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BATTLEFIELD FIRES FROM TACTICAL NUCLEAR WEAPONS(U)

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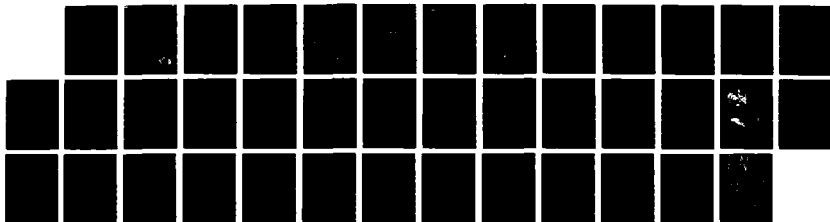
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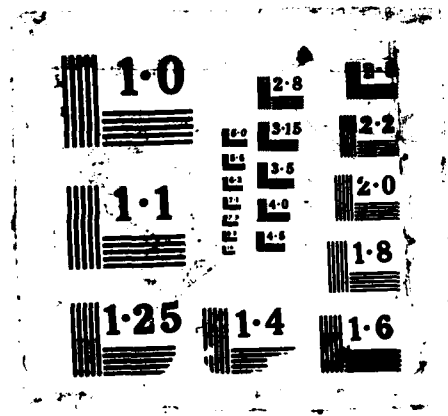
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**BATTLEFIELD FIRES FROM TACTICAL NUCLEAR
WEAPONS**

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R. D. Small
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15 November 1984

Technical Report

CONTRACT No. DNA 001-84-C-0271

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REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b. RESTRICTIVE MARKINGS			
2a. SECURITY CLASSIFICATION AUTHORITY N/A since Unclassified			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.			
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE N/A since Unclassified						
4. PERFORMING ORGANIZATION REPORT NUMBER(S) PSR Report 1453			5. MONITORING ORGANIZATION REPORT NUMBER(S) DNA-TR-86-235			
6a. NAME OF PERFORMING ORGANIZATION Pacific-Sierra Research Corporation		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Director Defense Nuclear Agency			
6c. ADDRESS (City, State, and ZIP Code) 12340 Santa Monica Boulevard Los Angeles, California 90025-2587			7b. ADDRESS (City, State, and ZIP Code) Washington, DC 20305-1000			
8a. NAME OF FUNDING / SPONSORING ORGANIZATION		8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER DNA 001-84-C-0271			
9c. ADDRESS (City, State, and ZIP Code)			10. SOURCE OF FUNDING NUMBERS			
			PROGRAM ELEMENT NO. 62715H	PROJECT NO. RM	TASK NO. RK	WORK UNIT ACCESSION NO. DH 846102
11. TITLE (Include Security Classification) BATTLEFIELD FIRES FROM TACTICAL NUCLEAR WEAPONS						
12. PERSONAL AUTHOR(S) Woodie, W. L.; Remetch, D.; and Small, R.D.						
13a. TYPE OF REPORT Technical Report		13b. TIME COVERED FROM 840615 TO 841115		14. DATE OF REPORT (Year, Month, Day) 841115		
15. PAGE COUNT 36						
16. SUPPLEMENTARY NOTATION This work was sponsored by the Defense Nuclear Agency under RDT&E RMC Code B3500844662 RM RK 00102 25904D.						
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)			
FIELD	GROUP	SUB-GROUP				
13	12		Fire Spread Tactical Nuclear Weapons			
15	7		Ignition Thermal Ignition			
19. ABSTRACT (Continue on reverse if necessary and identify by block number)						
→ Fires from tactical weapon exchanges in open terrain can be an important factor in assessing casualties and damage as well as managing troop deployments and operations. In addition to "prompt" thermal effects and fire starts, spread may also be an important factor on the battlefield. In this report, a model describing the initiation and spread of battlefield fires is presented. The initial ignition distribution is related to the weapon yield, slant range, local atmospheric properties, fuel type and ignition threshold. The fire spread analysis is based on an established U.S. Forest Service prediction algorithm. The present tactical ignition and fire spread (TIFS) model predicts the fire movement over variable terrains and accounts for ambient wind vectors, moisture, changing vegetation, and an arbitrary number of firebreaks. An example calculation illustrating the initial fire area and subsequent						
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED			
22a. NAME OF RESPONSIBLE INDIVIDUAL Sandra E. Young			22b. TELEPHONE (Include Area Code) (202) 325-7042		22c. OFFICE SYMBOL DNA/CSTI	

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19. ABSTRACT (Continued)

spread in a complex terrain is presented for a 10-KT explosion. The results show the fires extending the effective weapon-damage radius, and identify regions to which the fires do not spread.

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PREFACE

This report was prepared for the Defense Nuclear Agency (DNA) under contract DNA 001-84-C-0271 and supervised by Dr. Michael J. Frankel.

In previous Pacific-Sierra Research Corporation studies of fires started by nuclear weapon bursts, the physics of large area urban fires were considered. In this report, we examine fires started in battlefield areas by tactical nuclear bursts. The fires may spread far beyond the initial ignition zone. A computer program that calculates the initial ignition radius and the subsequent fire spread has been developed. A version of the tactical fire and spread program has been developed for inclusion in a battlefield assessment algorithm.

This report was presented at the DNA Conference on Large Scale Fire Phenomenology, September 1984, in Gaithersburg, Maryland, and will appear in the conference proceedings.

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CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY $\longrightarrow$ BY $\longrightarrow$ TO GET
TO GET $\longleftarrow$ BY $\longleftarrow$ DIVIDE

angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter ² (m ²)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm ²	4.184 000 X E -2	mega joule/m ² (MJ/m ²)
curie	3.700 000 X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_F = (t_K + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U. S. liquid)	3.785 412 X E -3	meter ³ (m ³)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch ² (ksi)	6.894 757 X E +3	kilo pascal (kPa)
knap	1.000 000 X E +2	newton-second/m ² (N-s/m ²)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N-m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot ²	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch ² (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot ² (moment of inertia)	4.214 011 X E -2	kilogram-meter ² (kg-m ²)
pound-mass/foot ³	1.601 846 X E +1	kilogram/meter ³ (kg/m ³)
rad (radiation dose absorbed)	1.000 000 X E -2	*Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0°C)	1.333 22 X E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

Weapon systems are vulnerable to fire damage; however, there are currently no algorithms available to analyze this threat. Traditionally, there has been considerable uncertainty associated with the prediction of fire effects, and thus a reluctance to account for battlefield fires. In some cases, localized fires can spread large distances, and influence a battle area for a prolonged period of time.

On the nuclear battlefield, fires and fire spread may be a much greater threat. The thermal flash (even from low-yield weapons) can endanger equipment and personnel at large distances from the burst (especially for airbursts), and fire starts over large areas may result. The occurrence of sustainable ignitions depends on many factors, only some of which are weather dependent. Enough thermal energy is available such that ignitions are likely to occur, despite snow cover or precipitation. Furthermore, it is possible that these fires may spread from the initially ignited areas, greatly increasing the threat.

A large number of ignitions does not imply spread. However, should the fires spread, damage radii may be greatly increased, positions threatened, and operations restricted by the course and anticipated arrival time of the fire front. Also, smoke from either fixed or spreading fires might conceal operational movements, limit the use of optical imaging devices, and in general, influence battle management.

Conditions at the time of burst may not favor either an extensive ignition distribution or fire spread from the initial burning area. In western Europe, for example, fire spread is not probable during most of the year. Snow cover or wet conditions reduce the probability of fire spread. Nevertheless, periods of dryness favoring extensive spread can occur in normal weather patterns.

In this report, we summarize the development of a fire initiation and fire spread model for the nuclear battlefield. Although this study represents only a first battlefield fire model, the results indicate the potential effect with a fair degree of confidence. The model was developed using established routines that calculate wildland ignitions from a prescribed nuclear burst, and fire spread in an arbitrary terrain. The spread calculations are based on tested methods and routines developed by the U.S. Forest Service for a variety of vegetations, terrains, and weather conditions.

In Sec. 2, the fire-start model is described. The spread prediction method is outlined in Sec. 3, and an example calculation is presented in Sec. 4.

SECTION 2

INITIAL IGNITIONS

Fire starts from a nuclear burst are influenced by the weapon parameters, vegetation and terrain, and weather conditions. All are important variables and not completely independent. For example, shadowing by forest stands or terrain features can reduce the ignition radius for very low (or surface) heights of burst.

In the tactical ignition and fire spread code (TIFS) we have developed, standard methods are used to predict (thermal) fire starts. There are, nevertheless, several approximations in the treatment of initial ignitions. Blast modification of the fuel bed and subsequent changes in the fire-start distribution are not considered. In general, such effects are not well modeled. The transport of flaming material from high overpressure areas may increase the number of ignitions at larger radii, assuming of course that the nascent ignitions are maintained. It is not clear, however, that such redistribution occurs. It also has been argued (and demonstrated in simple shock-tube tests) that the blast wave may actually blow out ignitions in high overpressure regions. Both of those effects support an annular fire hypothesis, and make subsequent fire spread likely.

Another blast modification of the fuel bed involves stripping of branches and toppling of trees (in high overpressure regions). A layering of live material over dead fuels results. Since live fuels do not usually sustain ignitions, the number of fire starts may be overestimated.

Other factors also modify forest ignitions. The canopy shields dead fuel material on the forest floor from the thermal radiation. Thus, ignitions will probably be spotty (although extensive) and dependent on season and foliage. If there is extensive dead material in the trees, crown fires are likely. Although not unusual, such fires do not occur often. It is also possible that the vapor (steam) from desiccation of the canopy could absorb some of the thermal radiation

and limit the number and extent of ignitions. This, however, may be a more important consideration for multiple burst attacks.

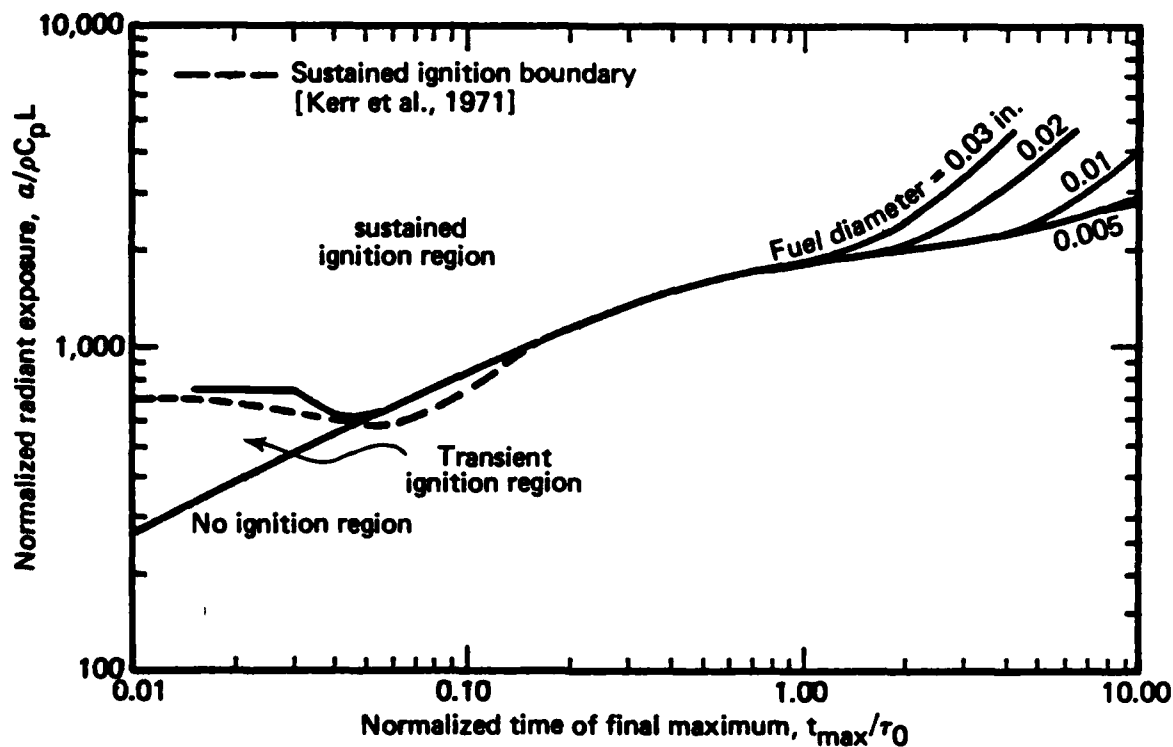
Although there are several unresolved issues, each of which warrants research, a large number of ignitions are probable. For fuel beds other than forests (such as brush, grass fields, croplands, etc.), many of the modifying effects do not significantly influence the fire-start distribution.

The type of vegetation, in particular its ignition threshold, is the second principal parameter needed to determine the fire-start distribution. Threshold levels have been determined experimentally for many fuels, and parameter influences such as yield, orientation, dimensions, albedo, have been investigated. Sufficient information is available to prescribe ignition conditions for most wildland fuels; however, more data would be useful.

Moisture is an important variable both for the calculation of sustained fire starts and prediction of fire spread. It is doubtful there would be large numbers of ignitions if there is heavy precipitation or snow cover. Similarly, the fire intensity and the probability of fire spread depend on the absorbed fuel moisture. At some level (moisture of extinction), fires do not spread. The amount of fuel moisture can vary significantly with the weather--principally with the frequency and amount of precipitation. For most applications, it is the moisture levels in the 1- and 10-h time lag classes (fuel sizes to 1 in.) that are important. Although in this first TIFS model, only a simple moisture correction based on humidity is used, the more elaborate National Fire Danger Rating System (NFDRS) method could be implemented.

The surface heating experienced by thin tinder fuel elements during a specified exposure is described by one universal function over a wide range of yield and fuel parameters. That function, shown in Fig. 1 [Kerr et al., 1971*], is built into the current computer model. For a given normalized fireball duration (pulse duration divided by

* See Table 4-2.



Source: Kerr et al. [1971].

Figure 1. Ignition thresholds for black α -cellulose exposed to simulated weapon pulse.

the thermal relaxation time of the fuel particle), Fig. 1 indicates the normalized radiant exposure required to raise the surface of the fuel to ignition temperature.

The physical parameters of the fuel particles needed to predict ignition criteria have been measured in previous studies [Kerr et al., 1971]. The three parameters used in the TIFS ignition model include (1) the thermal relaxation time, τ_0 sec; (2) the normalized specific heat $\rho C_p L$ (cal/cm²-°C); and (3) the average absorption coefficient A (dimensionless). Values for some typical forest fuels are shown in Table 1 [Kerr et al., 1971]. Predicted and measured ignition thresholds for those fuels agree to within ± 30 percent.

An ignition decision in TIFS is computed as follows. First, based on the particular fuel thermal relaxation time τ_0 , the ratio $t_{\max}/\tau_0$ is evaluated. The source parameter $t_{\max}$ is the time to peak radiant intensity and is given by [Glasstone and Dolan, 1977]

Table 1. Material parameters for ignition determination of typical weathered wildland fuels.

Fuel Type	L Thickness (cm)	ρ Specific Gravity	τ_0 Relaxation Time (s)	$\rho C_p L$ Normalized Specific Heat (10^{-3} cal/ $^{\circ}$ C cm 2)	A Absorbtivity (dimensionless)
Cheatgrass leaves	0.011	0.25	0.05	0.82	0.3
Wheat straw	0.037	0.35	0.64	3.89	0.6
Beech leaves	0.009	0.39	0.04	1.05	0.6
Chestnut oak leaves	0.018	0.37	0.15	2.00	0.8
Rhododendron leaves	0.025	0.50	0.32	3.75	0.8
Shortleaf pine needles	0.058	0.52	1.73	9.05	0.8
Engleman spruce leaves	0.074	0.56	2.87	12.40	0.7

$$t_{\max} = 0.043W^{0.43} \left(\frac{\rho}{\rho_0} \right)^{0.42} \text{ s} , \quad (1)$$

where W is the yield in kilotons, and ρ/ρ_0 is the air density at the burst point normalized to the sea level value. From Fig. 1, the required normalized radiant exposure T_{req} for sustained ignition is determined. Using the absorption coefficient and the normalized specific heat of the fuel, the value of Q_{req} , the incident radiant exposure (cal/cm^2) needed to ignite the dry fuel is determined. In order to account for the moisture content of the fine dead fuel, the radiant exposure needed for ignition of dry fuel is increased by a factor $(1 + \omega/2)$ [Kerr et al., 1971], where ω is the local relative humidity. Thus, for moist fuel the required radiant exposure is

$$Q_{\text{req}}^{\text{wet}} = Q_{\text{req}}^{\text{dry}} \left(1 + \frac{\omega}{2} \right) . \quad (2)$$

The delivered radiant exposure Q_{del} is calculated using the local atmospheric visibility conditions and slant range. If Q_{del} is greater than Q_{req} , ignition occurs; for smaller values, ignitions are not sustained.

The delivered radiant exposure [Small and Brode, 1983], modified by an exposure function $P_e(\theta)$, is given by

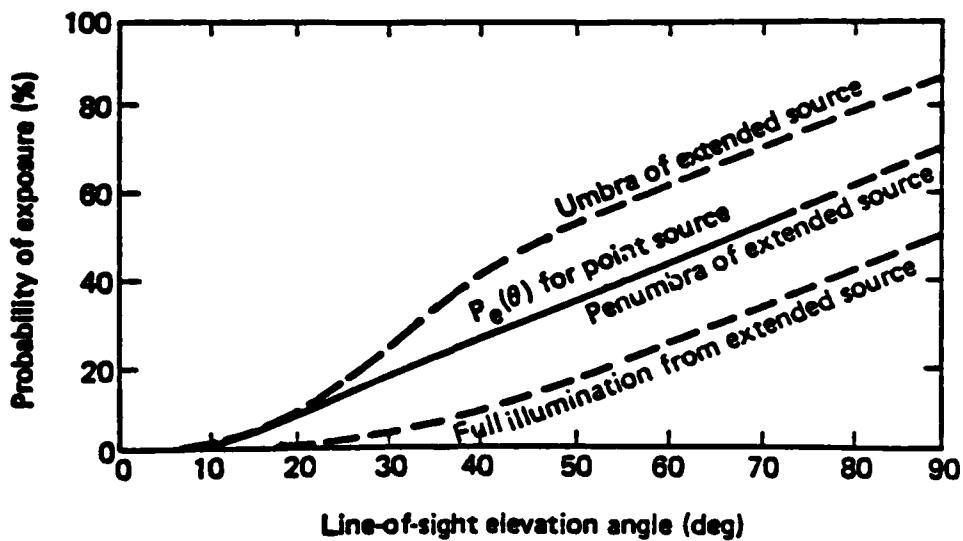
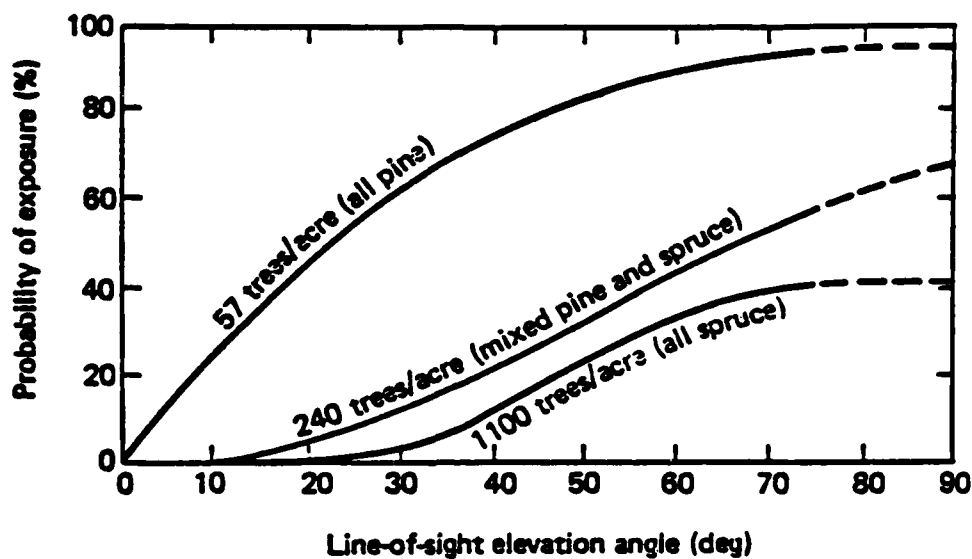
$$Q_{\text{del}} = P_e(\theta) \frac{W}{\tilde{R}^2} \left(1 + \frac{a\tilde{R}}{V} \right) e^{-b\tilde{R}/V} \text{ cal}/\text{cm}^2 , \quad (3)$$

where W is the yield in kilotons, $\tilde{R}$ the slant range in miles, V the visibility lengths in miles, and a , b are dimensionless coefficients that describe the atmospheric albedo and absorption, respectively. Median values are $a = 1.5$, $b = 2.5$. The $P_e(\theta)$ accounts for a covering forest canopy and defines the probability of fuel exposure; θ is the elevation angle between the fireball and the horizon.

The probable forest floor exposure depends on tree type, distribution and density, tree foliage condition (season), and tree height. In Kerr et al. [1971], an exposure probability function for a standard northern European forest is described. Figure 2 shows that function for a point source and an extended source fireball with an apparent diameter of 10 deg. For the current version of the TIFS computer model, we have assumed $P_e = 1/2$ for all angles.

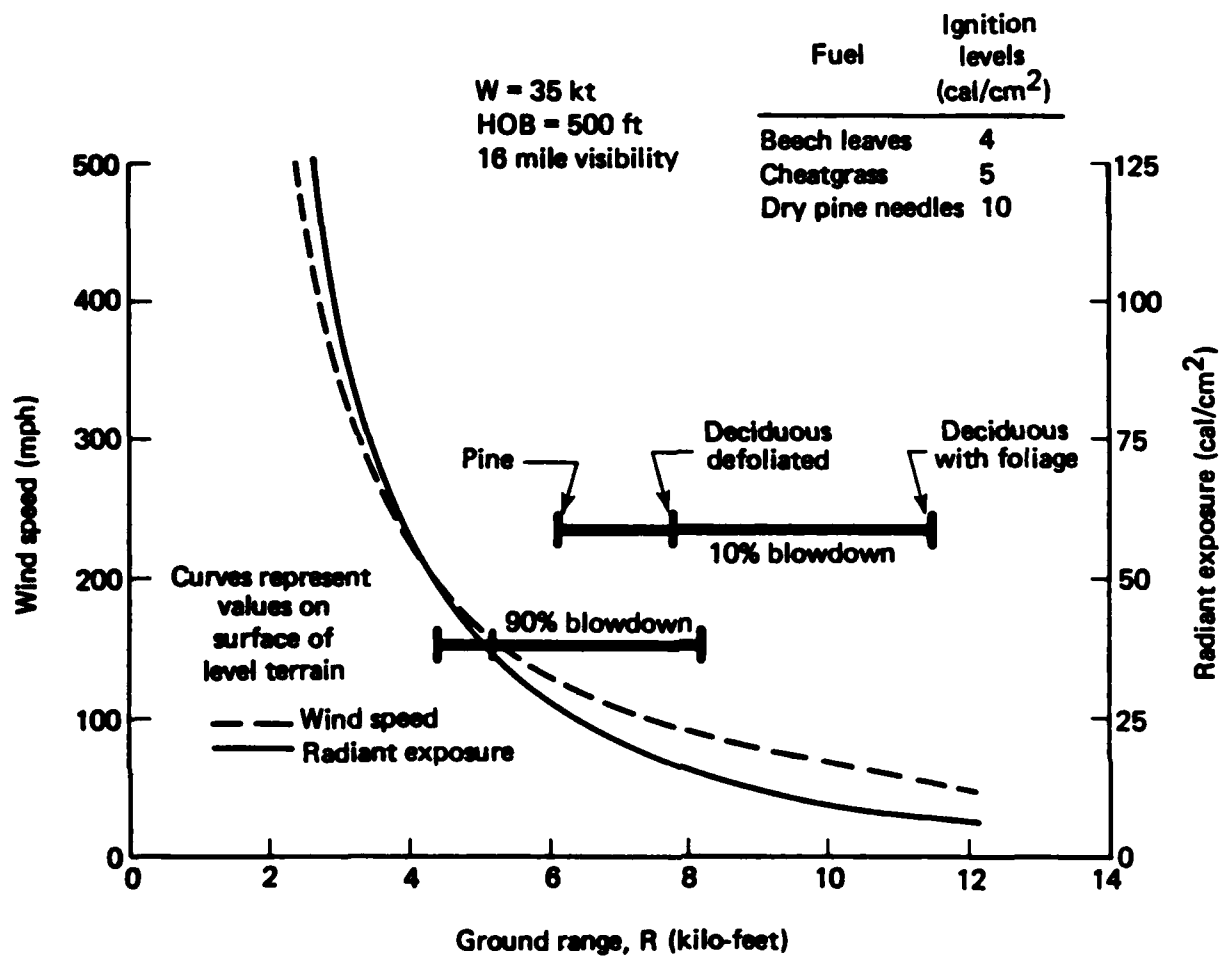
The effect of blast winds on the newly ignited flames is not included in the current model. In several atmospheric tests it was observed that the blast wave extinguished some flames (though not all) [Arnold, 1952]. In general [Smiley, 1980], flame extinction is not expected below about 5 psi (wind speed = 100 mph). Figure 3 shows radiant exposure and blast wind speed versus ground range for a 35 KT weapon detonated at a height of 500 ft. The 100 mph level occurs at a ground range of about 8000 ft. The corresponding radiant exposure is about 15 cal/cm².

This level of radiant exposure is sufficient to ignite dry fine fuels provided there is no forest canopy, but falls short of the required ignition level when the probability of exposure due to a dense canopy is taken into account. For many field conditions, there are a variety of terrain factors that could modify both the expected wind speed and canopy cover. With enough variety in the forest fuel geometry, many scattered points of sustained ignition could persist even after the blast wave arrival and that some flaming fuels could be transported to unignited areas. If even one point of ignition survives, the possibility of fire spread is preserved.



Sources: Kerr et al. (1971).

Figure 2. Probability of forest floor exposure as function of source elevation angle for various conditions of forest canopy.



Source: Kerr et al. [1971].

Figure 3. Blowdown velocities and radiant exposures from 35-KT burst 500 ft above level terrain.

SECTION 3

FIRE SPREAD

There are many parameters that influence the course and rate of a spreading fire. The particular fuel composition, distribution, and loading; weather and its influence on fuel moisture levels; wind and terrain features; all affect the fire intensity and the forward transmission of heat. In general, such parameters are difficult to characterize, and rigorous analysis at best can only calculate spread for simple idealized fuels and geometries.

The U.S. Forest Service fire-spread routines used in TIFS are based on an integral formulation [Fransden, 1971] that relates the quasi-steady propagation of a combustion wave to the forward flux of heat (principally radiative and convective transfer). The methodology developed by Rothermel [1972] and Albini [1976a,b] substitutes in the energy formulation, empirical relations describing complex physical phenomena for analytical terms. Two algebraic relations form the basis of the empirical development. The first treats the reaction intensity of a given fuel, and requires characterization of the effective fuel properties. The second considers the rate of spread and is defined by an energy flux propagation equation that includes the influence of parameters such as wind and slope.

The fire's reaction intensity I_R (the energy released per unit area per unit time in the reaction zone) is proportional to the fuel loading w , the fuel heat content h , and the reaction time τ_R (the time taken for the fire front to travel a distance equivalent to the depth of one reaction zone) by

$$I_R = \frac{wh}{\tau_R} \eta_M \eta_S \quad (4)$$

where η_M and η_S are moisture and mineral content damping coefficients. The reaction intensity depends on the fuel, and determines the amount

of energy available for transmission forward to unburned fuel elements. The required coefficients and properties have been measured and cataloged for several fuel models [Anderson, 1982].

The propagating flux I_p (the amount of heat entering the unburned fuel bed per unit area per unit time), the rate of spread R , the effective fuel bulk density ρ_e (the mass per unit volume of fuel involved in the ignition process), and the heat of ignition Q_{ig} are related by

$$R = \frac{I_p}{\rho_e Q_{ig}} (1 + \phi_s + \phi_w) , \quad (5)$$

where the functions ϕ_w and ϕ_s account for the effect of wind and slope. The sum of horizontal and vertical heat fluxes is represented by I_p . Equations (4) and (5) are related by the ratios

$$\epsilon = \rho_e / \rho_b , \quad (6)$$

and

$$\xi = I_p / I_R , \quad (7)$$

where ρ_b is the fuel bulk density and ξ is the forward heat transmission parameter. The factor ϵ represents the fraction of fuel heated to ignition and is related to the characteristic surface area to volume ratio σ , for a particular fuel. The transmission parameter ξ is also related (empirically) to fuel parameters such as σ and the "packing ratio" β . For zero wind and slope conditions

$$\xi = \frac{\exp[(0.792 + 0.681 \sqrt{\sigma})(\beta + 0.1)]}{192 + 0.259\sigma} . \quad (8)$$

When similar expressions are substituted for ϕ_s and ϕ_w [see Eq. (5)], fire spread for more general conditions can be calculated.

The above equations form the framework of the fire-spread model; the various quantities required are either physical constants related to the fuel or functional fits of experimental data. Multiple fuel classes are included by an appropriate weighting of the parameters. The U.S. Forest Service spread model has been validated in a number of comparisons between predictions and field results [Andrews, 1980].

SECTION 4

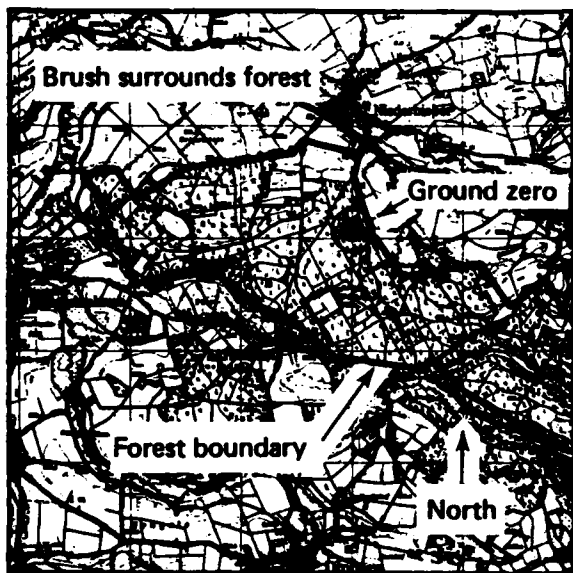
SAMPLE CALCULATION

An example problem chosen to demonstrate the utility of TIFS considers a possible tactical encounter in a low, rolling, mountain pass typical of western Europe. In the example, a forested ridge rising from a brush-covered plain is presumed to have an enemy location on its northeast flank. A 10-KT weapon is detonated at a 200 m height of burst. The atmospheric visibility is assumed to be 10 km, and the dead fuel moisture content is assumed to be zero. The initial fire area and its subsequent spread in the battlefield area are the desired outputs.

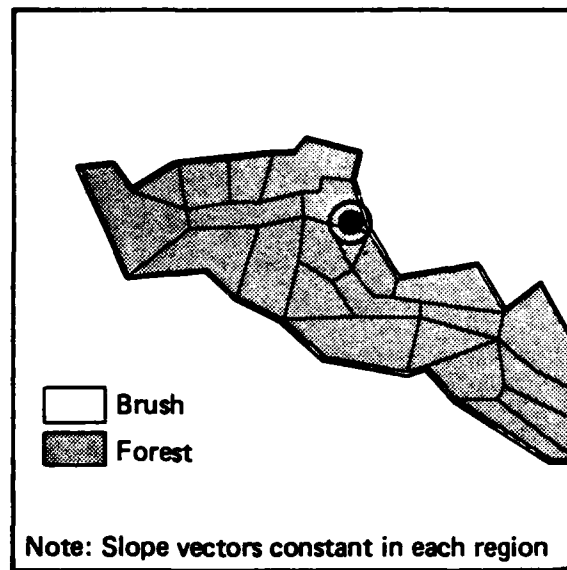
The terrain and fuel boundaries used as input for the example TIFS calculation are shown in Fig. 4, along with the calculated fire time-of-arrival contours. The source map used for this example contains the information on the forest type (deciduous or evergreen), roadway locations that act as potential firebreaks, and values of local slope (from elevation contours). The variation of direction and magnitude of slope in the forested area are used to define 23 region boundaries (see Fig. 4); in each region slope is assumed constant. In this example, a timber litter with understory fuel model is used for the 23 small forested regions, and a brush fuel model for the large surrounding region. In this version of TIFS, all regions have the same moisture content, but each region has a unique moisture of extinction according to fuel type.

Roadways indicated on the source map are considered potential firebreaks. Since there were many minor roads shown (probably serving as logging or residential roads), only a fraction were used in this calculation. The widths of the roads are not indicated on the source map, and, arbitrary width assignments varying from 4 to 20 m were made. The fire could cross a break if the tilted flame spans at least one-half the firebreak width in the wind direction [Woodie, Remetch, and Small, 1984]. Only about 10 percent of the firebreaks in

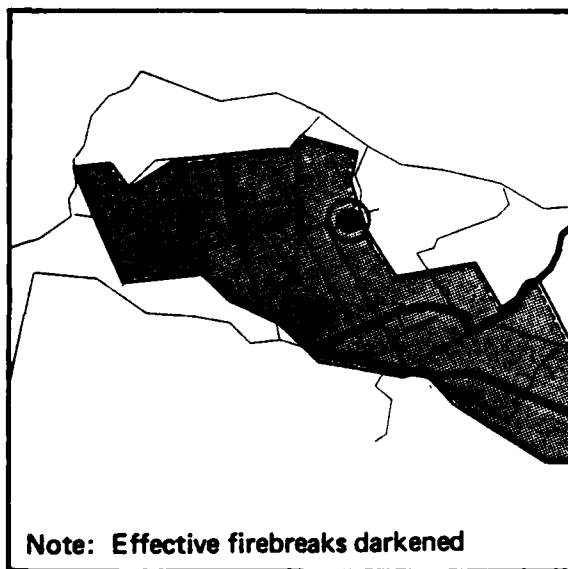
a. Source map.



b. Region boundaries.



c. Firebreaks.



d. Fire front time-of-arrival contours.

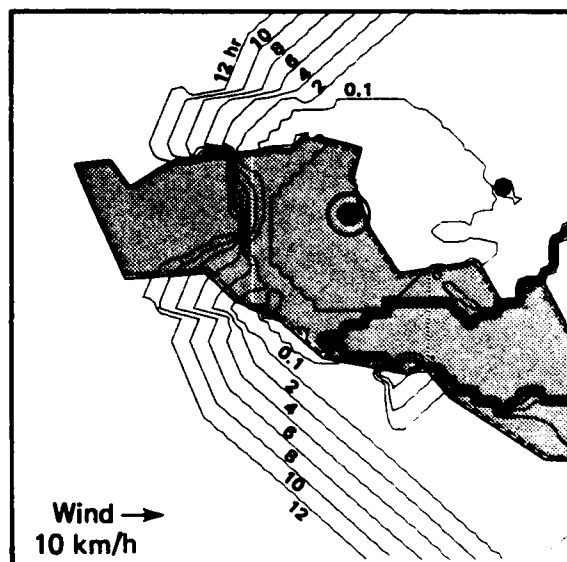


Figure 4. Sample calculation of fire spread resulting from 10-KT detonation over forest region surrounded by brush.

this example were effective in stopping the spread (indicated by the darkened lines).

The results of the fire-spread calculations for the example data are shown in Fig. 4 as fire front time-of-arrival contours. The time (in hours) elapsed since detonation is indicated on each contour line. The contour lines labeled "0.1" approximately outline the initial ignition area from the airburst. Had there been only one fuel type, the ignition area would have been nearly circular. The initial noncircular contour is due to greater ignition ranges for brush than for timber litter, terrain variations, and also the biasing ambient wind.

The fire front time-of-arrival contours shown in Fig. 4 provide a suggestion of possible use in tactical planning. In particular, the results define unburned forest sectors that could be used as friendly strongholds without fire-related limitations. Alternatively, enemy forces in those areas would survive the fire. There were two large sectors that escaped the advancing fire up to 12 h later. One includes the western quarter of the forested area, and the other a wedge-shaped sector covering approximately one-fourth of the forested area on the southeast side. The fire moved more rapidly in the surrounding brush-covered plains, especially in the westerly direction of the wind.

The prediction of safe areas, areas subject to intense burning, and the time for the fire to pass designated sectors suggests that criteria for both optimum weapon employment and troop movements can be developed. In this sample calculation, the fire did not spread to two sectors on the ridge. An alternative detonation point (in the eastern quadrant) would increase the area exposed to fire damage. A slightly larger yield weapon would also extend the range at which primary ignitions occur, thus obviating the firebreak effectiveness.

SECTION 5

CONCLUSIONS

The TIFS algorithm described here allows an estimate of potential fire effects on the nuclear battlefield. Although a first model, the use of well established routines and procedures for prediction of initial ignitions and fire spread provides some confidence in the algorithm. Certainly there are more effects that should be included and other models of effects that could be improved. Nevertheless, at least some statements can be made as to the effect of fire on the tactical battlefield. Future efforts might consider more general or additional fuel models, weather conditions, and terrains and the development of the TIFS algorithm into an operational program.

SECTION 6
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