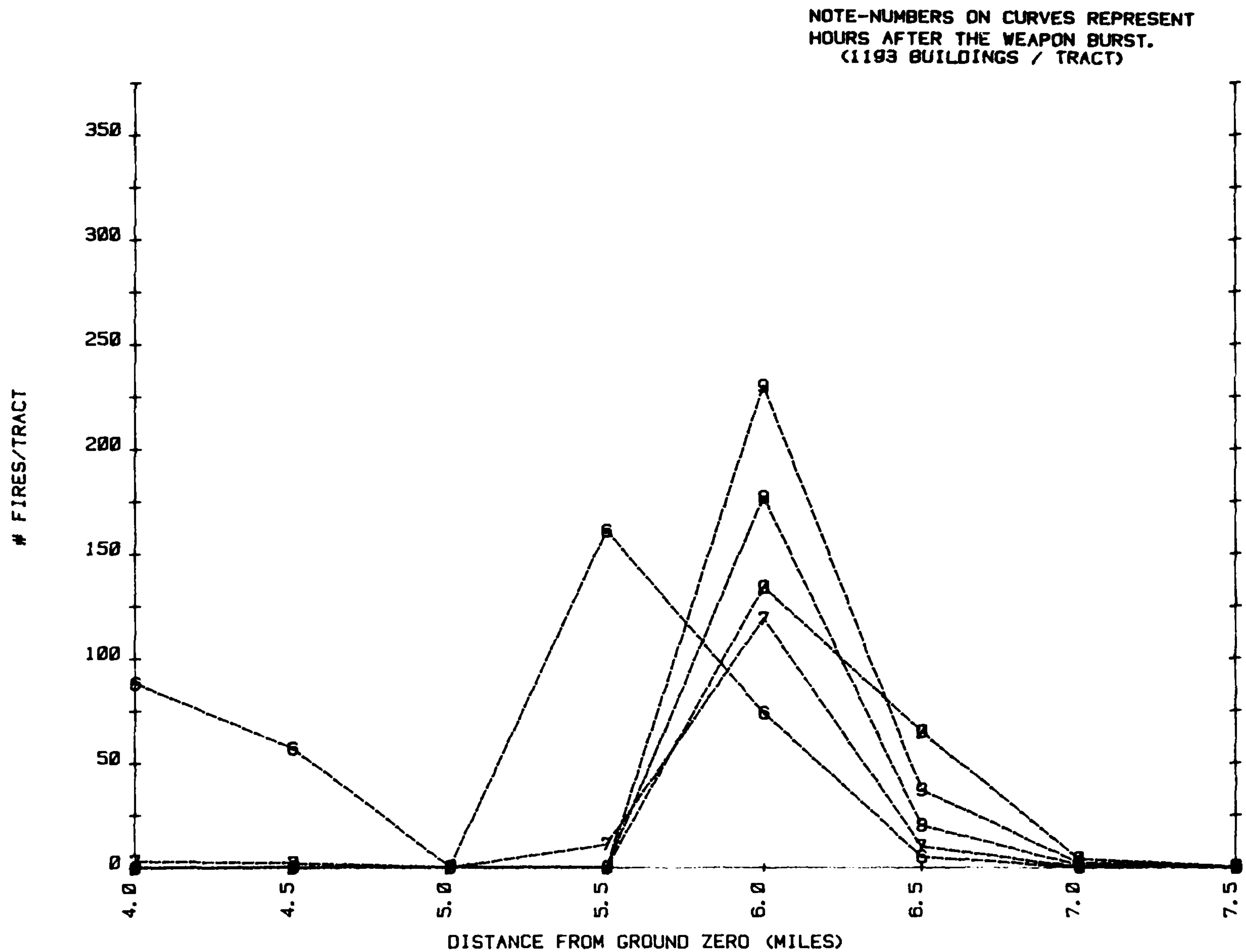


FIG. 27 FIRE SPREAD IN CITY - DOWNWIND [6-10 HRS]

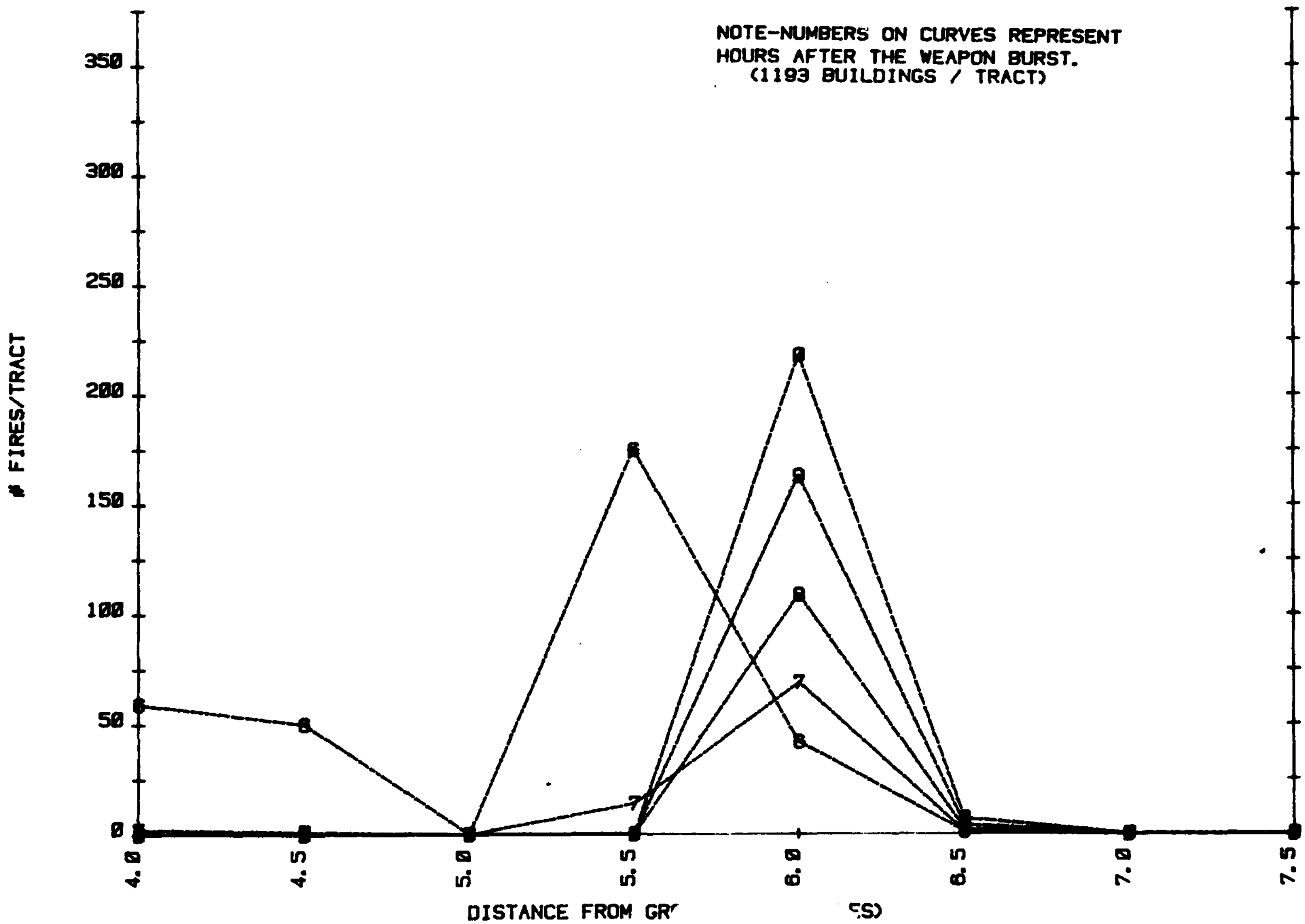


FIG. 28 FIRE SPREAD IN C1.(- CROSSWIND [6-10 HRS]

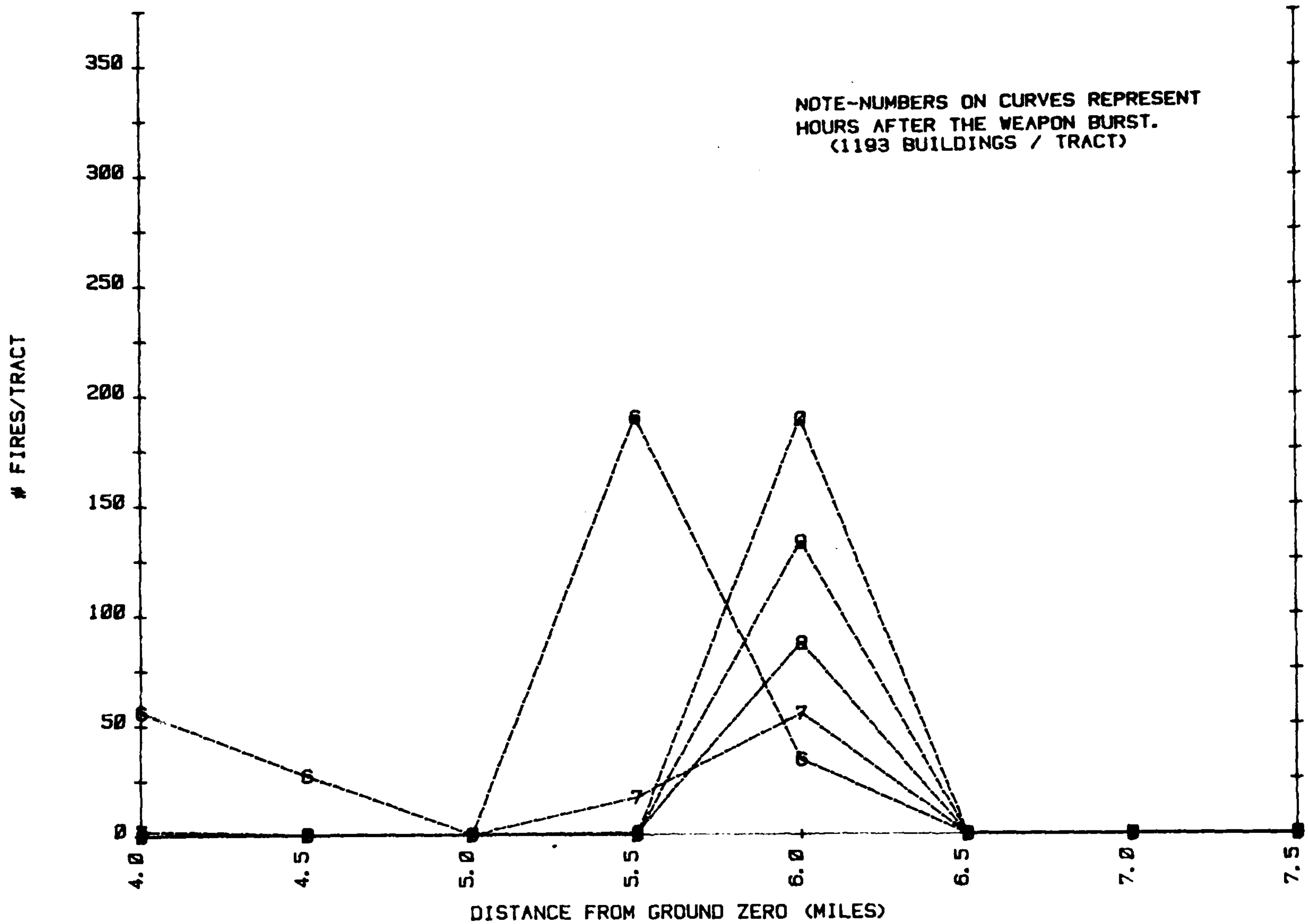


FIG. 29 FIRE SPREAD IN CITY - UPWIND [6-10 HRS]

6.3.2 Selection of Local Areas and Conditions for Further Study

Due to the relatively small effects of wind on fire development, local tracts for further study were selected in the region downwind of ground zero. Figure 30 is presented to identify those tracts studied as local areas of differing buildings density with fire prevention and/or firefighting activities included. Figure 30 represents a portion of the northeast sector from ground zero (north being the downwind direction). Each tract, as shown in the figure, is assigned a number identifier that indicates its tract order to the east of an arbitrary north-south line; and, to the south of an arbitrary east-west line. Coordinates were chosen such that ground zero is centered on tract 3, 26.

For calculation purposes, tracts were considered to be wholly of a single level of blast damage. For this purpose, each tract was assigned the damage level representing the majority of its area. Tract damage assignments are indicated in Figure 30. Tracts selected for further study are 5, 14; 6, 15; 4, 16; 5, 18; and 4, 21. All but tract 4, 21 is in the severe damage region and thus was not amenable to the Model's calculation techniques. Each tract was examined at a building density of 5 percent and 15 percent except tract 5, 18 which was only examined at 15 percent building density. For all tracts in the moderate and negligible blast damage regions, a series of 12 fire prevention/firefighting efforts were explored. These 12 cases are described in Table 13 where:

A = percent of ignitions prevented (preattack measures)

B = minimum number of fires extinguished per 15 minute period

C = percent of active fires extinguished per 15 minute period

D = maximum number of fires extinguished per 15 minute period

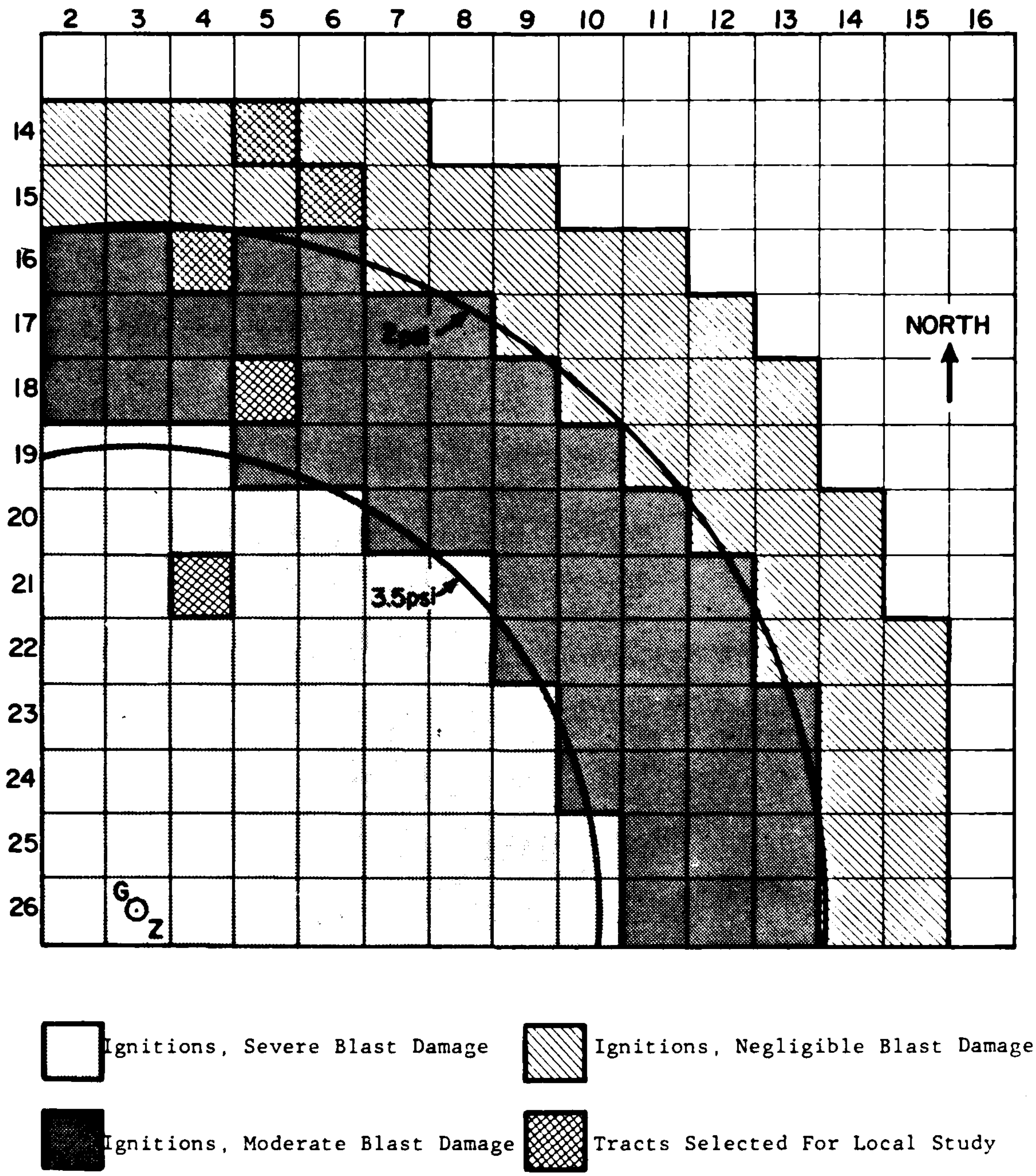


Fig. 30 Northeast Section of Target Area Showing Tract Designation, Tract Blast Damage Assignments, and Tracts Selected for Further Study on a Local Basis

That is, "A" percent of weapon ignitions were considered prevented; and, in any given 15 minute period, firefighting put out (or prevented). "C" percent of the active fires in a tract with an upper limit of "D" fires and a lower limit of "B" fires. Using these descriptions, the 12 cases studied for each tract/building density combination are shown.

TABLE 13. FIRE PREVENTION AND FIREFIGHTING ACTIVITIES

Case	Symbol*	A	B	C	D
1	1	0	0	0	0
2	2	0	0	20	5
3	3	0	0	20	15
4	4	0	0	10	5
5	5	0	1	10	5
6	6	0	5	20	15
7	7	0	5	100	5
8	8	90	1	10	5
9	9	50	5	20	15
10	Ø	50	1	10	5
11	+	90	0	0	0
12	*	95	0	0	0

*Symbols used on graphs to follow. Note that Table 13 is repeated as a foldout to permit its use with the following graphs.

Case 1 is provided to show fire spread when no fire prevention or firefighting occurs. Thus, it serves as a "worst case"; and, as a baseline study. Cases 11 and 12 indicate high efficiencies of fire prevention but no firefighting. Cases 3 to 7 have no fire prevention efforts; and a variety of firefighting efforts. Each represents a differing number of firefighting teams per tract (it may require more teams to do the same job in the blast damaged area). Setting a minimum firefighting effort for cases 5 and 6 was done to examine the importance, if any, of continued firefighting efforts in periods of few fires. Case 7 sets firefighting at a constant value of five fires per 15 minute period.

TABLE 13 (repeated). FIRE PREVENTION AND FIREFIGHTING ACTIVITIES

Case	Graph Symbol	A (percent weapon ignitions prevented)	B (minimum fires suppressed each 15 min)	C (percent of active fires suppressed each 15 min)	D (maximum fires suppressed each 15 min)
1	1	0	0	0	0
2	2	0	0	20	5
3	3	0	0	20	15
4	4	0	0	10	5
5	5	0	1	10	5
6	6	0	5	20	15
7	7	0	5	100	5
8	8	90	1	10	5
9	9	50	5	20	15
10	Ø	50	1	10	5
11	+	90	0	0	0
12	*	95	0	0	0

An indication of firefighting teams performance is provided by Salzberg et al, (Ref. 57) who described firefighting requirements to suppress all incipient fires prior to major building involvement (fires limited to one or two rooms). These requirements are presented as various combinations of self-help and brigade teams per weapon ignition, depicted graphically in Figure 31.

Cases 8 to 10 include both fire prevention and firefighting efforts. Cases 9 and 10 indicate the effect of changing level of firefighting under 50 percent ignition prevention (and can be contrasted to cases 5 and 6). Cases 8 and 10 can be combined with case 5 to indicate the effects of varying fire prevention levels supported by moderate firefighting activities. Thus a wide variety of fire prevention and firefighting efforts were studied singly and in combination.

6.3.3 Local Fire Development in Areas of Minimal Blast Damage

Tracts 5, 14 and 6, 15 were selected for further study as areas suffering little or no blast damage apart from broken windows. Tract 6, 15 lies adjacent to the area of moderate blast damage and has frequent weapon ignitions. Tract 5, 14 lies wholly within the undamaged area and receives few weapon ignitions. Both tracts were examined for building densities of 5 and 15 percent, for all 12 fire prevention/firefighting situations.

Tract 5, 14; No Blast Damage, Few Weapon Ignitions

Results are presented in Figures 32, 33, 34 and 35. As shown by Figure 32 (curve 1), the tract with 15 percent building density, even with limited ignitions, gradually develops in fire intensity until, at 9:15, almost 20 percent of the total tract buildings (230 out of 1193 buildings) are simultaneously burning, and the majority of the tract has been consumed. In the tract of lower, 5 percent, building density (nominally a more promising site for survival), fire frequency is still rising at 10 hours with about 10 percent of the total tract buildings burning simultaneously (Figure 34, curve 1). While this represents ($\frac{10}{20} \times \frac{5}{15} =$) 1/6 the number of fires per block compared to the higher density tract, it represents an unsatisfactory situation.

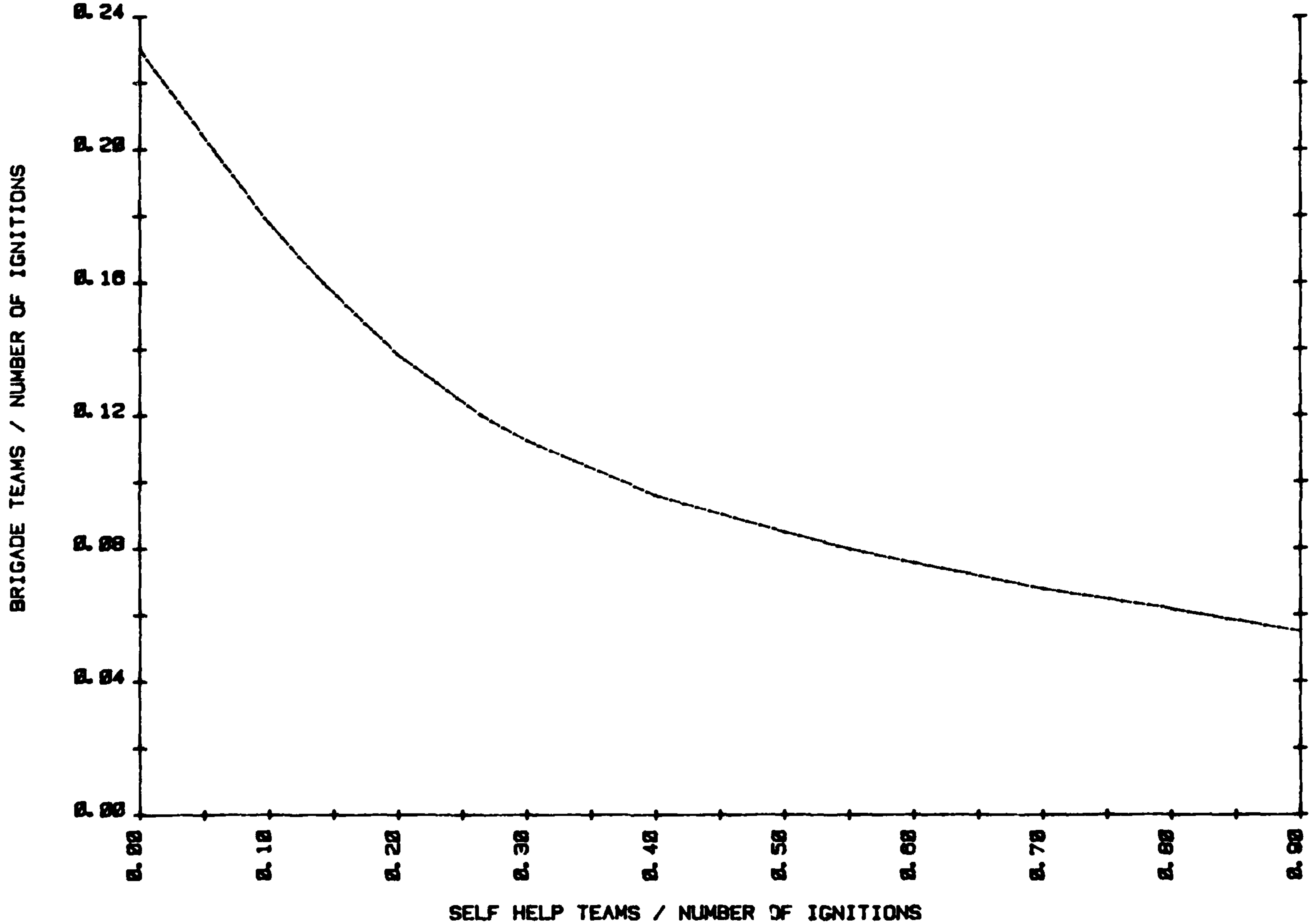
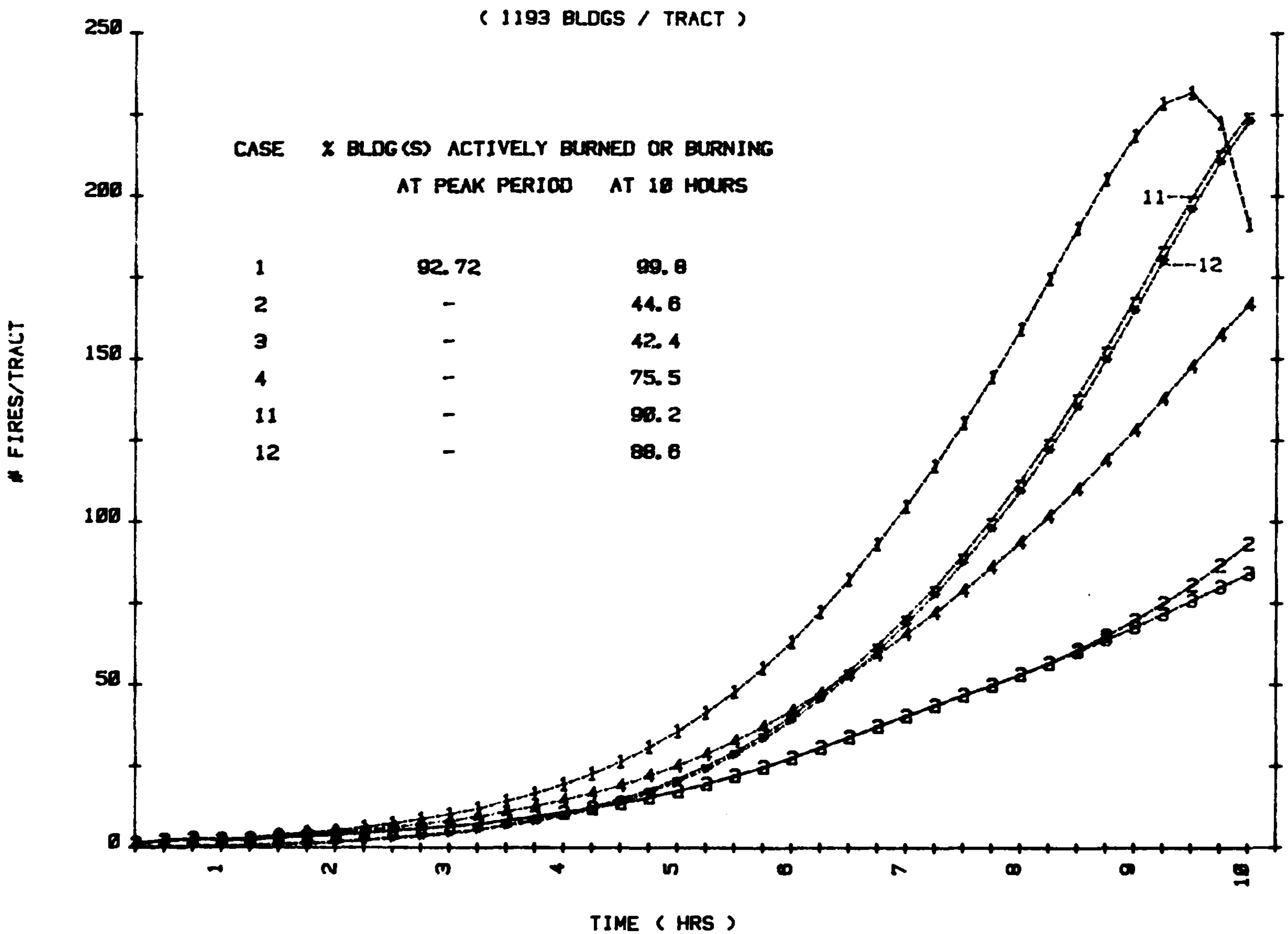


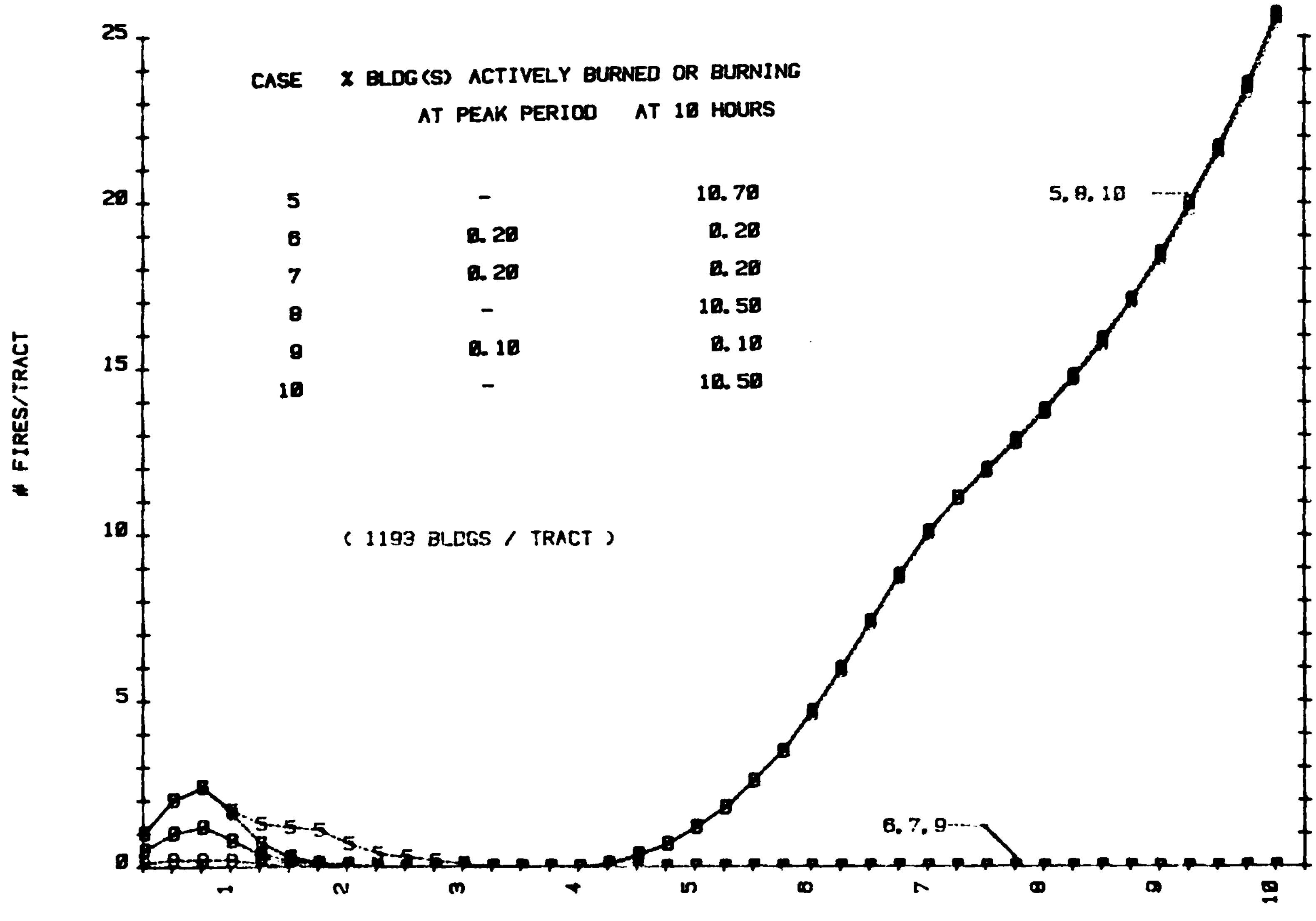
FIG. 31 NUMBER OF BRIGADE TEAMS VS. SELF-HELP TEAMS REQUIRED TO SUPPRESS ALL INCIPIENT FIRES (REF. 27)



CASE	% BLDG(S) ACTIVELY BURNED OR BURNING AT PEAK PERIOD	AT 10 HOURS
1	92.72	99.8
2	-	44.6
3	-	42.4
4	-	75.5
11	-	90.2
12	-	88.6

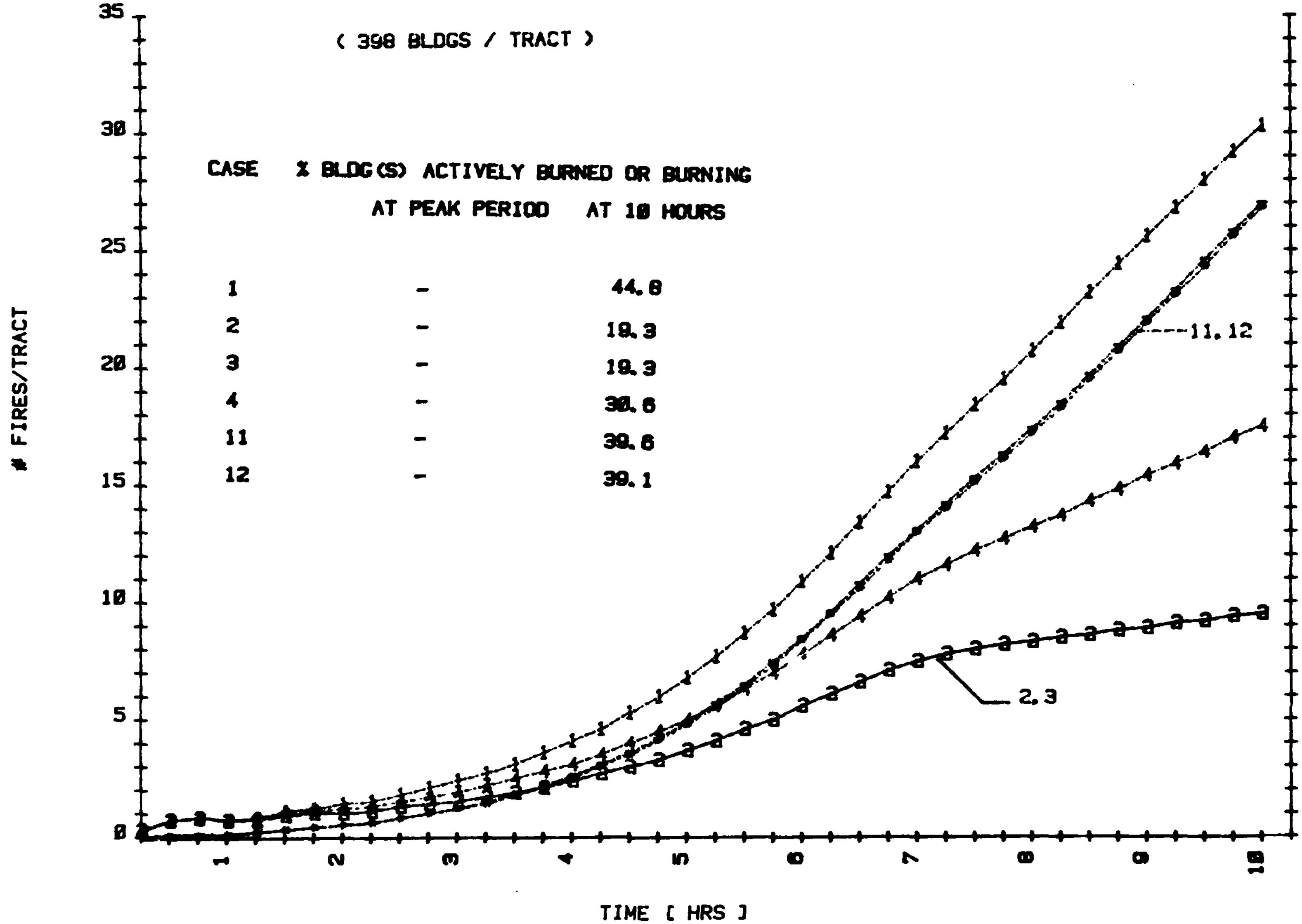
STAGE 3 FIRES IN TRACT 5.14 (NO BLAST DAMAGE); BLDG. DEN. =.15

FIG. 32



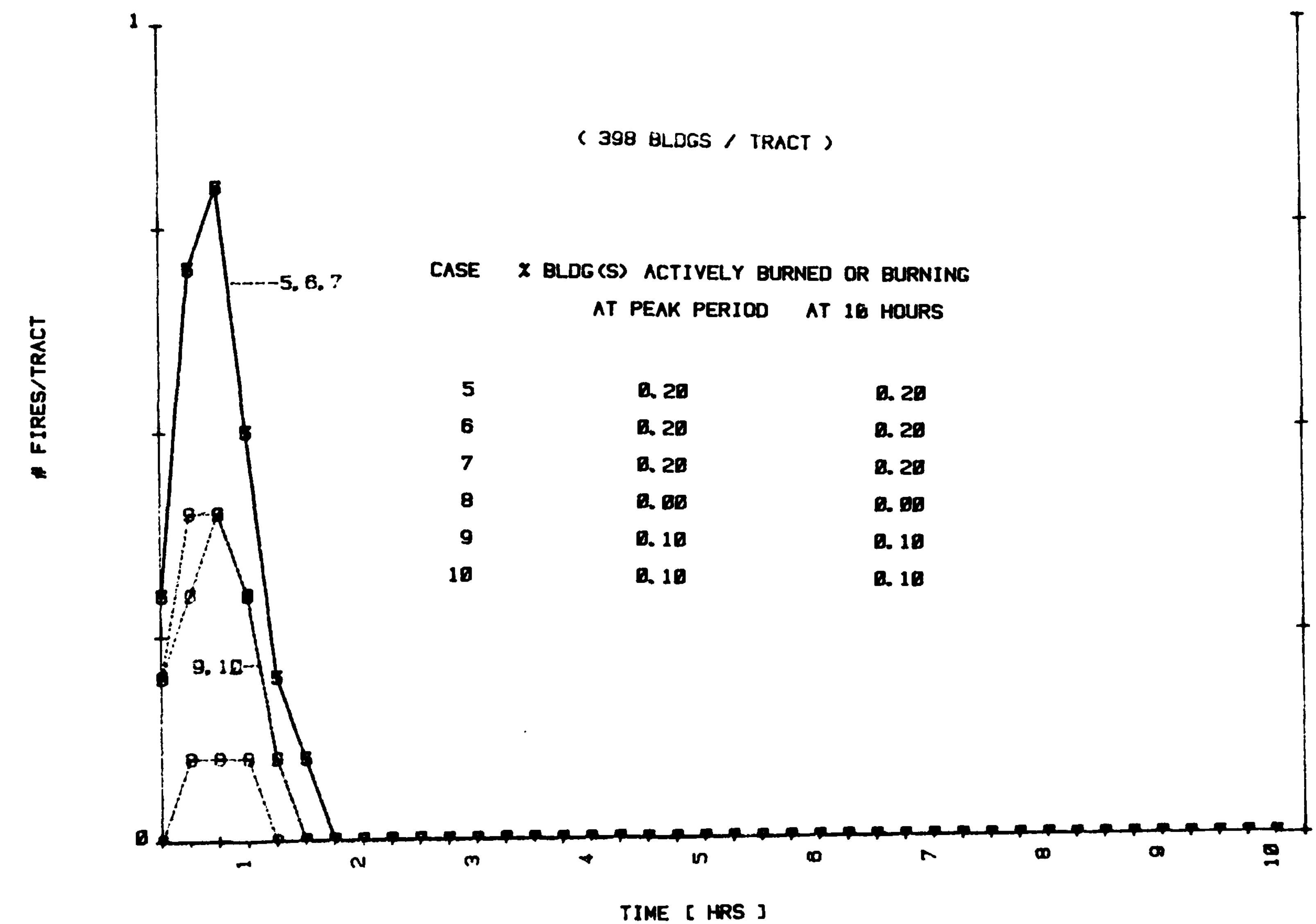
STAGE 3 FIRES IN TRACT 5.14 (NO BLAST DAMAGE); BLDG. DEN. =.15

FIG. 33



STAGE 3 FIRES IN TRACT 5.14 (NO BLAST DAMAGE): BLDG. DEN. =.05

FIG. 34



STAGE 3 FIRES IN TRACT 5.14 (NO BLAST DAMAGE); BLGD. DEN. =.05

FIG. 35

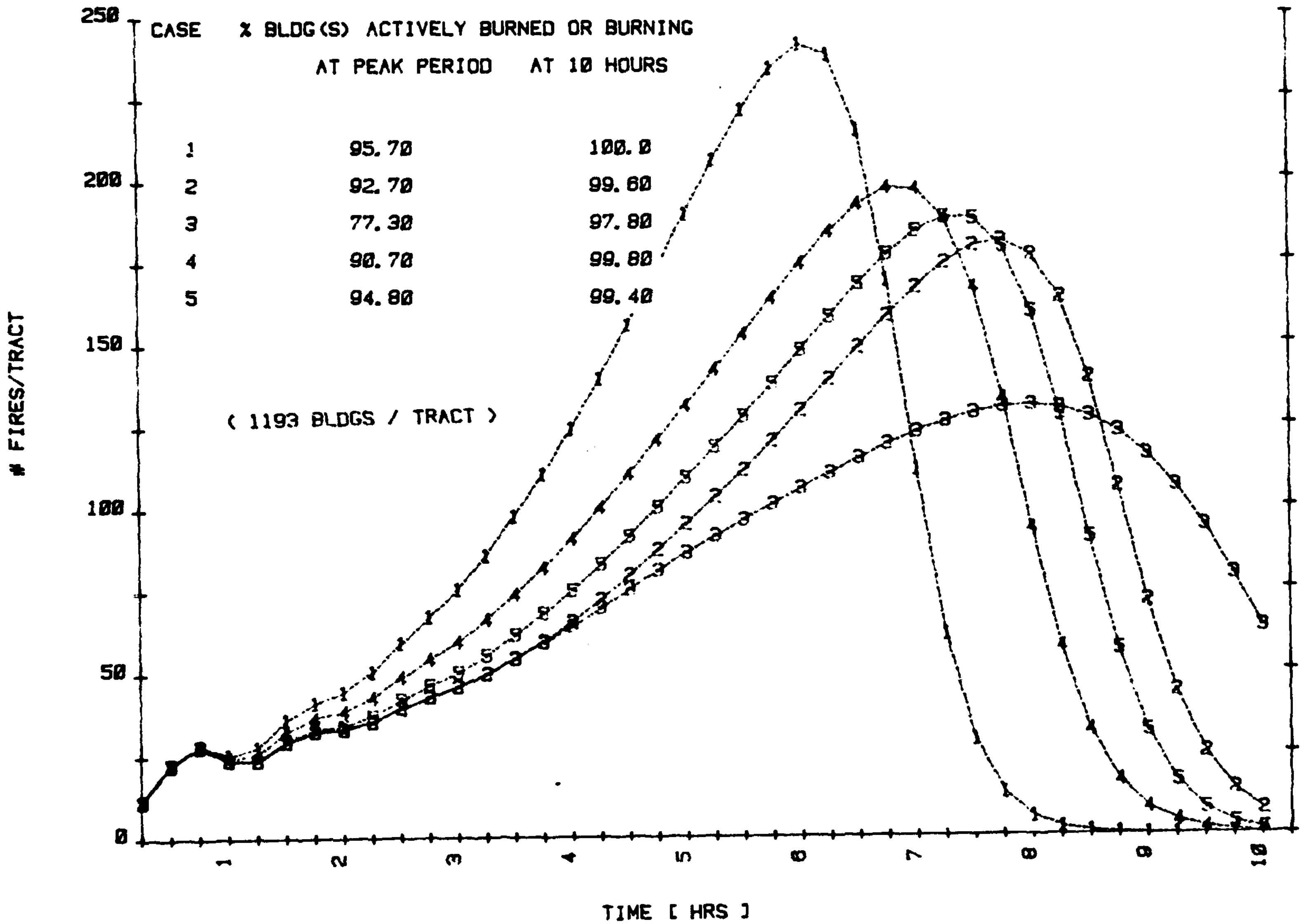
The continuing rise at 10 hours indicates that, again, most if not all of the tract will eventually burn if no firefighting action is taken. As shown by cases (curves) 11 and 12 of Figures 32 and 34, fire prevention efforts alone only delay the consequences of fire for about a period of 1 hour.

For the tract of 15 percent building density, a minimum firefighting effort of 5 suppressions every 15 minutes is required to effect permanent control (Figure 33, curves 6, 7, 9); although moderate firefighting (10%) with a minimum suppression of one fire every 15 minutes delays the initiation of rapid fire development for about 5 hours (Figure 33, curves 5, 8, 10), growing to 2 percent of buildings active burning at 10 hours; and still growing. For the low building density tract, a moderate firefighting effort (10%) offers control (Figure 35) as long as a minimum of one fire per 15 minute period is suppressed (Figure 35, curve 5 vs Figure 34, curve 4).

Tract 6, 15; No Blast Damage, Frequent Weapon Ignitions

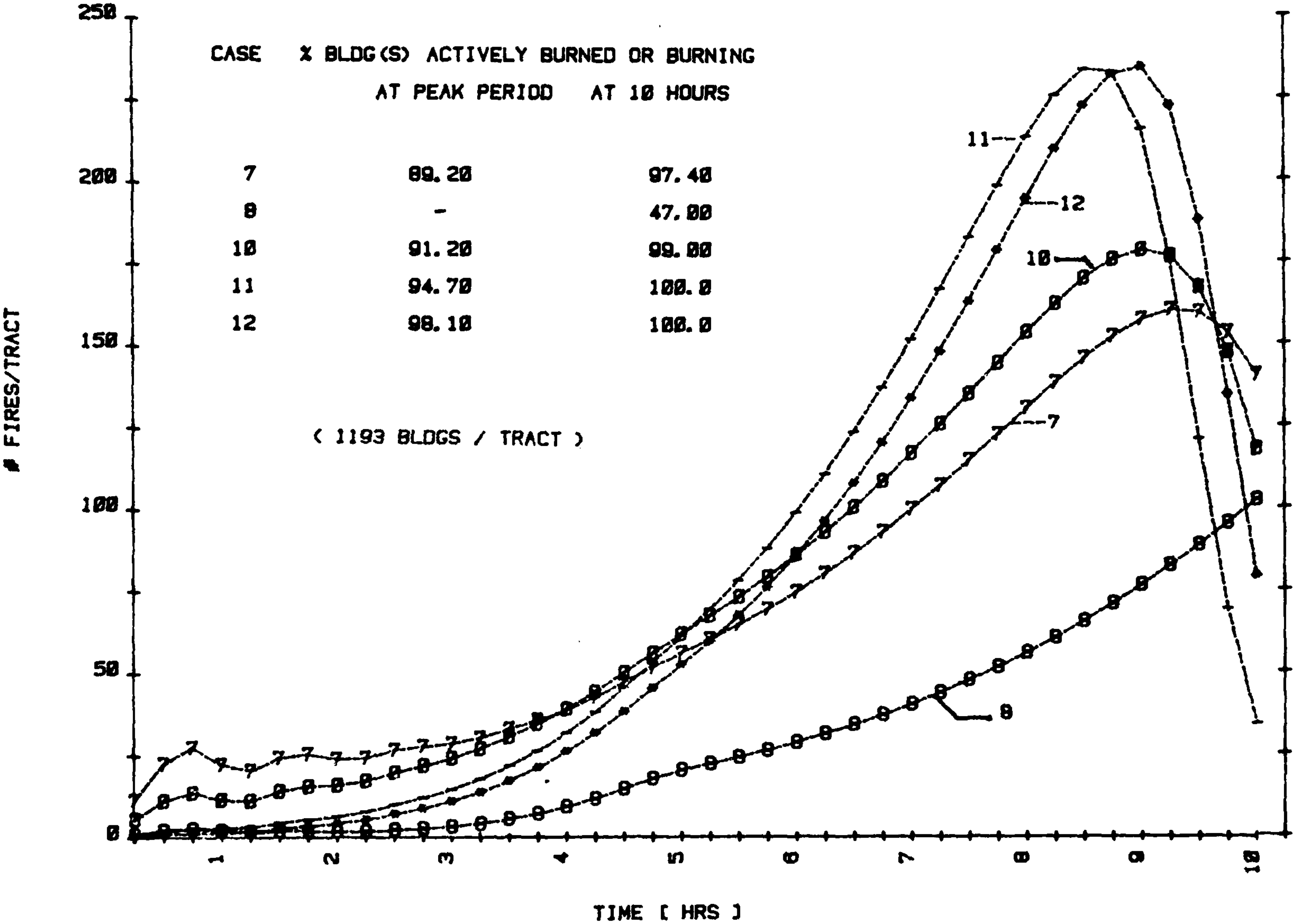
Results are presented in Figures 36 through 41. Figure 36 indicates that the high building density version of this tract, without fire prevention or firefighting, reaches a peak fire intensity of about 20 percent of all tract buildings simultaneously burning at about 5-3/4 hours with most of the remaining buildings already burned. Fire prevention alone, delays the peak several hours; but, is otherwise ineffective (Figure 37, curves 11, 12). The lower (building) density tract peaks at about 7 hours without prevention or suppression efforts, with some 9.4 percent of the total buildings simultaneously aflame (Figure 39, curve 1). Again, fire prevention efforts alone result in only a delay of several hours to a similar peak fire (Figure 40, curves 11, 12).

For the high building density tract, massive firefighting efforts are required to provide limited fire spread (Figure 38, curve 6); and, with fire prevention added, a definite benefit is gained (Figure 38, curve 9). All lesser combinations of fire prevention and firefighting allow substantial fire development with, for the most part, only marginal time delays (Figures 36, 37).



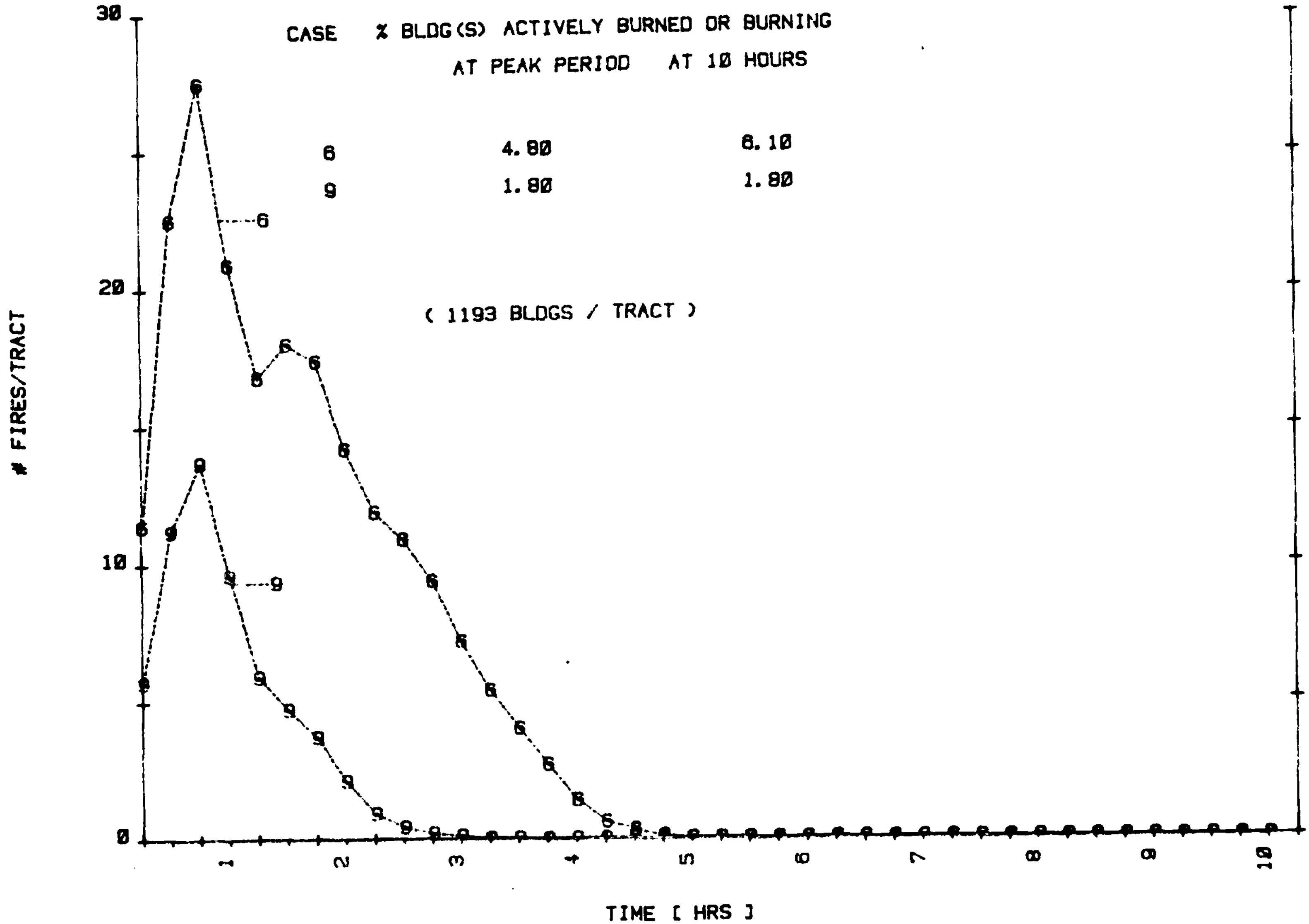
STAGE 3 FIRES IN TRACT 6.15 (NO BLAST DAMAGE); BLDG. DEN.=.15

FIG. 36



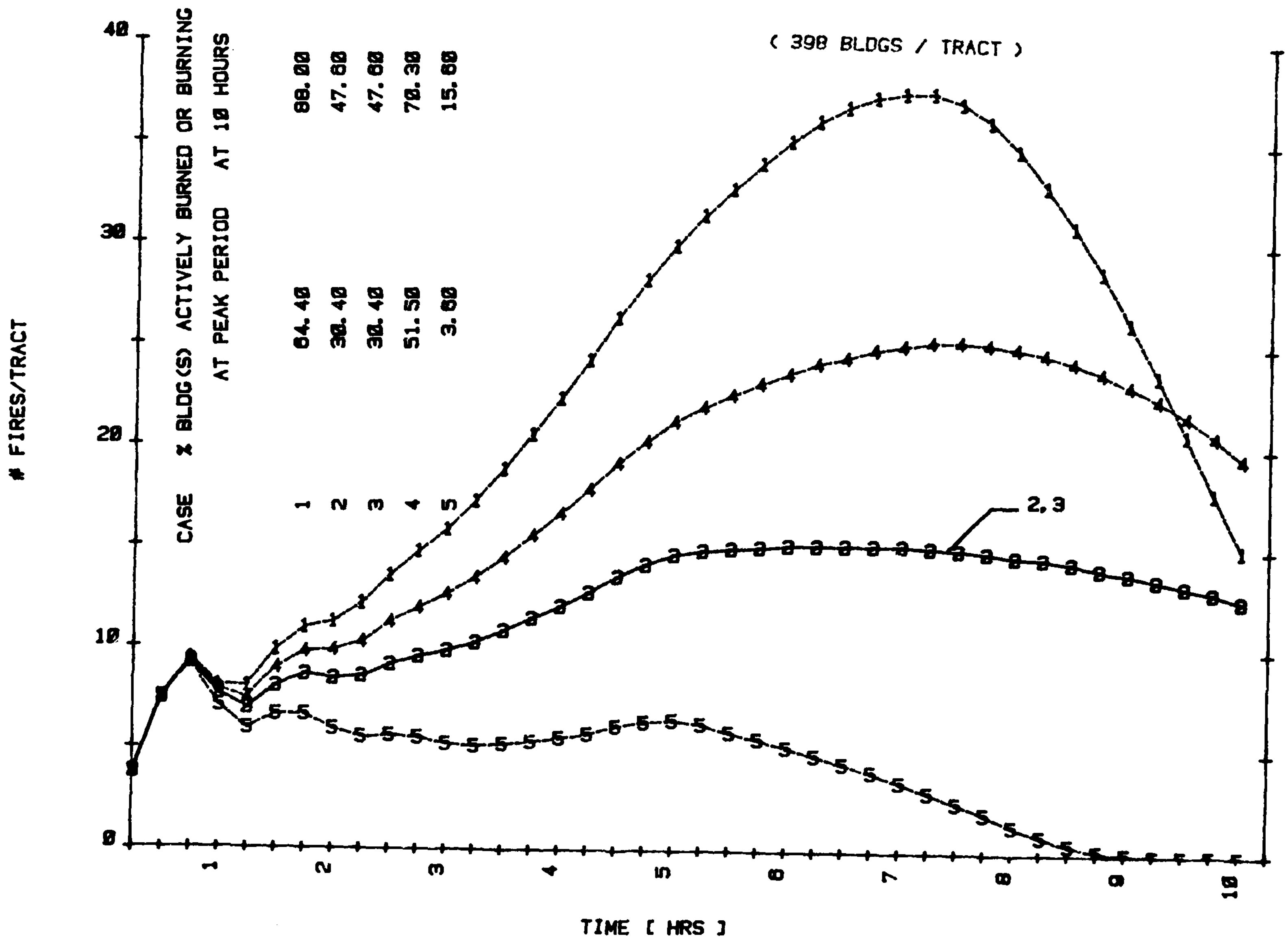
STAGE 3 FIRES IN TRACT 6, 15 (NO BLAST DAMAGE); BLDG. DEN. =. 15

FIG. 37



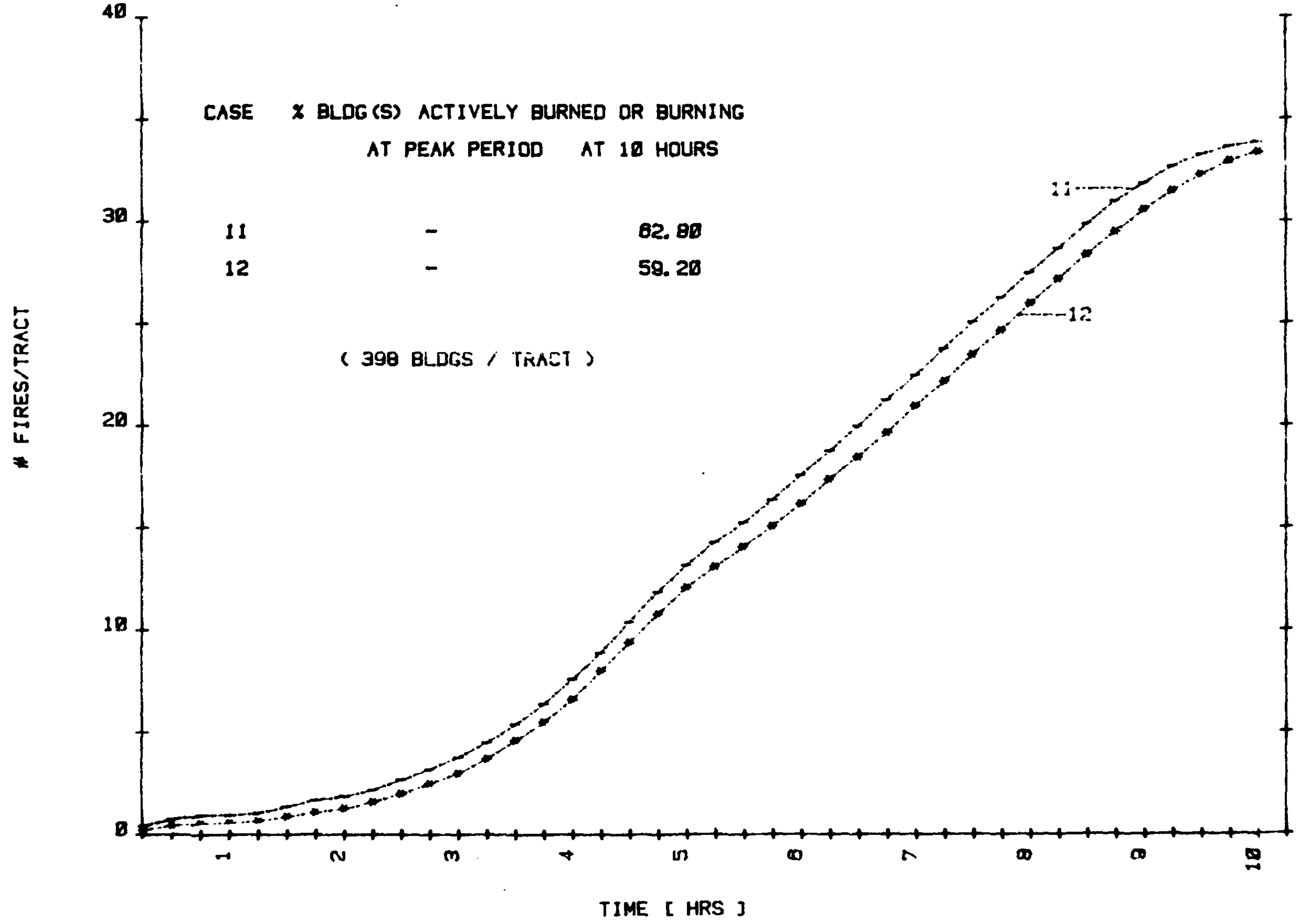
STAGE 3 FIRES IN TRACT 6.15 (NO BLAST DAMAGE); BLDG. DEN. =.15

FIG. 38



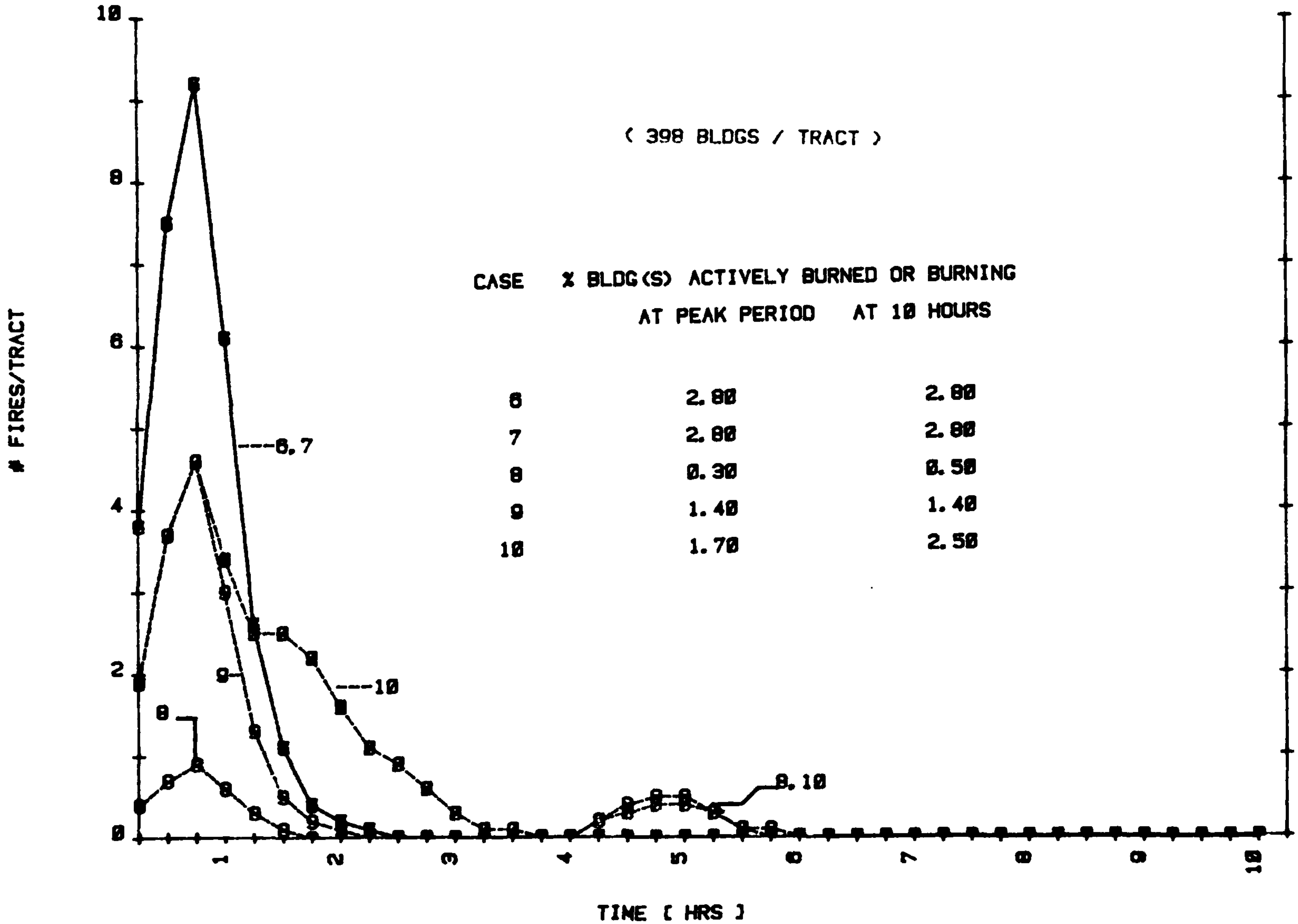
STAGE 3 FIRES IN TRACT 6,15 (NO BLAST DAMAGE); BLDG. DEN.=.05

FIG. 39



STAGE 3 FIRES IN TRACT 6.15 (NO BLAST DAMAGE); BLDG. DEN. =.05

FIG. 40



STAGE 3 FIRES IN TRACT 6,15 (NO BLAST DAMAGE); BLDG. DEN.=.05

FIG. 41

The low density tract is just barely controlled with moderate (10%) firefighting (Figure 39, curve 5); and, the minimum of one fire suppression per 15 minutes is required (compare curves 4 and 5 of Figure 39). Increases in fire suppression or the addition of fire prevention measures provide added benefit (all curves, Figure 41).

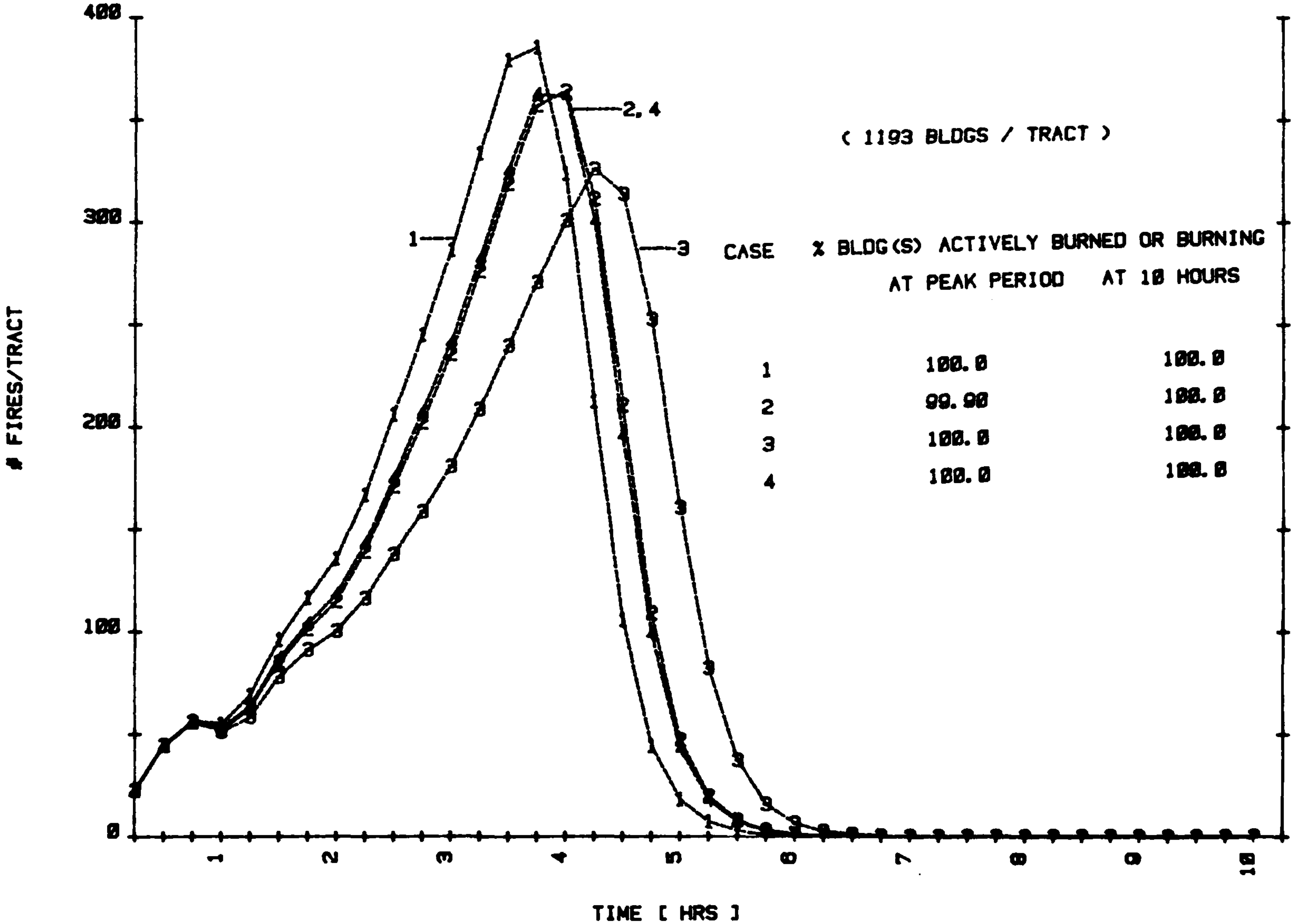
6.3.4 Local Fire Development in Areas of Moderate Blast Damage

Tracts 4, 16 and 5, 18 were selected for further study in the area suffering moderate blast damage. Tract 4, 16 lies nearer the outer bound of this region but has the greater weapon ignition frequency since overpressures at tract 5, 18 put out more fires (0.045 fires per building in tract 4, 16; 0.016 fires per building in tract 5, 18). Tract 5, 18 was examined at building densities of both 5 and 15 percent of ground area. Tract 4, 16 was examined at 5 percent building density only. All 12 fire prevention/fire-fighting levels of effort may require slightly larger numbers of brigades and self-help teams due to scattering of debris in this region, particularly in tract 5, 18.

Tract 4, 16; Moderate Blast Damage; Frequent Weapon Ignitions

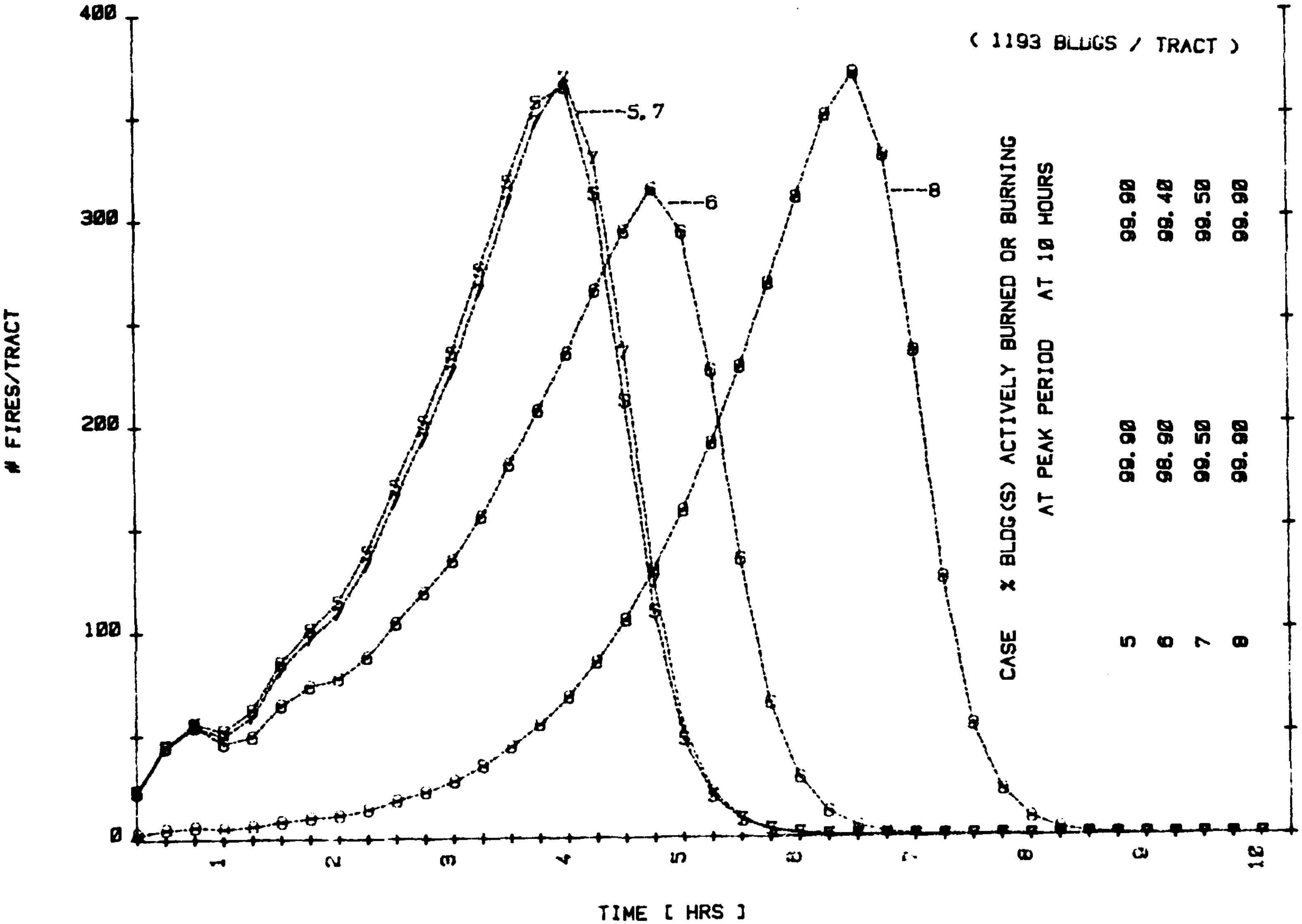
Results are presented in Figures 42 through 47. As shown in Figure 42 (curve 1), the decreased compartmentation of these blast damaged structures have lead to increased rates of fire spread, producing a peak fire (without fire prevention or firefighting efforts) in about 3½ hours involving the simultaneous burning of over 30 percent of all buildings in the tract, with the majority of other buildings already burned. As shown by Figures 42, 43, and 44 none of the various combinations of fire prevention and/or firefighting activities prevented similar results from occurring, although several combinations produce several hours delay to peak fire.

In the low density (5%) tract without fire prevention or fire-fighting efforts, peak fire conditions also were quickly achieved (about 4 hours) with about 24 percent of all structures simultaneously aflame (Figure 45, curve 1). As shown on Figure 46, massive (20%) firefighting efforts were required for control (Figure 46, curves 6 and 9). Also, the somewhat academic case of constant suppression of 5 fires each 15 minutes produced (barely) success (Figure 46, curve 7).



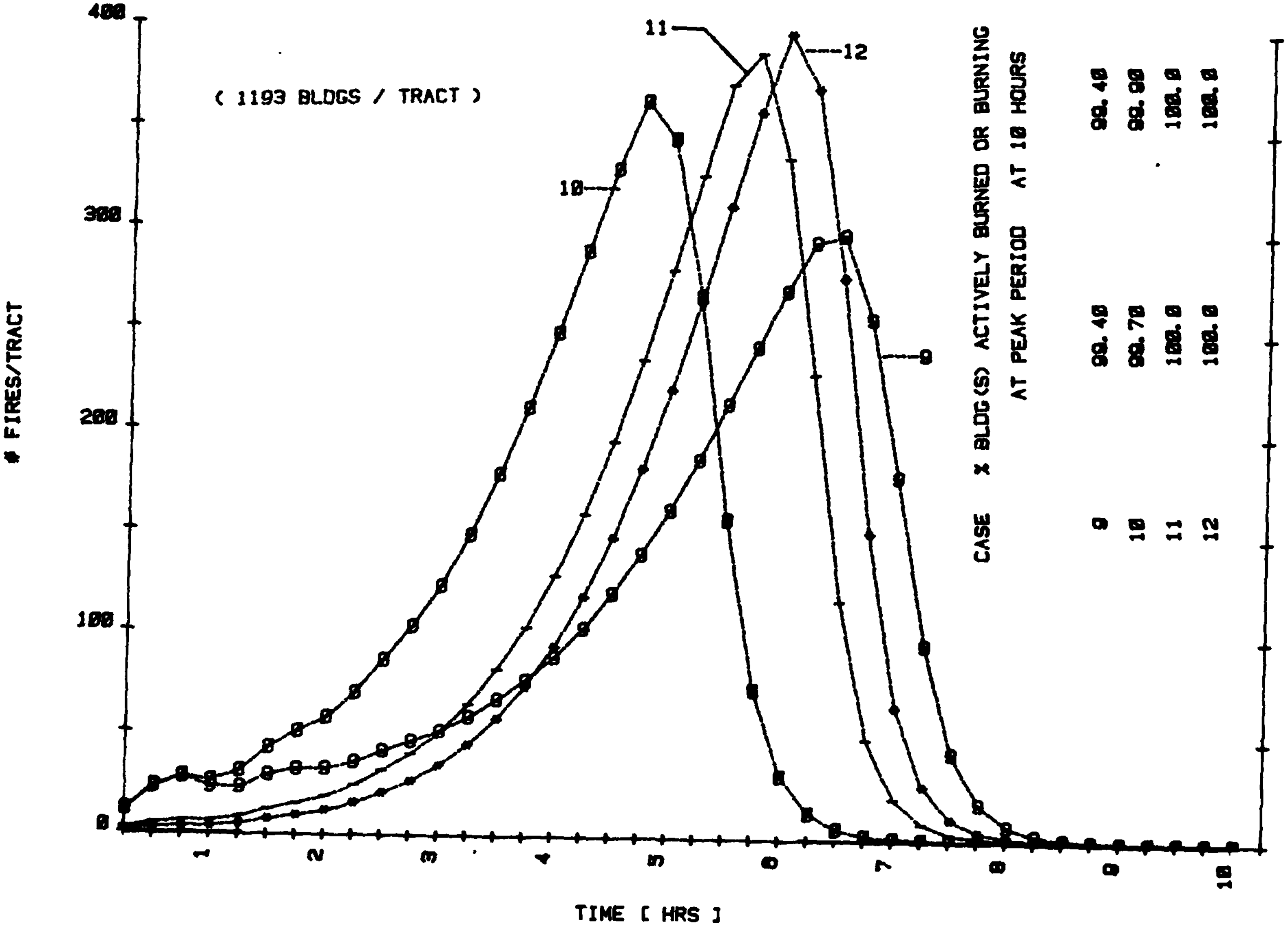
STAGE 3 FIRES IN TRACT 4.16 (MOD. BLAST DAMAGE); BLDG. DEN. =.15

FIG. 42



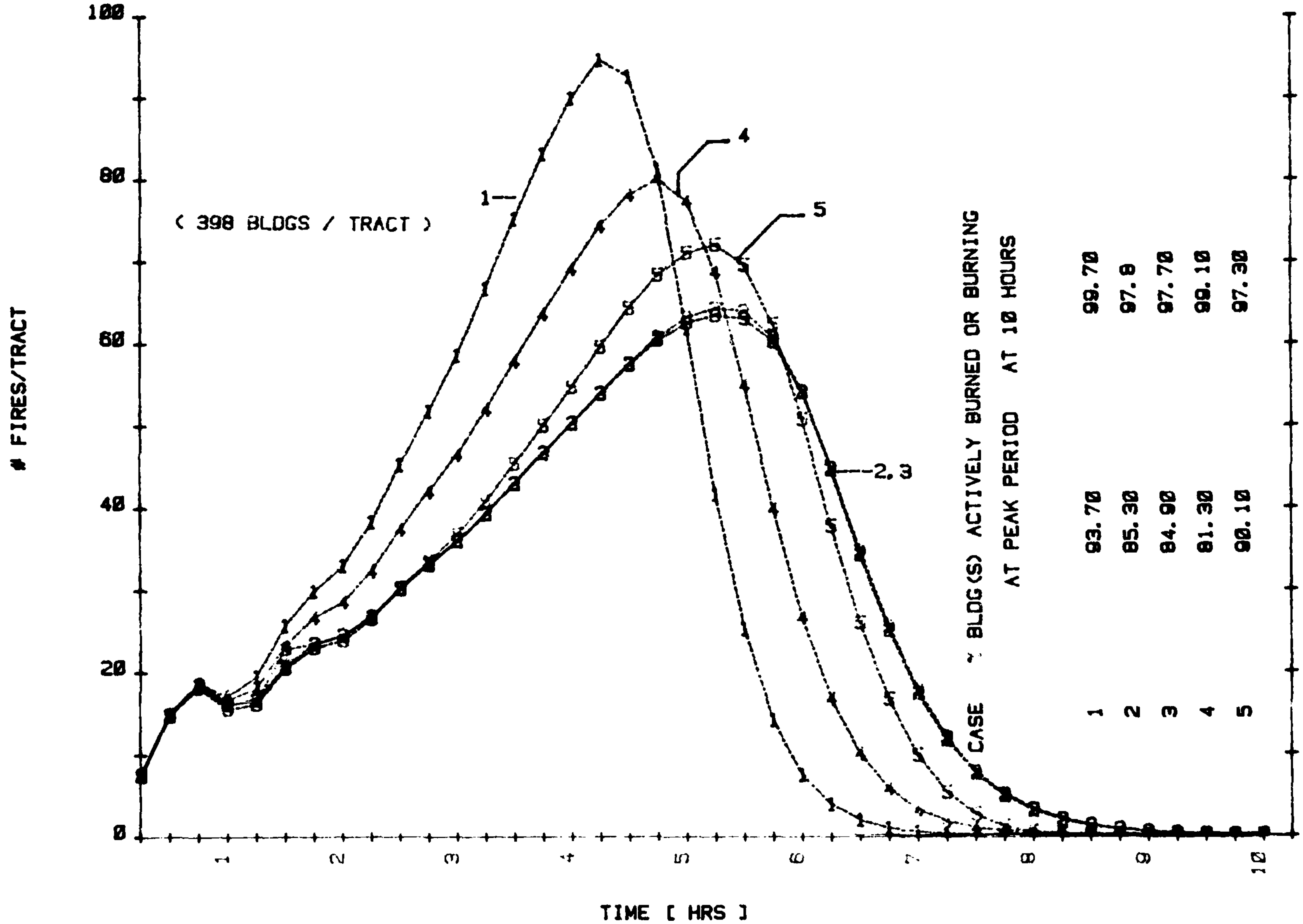
STAGE 3 FIRES IN TRACT 4,16 (MOD. BLAST DAMAGE); BLDG. DEN. =.15

FIG. 43



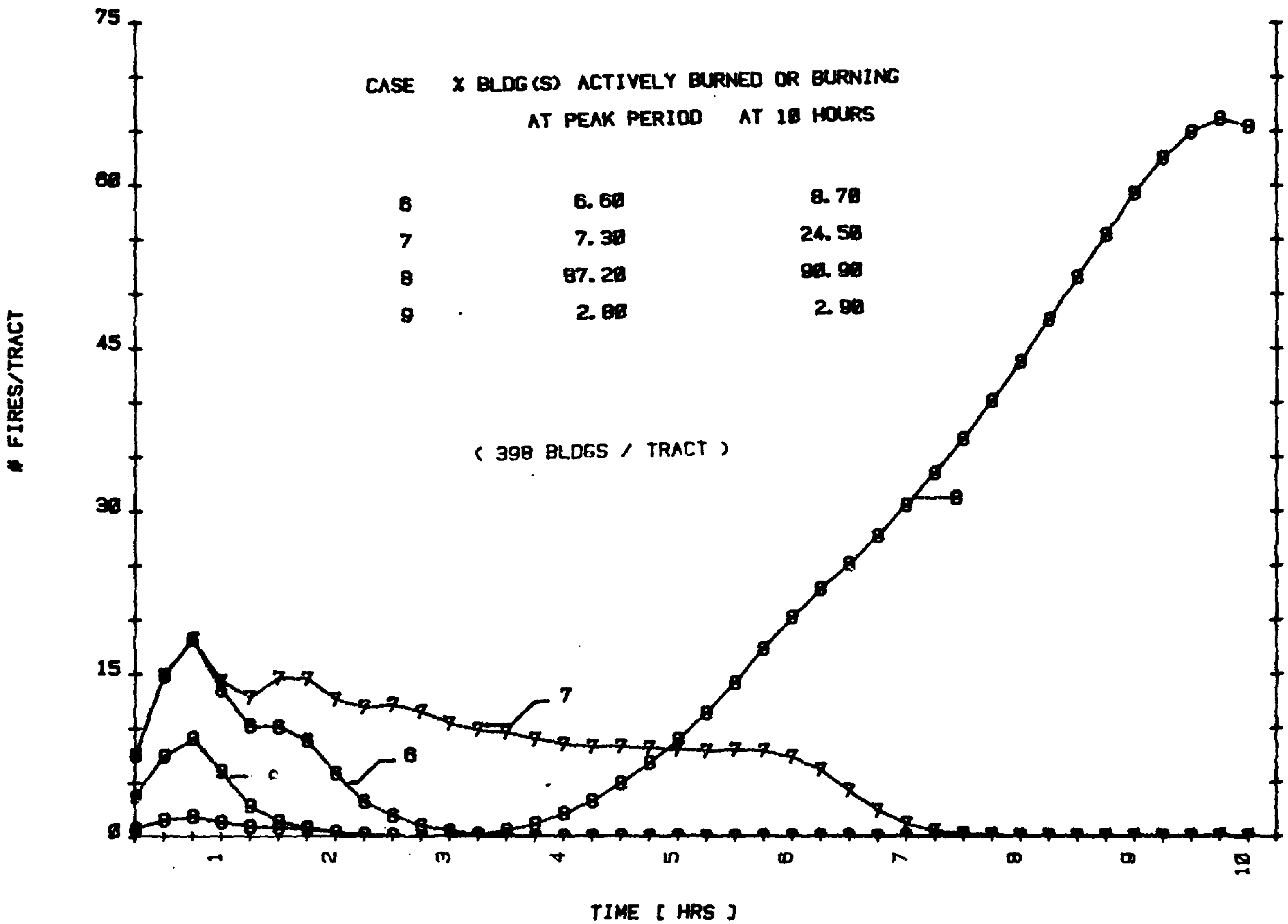
STAGE 3 FIRES IN TRACT 4.16 (MOD. BLAST DAMAGE), BLDG. DEN. =.15

FIG. 44



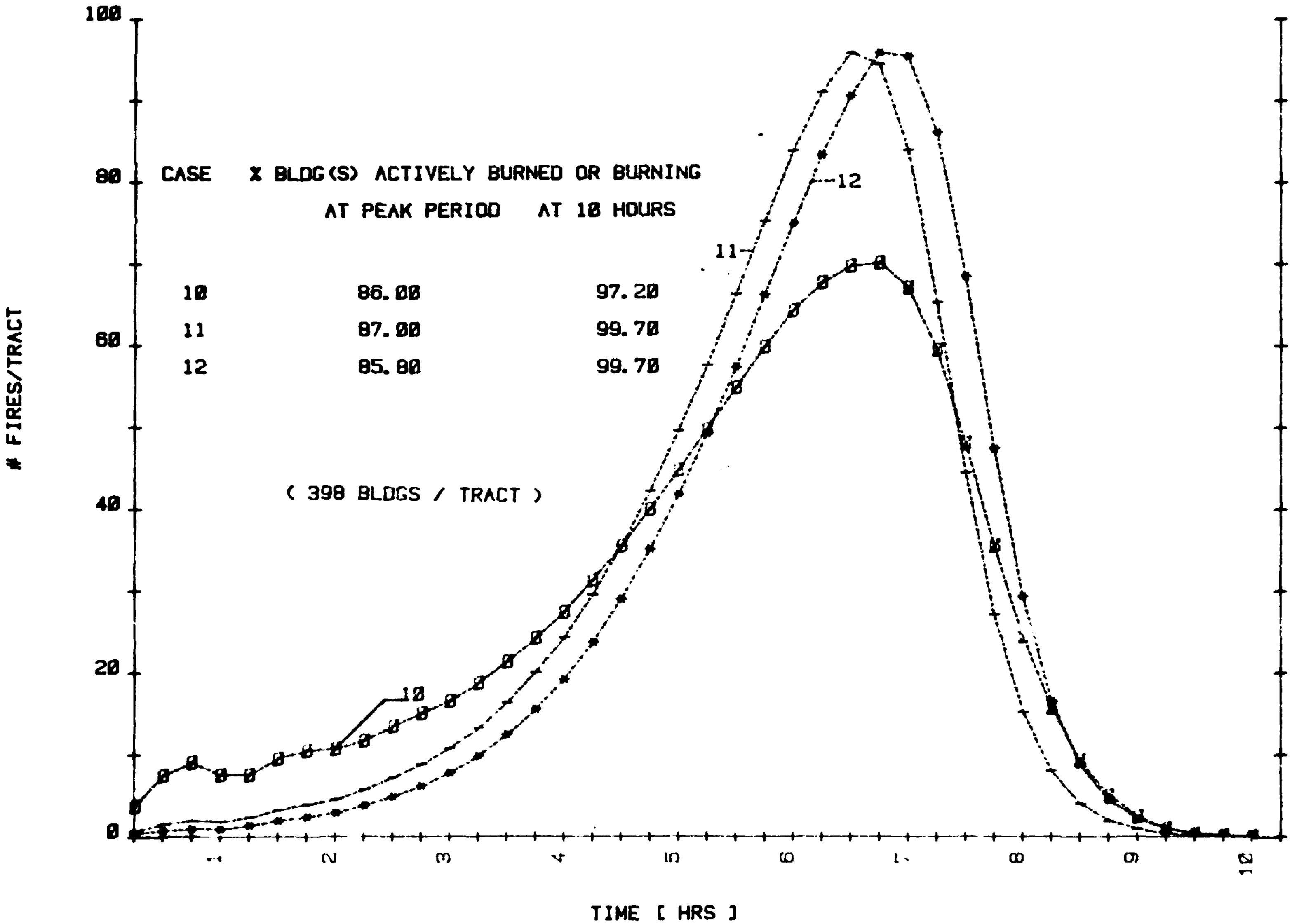
STAGE 3 FIRES IN TRACT 4,16 (MOD. BLAST DAMAGE); BLDG. DEN.=.05

FIG. 45



STAGE 3 FIRES IN TRACT 4.16 (MOD. BLAST DAMAGE); BLDG. DEN.=.05

FIG. 46



STAGE 3 FIRES IN TRACT 4,16 (MOD. BLAST DAMAGE); BLDG. DEN.=.05

FIG. 47

As shown by curve 8 of Figure 46, the 90 percent prevention of ignitions was insufficient to permit fire control with a moderate (10%) effort. Other cases examined produced, at best, several hours delay (Figures 45, 47).

Tract 5, 18; Moderate Blast Damage, Moderate Weapon Ignitions

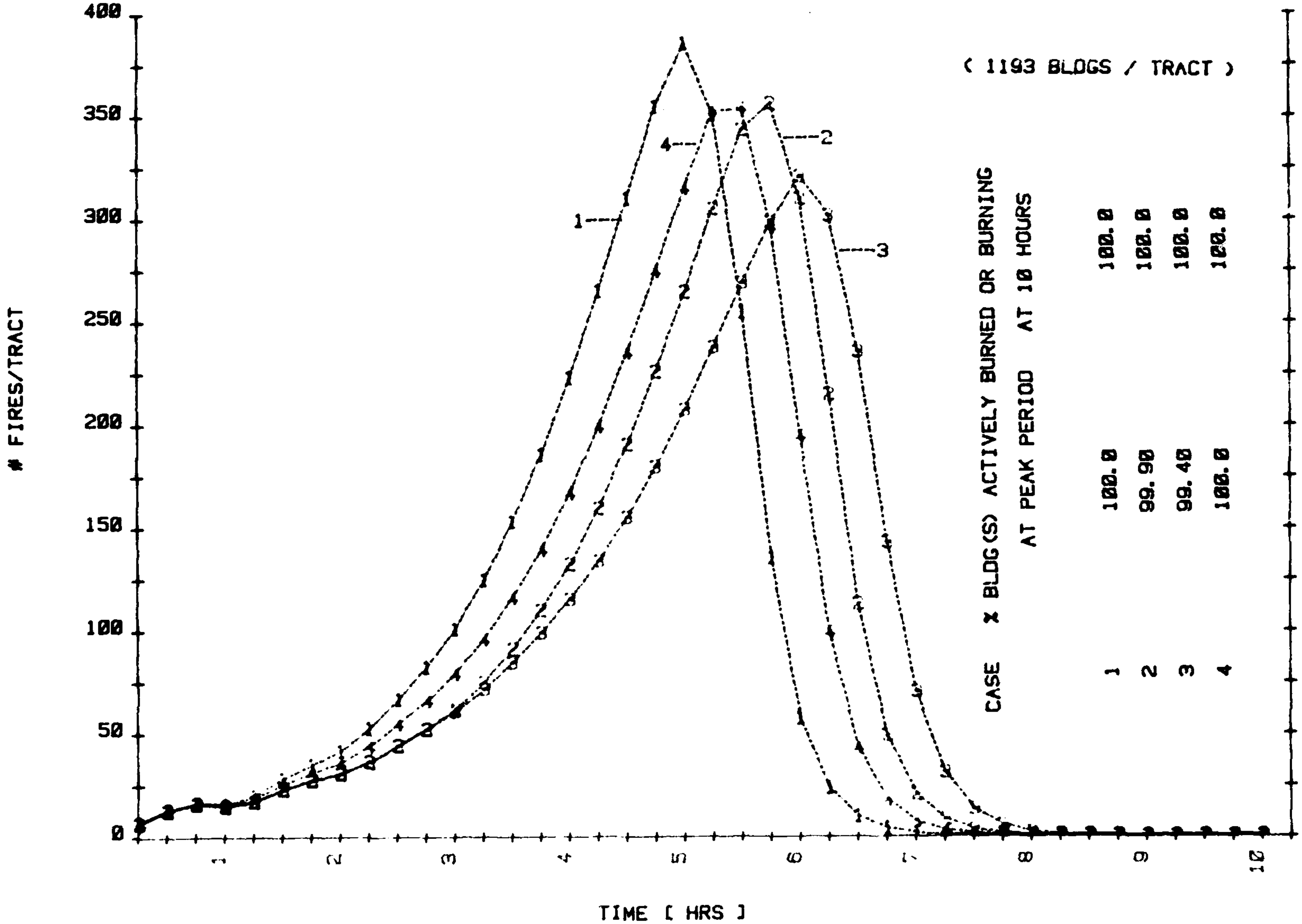
Results are shown in Figures 48, 49 and 50. As mentioned earlier, this tract was examined only at a building density of 15 percent of ground area. The reduced ignition frequency, compared to tract 5, 16, results in some delay in rapid fire development; but, other than this modest time delay, little other effect is noted. Only massive firefighting following a 50 percent ignition prevention shows a decided impact on the results (Figure 50, curve 9); and, even this case is being lost at 10 hours.

On the basis of the relative impact of location on fires in the 15 percent building density tracts, fires in tract 5, 18 with 5 percent building density is expected to be somewhat less severe than that reported for tract 4, 16 at the 5 percent building density.

6.3.5 Local Fire Development in Areas of Severe Blast Damage

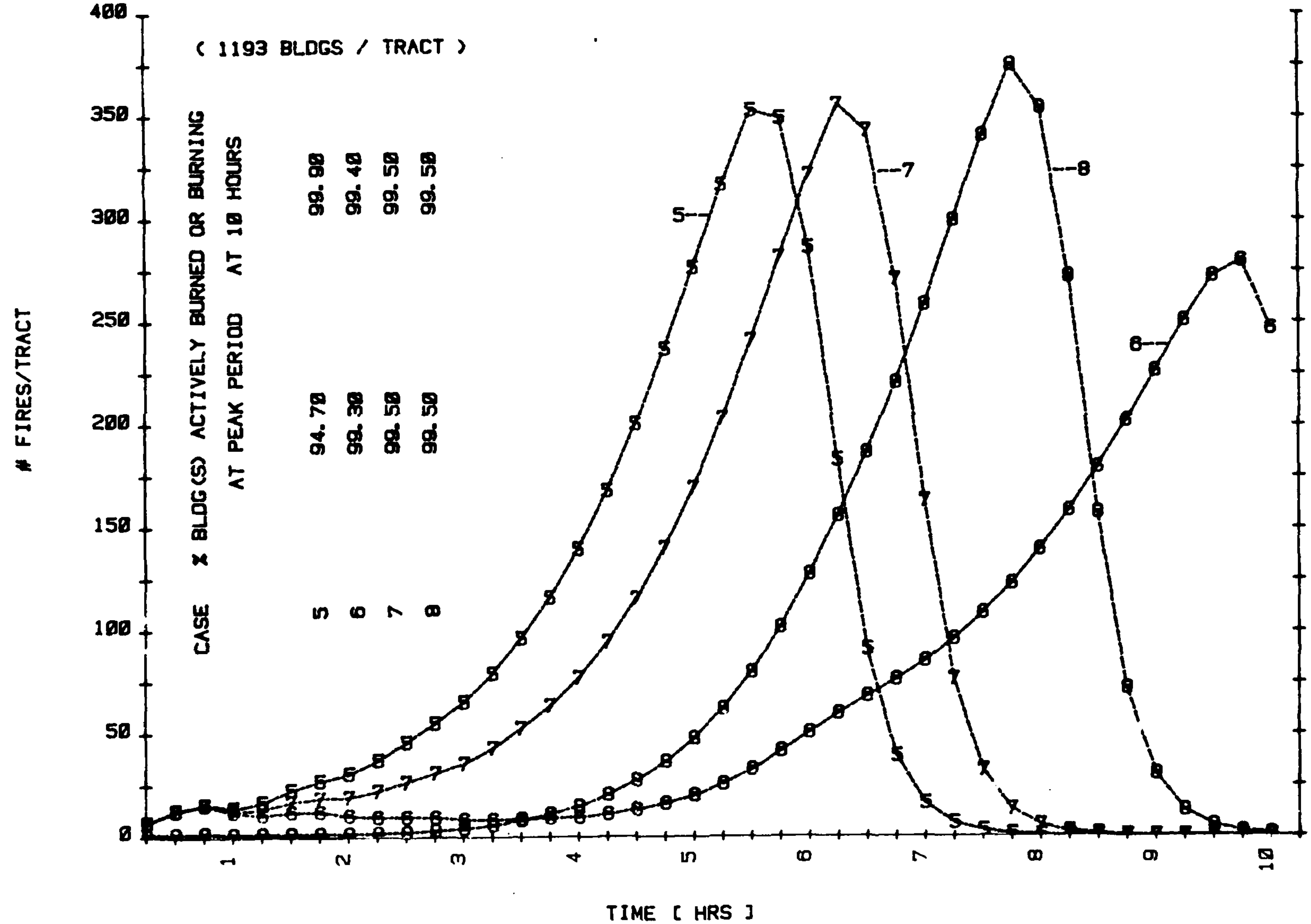
The area of severe blast damage is considered to extend 3.7 miles (3.5 psi) from ground zero. In that region, ignition frequency varies from 0.0156 fires per building up to 0.2485 fires per building. As stated in Section 4.3, at most blast angles, the debris tends to occur in one-half block segments with potential fire breaks at the street and alley boundaries, at least near the perimeter of the severe damage area. (Since garages were not included in the analysis; and all buildings were placed identically on their lots, it is possible that only the streets will retain fire break potential in a more realistic building pattern.) Thus, each segregated debris pile will contain debris from 16 (or 32) houses.

For tract 4, 21, selected for study, the ignition frequency is expected to be 0.0226 ignitions per house (2.5 miles from ground zero).



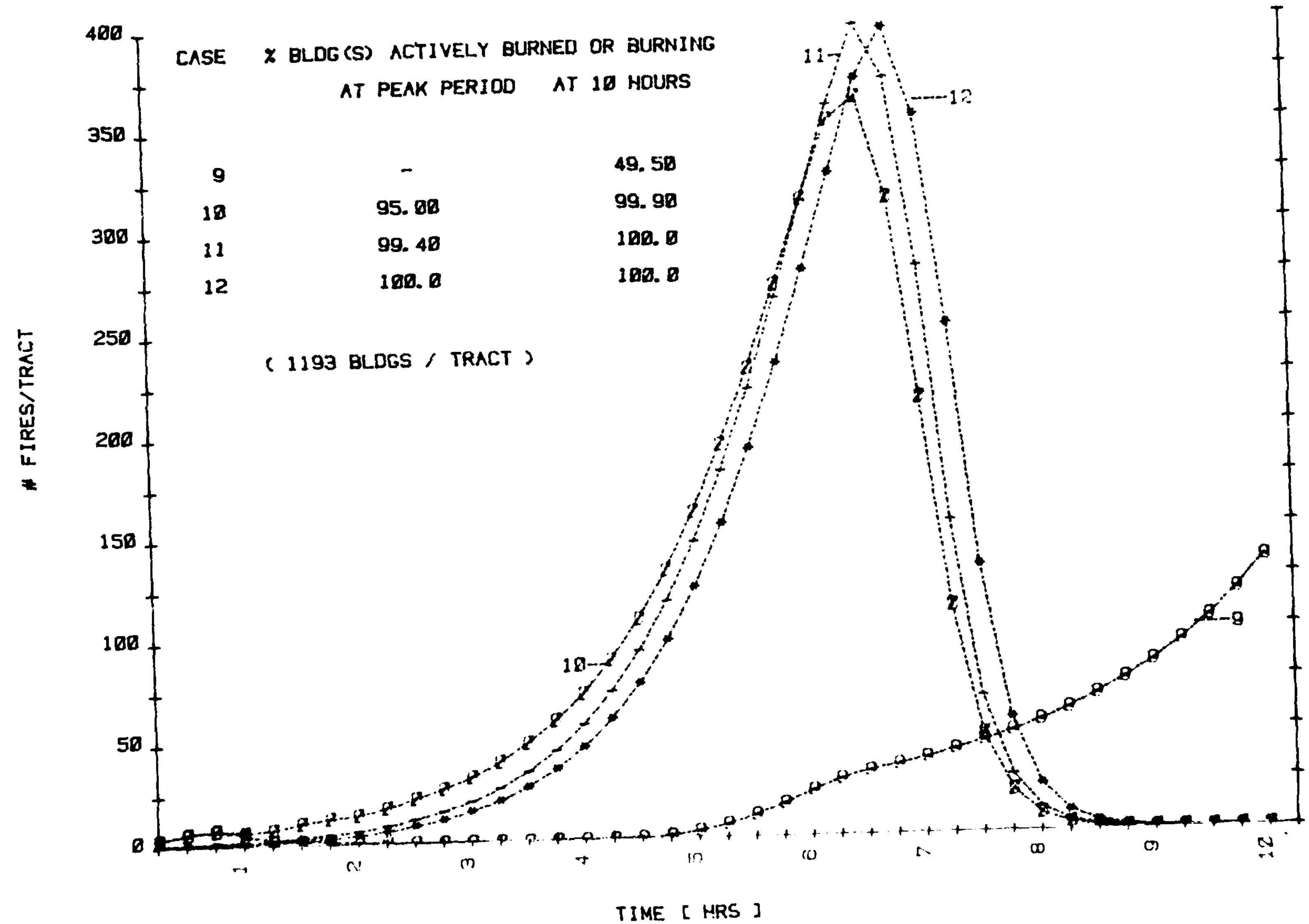
STAGE 3 FIRES IN TRACT 5.18 (MOD. BLAST DAMAGE); BLDG. DEN. =.15

FIG. 48



STAGE 3 FIRES IN TRACT 5.18 (MOD. BLAST DAMAGE) BLDG. DEN.=.15

FIG. 49



STAGE 3 FIRES IN TRACT 5.18 (MOD. BLAST DAMAGE); BLDG. DEN. =.15

FIG. 50

For the 16 house half block, the probability of ignition is at least 36 percent (16 x 0.0226 x 100). (Probability of an ignition in each block exceeds 72%.) This number is probably somewhat low since external fuels can be expected to contribute further ignition sources that can develop into debris fires in this severe damage region.

Figures 9 through 17, presented earlier, describe the gross debris distribution. To obtain an approximation of the fraction of the debris that is combustible, two segments of the "normal blast" distributed debris were further analyzed. These were taken near mid-block where the debris pattern consists of repetitive "waves" of debris. The sections were located approximately on section lines 2 and 5 as shown in Figure 9. The analysis consisted of examining each piece or fraction of a piece in each unit rectangle of ground area and distributing its total weight into weight of combustible and weight of noncombustible based on its function in the original house. The total weight of combustible and the total weight of non-combustible were then summed for each rectangle; and, provided an average value of percent combustible for the rectangle. No averaging across sections was done (method used for Figures 10 through 17); and thus peaks and valleys are accentuated. Figures 51 and 52 present the results obtained for the profiles near section lines 2 and 5 respectively (see Figure 9). From these, the bulk of the debris pile is 60 to 70 percent combustible.

Wiersma (Ref. 58) presents experimental results for a fuel ($12 \ lb/ft^2$) pile having 50 percent combustibles in a 7 mph wind which indicate an average flame spread rate of 1 ft per minute. A ($12 \ lb/ft^2$) fuel pile of 100 percent combustible spread flames at an average rate of 1.8 ft per minute. A wind speed of 3 to 3.5 mph produced flame spreads of 1.5 to 2.6 ft per minute for similar debris piles. As the pile sizes grew large, the wind effects appear to decrease. Thus, it appears reasonable that, for the deeper piles considered here, a flame spread rate of 1 ft per minute in all directions can be assumed. On this basis, the half-block of debris, ignited at one end, would be totally involved in about 10 hours. If suffering a single ignition near the middle of the pile, this time is reduced to 5 hours.

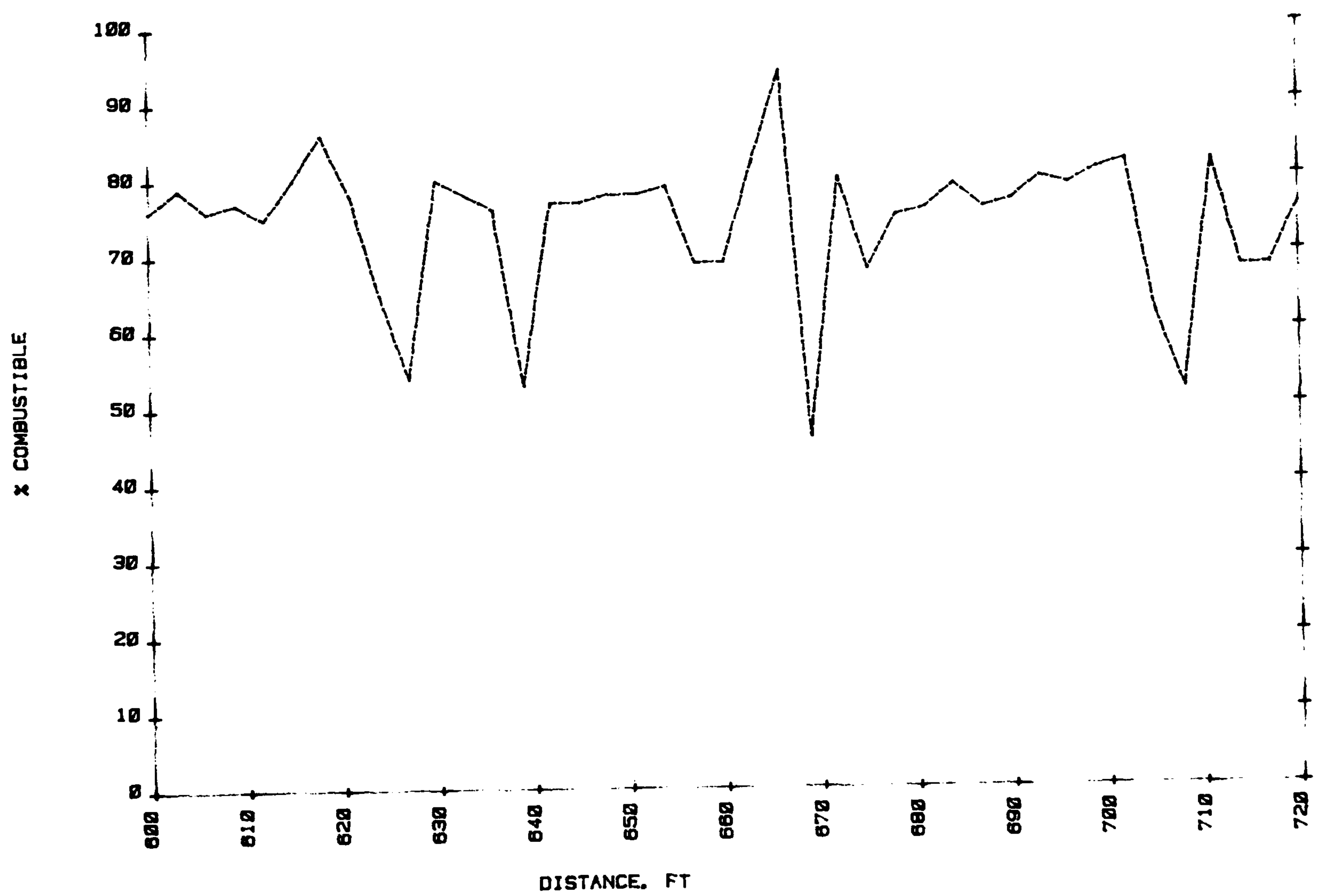


FIG. 51 DEBRIS CHARACTERIZATION NEAR SECTION LINE 2 OF FIG. 9 (NORMAL BLAST)

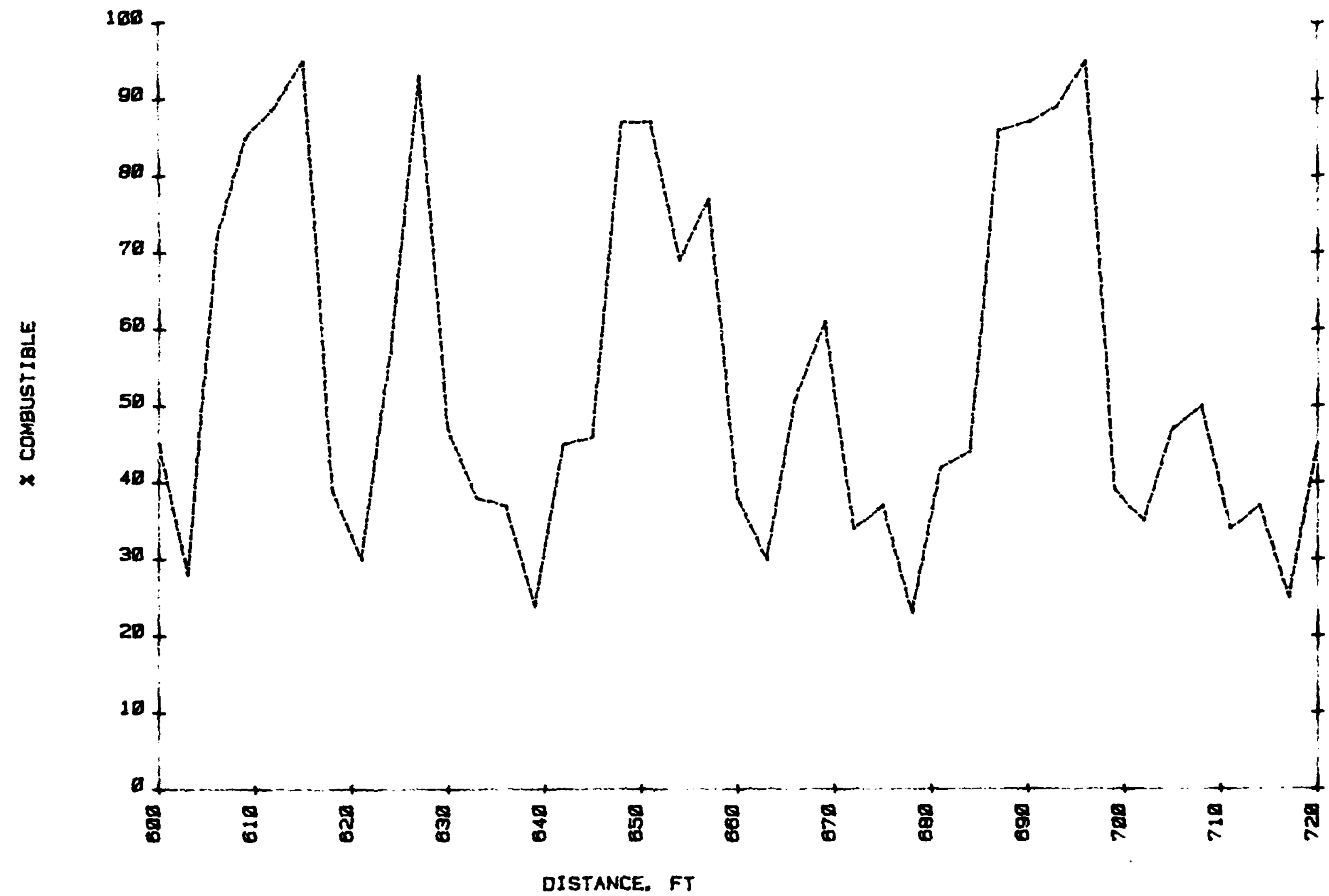


FIG. 52 DEBRIS CHARACTERIZATION NEAR SECTION LINE 5 OF FIG. 9 (NORMAL BLAST)

7. THE EFFECTS OF FIRES ON BASEMENT SHELTERS AND PEOPLE SURVIVABILITY

Although the city considered in the previous chapters consists of identical framed buildings, the fire effects information produced is capable of providing qualitative judgements on the effectiveness of several different below grade personnel shelters. Three types of shelters are postulated and their effectiveness in providing protection in a blast-fire environment is evaluated in terms of specific fire environments and fire prevention and suppression measures considered in the previous chapter. The three shelters are described as follows:

1. Conventional basement of the TEAPOT HOUSE strengthened to provide additional blast protection. This includes strengthening the floor system over the basement with additional supports for joists and girders, blocking of windows and doors leading into the basement and mounding the structure with soil up to the first floor level. A mechanical ventilation system is also assumed to be provided.

2. Preengineered (slanted) dual-purpose shelter. In this case, instead of a wood joist floor system over the basement, the residential building is assumed to have a reinforced concrete slab. The peripheral walls are concrete block as is the case with the TEAPOT HOUSE. Window wells and doors are adequately blocked off, the structure is mounded with soil to the first floor level and a mechanical ventilation system is provided.

3. Expedient, single purpose buried pole-type shelter (Ref. 59) placed in an open area behind a residence in the rearmost portion of the back yard.

These shelters are first assumed to be located in local areas of moderate and light blast damage and then in areas of severe blast damage. Their effectiveness in providing protection both against the blast and the fire environment is discussed in the following sections.

7.1 Shelters in Local Areas of Moderate or Negligible Blast Damage

It will be recalled (see Table 6) that moderate blast damage for this category of buildings occurs in the overpressure range from 2 to 3.5 psi. In this range each of the shelters described above has sufficient blast resistance so that blast effects, i.e., primary blast, dynamic pressure and debris from the breakup of the building should not present a serious hazard to shelter occupants. A conventional basement (such as the TEAPOT HOUSE basement) is capable of being upgraded to provide blast protection far in excess of 3.5 psi. It will be recalled that the TEAPOT HOUSE located at the 5 psi overpressure range in Nevada (Ref. 60) was totally destroyed. However, the basement was mostly unaffected. "...only in limited areas did a complete breakthrough from the first floor to the basement occur, the rest of the basement was comparatively clear and the shelters located there were unaffected" (Ref. 60). The probability of people survival in the TEAPOT HOUSE in Nevada was very nearly 1.0 against blast effects.

As indicated in the previous chapter, no major differences in fire effects are expected between those in areas of moderate blast damage, and those where blast damage is negligible. In both of these cases, most of the structural fuels remain on site. Thus, these two regions are considered together.

In both regions, fire prevention/suppression efforts are necessary to prevent a general burnout of the local areas at either (5% and 15%) building density studied. Without such a combined effort, buildings over and around the shelter areas are expected to burn.

7.1.1 Conventional Basement

The basement with the wood joist overhead floor will fill with smoke and toxic gases once the residence is ignited. This is due to the fact that the first story walls being hollow will conduct the gases between the studs and into the basement. SRI has demonstrated by experiment that this occurs even if the first story floor is covered with soil. No data are available for the situation with soil in the stud spaces. To place soil between the wall stud spaces would require ripping out significant portions of the wallboard and perhaps weakening the structure in the process.

In the lower (5%) building density region firefighter efforts might be successful in protecting the structure over the basement from burning. In more densely built up areas this would be much more difficult to achieve unless the building housing the shelter was located in a locally low density region or uniquely separated from surrounding structures.

The probability of people survival in such basements would be directly related to the probability that the building above the basement does not burn. Without fire prevention/suppression efforts the probability of survival would be very low in which case the shelter would need to be evacuated.

7.1.2 Preengineered Shelter

Burnout of a standing building over a basement covered with a reinforced concrete slab has been shown to offer minimal effects on the heat environment in the basement below (Ref. 19); and, a number of simple countermeasures have been demonstrated to further minimize shelter heating (Ref. 19, 20). Fresh ventilation air is expected to be readily available (Ref. 18, 19, 20, 21). Thus, this type of shelter can be protected against fire effects with very limited fire prevention/suppression efforts. This would include removal of burning or smoldering debris from basement entranceways and fresh air intakes. The probability of people survival in such basement shelters is therefore high and is only weakly dependent on the probability that the building above the shelter does not burn.

7.1.3 Expedient Shelter

Since residential structures are expected to remain essentially on site in these regions of blast damage, shelter occupants in expedient, pole type shelters should find no need for any specific remedial action against fire effects. The probability of people survival in such shelters is therefore very close to 1.0.

7.2 Shelters in Local Areas of Severe Blast Damage

For this category of structures, severe damage is considered to occur at free-field overpressure ranges greater than 3.5 psi (see Table 6).

7.2.1 Conventional Basement

There is little hope that occupants of shelters with wood joist overhead floor systems can remain within the shelters over any extended time period in ignited portions of the severe blast damage region. Blast damage to shelters and ignited debris piles combine to produce highly hazardous environments. Only a very fortuitous weapon direction relative to the housing pattern would prevent a collection of significant debris from the building housing the shelter and/or from its immediate neighbors. The probability of people surviving fire effects in these types of shelters in regions of severe blast damage would be low and certainly less than 0.5.

7.2.2 Preengineered Shelter

The basement with a reinforced concrete overhead slab and protected openings is still expected to be habitable in terms of shelter heating as will be shown below. Viable air supplied may be available particularly in the lower building areas. However, this is not a certainty. Local variations in the built-up areas may detrimentally affect air quality in such areas.

Returning to the question of shelter heating, one can project the following potential fuel loadings over the shelter room (treating Figures 10 through 17 as 60 to 70% combustible).

- Up to about 25 lb/ft^2 for the 5% building density
- Up to about 75 lb/ft^2 for the 15% building density

Thus, the extremely high combustible load of the TEAPOT HOUSE provides a most severe fire exposure to a dual-purpose shelter placed underneath, for the "normal" blast direction. Even the 30 degree blast direction produces significant debris on a large portion of the shelter roof. Shelter Test 70-6 (Ref. 19) and Shelter Test 72-14 (Ref. 20) give an indication of the magnitude of shelter heating for a 12 inch overhead concrete slab and indicate a strong need for countermeasures if the shelter is to remain habitable. Possible countermeasures may include removal of debris from over the shelter, the air intake vents and entranceways, putting out fires or evacuation. The probability of people surviving fire effects remains moderate.

7.2.3 Expedient Shelter

The expedient, single purpose pole shelter, assumed to be earth covered and under less debris, should suffer only minor shelter heating problems. However, there may be a period during which air quality is a problem. This may be mitigated by means of preattack and/or postattack countermeasures. The probability of people survival in this shelter in regions of major blast damage should remain high, greater than 0.5.

7.3 Probability of Survival

The probability of people survival, P(S) in a shelter can be expressed as follows.

$$P(S) = P(S_{sc})\ P(S_{ur})\ P(S_{fe})\ P(S_{fr}) \tag{1}$$

where $P(S_{sc})$ = probability of surviving structural collapse, i.e., debris effects

$P(S_{ur})$ = probability of surviving prompt nuclear radiation

$P(S_{fe})$ = probability of surviving fire effects

$P(S_{fr})$ = probability of surviving fallout radiation.

For the range of overpressures of interest to this study, i.e., less than about 10 psi primary blast is not a problem and is therefore not considered. Also, for below grade; basement type shelters dynamic pressures in this overpressure range should not pose a serious hazard and are also not considered. Procedures for determining the probability of survival against structural collapse and nuclear radiation are given in References 61 and 62.

$P(S_{fe})$ is a function of the probability of ignition which in turn is a function of preattack countermeasures, and the probability of fire suppression. $P(S_{fe})$ is also strongly dependent on the type of shelter and its location, i.e., zone of moderate or light structural blast damage, or zone of major structural damage. For example, for the wood framed basement shelter (category 1), $P(S_{fe})$ is a very strong function of the probability of ignition and the probability of suppressuon, because the shelter has a low resistance to fire effects. Thus, if the probability of ignition is 1.0 and the probability of suppression is 1.0, then the probability of people survival, $P(S_{fe})$ is also 1.0. On the other hand, if the probability of ignition is 1.0 and the probability of suppression is zero, i.e., the fire is too large to be put out with available means, then $P(S_{fe})$ would be zero unless the people are evacuated.

For the category 2 shelter, i.e., basement shelter with a reinforced concrete overhead slab, the probability of surviving fire effects is still a function of the probability of ignition, however, depending on the level of blast damage in the area we may be more concerned with some level of mitigation (removal of burning debris from air intakes, etc) than with suppression of the fire itself.

In the case of the category 3 (expedient, pole type shelter, the probability of surviving fire effects depends on where the shelter is located. If located in an open area in the zone of moderate to light blast damage then the probability of surviving fire effects is very nearly 1.0. If located in the zone of severe blast damage, the probability of surviving fire effects depends on the ability of individuals in clearing the areas around the entranceways and the air intake vents.

$P(S_{fe})$ is a complicated, nonlinear function which depends on the type of shelter structure, the local blast environment, local fire environment and on preattack and postattack countermeasures including evacuation. Information generated in this preliminary study and that available in the open literature is not sufficient to define this function in any more detail than was done in this chapter. More work, along the lines conducted in this study would be required.

8. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

The objective of the research study described in this report was (1) to perform a preliminary analysis of hazards to sheltered personnel in a blast-fire environment produced by the detonation of a nuclear weapon, and (2) to lay the groundwork for developing a formal methodology for estimating the probability of survival in a blast-fire environment.

Previous civil defense studies dealing with people survivability have been primarily concerned with the prompt effects, i.e., thermal radiation, prompt nuclear radiation, primary and secondary blast. Studies dealing with fire effects have only indirectly addressed the problem of people survivability and were primarily concerned with the character of the fires and associated hazards. In fact until very recently blast and fire effects have been treated as separate, uncoupled problems.

This effort began by selecting four buildings which would be used for constructing a variety of different city blocks and then portions of cities. These would then be used to site shelters and to study the effects of blast and fires on shelter occupants. This included two single-family residences, a low-rise multi-family residence and a high rise residential building. All are real buildings and represent a realistic sample of residential construction in terms of possible structural systems and building materials. The TEAPOT HOUSE had been built and tested in Nevada. The other three buildings exist in Chicago, Illinois at this time and are of recent (1978-79) construction. Building plans were obtained from local builders.

With the four buildings it is possible to postulate a variety of different city blocks. In fact a total of 17 different city blocks can be defined if we form combinations of four items taken one, two, three and four at a time. These blocks can then be combined in a large number of ways to form towns, cities or portions of cities. Such an inhabited land area would then be subjected to simulated nuclear weapon attacks which would result in debris distributions and corresponding fires. Prompt effects and fire hazards in selected blocks containing shelters would be quantified and the probability of survival for shelter occupants determined.

Each of the four buildings was analyzed to determine overpressures necessary to produce incipient collapse and breakup. On the basis of this analysis a debris catalog was determined for each building. A debris catalog contains all of the pieces a building breaks into when subjected to incipient collapse overpressure.

Each debris piece in the catalog is described in terms of the following parameters, i.e., weight, size, largest and smallest projected areas, center of gravity coordinates of the initial position prior to separation from the building, velocity and acceleration at the time of separation. In addition to building parts, the debris catalog also includes a typical (basic) set of furniture items.

In a given attack situation each debris piece is subjected to the blast loading experienced at the location of the subject building so as to determine its final location downstream. The given city block in which the debris distribution is to be determined may receive debris from several upstream and downstream blocks and thus a large number of buildings. In determining the makeup of a debris pile the task is to determine which of the pieces in the given portion of the city will be deposited on the block under observation and in what order in terms of arrival time. The latter is an important consideration since arrival time is the parameter which determines the variation of debris pieces with depth at a given location. The task of determining the makeup of a debris pile is obviously too difficult for hand calculation. Depending on the building density, at any one time we may be dealing with several thousand to several tens of thousand debris pieces. To expedite the process, a computerized procedure was necessary. The debris analysis program was formulated and written. This program is described in Appendix A of this report and has the following general functions and capabilities.

1. Store and retrieve debris catalog data for subject buildings.

2. For a given attack condition determine debris trajectories, final ranges and times of arrival for each debris piece in the catalog.

3. Determine which debris pieces from which city blocks combine to form a debris pile in the city block of interest. Determine the spacial distribution of debris pieces in the block.

4. Provide information (printout and/or contour plots) on the makeup of the debris pile for use in fire ignition and fire spread analysis.

When the debris piles were determined and described, the next step in the process was to determine the time dependent fir environment. Time dependent fire effects were first determined for the entire city. The IITRI Ignition Model was updated to reflect recent analyses of blast modification of sustained ignitions (primary fires); and, combined with predictions of secondary fires to describe the initial ignition pattern over the city from a 1 MT near-surface burst. The IITRI fire spread model was applied directly to the area of light damage, and then modified, and applied to the moderate damage regions. Fires in the area of severe damage were assessed, assisted by results of past debris fire experiments.

Fire spread throughout the city was assessed for a 15 percent building density assuming no concerted firefighting efforts. Individual tracts were then reevaluated to establish the impact of fire prevention and firefighting efforts on local fire progress and severity. On the basis of these results, qualitative evaluations of people survivability in the three different shelter types were made.

8.2 Conclusions

This study has taken a first comprehensive look at a very complex and a very difficult problem, i.e., evaluation of hazards and the probability of people survival in a blast-fire environment produced by the detonation of a 1 MT nuclear weapon. In spite of the difficulties encountered in this study, a great deal of work has been done and a great deal has been accomplished as described next.

A computer algorithm for determining the makeup of debris piles produced by the breakup of buildings when a large inhabited area is subjected to the detonation of a nuclear weapon has been formulated and programmed. A comparable research tool did not exist in the public domain.

The IITRI fire ignition and fire spread computer programs were modified to be able to predict ignition and spread of fires in regions where buildings are modified by blast. This capability did not exist either. A city consisting of basically one building type but three different below grade shelters located in selected city blocks, was quantitatively described and subjected to a 1 MT simulated weapon attack with the weapon detonated near the ground surface. Corresponding blast effects were applied to the subject buildings. On this basis three zones of blast damage were identified i.e., severe, moderate and light blast damage. A debris transport analysis was performed resulting in debris distribution. Debris piles on selected city blocks were quantified in terms of height and composition at different locations on the block. Using the modified fire ignition and fire spread computer programs, a time dependent fire environment corresponding to the imposed attack condition was determined.

The three personnel shelters studied include (1) a conventional wood framed basement upgraded for additional blast resistance, (2) a conventional residential basement with a reinforced concrete overhead slab, and (3) an expedient wood pole-type, below grade shelter.

The first category shelter was found to be only marginally effective even in the zone of light blast damage. Probability of people survival in such a shelter is strongly dependent on the probability of ignition and the corresponding fire supression measures. This type of shelter is not recommended in fire-prone areas without substantial countermeasures. Category 2 shelter is quite effective in zones of light to moderate damage requiring few countermeasures. In areas of severe blast damage, and due to large quantities of burning debris, the effectiveness of this shelter is diminished. Significant countermeasures are required to maintain its effectiveness. The expedient, pole-type shelter proves to be the most effective of the three. This is due to the fact that this shelter can be sited in open areas away from potential debris sources, thus minimizing the problem of burning debris in its immediate vicinity.

With the completion of this study the groundwork has been laid for the development of a consistent, formal methodology for estimating the probability of people survival in a blast-fire environment, when in shelters or when in the open.

8.3 Recommendations

It is recommended that the study reported here be continued with the object of developing a methodology for predicting the probability of people survival in a blast-fire environment. Reliable information in this subject area is currently very limited and therefore the development of needed information deserves serious consideration.

Such information can be used for casualty assessment, siting of shelters in risk and host areas, and evaluating the effectiveness of different shelter concepts. The information on the extent and makeup of debris piles may also be useful for the planning of post-attack rescue and cleanup operations.

The computer program developed on this study should be fully checked out, documented and made available to interested users in agencies engaged in similar research efforts.

APPENDIX A: USE OF DEBRIS ANALYSIS PROGRAMS

The three debris analysis programs described here are meant to be used in two major steps. The first step involves the use of the TRAJCT program. An iterative process is suggested to determine adequate and efficient input parameters for use with the TRAJCT program. In the second step the RANGER and BLOCK programs are used to convert the calculated trajectories into debris pile descriptions.

As previously described, 18 input parameters are required by the TRAJCT program to determine the trajectory of a debris piece. More than one debris piece can be described by one set of parameters. Efficiency requires that as many debris pieces as possible are described by each set. However an accurate answer is not possible for a group that is too diverse. The diversity of the group is controlled by the eight covariance input parameters. The accuracy of the answer is suggested by the relations between the range, the expected range and the standard deviation of the range and the time to rest, expected time and standard deviation of the time. The expected values and standard deviations are calculated by decision theory and are a function of the covariance parameters. In general, the expected values are brought nearer to the deterministic values by decreasing the covariances. This implies selecting a smaller debris group.

The TRAJCT program calculates the partial contributions to the standard deviations in expected range and expected time due to eight input parameters. These values are useful in deciding which parameters must be changed when a more selective debris group is required.

Two input parameters are not included in the partial contribution scheme, the number of bounces, NB, and the differential increment for the partial differentiation, FX. NB, which controls the number of times that the debris piece is allowed to strike the ground, is required to model the collision properties of different debris types and because the program becomes numerically unstable for larger numbers of bounces. TRAJCT should be run for several values of NB to determine an effective value. FX controls the differentiation step in the numerical partial differentiation scheme. This variable can sometimes be adjusted to eliminate numerical instability in the solution scheme.

When satisfactory sets of input parameters have been determined, TRAJCT runs should be made for all of the sets. If more than one run is necessary, all of the output files should be combined into one file. This combined file should be used as an input file for a RANGER run. The RANGER run also requires a file with initial debris coordinates. The file can be created with the interactive DATA program.

The output file of the RANGER run can then be used as input to the BLOCK routine. A file with structure locations is also needed and can be created with the DATA program. The output file of the BLOCK program describes debris distribution over a given area. Further processing of this file is fairly simple if desired.

A.1 Use of DATA Program

DATA is an interactive program to create input files for the TRAJCT, RANGER and BLOCK routines. While not absolutely necessary for the debris analysis, DATA provides a quick and fairly easy input system. Some errors are caught by the program and can be corrected immediately; others should be corrected using a system file-editing routine. All input to the program is from a terminal and free of format requirements. The program prompts for the expected values and automatically formats the output to the specifications of the intended program.

DATA can create files for all three different programs. The initial prompt in DATA is to pick the desired file type, TRAJCT, BLOCK or RANGER. DATA must be rerun for each new file. Once the option has been chosen, DATA prompts for the required information. DATA asks for most values by their name used in the intended program. Definitions and units can be found in the following program usage descriptions.

Input for the TRAJCT and RANGER programs is an extremely time consuming process. DATA can be stopped during these two input sessions and restarted later. To stop the TRAJCT input loop, respond to any prompt with a nonnumeric character and a carriage return. To complete the file, rerun DATA, enter the same file name, then answer "Y" to the "RESTART?" prompt. The RANGER input loop can only be successfully stopped after the "ENTER ICLASS, NB, IDTYP." prompt. The restart is similar to the TRAJCT restart.

A.2 TRAJCT Input

To calculate the nominal values, expected values and standard deviations of range and time for a debris group, TRAJCT requires eleven parameters to describe the physical characteristics of the group, six parameters to describe the blast environment and another parameter to control the numerical differentiation scheme.

Five of the debris group parameters are the mean values of weight, maximum surface area, minimum surface area, height, and vertical angle, WE, AMAX, AMIN, HH and BB respectively. Five others are the coefficients of variation of each of these properties, COVWE, COAMA, COAMI, COVHH, and COVBB. The last is the number of bounces, NB, that the debris particle would take. This parameter covers the collision properties of the particle. All eleven of these parameters must be input for each group.

The six blast parameters are the peak dynamic wind velocity, VO, the duration of the positive phase of the dynamic wind pressure, TO, the velocity of the shock wave, US, and the coefficients of variation of each, CVO, CTO and CUS. Each of these parameters is constant for all the groups included in one run.

The final input parameter, FX, controls the differentiation step. The value FX = 0.05 was found to be acceptable for almost all calculations.

Details of the input format are shown in Table A.1. Definitions of all input parameters are in Table A.2.

A.3 Output File for TRAJCT

The output file of the TRAJCT routine contains five records containing thirty-four values for each debris group. The first record in the file is an echo of the input variables IC and FX. The remainder are organized in sets of five containing the debris group information. Along with a echo of the input data, the first record lists the range, R, the expected range, ER, the standard deviation of the range, SR, the time-to-rest, T, the expected time, ET and the standard deviation of the time, SR. The second two records are input data echos. The fourth record contains the partial contributions of each of eight input parameters to the total deviation of the range. The fifth record lists the partial contributions of the eight parameters to deviation in the time-to-rest. The details are shown in Table A.3.

TABLE A.1 INPUT FILE FOR TRAJCT

PDP-11 File Name - TRAJIN
Logical Unit Number - 5

Record Number	Name	Units	Column Number	Format	Comment
1	IC	Integer	1- 5	I5	Number of groups
	FX	Decimal	6-13	F8.0	Differentiation step
2	VO	ft/sec	1-10	F10.0	Peak Wind Velocity
	TO	sec	11-20	F10.0	Phase Duration
	US	ft/sec	21-30	F10.0	Shock Velocity
	CVO	Decimal	31-40	F10.0	Coefficient of Variation
	CTO	Decimal	41-50	F10.0	
	CUS	Decimal	51-60	F10.0	
For each debris group, include two records in the format of records 3 and 4.					
3	IDTYP	Integer	1- 5	I5	Group ID
	WE	lbsf	6-13	F8.0	Weight
	AMAX	sq ft	14-21	F8.0	
	AMIN	sq ft	22-29	F8.0	
	HH	ft	30-37	F8.0	Height
	BB	radians	38-45	F8.0	Angle (≠ 0.)
4	NB	Integer	1- 5	I5	Number of bounces
	COVWE	Decimal	6-13	F8.0	
	COAMA	Decimal	14-21	F8.0	
	COAMI	Decimal	22-29	F8.0	
	COVHH	Decimal	30-37	F8.0	
	COVBB	Decimal	38-45	F8.0	
5	Same as Record Number 3				Group number 2
6	Same as Record Number 4				

TABLE A.2 DEFINITIONS OF INPUT VARIABLES

IC	-	Number of debris groups in this run
FX	-	Coefficient for numerical differentiation (Use FX = 0.05 for most cases)
VO	-	Peak wind velocity following shock wave
TO	-	Duration of the positive phase of the dynamic wind pressure
US	-	Velocity of the shock wave
CVO	-	Coefficient of variation of peak wind velocity
		Note: In this program, all coefficients of variation are defined as the standard deviation of a property divided by the mean value of the property.
CTO	-	Coefficient of variation of positive phase duration
CUS	-	Coefficient of variation of shock wave velocity
IDTYP	-	Five digit integer code to identify debris group
WE	-	Mean weight of debris pieces in debris group
AMAX	-	Mean value of area of largest side of pieces in group
AMIN	-	Mean value of area of smallest side of pieces in group
HH	-	Mean value of height above ground for pieces in group
BB	-	Vertical angle between plane containing largest side of debris piece
NB	-	Number of bounces. The number of times that the debris piece strikes the ground before TRAJCT stops it
COVWE	-	Coefficient of variation of the weights of the group
COAMA	-	Coefficient of variation of the maximum areas of the group
COAMI	-	Coefficient of variation of the minimum areas of the group
COVHH	-	Coefficient of variation of the heights of the group
COVBB	-	Coefficient of the BB-angle of the group

TABLE A.3 TRAJCT OUTPUT FILE

Record Number	Variable Name	Units	Column Number	Format
1	IC	Integer	1-10	I10
	FX	Decimal	11-18	F8.4

For every debris group there should be five records in the following format.

Record Number	Variable Name	Units	Column Number	Format
2	IDTYP	Integer	1- 6	I6
	NB	Integer	7- 8	I2
	R	ft	9-16	F8.2
	ER	ft	17-24	F8.2
	SR	ft	25-32	F8.3
	T	sec	33-40	F8.4
	ET	sec	41-48	F8.4
	ST	sec	49-56	F8.4
3	WE	lbsf	1- 9	F9.2
	AMAX	sq ft	10-17	F8.4
	AMIN	sq ft	18-25	F8.4
	HH	ft	26-33	F8.4
	BB	radians	34-41	F8.4
4	COVWE	Decimal	1- 9	F9.4
	COAMA	Decimal	10-17	F8.4
	COAMI	Decimal	18-25	F8.4
	COVHH	Decimal	26-33	F8.4
	COVBB	Decimal	34-41	F8.4
5	PR(WE)	Decimal	1- 9	F9.3
	PR(AMAX)	Decimal	10-17	F8.3
	PR(AMIN)	Decimal	18-25	F8.3
	PR(HH)	Decimal	26-33	F8.3
	PR(BB)	Decimal	34-41	F8.3
	PR(VO)	Decimal	42-49	F8.3
	PR(TO)	Decimal	50-57	F8.3
	PR(US)	Decimal	58-65	F8.3
6	PT(WE)	Decimal	1- 9	F9.3
	PT(AMAX)	Decimal	10-17	F8.3
	PT(AMIN)	Decimal	18-25	F8.3
	PT(HH)	Decimal	26-33	F8.3
	PT(BB)	Decimal	34-41	F8.3
	PT(VO)	Decimal	42-49	F8.3
	PT(TO)	Decimal	50-57	F8.3
	PT(US)	Decimal	58-65	F8.3

A.4 RANGER Input Requirements

RANGER requires three input files plus terminal input to initiate the run. One input file is the output file of a TRAJCT run. This file should contain range and time values for every debris group. If more than one TRAJCT run was needed, all the TRAJCT output files should be combined into one file to be used as the RANGER input file. When RANGER is run, it will ask for the name of this file. The second input file contains information to link the coordinates of groups of debris pieces to the appropriate range and time values. This file should be created by a DATA run. The file format is shown in Table A.4. Definitions are contained in Table A.5. RANGER will ask for the name of the file with "X-Y DATA" when it wants this file. The third input file is a data file with points taken from a normal curve. The file is explained in the theoretical discussion of RANGER in Section 3. A copy of the file is included in Table A.6. The data should be loaded as is into a file named "NORMAL.DAT".

TABLE A.4 INPUT FORMAT FOR RANGER FILE

Record Number	Variable Name	Units	Column Number	Fortran Format	Comment
1	NC	Integer	1-10	I10	Number of groups
For each debris group, make one heading record followed by the appropriate amount of coordinate records.					
2	IDRAN	Integer	1- 5	I5	RANGER ID
	IDMAT	Integer	6-10	I5	Material code
	NICC	Integer	11-15	I5	Number of pieces
	ID1	Integer	16-22	I7	ID for first piece
For each debris piece in group repeat following record format.					
3	X	ft	1- 8	F8.0	X-coordinate
	Y	ft	9-16	F8.0	Y-coordinate

TABLE A.5 DEFINITIONS OF RANGER INPUT VARIABLES

NC	-	Total number of debris groups for this run
IDRAN	-	The position of the group range and time information in the TRAJCT output file. The groups are numbered sequentially from the first group in the TRAJCT output
IDMAT	-	Material code to aid post-processing. Any convenient five digit number is compatible.
NICC	-	Number of debris piece coordinates which will follow this record. Each X-Y coordinates corresponds to one debris piece
ID1	-	The debris piece ID for the piece corresponding to the first coordinate. The remaining pieces will be numbered sequentially from ID1. This ID uniquely identifies each debris piece throughout the analysis.

TABLE A.6 INPUT FILE FOR NORMAL STATISTICS

.0000	.0040	.0080	.0120	.0160	.0199	.0239	.0279	.0319	.0359
.0398	.0438	.0478	.0517	.0557	.0596	.0636	.0675	.0714	.0753
.0793	.0832	.0871	.0910	.0948	.0987	.1026	.1064	.1103	.1141
.1179	.1217	.1255	.1293	.1331	.1368	.1406	.1443	.1480	.1517
.1554	.1591	.1628	.1664	.1700	.1736	.1772	.1808	.1844	.1879
.1915	.1950	.1985	.2019	.2054	.2088	.2123	.2157	.2190	.2224
.2257	.2291	.2324	.2357	.2389	.2422	.2454	.2486	.2517	.2549
.2580	.2611	.2642	.2673	.2704	.2734	.2764	.2794	.2826	.2852
.2881	.2910	.2939	.2967	.2995	.3023	.3051	.3078	.3106	.3133
.3159	.3186	.3212	.3238	.3264	.3289	.3315	.3340	.3365	.3389
.3413	.3438	.3461	.3485	.3508	.3531	.3554	.3577	.3599	.3621
.3643	.3665	.3686	.3708	.3729	.3749	.3770	.3790	.3810	.3830
.3849	.3869	.3888	.3907	.3925	.3944	.3962	.3980	.3997	.4015
.4032	.4049	.4066	.4082	.4099	.4115	.4131	.4147	.4162	.4177
.4192	.4207	.4222	.4236	.4251	.4265	.4279	.4292	.4306	.4319
.4332	.4345	.4357	.4370	.4382	.4394	.4406	.4418	.4429	.4441
.4452	.4463	.4474	.4484	.4495	.4505	.4515	.4525	.4535	.4545
.4554	.4564	.4573	.4582	.4591	.4599	.4608	.4616	.4625	.4633
.4661	.4649	.4656	.4664	.4671	.4678	.4686	.4693	.4699	.4706
.4713	.4719	.4726	.4732	.4738	.4744	.4750	.4756	.4761	.4767
.4772	.4778	.4783	.4788	.4793	.4798	.4803	.4808	.4812	.4817
.4821	.4826	.4830	.4834	.4838	.4842	.4846	.4850	.4854	.4857
.4861	.4864	.4868	.4871	.4875	.4878	.4881	.4884	.4887	.4890
.4893	.4896	.4898	.4901	.4904	.4906	.4909	.4911	.4913	.4916
.4918	.4920	.4922	.4925	.4927	.4929	.4931	.4932	.4934	.4936
.4938	.4940	.4941	.4943	.4945	.4946	.4948	.4949	.4951	.4952
.4953	.4955	.4956	.4957	.4959	.4960	.4961	.4962	.4963	.4964
.4965	.4966	.4967	.4968	.4969	.4970	.4971	.4972	.4973	.4974
.4974	.4975	.4976	.4977	.4977	.4978	.4979	.4979	.4980	.4981
.4981	.4982	.4982	.4983	.4984	.4984	.4985	.4985	.4986	.4986
.4987	.4987	.4987	.4988	.4988	.4989	.4989	.4989	.4990	.5000

0 0 1 0 0 1 -1 0 0 -1 1 1 -1 -1 1 -1 -1 1 2 0 -2 0 0 2 0 -2
2 1 -2 -1 2 -1 -2 1 1 2 -1 -2 1 -2 -1 2 2 2 -2 -2 2 -2 -2 2

A.5 RANGER Output

RANGER writes a debris list for every grid point with at least one part of a debris piece located there. The first line lists the I-coordinate and the J-coordinate of the point and the number of debris pieces at the point. Each of the following lines describes one debris piece at the point. The line lists the debris piece ID, the time-of-arrival of the piece, T, the material code of the piece, IDMAT, and the size coefficient of the piece, SIZE. The format of the output file is shown in Table A.7. Variable definitions are in Table A.8.

TABLE A.7 RANGER OUTPUT

Record Number	Variable Name	Unit	Column Number	Fortran Format	Comment
1	ND	Integer	1- 8	I8	Number of debris parts
	NI	Integer	9-14	I6	Length of I-axis
	NJ	Integer	15-20	I6	Length of J-axis
	XUNIT	ft	21-26	F6.2	Length of unit
	YUNIT	ft	27-32	F6.2	Width of unit
For each grid point one record of type 2 is followed by a list of records of type 3.					
2	I	Integer	1- 5	I5	
	J	Integer	6- 9	I4	
	KOUNT	Integer	10-13	I4	
3	IDDEB	Integer	1- 7	I7	Debris ID
	ET	sec	8-14	F7.3	Time -of-arrival
	IDMAT	Integer	15-18	I4	Material code
	SIZE	Decimal	19-25	F7.7	Size coefficient

TABLE A.8 DEFINITIONS OF RANGER OUTPUT VARIABLES

ND	-	Total number of debris piece entries. Each debris piece may cover several grid points and therefore have as many entries.
NI	-	The length in unit rectangles of the output grid in the X-direction.
NJ	-	The length in unit rectangles of the grid in the Y-direction.
XUNIT	-	The X-direction length of a unit rectangle in feet.
YUNIT	-	The Y-direction length of a unit rectangle in feet.
I	-	The I-coordinate of a grid point. I = X-coordinate/XUNIT + 3.
J	-	The J-coordinate of a grid point. J = Y-coordinate/YUNIT + 3.
KOUNT	-	The total number of debris entries at this grid point.
IDDEB	-	The unique debris piece identifier.
ET	-	Time-of-arrival of a debris piece.
IDMAT	-	Material code of debris piece.
SIZE	-	Size coefficient. The fraction of the total debris in this grid rectangle.

A.6 BLOCK Input

BLOCK uses two input files. One file is an output file of a RANGER run. The second file is created by a DATA run. This file contains the name of the RANGER file to be used, the dimensions of the area to be studied and the locations of structures on the block. The dimensions and locations are given in I-J units which are the same as the ones in the RANGER run. Table A.9 shows the format of this file. Definitions are in Table A.10.

A.7 BLOCK Output

The BLOCK output file is exactly the same as a RANGER output file except that a two-digit house code has been added to IDDEB. The first two digits of IDDEB now indicate the house number from which the debris piece came.

TABLE A.9 BLOCK INPUT FILE FORMAT

Record Number	Variable Name	Units	Column Number	Fortran Format	Comment
1	NAME1	Character	1-11	1H,5A2	RANGER filename
2	NHOUSE	Integer	1- 6	I6	Number of Structures
	NIB	Integer	7-12	I6	Unit length of block
	NJB	Integer	13-18	I6	Unit width of block
3	IH1(1)	Integer	1- 6	I6	I-coord of structure
	JH1(1)	Integer	7-12	I6	J-coord of structure
	IH1(2)	Integer	13-18	I6	
	JH1(2)	Integer	19-24	I6	
	.	.	.	.	
	.	.	.	.	
	.	.	.	.	
	JH1(6)	Integer	67-72	I6	

Repeat record type 3 until all structures are included.

4	NAME2	Character	1-11	IH,5A2	Output filename

TABLE A.10 DEFINITIONS OF BLOCK INPUT VARIABLES

NAME1	-	PDP-11 filename of file with RANGER output to be used as BLOCK input.
NHOUSE	-	Total number of structures on block.
NIB	-	I-axis length of area to be analyzed and listed.
NJB	-	J-axis length of same area.
IH1,JH1	-	I-J coordinates of X-Y origin of structure.
NAME2	-	PDP-11 filename for output.

A.8 Further Output Processing

Additional output processing can be useful for the BLOCK output file. Two codes were written to process the BLOCK output for the IITRI analysis. These codes are specific for the structure studied however, and are not included in this report.

APPENDIX B: LISTINGS OF IITRI DEBRIS CODES

B.1 Data

```
  FORTRAN IV     V02.2-1          FRI 09-JAN-81 01:25:03          PAGE 001
DATA,DATA/-SP=DATA

           DIMENSION NAME(5),IHH(40),JHH(40),BB(3)
           BB(1)=6.283185
           BB(2)=1.570796
           TYPE *," ENTER OPTION "1" , "2" OR "3"."
           TYPE *,"   OPTIONS:      1. TRAJCT DATA"
           TYPE *,"                 2. BLOCK DATA"
           TYPE *,"                 3. X & Y DATA"
           ACCEPT 33, IANS
     33    FORMAT(I1)
           IF(IANS.EQ.2) GO TO 201
           IF (IANS.EQ.3)  GO TO 301
           TYPE *,'ENTER FILENAME FOR DATA. '
           ACCEPT 9,NAME
     9     FORMAT(5A2)
           CALL ASSIGN(1,NAME,10)
           WRITE(5,2056)
     2056  FORMAT('  RESTART?  ("Y" OR "N")  ',$)
           READ(5,2057) ISTART
     2057  FORMAT(A1)
           IF(ISTART.EQ.'N') GO TO 2010
           READ(1,2012) IC,FX
     2012  FORMAT(I5,F8.0)
           READ(1,2013) VO,TO,US,CVO,CTO,CUS
     2013  FORMAT(6F10.0)
           DO 2020 LLL=1,1000
             READ(1,2011,END=2030) KKLL
     2011    FORMAT(A1)
     2020  CONTINUE
     2010  TYPE *," ENTER NUMBER OF DEBRIS TYPES AND DIFFERENTIATION
          1STEP. "
           ACCEPT *,IC,FX
           TYPE *," ENTER VO,TO AND US."
           ACCEPT *,VO,TO,US
           TYPE 8
     8     FORMAT(1H ," ENTER COVVO,COVTO,COVUS."
          1/,"  NOTE: COVVO= STANDARD DEV. OF VO/MEAN OF VO.  ")
           ACCEPT *,CVO,CTO,CUS
           WRITE(1,10) IC,FX
     10    FORMAT(1H ,I4,F8.4)
           WRITE(1,11) VO,TO,US,CVO,CTO,CUS
     2030  TYPE 30
     11    FORMAT(1H ,F9.2,5F10.3)
     30    FORMAT(1H ," FOR EACH DEBRIS PIECE,ENTER ",/,
          1"  HEIGHT   AMAX   AMIN  WEIGHT ICLASS ANGLE",/,
          2"  (FT)   (SQFT) (SQFT) (LBS)          (RAD)",/,
          3"     THEN ENTER"//
          4"  NB  COVWE  COVAMA COVAMI COVHH COVBB",///)
           DO 100 II=1,IC
     122     NUM=0
             WRITE(5,2054) IDTYP+1
     2054    FORMAT('  #',I4,'- ',$)
             READ(5,*,ERR=1010) HH,AMAX,AMIN,WE,IDTYP,BB
     2001   WRITE(1,15) IDTYP,WE,AMAX,AMIN,HH,BB
     123     NUM=3
```

```
15      FORMAT(1H ,I4,F8.2,4F8.4)
        READ(5,*,ERR=101) NB,CHH,CAMA,CAMI,CWE,CBB
        WRITE(1,16) NB,CWE,CAMA,CAMI,CHH,CBB
16      FORMAT(1H ,I4,5F8.4)
        GO TO 100
101     TYPE *,' LAST ENTRY CONTAINED AN ERROR.'
        TYPE *,' DO YOU WANT TO CONTINUE? (Y OR N) '
        ACCEPT 32,ANS
32      FORMAT(A1)
        IF(ANS.EQ.'N') GO TO 112
        WRITE(5,2055)
2055    FORMAT('  RETYPE ENTRY ')
        IF(NUM.EQ.3) BACKSPACE 1
        GO TO 122
100   CONTINUE
112   CALL CLOSE(1)
      CALL CLOSE(5)
      STOP
201   TYPE *,' ENTER INPUT FILE NAME FOR BLOCK PROGRAM.'
      ACCEPT 9,NAME
      CALL ASSIGN(1,'BLOCK.DAT')
      TYPE *,' ENTER NUMBER OF HOUSES IN BLOCK.'
      ACCEPT *,NHOUSE
      TYPE *,' ENTER NUMBER OF ROWS IN BLAST DIRECTION.'
      ACCEPT *,NIB
      TYPE *,' ENTER NUMBER OF ROWS NORMAL TO BLAST.'
      ACCEPT *,NJB
      WRITE(1,17) NAME
17    FORMAT(1H ,5A2)
      TYPE *,' ENTER OUTPUT FILE NAME FOR BLOCK PROGRAM.'
      ACCEPT 9,NAME
      WRITE(1,18) NHOUSE,NIB,NJB
18    FORMAT(1H ,I5,2I6)
      DO 200 JJ=1,NHOUSE
          TYPE *,' ENTER I,J COORDINATES FOR HOUSE #',JJ
          ACCEPT *,IH1(JJ),JH1(JJ)
200     CONTINUE
        WRITE(1,19) (IH1(KK),JH1(KK),KK=1,NHOUSE)
19      FORMAT(1H ,I5,11I6)
      WRITE(1,17) NAME
      CALL CLOSE(1)
      STOP
301   CALL XYDAT
      STOP
      END
```

```
DATA,DATA/-SP=DATA

              SUBROUTINE XYDAT
              DIMENSION NAME(5)
              DIMENSION X(200),Y(200)
              WRITE(5,51)
      51      FORMAT($,'    FILENAME FOR OUTPUT?    ')
              READ(5,52) NAME
      52      FORMAT(5A2)
              CALL ASSIGN(2,NAME)
              WRITE(5,53)
      53      FORMAT($,'    NUMBER OF CLASSES TO BE PROCESSED?   ')
              READ(5,*) NC
              WRITE(2,24) NC
      24      FORMAT(I10)
              DO 100 IIII=1,NC
      901       WRITE(5,54)
      54        FORMAT($,'    ENTER NGROUP,IDTYP.   ')
                READ(5,*) NGROUP,IDTYP
                WRITE(5,55)
      55        FORMAT($,'    NUMBER OF PIECES IN THIS CLASS?   ')
                READ(5,*) NICL
      902       WRITE(5,57)
      57        FORMAT($,'    IDDEB FOR FIRST DEBRIS PIECE IN CLASS?   ')
                READ(5,*) ID1
                WRITE(5,151)  NGROUP,IDTYP,NICL,ID1
      151       FORMAT(//,I10,I8,I6,I5,//,'    OK? ("Y" OR "N")  ')
                READ(5,58) ANS
      58        FORMAT(A1)
                IF (ANS.EQ.'N') GO TO 901
      903       WRITE(5,59)
      59        FORMAT('    ENTER X AND Y VALUES')
                DO 110 III=1,NICL
      190         READ(5,*,ERR=119)  X(III),Y(III)
                  GO TO 110
      119         WRITE(5,152) III
      152         FORMAT('    REENTER #',I4,'.')
                  GO TO 190
      110       CONTINUE
      904       WRITE(5,153)((III,X(III),Y(III),III=1,NICL))
      153       FORMAT(I10,2F10.3)
                WRITE(5,154)
      154       FORMAT(/,$,'    OK? ("Y" OR "N")   ')
                READ(5,58) ANS
                IF (ANS.EQ.'Y') GO TO 201
                WRITE(5,155)
      155       FORMAT($,'    WANT TO CHANGE ALL? ("Y" OR "N")   ')
                READ(5,58) ANS
                IF(ANS.EQ.'Y') GO TO 903
                WRITE(5,156)
      156       FORMAT($,'    NUMBER OF CHANGES?   ')
                READ(5,*) NCH
                WRITE(5,157)
      157       FORMAT('    ENTER I,X(I),Y(I).')
                DO 120 NN=1,NCH
                  READ(5,*) K,X(K),Y(K)
```

```
DATA,DATA/-SP=DATA

0058  120     CONTINUE
0059          GO TO 904
0060  201     WRITE(2,21) NGROUP,IDTYP,NICL,ID1
0061  21      FORMAT(I5,I5,I5,I7)
0062          WRITE(2,22)((X(KK),Y(KK),KK=1,NICL))
0063  22      FORMAT(2F8.3)
0064  100   CONTINUE
0065        CALL CLOSE(2)
0066        CALL CLOSE(5)
0067        RETURN
0068        END
```

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT .MAIN.

LOCAL VARIABLES, .PSECT $DATA, SIZE = 000434 (142. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET	NAME	TYPE	OFFSET
AMAX	R*4	000352	AMIN	R*4	000356	ANS	R*4	000414
CALA	R*4	000374	CAMI	R*4	000400	CBB	R*4	000410
CHH	R*4	000370	CTO	R*4	000324	CUS	R*4	000330
CVO	R*4	000320	CWE	R*4	000404	FX	R*4	000300
HH	R*4	000346	IANS	I*2	000272	IC	I*2	000276
IDTYP	I*2	000344	II	I*2	000340	ISTART	I*2	000274
JJ	I*2	000426	KK	I*2	000430	KKLL	I*2	000336
LLL	I*2	000334	NB	I*2	000366	NHOUSE	I*2	000420
NIB	I*2	000422	NJB	I*2	000424	NUM	I*2	000342
TO	R*4	000310	US	R*4	000314	VO	R*4	000304
WE	R*4	000362						

LOCAL AND COMMON ARRAYS:

NAME	TYPE	SECTION	OFFSET	-------SIZE-----	DIMENSIONS
BB	R*4	$DATA	000252	000014 (6.)	(3)
IH1	I*2	$DATA	000012	000120 (40.)	(40)
JH1	I*2	$DATA	000132	000120 (40.)	(40)
NAME	I*2	$DATA	000000	000012 (5.)	(5)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE
ASSIGN	R*4	CLOSE	R*4	XYDAT	R*4				

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT XYDAT

LOCAL VARIABLES, .PSECT $DATA, SIZE = 003162 (825. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET	NAME	TYPE	OFFSET
ANS	R*4	003142	IDTYP	I*2	003134	ID1	I*2	003140
II	I*2	003150	IIII	I*2	003146	IIIII	I*2	003130
K	I*2	003156	KK	I*2	003160	NC	I*2	003126
NCH	I*2	003152	NGROUP	I*2	003132	NICL	I*2	003136
NN	I*2	003154						

LOCAL AND COMMON ARRAYS:

NAME	TYPE	SECTION	OFFSET	-------SIZE-----	DIMENSIONS
NAME	I*2	$DATA	000000	000012 (5.)	(5)
X	R*4	$DATA	000012	001440 (400.)	(200)
Y	R*4	$DATA	001452	001440 (400.)	(200)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE
ASSIGN	R*4	CLOSE	R*4						

B.2 TRAJCT

```
 FORTRAN IV      V02.2-1          FRI 09-JAN-81 01:43:03          PAGE 001
TRAJCT,TRAJCT/-SP=TRAJCT

      C
      C * * PROGRAM TO STATISTICALLY ANALYZE BLAST DEBRIS TRANSPORT
      C * * COMPUTES EXPECTED VALUE AND VARIANCE OF RANGE AND TIME
      C     CONTRIBUTION OF EACH INPUT VARIABLE TO VARIANCE
      C
            DIMENSION E(7),V(7),A(7),DR(7),DT(7),DDR(7),DDT(7),PR(8),PT(8)
            DIMENSION STD(7)    ,NAME(5)
            COMMON NB
            CALL ASSIGN(5,'TI:')
            WRITE(5,55)
      55    FORMAT($,'    NAME OF INPUT FILE?   (10 CHAR MAX)   ')
            READ(5,56) NAME
      56    FORMAT(5A2)
            CALL ASSIGN(1,NAME)
            WRITE(5,57)
      57    FORMAT($,'    NAME OF OUTPUT FILE? (10 CHAR MAX)   ')
            READ(5,56) NAME
            CALL ASSIGN(2,NAME)
            CALL CLOSE(1)
            CALL CLOSE(2)
      C
      C * * ITERATE OVER CASES
      C
            READ(1,50)  IC,FX
      L
      L
      L
      L
      50    FORMAT(I5,F8.0)
            READ(1,49)  VO,TO,US,CVO,CTO,CUS
      49    FORMAT(6F10.0)
            E(6)=VO
            E(7)=TO
            STD(6)=COVVO*VO
            STD(7)=COVTO*TO
            V(6)=STD(6)**2
            V(7)=STD(7)**2
            FH=1.+FX
            FL=1.-FX
            WRITE(2,111) IC,FX
      111   FORMAT(1H ,I5,F8.4)
            DO 51 KK=1,IC
      C * * READ NOMINAL VALUES
            READ(1,1)  IDTYP,WE,AMAX,AMIN,HH,BB,
      1     FORMAT(I5,5F8.0)
      C * * INITIALIZE TIME AND VELOCITY
            TT=0.
            VV=0.
            WW=0.
            EE=0.
      C * * READ INPUT COEFFICIENTS OF VARIATION
            READ(1,3)  NB,  COVWE,COVAMA,COVAMI,COVHH,COVBB
      L
      L
```

```
 3    FORMAT(I5,5F8.0)
C * * SET EXPECTED VALUE AND VARIANCE OF INPUT
      E(1)=WE
      E(2)=AMAX
      E(3)=AMIN
      E(4)=HH
      E(5)=BB
      STD(1)=COVWE*WE
      STD(2)=COVAMA*AMAX
      STD(3)=COVAMI*AMIN
      STD(4)=COVHH*HH
      STD(5)=COVBB*BB
      V(1)=STD(1)**2
      V(2)=STD(2)**2
      V(3)=STD(3)**2
      V(4)=STD(4)**2
      V(5)=STD(5)**2
      CALL DAAB(WE,AMAX,AMIN,HH,BB,V0,T0,US,TT,VV,WW,EE,R,T)
      DO 5 I=1,7
      DO 6 J=1,7
 6    A(J)=E(J)
      DX=FX*STD(I)
      A(I)=E(I)+DX
      CALL DAAB(A(1),A(2),A(3),A(4),A(5),A(6),A(7),US,TT,VV,WW,EE,RH,TH)
      A(I)=E(I)-DX
      CALL DAAB(A(1),A(2),A(3),A(4),A(5),A(6),A(7),US,TT,VV,WW,EE,RL,TL)
C * * COMPUTE FIRST AND SECOND PARTIAL DERIVATIVES
      DR(I)=(RH-RL)/(2.*DX)
      DT(I)=(TH-TL)/(2.*DX)
      DDR(I)=(RH+RL-2.*R)/(DX)**2
      DDT(I)=(TH+TL-2.*T)/(DX)**2
 5    CONTINUE
C * * COMPUTE EXPECTED VALUE AND VARIANCE
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      DO 7 I=1,7
      SUM1=SUM1+DDR(I)*V(I)
      SUM2=SUM2+DDT(I)*V(I)
      SUM3=SUM3+DR(I)**2*V(I)
 7    SUM4=SUM4+DT(I)**2*V(I)
      ER=R+.5*SUM1
      ET=T+.5*SUM2
      VR=SUM3+(COVE*ER)**2
      VT=SUM4+(COVE*ET)**2
      SR=SQRT(VR)
      ST=SQRT(VT)
C * * COMPUTE INDIVIDUAL CONTRIBUTIONS TO UNCERTAINTY
      DO 8 I=1,7
      PR(I)=DR(I)**2*V(I)/VR
 8    PT(I)=DT(I)**2*V(I)/VT
      PR(8)=(COVE*ER)**2/VR
      PT(8)=(COVE*ET)**2/VT
```



```
      WRITE(2,10) IDTYP,NB,R,ER,SR,T,ET,ST
 10   FORMAT(1H ,I5,I2,2F8.2,F8.3,3F8.4)
      WRITE(2,13) WE,AMAX,AMIN,HH,BB
 13   FORMAT(1H ,F8.2,4F8.4)
      WRITE(2,14) COVWE,COVAMA,COVAMI,COVHH,COVBB
 14   FORMAT(1H ,5F8.4)
      WRITE(2,12) (PR(I),I=1,8),(PT(I),I=1,8)
 12   FORMAT(1H ,8F8.3,/,1H ,8F8.3)
 51   CONTINUE
      CALL CLOSE(1)
      CALL CLOSE(2)
      STOP
      END
```

```
0001          SUBROUTINE DAAB(WE,A    ,AMIN,HH,BB,U0,T0,US,TT,VV,WW,EE,X,T)
0002          COMMON NB
        C      DEBRIS ANALYSIS
        C
        C * * PLANE MOTION WITH/ROTATION, GRAVITY
        C
0003          S=AMIN/A
0004          E0=1.
0005          T = TT
0006          V = VV
0007          W = WW
0008          X = 0.
0009          Y = HH
0010          B = BB
0011          E = EE
0012          U = U0*(1.-TT/T0)*EXP(-E0*TT/T0)
0013          C = U-V
0014          H = B+ATAN(W/C)
0015          G = SQRT(C*C+W*W)
0016          F = 0.05*A/WE
0017          F1 = 1.2*F
0018          F2 = (1.-S)*F
0019          F3 = F2/(.8*SQRT(A)*(S*S+1.))
0020          I = 1
0021          M = 0
0022      200 CONTINUE
0023          I = I+1
0024          C = U-V
0025          H = B+ATAN(W/C)
0026          G = SQRT(C*C+W*W)
0027          D = G*G*C/ABS(C)
0028          DT = .1/(F1*(S+(1.-S)*SIN(H)*SIN(H))*ABS(C))
0029          IF (ABS(E) .LT. 1.)   GO TO 202
0031          DT1 = .1/ABS(E)
0032          IF (DT .GT. DT1)   DT = DT1
0034      202 CONTINUE
0035          IF (DT .GT. .1)   DT = .1
0037          IF (I .LT. 12)   DT = .01
0039          TSAVE=T
0040          T = T+DT
0041          IF (T .GT. 12.)   GO TO 100
0043          V = V+F1*D*DT*(S+(1.-S)*SIN(H)*SIN(H))
0044          W = W+F2*D*DT*SIN(2.*H)-32.2*DT
0045           XSAVE=X
0046          X = X+V*DT
0047          YSAVE=Y
0048          Y = Y+W*DT
0049          E = E+F3*D*DT*SIN(2.*H)
0050          B = B+E*DT
0051          T1 = (T-X/US)/T0
0052          U = U0*(1.-T1)*EXP(-E0*T1)
0053          IF (I .GT. 800)   GO TO 100
0055          IF (W .LT. 0. .AND. Y .LT. 0.)   GO TO 203
0057          GO TO 200
```

TRAJCT,TRAJCT/-SP=TRAJCT

```
0058     203  M = M+1
       C    CHECK FOR NUMBER OF BOUNCES
0059          IF (M .GE. NB) GO TO 100
0061          DELT=-YSAVE/W
0062          T=TSAVE+DELT
0063          X=XSAVE+V*DELT
0064          V = .5*V
0065          W = -.5*W
0066          Y=0.
0067          GO TO 200
0068      100 CONTINUE
       C * * RECOMPUTE X AND T AT Y=0
0069          DT=-YSAVE/W
0070          T=TSAVE+DT
0071          X=XSAVE+V*DT
0072          RETURN
0073          END
```

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT .MAIN.

LOCAL VARIABLES, .PSECT $DATA, SIZE = 001022 (265. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET	NAME	TYPE	OFFSET
AMAX	R*4	000612	AMIN	R*4	000616	BB	R*4	000626
COVAMA	R*4	000656	COVAMI	R*4	000662	COVBB	R*4	000672
COVE	R*4	000772	COVHH	R*4	000666	COVTO	R*4	000566
COVVO	R*4	000562	COVWE	R*4	000652	CTO	R*4	000552
CUS	R*4	000556	CVO	R*4	000546	DX	R*4	000712
EE	R*4	000646	ER	R*4	000756	ET	R*4	000762
FH	R*4	000572	FL	R*4	000576	FX	R*4	000526
HH	R*4	000622	I	I*2	000706	IC	I*2	000524
IDTYP	I*2	000604	J	I*2	000710	KK	I*2	000602
R	R*4	000676	RH	R*4	000716	RL	R*4	000726
SR	R*4	001002	ST	R*4	001006	SUM1	R*4	000736
SUM2	R*4	000742	SUM3	R*4	000746	SUM4	R*4	000752
T	R*4	000702	TH	R*4	000722	TL	R*4	000732
TT	R*4	000632	TO	R*4	000536	US	R*4	000542
VR	R*4	000766	VT	R*4	000776	VV	R*4	000636
VO	R*4	000532	WE	R*4	000606	WW	R*4	000642

COMMON BLOCK / /, SIZE = 000002 (1. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET	NAME	TYPE	OFFSET
NB	I*2	000000						

LOCAL AND COMMON ARRAYS:

NAME	TYPE	SECTION	OFFSET	------SIZE-----	DIMENSIONS
A	R*4	$DATA	000070	000034 (14.)	(7)
DDR	R*4	$DATA	000214	000034 (14.)	(7)
DDT	R*4	$DATA	000250	000034 (14.)	(7)
DR	R*4	$DATA	000124	000034 (14.)	(7)
DT	R*4	$DATA	000160	000034 (14.)	(7)
E	R*4	$DATA	000000	000034 (14.)	(7)
NAME	I*2	$DATA	000440	000012 (5.)	(5)
PR	R*4	$DATA	000304	000040 (16.)	(8)
PT	R*4	$DATA	000344	000040 (16.)	(8)
STD	R*4	$DATA	000404	000034 (14.)	(7)
V	R*4	$DATA	000034	000034 (14.)	(7)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE
ASSIGN	R*4	CLOSE	R*4	DAAB	R*4	SQRT	R*4		

```
FORTRAN IV STORAGE MAP FOR PROGRAM UNIT DAAB

LOCAL VARIABLES, .PSECT $DATA, SIZE = 000234 (    78. WORDS)

NAME    TYPE  OFFSET       NAME    TYPE  OFFSET       NAME    TYPE  OFFSET
 A      R*4 @ 000002       AMIN    R*4 @ 000004        B      R*4   000060
 BB     R*4 @ 000010       C       R*4   000074        D      R*4   000134
 DELT   R*4   000170       DT      R*4   000140        DT1    R*4   000144
 E      R*4   000064       EE      R*4 @ 000026        E0     R*4   000040
 F      R*4   000110       F1      R*4   000114        F2     R*4   000120
 F3     R*4   000124       G       R*4   000104        H      R*4   000100
 HH     R*4 @ 000006       I       I*2   000130        M      I*2   000132
 S      R*4   000034       T       R*4 @ 000032        TSAVE  R*4   000150
 TT     R*4 @ 000020       T0      R*4 @ 000014        T1     R*4   000164
 U      R*4   000070       US      R*4 @ 000016        U0     R*4 @ 000012
 V      R*4   000044       VV      R*4 @ 000022        W      R*4   000050
 WE     R*4 @ 000000       WW      R*4 @ 000024        X      R*4 @ 000030
 XSAVE  R*4   000154       Y       R*4   000054        YSAVE  R*4   000160

COMMON BLOCK /      /, SIZE = 000002 (    1. WORDS)

[illegible]

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME    TYPE   NAME    TYPE   NAME    TYPE   NAME    TYPE   NAME    TYPE
 ABS     R*4    ATAN    R*4    EXP     R*4    SIN     R*4    SQRT    R*4
```

B.3 RANGER

```
 FORTRAN IV      V02.2-1          FRI 09-JAN-81 01:49:32           PAGE 001
,RANGER/-SP=RANGA

0001          DIMENSION A(300),NAME(6),IDELT(25),JDELT(25),N2(5)
0002          DIMENSION IXY1(100),ET1(100),IDTYP1(100),NODE(100),SIZE1(100)
0003          EQUIVALENCE (A(1),ET1(1)),(A(101),SIZE1(1)),(A(201),IXY1(100))
0004          CALL ASSIGN(5,'TI:')
0005          WRITE(5,50)
0006    50    FORMAT(1H ,' ****LOCAL TO GLOBAL COORDINATE PROGRAM****'//
             1'     THIS PROGRAM LOCATES THE POST-BLAST RESTING PLACE OF EVERY'/
             2' DEBRIS PIECE IN A GIVEN BUILDING.  THE PROGRAM REQUIRES TWO'/
             3' INPUT FILES AND INTERACTIVE INPUT FROM A TERMINAL.  THE FIRST'/
             4' INPUT FILE MUST BE CREATED BY RUNS OF THE "FLYER" DEBRIS-'/
             5' TRANSPORT PROGRAM.'/
             6'     ENTER THE NAME OF THE "FLYER" FILE TO BE USED AS INPUT.')
0007          READ(5,49) NAME
0008    49    FORMAT(6A2)
0009          CALL ASSIGN(2,NAME)
0010          CALL ASSIGN(1,'FLYER.TEM')
0011          READ(2,20) IC
0012          DEFINE FILE 1 (IC,10,U,NEXT)
0013          NEXT=1
0014          DO 888  NN=1,IC
0015            READ(2,21)  ID,NB2,R,ER,SDR,T,ET,SDT,AMAX
0016    21      FORMAT(I6,I2,6F8.0/9X,F8.0///)
0017            WRITE(1'NEXT) ER,SDR,ET,SDT,AMAX
0018   888    CONTINUE
0019          CALL CLOSE(2)
0020          NN=300
0021          ND=0
0022          WRITE(5,51) NN
0023    51    FORMAT(1H ,'     THE SECOND INPUT FILE SHOULD CONTAIN A TABLE OF'/
             1' THE STANDARD NORMAL DISTRIBUTION INDENTICAL TO TABLE III,P436'/
             2' OF "MATHEMATICAL STATISTICS" BY JOHN FREUND,2ND ED, 1972,'/
             3' PRENTICE-HALL.  THE FILE SHOULD BE CALLED "NORMAL.DAT".  THE'/
             4' VALUES IN THE TABLE SHOULD BE THE AREA UNDER THE STANDARD'/
             5' NORMAL CURVE(STD DEV=1,MEAN=0) FROM THE MEAN TO THE Z-VALUE'/
             6' TABLE VALUES SHOULD START AT THE AREA FOR Z=0 AND PROCEED FOR'/
             7' AT LEAST',I4,' Z INCREMENTS OF 0.001 .  THE FIRST ENTRY SHOULD'/
             8/' BE 0.000000, THE SECOND 0.004000, AND THE 300TH 0.498700.'/
             9' THE FILE CONSISTS OF 80-CHARACTER RECORDS,FORMAT(10F8.6)')
0024          WRITE(5,59)
0025    59    FORMAT(//'     HIT RETURN TO CONTINUE.')
0026          READ(5,58)  START
0027    58    FORMAT(A2)
0028          WRITE(5,52)
0029    52    FORMAT(///,'      ****GRID DIMENSIONS****'//)
0030          WRITE(5,53)
0031    53    FORMAT('      THIS PROGRAM CONSIDERS THE INITIAL COORDINATES AND FL
             1IGHT DISTANCE'/' OF A DEBRIS PIECE AND DETERMINES ITS FINAL RESTI
             2NG PLACE RELATIVE TO A'/' HORIZONTAL GRID.  SECTIONS OF THE GRID
             3ARE DEFINED BY I AND J'/' COORDINATES.  THE GRID ORIGIN IS THE SA
             4ME ONE USED FOR THE INITIAL'/' COORDINATES.  THE I-DIRECTION IS
             5 PARALLEL TO THE BLAST,AND THE'/' J-DIRECTION IS NORMAL TO THE BL
             6AST.  THE OVERALL SIZE OF THE GRID AND'/' THE UNIT SECTION
             7 SHOULD BE DETERMINED NOW.'/'      ALL LENGTHS IN FEET.'//'     EN
             8TER THE TOTAL LENGTH OF THE GRID IN BLAST DIRECTION.  ',$)
```

```
              READ(5,*) XTOT
              WRITE(5,54)
        54    FORMAT(1H$,'    ENTER TOTAL WIDTH OF GRID NORMAL TO BLAST.  ')
              READ(5,*) YTOT
              WRITE(5,55)
        55    FORMAT('     ENTER LENGTH OF UNIT RECTANGLE.  ',$)
              READ(5,*) XUNIT
              WRITE(5,56)
        56    FORMAT('     ENTER WIDTH OF UNIT RECTANGLE.  ',$)
              READ(5,*) YUNIT
              WRITE(5,61)
        61    FORMAT($,'    ENTER BLAST ANGLE.(CLOCKWISE FROM X-AXIS,DEGREES) ')
              READ(5,*) THETA
              THETR=THETA*.017453293
              COST=COS(THETR)
              SINT=SIN(THETR)
              NI=XTOT/XUNIT+4
              NJ=YTOT/YUNIT+4
              AUNIT=XUNIT*YUNIT
              WRITE(5,57) XTOT,YTOT,NI,NJ,XUNIT,YUNIT,THETA
        57    FORMAT(////21X,'****GRID DIMENSIONS FOR THIS RUN****'///
             126X,'GRID',F9.1,' BY',F6.1,' FEET'/
             233X,I6,' BY',I6,' UNITS'//
             316X,'UNIT RECTANGLE',F9.1,' BY',F6.1,' FEET'/
             519X,'BLAST ANGLE=',F6.2,' DEGREES.'////
             4'    ENTER THE NAME OF THE OUTUT FILE TO BE USED BY THIS RUN.')
              READ(5,49) NAME
              WRITE(5,12)
        12    FORMAT(25X,'****DEBRIS CLASS DATA****'///
             1'    THIS PROGRAM IS DESIGNED TO OPERATE ON LARGE CLASSES OF SIMI
             2LAR'/' DEBRIS PIECES.  THE RANGE WILL BE THE SAME FOR ALL OF THES
             3E PIECES'/' BUT THE INITIAL POSITIONS WILL BE DIFFERENT.  THE PRO
             4GRAM CAN VARY THE'/' RANGE  FOR THE DIFFERENT MEMBERS OF THE CLAS
             5S USING THE STATISTICAL'/' PARAMETERS FROM THE FLYER PROGRAM.'/)
              CALL ASSIGN(4,'NORMAL.DAT')
              READ(4,41) START,(A(IZ),IZ=1,NN)
        41    FORMAT(10F8.0)
              READ(4,42) (IDELT(III),JDELT(III),III=1,25)
        42    FORMAT(1X,26I3)
              CALL CLOSE(4)
              CALL ASSIGN(2,'RANGE2.TEM')
              WRITE(5,71)
        71    FORMAT('    NAME OF INPUT FILE WITH XY DATA FOR DEBRIS PIECES?')
              READ(5,49) N2
              CALL CLOSE(5)
              CALL ASSIGN(4,N2)
              READ(4,43) NC
        43    FORMAT(I10)
              DO 100 II=1,NC
                ND1=ND
                REM=0.
                READ(4,44) IDFLY,IDTYP,NICL,ID1
        44      FORMAT(I5,I5,I5,I7)
                NICL2=NICL/2
```

,RANGER/-SP=RANGA

```
15      FORMAT(A1)
20      FORMAT(I10)
        READ(1'IDFLY) ER,SDR,ET,SDT,AMAX
121     PIECE1=AMAX/AUNIT
        SIZE=AUNIT/AMAX
        IF(SIZE.GT.1.00) SIZE=1.00
        ERY=ER*SINT
        ERX=ER*COST
        SDRY=SDR*SINT
        SDRX=SDR*COST
        IF(NICL.GT.3) GO TO 130
        DO 120 IXY=ID1,ID1+NICL-1
          READ(4,45) XL,YL
45        FORMAT(2F8.0)
          X=XL+ERX
          Y=YL+ERY
          IL=X/XUNIT+3.0
          JL=Y/YUNIT+3.0
          IPIECE=PIECE1
          AREAP=AMAX
          DO 124 NNNN=1,IPIECE
            AREAP=AREAP-AUNIT
            I=IL+IDELT(NNNN)
            J=JL+JDELT(NNNN)
            WRITE(2) IXY,I,J,ET,IDTYP,SIZE
            ND=ND+1
124       CONTINUE
          SIZER=AREAP/AMAX
          IF(SIZER.LT.0.10) GO TO 120
          I=IL+IDELT(IPIECE+1)
          J=JL+JDELT(IPIECE+1)
          WRITE(2) IXY,I,J,ET,IDTYP,SIZER
          ND=ND+1
120     CONTINUE
        GO TO 100
130     CONTINUE
        Z1=0
        IZ1=1
        KK=1
        IXYY=ID1
149     CONTINUE
        DO 140 IZ=IZ1,NN
          IAREA=A(IZ)*NICL
          IF (IAREA.GE.KK) GO TO 141
140     CONTINUE
        IZ=NN
        IAREA=NICL2
141     Z2=IZ/100.
        ZAV=(2*Z1+Z2)/3.
        DRX=ZAV*SDRX
        DRY=ZAV*SDRY
        ER1X=ERX+DRX
        ER2X=ERX-DRX
        ER1Y=ERY+DRY
```

```
.RANGER/-SP=RANGA

0134            ER2Y=ERY-DRY
0135            ET10=ET+ZAV*SDT
0136            ET2=ET-ZAV*SDT
0137            IF (ET2.LE.0.) ET2=0.
0139            Z1=Z2
0140            IZ1=IZ
0141            DO 142 KKK=KK,IAREA
0142              READ(4,45) XL,YL
0143              X=XL+ER1X
0144              Y=YL+ER1Y
0145              IH=X/XUNIT+3.0
0146              JH=Y/YUNIT+3.0
0147              IXYL=IXYY+1
0148              IF(IXYL.GE.NICL+ID1) GO TO 1242
0150              READ(4,45) XL,YL
0151              X=XL+ER2X
0152              Y=YL+ER2Y
0153              IL=X/XUNIT+3.0
0154              JL=Y/YUNIT+3.0
0155              IPIECE=PIECE1
0156 1242         AREAP=AMAX
0157              DO 160 NNNN=1,IPIECE
0158                AREAP=AREAP-AUNIT
0159                I=IH+IDELT(NNNN)
0160                J=JH+JDELT(NNNN)
0161                WRITE(2) IXYY,I,J,ET10,IDTYP,SIZE
0162                ND=ND+1
0163                IF(IXYL.GE.NICL+ID1) GO TO 160
0165                I=IL+IDELT(NNNN)
0166                J=JL+JDELT(NNNN)
0167                WRITE(2) IXYL,I,J,ET2,IDTYP,SIZE
0168                ND=ND+1
0169 160          CONTINUE
0170              IXYY=IXYY+2
0171              SIZER=AREAP/AMAX
0172              IF(SIZER.LT.0.10) GO TO 142
0174              I=IH+IDELT(IPIECE+1)
0175              J=JH+JDELT(IPIECE+1)
0176              IXYHH=IXYY-2
0177              WRITE(2) IXYHH,I,J,ET10,IDTYP,SIZER
0178              ND=ND+1
0179              IF(IXYL.GE.NICL+ID1) GO TO 142
0181              I=IL+IDELT(IPIECE+1)
0182              J=JL+JDELT(IPIECE+1)
0183              WRITE(2) IXYL,I,J,ET2,IDTYP,SIZER
0184              ND=ND+1
0185 142        CONTINUE
0186            KK=IAREA+1
0187            IF (IXYY.LT.NICL+ID1) GO TO 149
0189 100      CONTINUE
0190 200      CONTINUE
0191          CLOSE(UNIT=1,DISP='DELETE')
0192          CALL CLOSE(4)
0193          REWIND 2
```

```
      CALL ASSIGN(1,'RANGER.TEM')
25    FORMAT(1H ,I7,I6,I6,2F6.2)
      CALL ASSIGN(3,'KOUNT.OUT')
      DO 600 JJ=1,NJ
        DO 700 II=1,NI
          KOUNT=0
          DO 800 NNN=1,ND
            READ(2,END=899) ID,I,J,ET,IDTYP,SIZE
            IF(J.NE.JJ) GO TO 800
            IF(I.NE.II) GO TO 800
            KOUNT=KOUNT+1
            WRITE(1) ID,ET,IDTYP,SIZE
800       CONTINUE
899       REWIND 2
      IF(KOUNT.NE.0) WRITE(3) II,JJ,KOUNT
700     CONTINUE
600   CONTINUE
      REWIND 1
      REWIND 3
      CLOSE(UNIT=2,DISP='DELETE')
      CALL ASSIGN(2,NAME)
      WRITE(2,25) ND,NI,NJ,XUNIT,YUNIT
      NIJ=NI*NJ
      DO 900 KKK=1,NIJ
        READ(3,END=1000) I,J,KOUNT
        READ(1) IXY1(1),ET1(1),IDTYP1(1),SIZE1(1)
        NODE(1)=1
        IF(KOUNT.EQ.1) GO TO 915
        DO 910 NREC=2,KOUNT
          READ(1) IXY1(NREC),ET1(NREC),IDTYP1(NREC),SIZE1(NREC)
          ET10=ET1(NREC)
          DO 950 NN=NREC-1,1,-1
            IDTOP=NODE(NN)
            IF(ET10.GE.ET1(IDTOP)) GO TO 955
            NODE(NN+1)=IDTOP
950       CONTINUE
          NN=0
955       NODE(NN+1)=NREC
910     CONTINUE
915     CONTINUE
        WRITE(2,31) I,J,KOUNT
31      FORMAT(1H ,3I4)
        DO 960 NNN=1,KOUNT
          ID=NODE(NNN)
          WRITE(2,921) IXY1(ID),ET1(ID),IDTYP1(ID),SIZE1(ID)
960     CONTINUE
900   CONTINUE
921   FORMAT(1H ,I6,F7.3,I4,F7.4)
1000  CLOSE(UNIT=1,DISP='DELETE')
      CALL CLOSE(2)
      CLOSE(UNIT=3,DISP='DELETE')
      STOP
      END
```

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT .MAIN.

LOCAL VARIABLES, .PSECT $DATA, SIZE = 003730 (1004. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET		NAME	TYPE	OFFSET
AMAX	R*4	003374	AREAP	R*4	003566		AUNIT	R*4	003452
COST	R*4	003436	DRX	R*4	003630		DRY	R*4	003634
ER	R*4	003550	ERX	R*4	003522		ERY	R*4	003516
ER1X	R*4	003640	ER1Y	R*4	003650		ER2X	R*4	003644
ER2Y	R*4	003654	ET	R*4	003364		ET10	R*4	003660
ET2	R*4	003604	I	I*2	003574		IAREA	I*2	003616
IC	I*2	003332	ID	I*2	003340		IDFLY	I*2	003474
IDTOP	I*2	003714	IDTYP	I*2	003476		ID1	I*2	003502
IH	I*2	003672	II	I*2	003464		III	I*2	003460
IL	I*2	003560	IPIECE	I*2	003564		IXY	I*2	003536
IXYHH	I*2	003700	IXYL	I*2	003676		IXYY	I*2	003614
IZ	I*2	003456	IZ1	I*2	003610		J	I*2	003576
JH	I*2	003674	JJ	I*2	003702		JL	I*2	003562
KK	I*2	003612	KKK	I*2	003670		KOUNT	I*2	003704
NB2	I*2	003342	NC	I*2	003462		ND	I*2	003400
ND1	I*2	003466	NEXT	I*2	003334	Eqv	NI	I*2	003446
NICL	I*2	003500	NICL2	I*2	003504		NIJ	I*2	003710
NJ	I*2	003450	NN	I*2	003336		NNN	I*2	003706
NNNN	I*2	003572	NREC	I*2	003712		PIECE1	R*4	003506
R	R*4	003344	REM	R*4	003470		SDR	R*4	003354
SDRX	R*4	003532	SDRY	R*4	003526		SDT	R*4	003370
SINT	R*4	003442	SIZE	R*4	003512		SIZER	R*4	003600
START	R*4	003402	T	R*4	003360		THETA	R*4	003426
THETR	R*4	003432	X	R*4	003550		XL	R*4	003540
XTOT	R*4	003406	XUNIT	R*4	003416		Y	R*4	003554
YL	R*4	003544	YTOT	R*4	003412		YUNIT	R*4	003422
ZAV	R*4	003624	Z1	R*4	003604		Z2	R*4	003620

LOCAL AND COMMON ARRAYS:

NAME	TYPE	SECTION	OFFSET	------SIZE-----		DIMENSIONS
A	R*4	$DATA	000002	002260 (	600.)	(300)
ET1	R*4	$DATA	000002	000620 (	200.)	(100)
IELT	I*2	$DATA	002276	000062 (	25.)	(25)
IDTYP1	I*2	$DATA	002454	000310 (	100.)	(100)
IXY1	I*2	$DATA	001134	000310 (	100.)	(100)
JDELT	I*2	$DATA	002360	000062 (	25.)	(25)
NAME	I*2	$DATA	002262	000014 (	6.)	(6)
NODE	I*2	$DATA	002764	000310 (	100.)	(100)
N2	I*2	$DATA	002442	000012 (	5.)	(5)
SIZE1	R*4	$DATA	000622	000620 (	200.)	(100)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE
ASSIGN	R*4	CLOSE	R*4	COS	R*4	SIN	R*4		

B.4 BLOCK

```
FORTRAN IV      V02.2-1         TUE 06-JAN-81 14:15:32          PAGE 001
BLOCK,BLOCK/-SP=BLOCK

0001          DIMENSION IH1(20),JH1(20),IPT(5000),NAME(5)
0002          DIMENSION NODE(200),ET(200),ID(200),IDTYP(200),SIZE(200)
0003          CALL ASSIGN(4,'BLOCK.DAT')
0004          READ(4,41) NAME
0005    41    FORMAT(1X,5A2)
0006          CALL ASSIGN(1,NAME)
0007          READ(4,42) NHOUSE,NIB,NJB
0008    42    FORMAT(3I6)
0009          READ(4,43) (IH1(NN),JH1(NN),NN=1,NHOUSE)
0010    43    FORMAT(6I6,6I6)
0011          READ(4,41) NAME
0012          CALL CLOSE(4)
0013          CALL ASSIGN(2,'BLOCK.TEM')
0014          READ(1,11) NDT,NI,NJ,XUNIT,YUNIT
0015          DEFINE FILE 2 (NDT,6,U,IREC)
0016    11    FORMAT(1X,I7,2I6,2F6.0)
0017          NIJ=NI*NJ
0018          NREC=1
0019          IREC=1
0020          READ(1,12) I,J,KOUNT
0021          IJ=(J-1)*NI+I
0022          DO 200 KK=1,NIJ
0023             IF(KK.LE.IJ) GO TO 205
0025             NREC=NREC+KOUNT
0026             READ(1,13,END=200) (ID(MMM),ET(MMM),IDTYP(MMM)
             1,SIZE(MMM),MMM=1,KOUNT)
0027    13       FORMAT(1X,I6,F7.0,I4,F7.0)
0028             DO 210 LL=KOUNT,1,-1
0029                WRITE(2'IREC) ID(LL),ET(LL),IDTYP(LL),SIZE(LL)
0030    210      CONTINUE
0031             READ(1,12,END=200) I,J,KOUNT
0032    12       FORMAT(1X,3I4)
0033             IJ=(J-1)*NI+I
0034    205      IPT(KK)=NREC
0035    200   CONTINUE
0036          CALL CLOSE(1)
0037          CALL ASSIGN(3,NAME)
0038          DO 300 II=1,NIB
0039             DO 320 JJ=1,NJB
0040                NTOT=0
0041                DO 340 KK=1,NHOUSE
0042                   IDELT=II-IH1(KK)
0043                   JDELT=JJ-JH1(KK)
0044                   IF(IDELT.LT.0.OR.IDELT.GE.NI) GO TO 340
0046                   IF(JDELT.LT.0.OR.JDELT.GE.NI) GO TO 340
0048                   IL=IDELT+1
0049                   JL=JDELT+1
0050                   IJL=(JL-1)*NI+IL
0051                   IPT1=IPT(IJL)
0052                   IPTN=IPT(IJL+1)
0053                   NREC=IPTN-IPT1
0054                   IF(NREC.LE.0) GO TO 340
0056                   FIND (2'IPT1)
0057                   NTOP=NTOT
```

```
                IHOUSE=KK*1000
                DO 360 LL=NREC,1,-1
                  III=NTOT+LL
                  READ(2'IREC) IDL,ET10,IDTYP(III),SIZE(III)
                  ID(III)=IDL+IHOUSE
                  ET(III)=ET10
                  IF(NTOP.EQ.0) GO TO 379
                  DO 370 MM=NTOP,1,-1
                    IDTOP=NODE(MM)
                    IF(ET10.GE.ET(IDTOP)) GO TO 379
                NODE(MM+LL)=IDTOP
370           CONTINUE
                  MM=0
379           NODE(MM+LL)=III
                  NTOP=MM
360             CONTINUE
                NTOT=NTOT+NREC
340           CONTINUE
              IF(NTOT.EQ.0) GO TO 320
              WRITE(3,34) II,JJ,NTOT
34            FORMAT(1H ,3I4)
              DO 375 NN=1,NTOT
                NNN=NODE(NN)
                WRITE(3,35) ID(NNN),ET(NNN),IDTYP(NNN),SIZE(NNN)
35              FORMAT(1H ,I6,F7.3,I4,F7.4)
375           CONTINUE
320         CONTINUE
300       CONTINUE
          CLOSE(UNIT=2,DISP='DELETE')
          CALL CLOSE(3)
          STOP
          END
```

FORTRAN IV STORAGE MAP FOR PROGRAM UNIT .MAIN.

LOCAL VARIABLES, .PSECT $DATA, SIZE = 031312 (6501. WORDS)

NAME	TYPE	OFFSET	NAME	TYPE	OFFSET		NAME	TYPE	OFFSET
ET10	R*4	031276	I	I*2	031224		IDELT	I*2	031250
IDL	I*2	031274	IDTOP	I*2	031304		IHOUSE	I*2	031270
II	I*2	031242	III	I*2	031272		IJ	I*2	031232
IJL	I*2	031260	IL	I*2	031254		IPTN	I*2	031264
IPT1	I*2	031262	IREC	I*2	031216	Eqv	J	I*2	031226
JDELT	I*2	031252	JJ	I*2	031244		JL	I*2	031256
KK	I*2	031234	KOUNT	I*2	031230		LL	I*2	031240
MM	I*2	031302	MMM	I*2	031236		NDT	I*2	031200
NHOUSE	I*2	031170	NI	I*2	031202		NIB	I*2	031172
NIJ	I*2	031220	NJ	I*2	031204		NJB	I*2	031174
NN	I*2	031176	NNN	I*2	031306		NREC	I*2	031222
NTOP	I*2	031266	NTOT	I*2	031246		XUNIT	R*4	031206
YUNIT	R*4	031212							

LOCAL AND COMMON ARRAYS:

NAME	TYPE	SECTION	OFFSET	------SIZE-----	DIMENSIONS
ET	R*4	$DATA	024372	001440 (400.)	(200)
ID	I*2	$DATA	026032	000620 (200.)	(200)
IDTYP	I*2	$DATA	026652	000620 (200.)	(200)
IH1	I*2	$DATA	000000	000050 (20.)	(20)
IPT	I*2	$DATA	000120	023420 (5000.)	(5000)
JH1	I*2	$DATA	000050	000050 (20.)	(20)
NAME	I*2	$DATA	023540	000012 (5.)	(5)
NODE	I*2	$DATA	023552	000620 (200.)	(200)
SIZE	R*4	$DATA	027472	001440 (400.)	(200)

SUBROUTINES, FUNCTIONS, STATEMENT AND PROCESSOR-DEFINED FUNCTIONS:

NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE	NAME	TYPE
ASSIGN	R*4	CLOSE	R*4						

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ASSESSMENT OF COMBINED EFFECTS OF BLAST AND FIRE ON PERSONNEL SURVIVABILITY (Unclassified)

Final Report

Contract DCPA01-79-C-0265
Work Unit 2564D

IIT Research Institute
June 1982

ABSTRACT: The objective of the study described was (1) to perform a preliminary analysis of hazards to sheltered personnel in a blast-fire environment produced by the detonation of a 1 MT nuclear weapon near the ground surface, and (2) to lay the basic groundwork for developing a consistent, formal methodology for estimating the probability of people survival in a blast-fire environment.

A portion of a city consisting of identical, single-family framed residences and three types of below-grade personnel shelters located in selected areas was formulated and subjected to a simulated, single weapon nuclear weapon attack. Zones of structural blast damage were identified and debris distribution in selected areas was determined. Debris piles were described in spacial coordinates and composition (combustible, noncombustible) at various locations of the city blocks. Time dependent fire effects were determined using existing fire ignition and fire spread computer programs developed at IITRI. Hazards were quantified and the probability of people survival was estimated in terms of shelter effectiveness when located in different zones of blast damage.

The three personnel shelters included (1) a conventional wood framed basement upgraded to provide additional blast resistance, (2) a conventional basement with a reinforced concrete overhead slab, and (3) an expedient, pole type below-grade shelter. The last shelter listed proved to be the most effective of the three in all blast damage zones and fire environments considered in this study.

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