COMBINED EFFECTS OF BLAST AND FIRE ON PERSONNEL SURVIVABILITY

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INTRODUCTION

This paper deals with the 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. Material for the paper was derived from a study by IIT Research Institute for the Federal Emergency Management Agency (Reference 1).

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 attack. Zones of structural blast damage were identified and debris distributions in selected areas were determined. Debris piles were described in spatial coordinates and composition (combustible, non-combustible) at various locations within the city. Time dependent fire effects were determined using existing fire ignition and fire spread computer programs. 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 framed basement, (2) a conventional basement having a reinforced concrete slab instead of a wood floor overhead and (3) an expedient, pole type below-grade shelter.

If sufficient lead time is available, each of the basements in the first two categories may be expediently upgraded to provide additional protection against the effects of blast and fires. Expedient upgrading of shelter space includes all of the following measures that can be applied in available time using readily available materials and equipment.

- Prevention of air blast entry
- Reduction of air blast loads on exterior surfaces

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- Structural strengthening against air blast
- Provision of radiation protection
- Fire prevention
- Provision of firefighting equipment

Expedient upgrading measures are considered.

Although the emphasis is on hazards produced by a nuclear weapon detonation, the results can also be viewed in the context of a large, conventional accidental explosion.

DESCRIPTION OF SHELTERS

<u>Basement Shelters</u> - Both basements are of a type that may be found in two-story framed, single-family residence except that one has an overhead wood joist floor, and the other a light reinforced concrete slab.

The building type studied can be considered to include all single-family, two story residences constructed with wood stud walls, wood joist floors and ceilings, and wood rafters or wood truss framing. The framing system may be "balloon", "platform" or any variation. Structure, space and wall openings are considered to be in general accord with municipal codes. Sizes range from 1000 to 2000 square feet for two to five bedrooms. Exterior wall coverings include wood, composition, stucco or metal siding over insulation board. Interior walls are primarily wood stud with gypsum board or plaster covering. Roofs include different shapes and slopes with wood or composition shingles and flat roofs of asphalt and felt built-up construction with gravel topping. Where they exist, basements are with the first floor at grade or several (1- to 3-ft) above grade. The floor over the basement generally consists of wood joists with flooring, however in special cases a light reinforced concrete slab is used. Basement foundation walls are of concrete block or plain concrete supported on wall footings. The basement floor is a concrete slab. There are windows leading into the basement.

A structural analysis suggests the following damage/distance characterization for the building.

TABLE 1 DAMAGE/DISTANCE CHARACTERIZATION FOR A TWO-STORY FRAMED HOUSE

Damage	Free-Field 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
Light (broken windows or none)	2.0	5.3

Expedient Pole Shelters - This type of shelter is constructed in an open trench using poles (logs) cut from local trees. Construction is reminiscent of a log cabin. This results in a long rectangular shelter having a roof, walls and floor consisting of poles covered with waterproofing and backfilled with soil. Complete plans for such shelters have been developed at ORNL (Oak Ridge National Laboratory) including blast doors and expedient ventilation systems (Ref. 2, 3). A number have been tested in the field (Ref. 3).

Strengths of the two basement shelters both as built and expediently upgraded are as indicated in Table 2. The estimated strength of the "small" pole shelter also is given.

TABLE 2 FREE FIELD OVERPRESSURES FOR INDICATED FAILURE PROBABILITIES

Shelter	Free Field Overpressure, psi		
Wood Floor Over Basement:			
As Built	2.0	2.8	4.0
Expediently Upgraded	3.3	5.1	8.3
Reinforced Concrete Floor Over Basement:			
As Built	3.0	3.9	5.0
Expediently Upgraded	6.0	7.8	10.0
Expedient Pole Shelter	30.0	40.0	50.0
Failure Probability, Percent	10	50	90

FAILURE DEFINITION

Failure, as used in Table 2, refers to incipient structural failure. This means that the structure or element has been loaded to the point where it will collapse without further addition of load. This also implies that the structure that has failed is damaged to the point where repair is either impossible or grossly uneconomical.

Since there is no single air blast parameter that will serve as a unique measure of structural failure, this paper uses the free field overpressure as the index measure. The index free field overpressure is that value which would exist (in the free field) at the location of the structure.

WEAPON EFFECTS

Weapon effects considered include the prompt effects of thermal radiation and blast produced by a 1MT nuclear weapon detonated near the ground surface. Prompt nuclear radiation is neglected and, therefore, these results are valid for shelters having adequate (1- to 2-ft of soil) radiation shielding over its periphery. Thermal radiation is not an important casualty mechanism for people in basements, but is important as the mechanism for primary ignitions. The effects of blast that are considered include loading of shelters, debris formation and translation, and the suppression of some of the initial ignitions produced by thermal radiation. Corresponding casualty mechanisms include primary blast, impact and crushing of people by debris from failed portions of structures, and the effects of fires.

FIRE EFFECTS

Examination of fire effects on personnel shelters requires that each building or local area to be studied must be considered as part of a larger, or total, city area in order to assess fire spread to the local area from its surroundings. A hypothetical city was formulated and was considered to extend in all directions from ground zero beyond any fire or blast affected areas. It had the following characteristics.

1. All buildings are two-story framed residential houses
2. Overall city building density is 15 percent
3. Local area (tract) building density is either 5 or 15 percent

4. All tracts are 1/2- by 1/2-mile.
5. Building separation (distribution) within tracts is a function of building density and building plan areas (based on a survey of residential areas of Detroit, Michigan (Ref. 4).
6. Building separation across tract boundaries is considered to be 100-ft for 90 percent of tract perimeter and infinite, i.e. no fire brand crossing for the remaining ten percent.
7. Trees and bushes are bare (the season is late fall, winter or early spring)

The city was subjected to a simulated nuclear weapon attack consisting of a single 1-MT weapon detonated near the ground surface. The post-blast state of the city was determined by performing a structural analysis on the characteristic building followed by a debris transport analysis. The structural analysis resulted in 1) zones of blast damage identified as severe, moderate and light (see Fig. 1), and 2) the number of debris pieces produced by the building, their size and weight. The debris included building fragments and furnishings. The time-dependent debris trajectory analysis produced a spacial distribution of debris which was described in terms of debris weight, depth and composition (combustible, noncombustible) as a function of ground location. Time dependent fire effects were then determined for the simulated city.

The initial ignition pattern was determined using an analysis which considered the modification of primary sustained ignitions by the blast wave and included predictions of secondary fires. Fire spread throughout the city was assessed for a 15 percent building density assuming no concerted firefighting efforts. Fire spread was due to radiation, convection and fire brands. Individual tracts (local areas) were subsequently re-evaluated to establish the impact of fire prevention and firefighting efforts on local fire progress and severity. Each tract was considered to be wholly of a single level of blast damage and was assigned the damage level representing the majority of its area. The tracts considered for re-evaluation were located as shown in Fig. 1. Twelve combinations (cases) of fire prevention and firefighting activities were considered for each of these tracts as identified in Table 3, and are defined as follows:

A = percent of primary 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

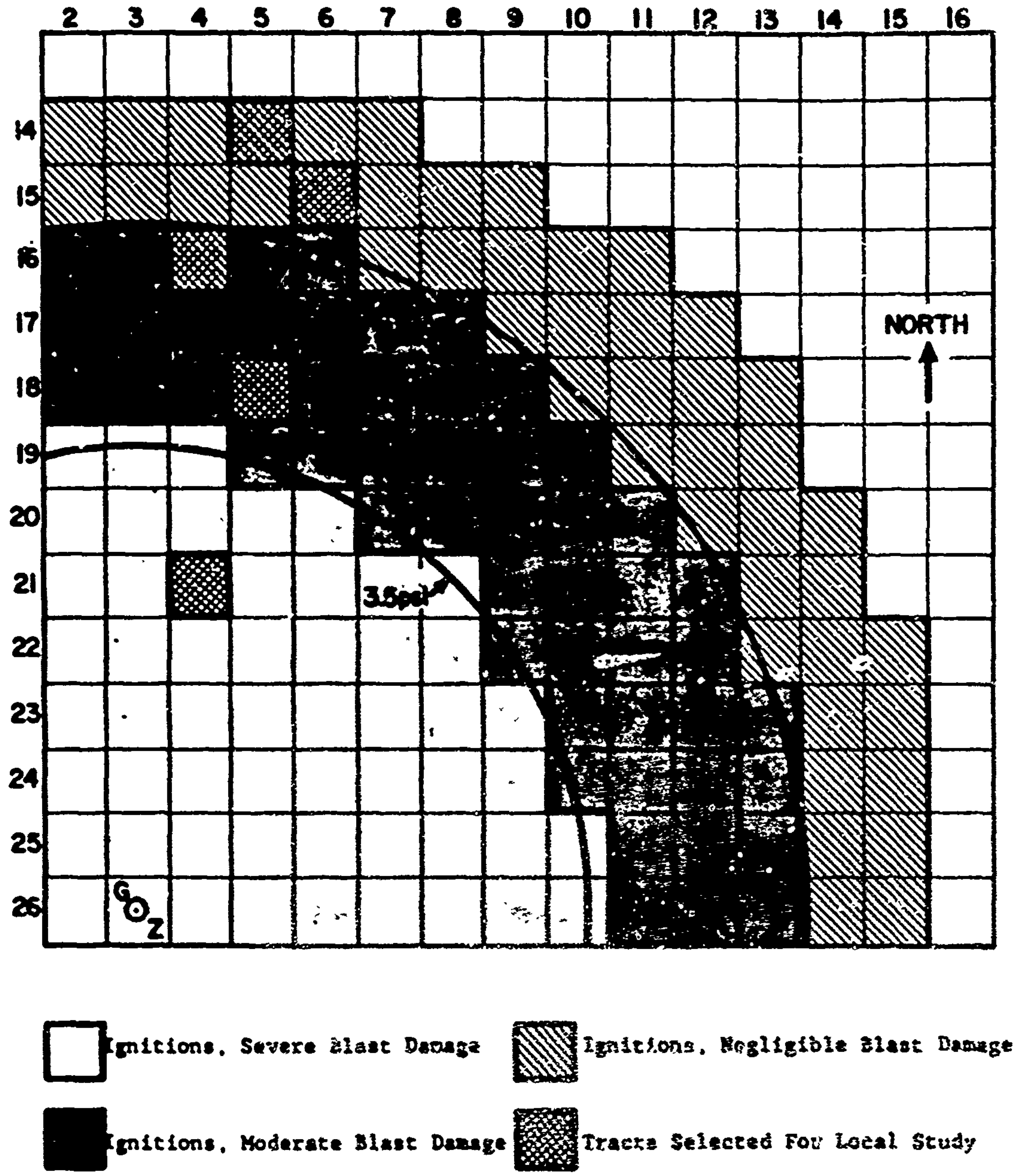

Figure 1 Northeast Section of Target Area

Tract Designation, Blast Damage, and
Tracts Selected For Further Study On A Local Basis

TABLE 3 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

In "A" we are dealing with preattack countermeasures capable of preventing a percentage of primary ignitions. "C" is the percent of active fires in the tract extinguished in each 15 minute period with a lower bound of "B" fires and an upper bound of "D" fires.

Case 1 is provided to show fire spread when no fire prevention or firefighting occurs. It serves as the "worst case" for comparison. Cases 11 and 12 indicate high efficiencies of fire prevention but no firefighting. Cases 2 to 7 have no fire prevention efforts, but 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.

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.

SELECTED RESULTS OF FIRE DEVELOPMENT

Examples of fire development calculations are presented for tract (5, 14), see Figure 1. This tract lies wholly within the area of negligible blast damage and receives few weapon ignitions. It is examined for building densities of 5 and 15 percent, and for all twelve fire prevention/firefighting situations.

Results are presented in Figures 2, 3, 4 and 5. As shown in Figure 2 (curve 1), the tract with 15 percent building density, even with limited ignitions, gradually develops in fire intensity until, at 9.56 hours after detonation, 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 same tract at 5 percent building density (Figure 4, curve 1), nominally a

* An indication of firefighting team's performance is provided in Reference 5 which describes firefighting requirements to suppress all incipient fires prior to major building involvement.

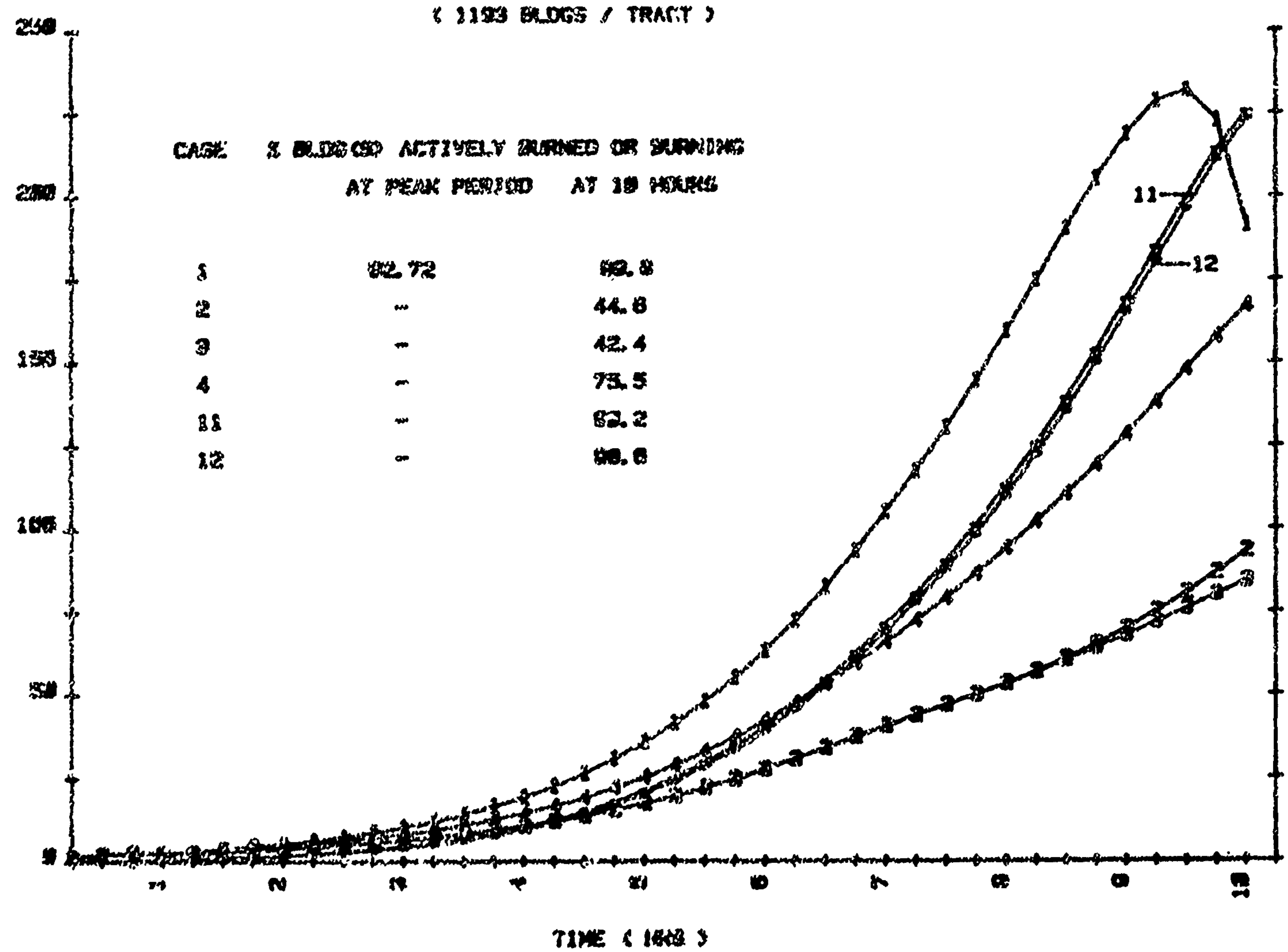

FIGURE 2 ACTIVE FIRES IN TRACT 5.14 (NO BLAST DAMAGE):
(BUILDING DENSITY = .15

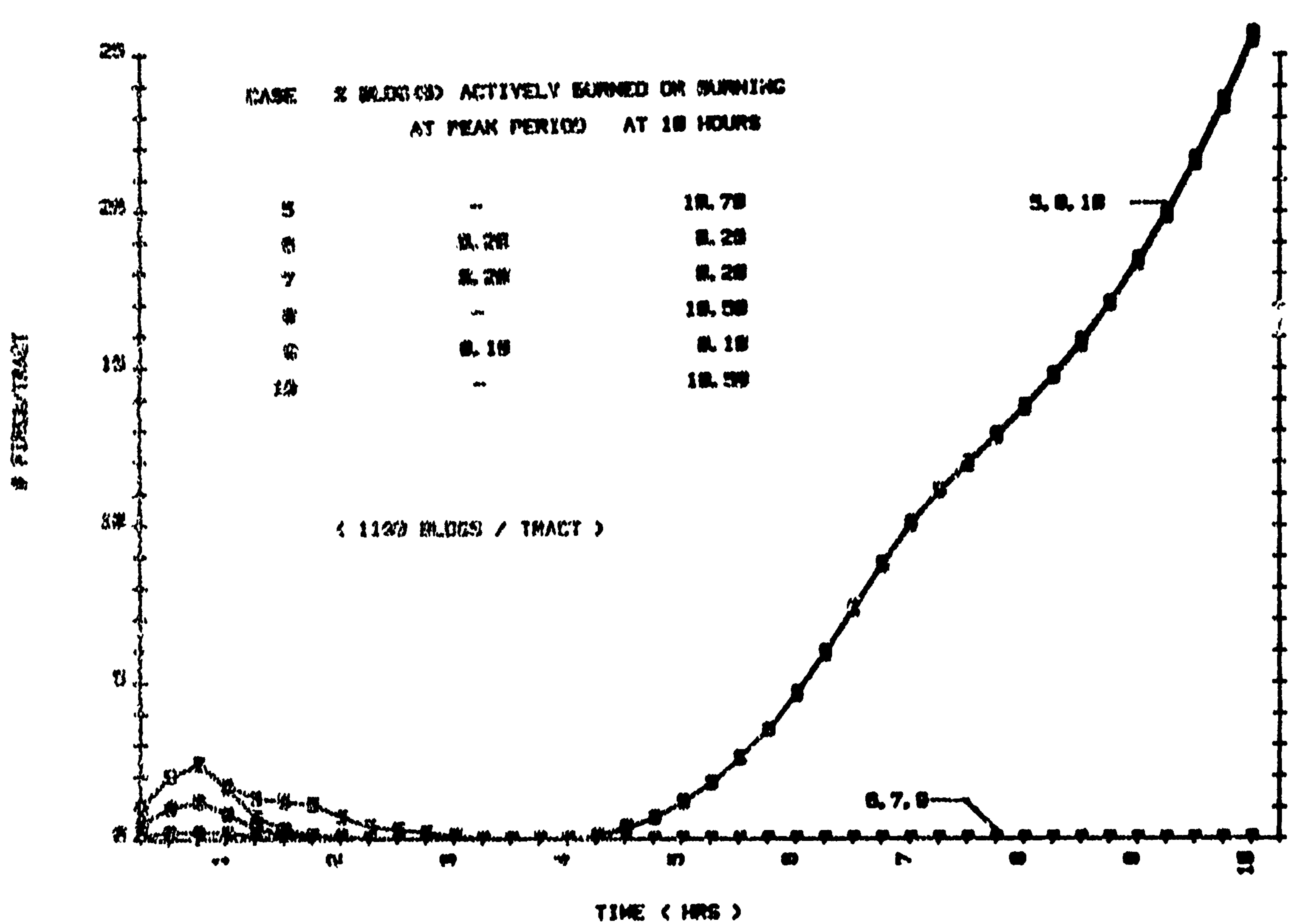

FIGURE 3 ACTIVE FIRES IN TRACT 5.14 (NO BLAST DAMAGE):
(BUILDING DENSITY = .15

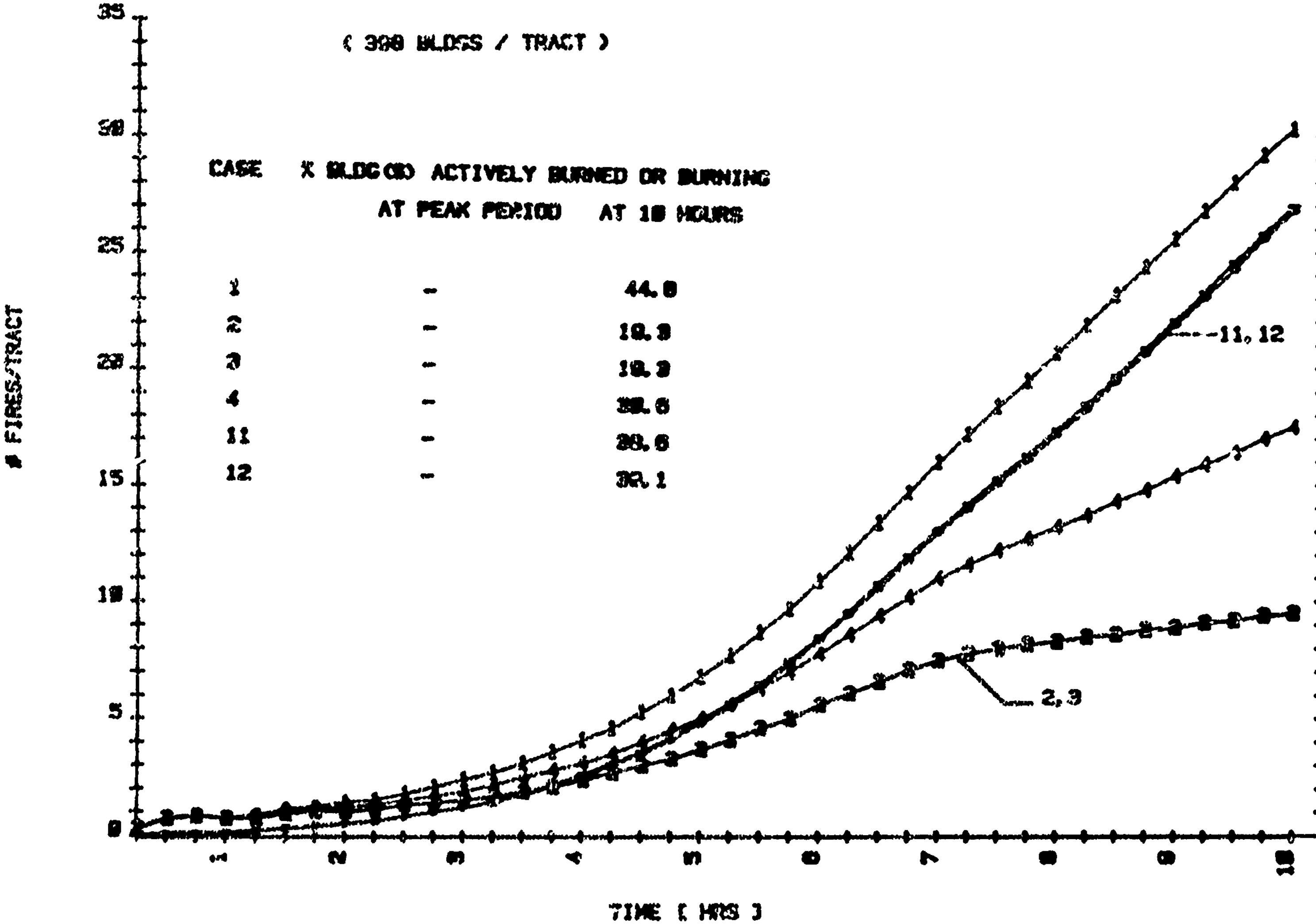

FIGURE 4 ACTIVE FIRES IN TRACT 5.14 (NO BLAST DAMAGE): BUILDING DENSITY = .Ø5

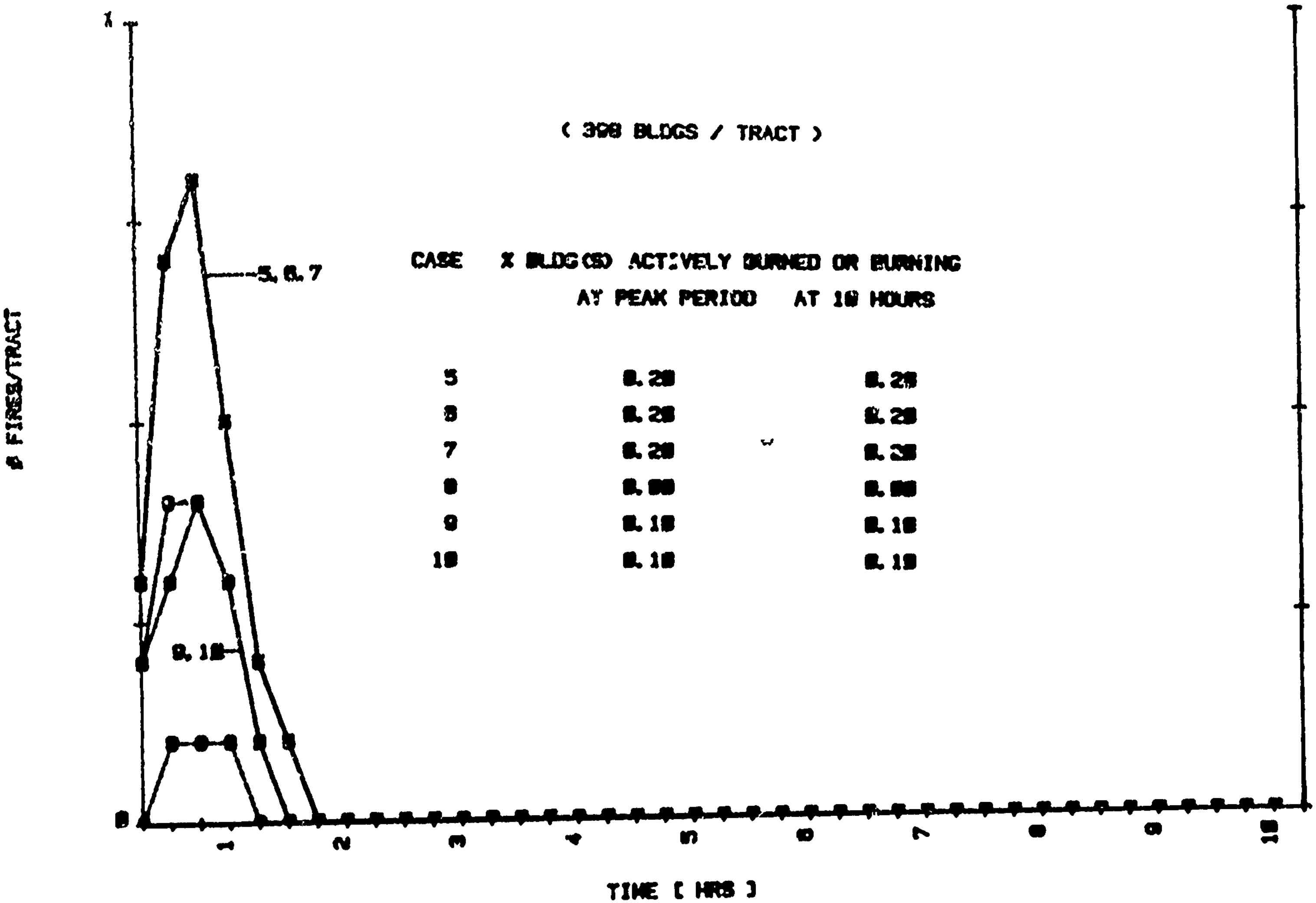

FIGURE 5 ACTIVE FIRES IN TRACT 5.14 (NO BLAST DAMAGE): BUILDING DENSITY = .05

more promising site for survival, fire frequency is still rising at 10 hours with about 10 percent of the total tract buildings burning simultaneously. While this represents (10/20) (5/15) = 1/6 the number of fires per block as compared to the higher density tract, it still represents an unsatisfactory situation, and, 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 curves 11 and 12 of Figures 2 and 4, fire prevention efforts alone only delay the consequences of fire for about 1 hour (compare curves 11 and 12 with 1 in Figures 2 and 4).

For the tract of 15 percent building density, a minimum fi ghting effort of 5 suppressions every 15 minutes i ired to affect permane ontrol (Figure 3, 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 3, curves 5, 8, and 10), growing to 2 percent of buildings active burning at 10 hours; and still growing. For the low building density tract, a moderate firefight effort (10%) offers control (see Figure 5) as long as a minimum of one fire per 15 minute period is suppressed (compare Figure 5, curve 5 with Figure 4, curve 4).

PROBABILITY OF SURVIVAL

Basic Considerations - The probability of people survival, P(S) in a shelter can be expressed as follows (Ref. 6).

$$P(S) = P(S_{sc})P(S_{nr})P(S_{fe})P(S_{fr}) \qquad (1)$$

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

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

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

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

$P(S_{sc})$ can be expressed as follows:

$$P(S|\bar{F})P(\bar{F}) + P(S|F)P(F) \qquad (2)$$

where $P(S|\bar{F})$ = probability of people survival given that the shelter does not fail

$P(\bar{F})$ = probability of shelter structure survival

$P(S|F)$ = probability of people survival given that the shelter fails (collapses)

$P(F)$ = probability of shelter collapse = $1 - P(\bar{F})$

As indicated previously, the basement shelters considered can be expediently upgraded to increase the overpressure at which collapse occurs to at least the values given in Table 2. Thus, fifty percent of framed basement shelters would survive, $P(\bar{F}) = 0.5$, to at least the range of 5.1 psi, basements with reinforced concrete roof slabs to at least the 7.8 psi range, and expedient pole shelters to at least the 40 psi range. These values extend well into the region of major blast damage as defined in Figure 1. For these types of shelters no casualties are expected due to debris effects prior to shelter collapse and, therefore, $P(S|F)$ can be set equal to 1.0, and from (2), $P(S_{sc}) = 1.0$. Assuming that a sufficient depth of soil cover has been provided in each case, then $P(S_{fr}) = 1.0$. Fallout radiation should not be a serious problem for people in shelters which have adequately survived blast effects, providing that fires can be prevented or mitigated.

<u>The Effects of Fires on People Survival - Shelters in Local Areas of Light and Moderate Damage</u> - The results of analysis conducted in the course of this study (Ref. 1) indicate that no major differences in fire effects are expected between those shelters in regions of moderate damage and regions of light damage because most of the fuel remains on the site, and not much fuel is transported in from the region of severe blast damage. These two regions are thus treated together.

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

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, past the joists, and into the basement. This has been demonstrated by experiment.

In the lower (5 percent) 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 uniquely separated from surrounding structures.

The probability of people survival in basements with wood joist overhead floors 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 ($P(S_{fn})$), would be very low in which case the shelter would need to be evacuated.

Burnout of a standing building over a basement with a reinforced concrete overhead slab has been shown to offer minimal effects on the heat environment in the basement below (Ref. 7); and, a number of simple countermeasures have been demonstrated to further minimize shelter heating (Ref. 7, 8). Fresh ventilation air is expected to be readily available (Ref. 7,8,9,10). Thus, this type of shelter can be protected against fire effects with limited fire prevention/suppression efforts, such as removal of burning or smoldering debris from basement entranceways and fresh air intakes. The probability of people survival in such a basement is, therefore, high in regions of light to moderate damage, and is only weakly dependent on the probability that the building above the shelter does not burn.

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 surviving fire effects in such shelters is, therefore, very close to 1.0.

The Effects of Fires on People Survival - Shelters In Local Areas of Severe Damage - As shown in Figure 1, severe damage is considered to occur at free-field overpressure ranges greater than about 3.5 psi. In this region damaged shelters and ignited debris piles combine to produce a highly hazardous environment. The debris piles estimated for this region are certainly not continuous nor uniformly distributed. However, the probability is high that the maximum fuel loading over the shelter may be up to 25 lbs per sq ft for 5 percent building density and up to 75 lbs per sq ft for the 15 percent building density. These are extremely high combustible loads. It is very doubtful that shelter occupants in basement shelters with wood floor overhead systems can remain within for any extended time period in ignited portions of this region.

Based on results of previous studies dealing with debris fires (Ref. 9, 10), habitability in reinforced concrete basement shelters under ignited debris piles having high fuel loads is possible only when the shelter envelope is undamaged and effective remedial action is taken. This would include removal of burning debris from the shelter roof*, ventilation openings and entranceways and putting out fires. In the case of a blast damaged shelter, people probably would need to be evacuated.

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 post-attack countermeasures. The probability of people survival in this shelter in regions of major blast damage should remain high.

Assuming that the two basement shelters are expediently upgraded, are undamaged when subjected to the blast load, and remedial action is taken by the shelter occupants, then the probability of people survival is estimated as shown in Table 4.

TABLE 4 PROBABILITY OF PEOPLE SURVIVAL, P(S)

Shelter Type	Region of Light to Moderate Damage	Region of Severe Damage
1. Upgraded Wood Framed, Basement Shelter	∿ 0.5	< 0.5
2. Upgraded Reinforced Concrete, Basement Shelter	∿ 0.9	> 0.5 < 1.0
3. Expedient, Pole Shelter	1.0	< 1.0

CONCLUSIONS

The study described has taken a first comprehensive look at the problem of evaluating the hazards and the probability of people survival in a blast-fire environment produced by the detonation of a 1-MT nuclear weapon.

* A water layer on the roof is the viable alternative (Ref. 7)

A computer algorithm for determining the makeup of debris piles produced by the breakup of buildings when subjected to a blast load from a nuclear weapon was formulated, programmed and used in the study described.

Fire ignition and fire spread was predicted using existing computer programs (References 4, 12-15) which were modified to be able to predict ignition and spread of fires in regions where buildings are damaged by the blast.

The three personnel shelters studied include (1) a conventional wood framed basement, (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 suppression 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 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 major debris sources, thus minimizing the problem of burning debris in its immediate vicinity.

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