The fire losses are caused by heat released by combustion. Every means to prevent a part of the process of combustion is effective for suppressing fires. When studies on new type of fires start, the most important knowledge is of basic phenomena concerning combustion.

The aspects of combustion are closely related to heat and mass transfer phenomena, which strongly depend on flow fields. A few well-known phenomena in fires are explained on the basis of knowledge about heat and mass transfer phenomena.

Knowledge in aerodynamics is extremely important for understanding phenomena in fires. Most of scale effects are attributable to aerodynamic aspects. The difference of gas densities would be one of the most effective matters in considering the scale effect.

A number of examples in the past indicate that the best way for future fire safety is to accumulate knowledge of basic fire phenomena. Thus, in the future fire science, basic fire phenomena will be main subjects to explore.

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On the Modeling of Forest Fires: from Physical Background toward Practical Output

H.P. TELITSYN
Gassinski Model Forest Association
Kalinina, 106
Troitskoe, Nanaiskii District
Khabarovsk Territory 682350, Russia
E-mail: forestry@trk.kht.ru

A.I. KARPOV
Khabarovsk State University of Technology
Tikhookeanskaya, 136
Khabarovsk 680035, Russia
E-mail: karpov@niikt.khstu.ru

ABSTRACT

The problem of elaboration of the system for forest fire behavior prediction is considered including the formulation of fire spread mathematical model based on the radiation heat transfer mechanism, classification of natural fuels using the forest inventory data, approximation of fire perimeter propagation, programming realization of fire simulation code and overall arrangement.

KEYWORDS – Forest fire, Fire spread model, Flame radiation, Forest fuel, Computer simulation, Fire behavior system

NOMENCLATURE

C - Specific heat of fuel;
D - Width of burning zone;
H - Flame height;

h Thickness of fuel bed;
k_1, k_2, k_3 - Coefficients of Eq.(17);
L - Flame length above fuel surface;
l - Free path of radiation;
M - Moisture content of fuel;
P_1, P_2 - Tangent points, Fig.3;
Q - Heat of vaporization;
q - Heat flux;
R - Rate of fire spread;
T - Temperature;
U - Wind velocity;
V - Buoyancy velocity;
W - Fuel loading;

Greek

γ - Angle between flame and fuel's surface;
ε - Emissivity;
θ - Angle between global and local coordinate systems;
ν - Surface-to-volume ratio;
ρ - Bulk density of fuel;
σ - Stefan-Boltzmann constant;
Φ - Flame angle factor;

Subscripts

0 - Initial;
eff - Effective;
F - Flame;
I - Inward;
m - Meteorological data;
O - Outward;
S - Surface;

Superscripts

$*$ - Global coordinate system;

Abbreviations

GIS - Geographic information system.

INTRODUCTION

Generally speaking, no words are needed to say that the forest fire[1] research is the problem of great significance. By itself, the burning process in wild nature is usual thing, but the impact of massive forest fires on the environment results severe damage to natural resources, ecological situation and wildlife. The development of system, allowing to predict forest fire characteristics, provides a highly desired tool for the fire fighting practice to minimize suppression cost and time, and possible loss. As the other global natural disasters, forest fire is a very complicated object for investigation. Every large forest fire (as a forest itself) is a unique phenomenon occurring in a medium of uncertain local conditions. Thus, the models for the prediction of forest fire behavior usually suffer from lack of confidence from the practical management. In a recent survey paper, Albini [1] has outlined the basic scope of wildland fire research, its motivations, main centers, present achievements and conceptual differences between wildfire and fire in human-made structures. Following his ideology, we are going to describe here our contribution to this "challenging, intriguing, and poorly funded field of research" [1].

The objectives of present research are laid within the rather wide frames of the problem of forest fire modeling. The final purpose of forest fire modeling required by practice is the estimation of the fire perimeter's propagation in time and space with reasonable accuracy along with other parameters such a fire intensity on leading edge and response time for suppression tools. A significant number of studies have been devoted to forest fire research with emphasis on different parts of investigation, among which we would distinguish the following main components:

- Fire spread model allowing to predict the local flame propagation rate in dependence upon forest fuel parameters, terrain and weather conditions.
- Forest fuel classification based on forest inventory data, providing the parameters affecting the fire spread process.
- Algorithm for approximation of fire perimeter to simulate the fire propagation process and its interaction with the tools involved to fire suppression.
- Overall design of the system for forest fire behavior prediction, as a computer code, which would be simple in use in fire fighting practice and would be arranged as an integrated part of a general system for monitoring of forest resources with high level of compatibility between mapping and database processing

There are implementations of such systems developed in the countries of considerable forest resources. The first of them is BEHAVE – Fire Behavior Prediction and Fuel Modeling System [2-5] generated by US Forest Service in mid-1980s. Later, FARSITE – Fire Area Simulator [6] using the GIS technology [7] was created, which provides the spatial simulation of fire growth using the fire models of BEHAVE. The Canadian Forest Fire Behavior Prediction System [8,9] has been developed employing their original fire spread model and fuel type description. Certain actions toward the creation of National Bushfire Model are made [10] in Australia, but the final result has not yet been reported. The appropriate research

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[1] Here we use the term 'forest fire' through the paper (just due to authors' native language custom) implying that it has the equal meaning with more appropriate 'wildland fire' or Australian 'bushfire'. The same relates to equality between 'forest', 'vegetation' and 'natural' fuel.

basis has been gained in Russia [11] and China [12], but elaboration of nationally recognized fire behavior prediction system faces a definite lack of governmental support. Concerning the Asia region, it has to be noted that Indonesia also needs some activity in this direction since it suffers from severe wildland fires [13].

Below, our view-point on the elaboration of computer code for the prediction of forest fire behavior is presented. We intend to trace the above mentioned steps of this process, to stress the weak spots and to outline the ways to the possible improvements.

FIRE SPREAD MODEL

First, a mathematical model is to be involved to predict the fire's local spread rate. A significant number of fire spread models related to forest fires has been proposed which are analyzed in a comprehensive review of Weber [14]. According to classification of [14], statistical, empirical and physical models are distinguished. The typical example of empirical group is Rothermel's model [15], on which the BEHAVE system is based. In presented study the model of Telitsyn [16-21] is used, which has been developed essentially on the physical basis in the spirit of approaches proposed by Emmons [22], Albini [23], van Wagner [24] and Thomas [25].

The sketch of fire spread model is shown in Fig.1. The energy balance in a fuel bed moving with a steady velocity R is expressed in general form as

$$\int_S q_S dS = R\rho[C(T_S - T_0) + QM]h \tag{1}$$

Since radiation is assumed here to be dominant heat transfer mechanism the heat flux is expressed by Stefan-Boltzmann law:

$$q = \varepsilon\sigma(T_F^4 - T_S^4) \tag{2}$$

The other heat transfer mechanisms (due to conduction and convection, including turbulence) which possibly are not negligible could be expressed, with a certain degree of roughness, in terms of radiation heat flux by introducing an appropriate value of emissivity ε in Eq.(2) unless a physical disagreement be found out. Actually, this has been done because emissivity has been determined through experimental data on fire spread rates. By the primary concept employed in a model [18], two modes of heat flux have been distinguished: the 'inward' radiation describing the heat transfer inside a fuel bed and the 'outward' (external or flaming, by other words) one corresponding to heat flux from the flame zone absorbed on a fuel's surface along a fuel bed. Thus, the left-hand integral of Eq.(1) is written as

$$\int_S q_S dS = q_I h + q_O \Phi L \tag{3}$$

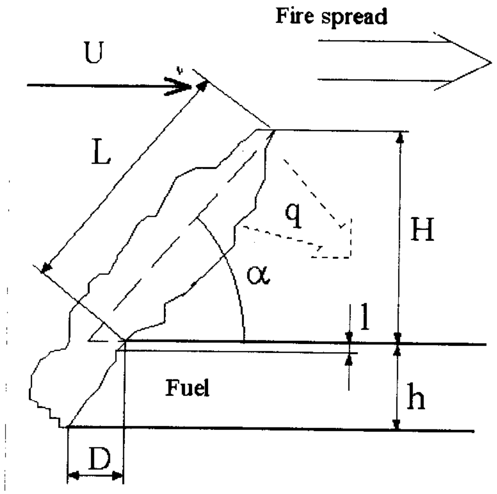

FIGURE 1. Fire spread model.

Two different modes of heat flux correspond to different physical meanings of fuel loading. While the inward heat flux relates to the overall fuel loading of fuel bed in conventional sense $W = \rho h$, the outward heat flux absorbed on a fuel's surface heats up the thin fuel's layer adjacent to surface. For this case the effective fuel loading is expressed as $W_{eff} = \rho_{eff} h_{eff}$ where ρ_{eff} is a particles density of which the foliage consists. Involving the free path of radiation in a fuel, the effective fuel loading can be expressed as

$$W_{eff} = \rho l \tag{4}$$

where free path of radiation is determined through the correlation between fuel's bulk density, particles density and surface-to-volume ratio:

$$l = \frac{1}{\nu}\frac{\rho_{eff}}{\rho} \tag{5}$$

Thus, the formula for fire spread rate is derived from Eq.(1) as

$$R = \frac{\varepsilon_I \sigma(T_F^4 - T_S^4)}{\rho[C(T_S - T_0) + QM]}\left(1 + \frac{\varepsilon_O \Phi L}{\varepsilon_I l}\right) \tag{6}$$

The model has been tested [18] using a large amount of available experimental information, which results the following approximation for emissivity

$$\varepsilon_O = 1 - \exp(-0.16D) \qquad (7)$$

$$\varepsilon_I = 1 - \exp[-0.16(L + 0.4)] \qquad (8)$$

where width of burning zone D and flame length L are considered as a characteristic parameters of large-scale flame. Apparently, the dependence of emissivity upon the both parameters shows the same correlation for both introduced modes of heat flux, but some correction factor (0.4) is included into the formula for inward radiation emissivity, Eq.(8). This coefficient stands for the case of fire of minimal intensity (for example, the fire spreading downward along a vertical layer of fuel or fire spreading opposite to the strong wind) where flame length over the fuel's surface becomes negligible and outward heat flux vanishes in Eq.(6). Such fire spread process is governed by heat transfer from glowing ember to virgin fuel.

The additional correlation for burning zone width, flame angle factor, angle itself, buoyancy velocity, flame height and flame length are estimated as follows [16,18]:

$$D = l + \frac{\varepsilon_O \Phi L}{\varepsilon_I} \qquad (9)$$

$$\Phi = \frac{1 + \cos\gamma}{2} \qquad (10)$$

$$\cos\gamma = \frac{U}{\sqrt{U^2 + V^2}} \qquad (11)$$

$$V = 2.5H^{0.5} \qquad (12)$$

$$H = A_H (WR)^{0.5} \qquad (13)$$

$$L = H / \sin\gamma \qquad (14)$$

and other parameters of Eq.(6) which are assumed to be constants are shown in Table 1.

The non-linear equations (6)-(14) for the prediction of fire spread rate were solved by successive substitutions. The convergent solution has been achieved for whole range of investigated input data. The coefficient A_H in Eq.(13) has been estimated [18] through the comparison of calculated results with available experimental data. It resulted $A_H = 2...7$ depending upon the fuel's type.

Field observations of the effect of wind on the forest fire spread rate showed the nearly linear character [19]:

$$R = R_*(1 + kU) \qquad (15)$$

TABLE 1. Constant parameters of model .

Symbol	Value	Unit
T_F	1200	K
T_S	573	K
T_0	293	K
C	1400	$J/(kg \cdot K)$
Q	26000	J/kg
σ	$5.67 \cdot 10^{-8}$	$W/(m^2K^4)$

where k is a constant close to unity and R_* is the spread rate in 'no-wind' conditions which is determined from Eqs.(6), (10) and (11) as

$$R_* = \frac{\varepsilon_I \sigma (T_F^4 - T_S^4)}{\rho[C(T_S - T_0) + QM]}\left(1 + \frac{\varepsilon_O H}{2\varepsilon_I l}\right) \qquad (16)$$

From analysis of Eqs.(6), (15) and (16) one should note that linear dependence expressed by Eq.(15) is rather hardly expected as an explicit correlation, but such assumption is usually considered reasonable due to character of dependence of flame angle factor upon wind velocity through Eqs.(10) and (11).

For the prediction of local fire spread rate the employment of Eq.(6) requires the information on local fuel properties such a moisture, fuel loading and density, which, relating to the investigation of fire spread process in the conditions of real forest, are not available as a continuous parameters in time and space. Hence, some discrete classification is to be introduced for fuel types within which the overall fuel's characteristics are assumed to be uniform.

CLASSIFICATION OF FUELS TYPES

The next step toward the development of practically applicable model is getting over the gap between characteristics required to calculate the fire spread rate and information on forest properties available from inventory data which do not reveal explicitly a single parameter ever mentioned above. The typical approach (for example [8,26-28]) to do that is a supervised evaluation of vegetation characteristics according to accepted fire behavior model. The result is a mostly descriptive matter with limited use of quantitative parameters of standard inventory data. Since computer database is being used for inventory data collection and analysis, the partial use of unsupervised data processing is a way to automate this work. Such problem has been studied in [7], but the algorithm of fuels layer creation has not been described in details.

In order to approach the mathematical model to practical needs, the formula for fire spread rate is expressed as

$$R = k_1(k_2 - 1)(1 + k_3 U_m) \qquad (17)$$

Here k_2 is Fire Danger Index, k_1 is 'basic' spread rate, k_3 is coefficient standing for effect of wind on the spread rate and U_m is wind velocity obtained from meteorological data.

The combination of factors containing k_1 and k_2 in Eq.(17) represents the spread rate R_* under the absence of wind as defined by Eq.(16). Unlike a bulk density and fuel loading which can be assumed constant for some fuel type, the moisture content is a certain function of weather. According to regulations of Federal Forest Service of Russia, Fire Danger Index is counted by integer numbers from 1 (zero probability of fire) to 5 (maximal fire danger). In physical sense, higher values of Fire Danger Index decreases the moisture content M in Eq.(6) which has an influence of inverse proportion on the fire spread rate. Since the typical dependence of fire spread rate upon the moisture has low curvature character (e.g. [29]), it is assumed that the Fire Danger Index itself has a linear influence on the spread rate. The 'basic' spread rate k_1 is determined from Eq.(16) using the fuel's properties such a bulk density, fuel loading and moisture content corresponding to 'basic' condition, i.e. when the Fire Danger Index is 2.

The simplified algorithm for fuels classification presented below is an attempt to combine directly the inventory data and fire spread model. On the present stage the analysis is limited by the condition of spring and fall season as a most fire dangerous period. Hence, the effect of green fuel component is excluded and crown properties are determined by coniferous species only. According to Eq.(17), two parameters, k_1 and k_3, have to be estimated. As it is assumed here the 'basic' spread rate k_1 is affected mostly by the underwood characteristics such a type of dominant species and its density. The effect of wind velocity on the spread rate is described by coefficient k_3, which depends upon the canopy closure of conifers. Both coefficients are divided into four categories, which give 16 possible fuels types. However, not all of them can exist such a combination of high canopy closure and dry underwood species. Totally 12 types have been distinguished as indicated in Table 2.

APPROXIMATION OF FIRE PERIMETER

Two approaches are generally used for the modeling of the fire perimeter growth, namely, there are point technique [30] and curve expansion algorithm [31-33]. First of them, despite having conceptual simplicity of coding, faces nevertheless conceptual difficulty to describe fire spread behavior, mainly due to limited number of directions for fire propagation [7] if conventional orthogonal grid is used. Therefore, we use second approach based on the Huygens' wavelet propagation principle first applied for modeling of wildland fire by Anderson et al. [31] and employing detailed technique of elliptical propagation of fire front proposed by Knight and Coleman [33].

TABLE 2. Parameters of fuels classification.

No.	Coniferous canopy closure, percent	k_3	Underwood		k_1, *m/hour*
			Type of species	Density	
1	0-20	1.0	Non-moist	Any	12
2	0-20	1.0	Moist	Low	10
3	0-20	1.0	Moist	Moderate	4
4	0-20	1.0	Moist	High	2
5	20-40	0.5	Non-moist	Any	12
6	20-40	0.5	Moist	Low	10
7	20-40	0.5	Moist	Moderate	4
8	20-40	0.5	Moist	High	2
9	40-60	0.3	Non-moist	Any	4
10	40-60	0.3	Moist	Any	2
11	60-80	0.1	Non-moist	Any	4
12	60-80	0.1	Moist	Any	2
	80-100	0.1	Any	Any	2

Fire perimeter is approximated as a curve F_t consisting of lines connecting the points fixed on the fire front at time t (Fig.2). Each point is considered as a source of fire, propagating independently for an assigned time step Δt. Parameters of each ellipse depend upon the local fuel properties and weather conditions at considered point on fire front at time t. The outer envelope formed by these ellipses defines the location of fire front $F_{t+\Delta t}$ at time $t+\Delta t$.

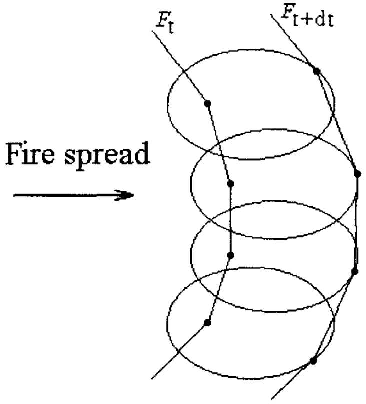

FIGURE 2. Huygens' principle for elliptical fire propagation.

Parameters of ellipse with the focus located at the origin of coordinate system and x - coordinate coinciding with wind direction are expressed as

$$\frac{(x-c)^2}{a^2}+\frac{y^2}{b^2}=1 \tag{18}$$

$$b=\sqrt{a^2-c^2} \tag{19}$$

Parameters a и c are defined through the fire spread rates as

$$a=R_{front}\Delta t-c \tag{20}$$

$$c=\frac{\Delta t}{2}\left(R_{front}-R_{back}\right) \tag{21}$$

where front and back fire spread rates are derived from Eq.(17) as

$$R_{back}=k_1(k_2-1) \tag{22}$$

$$R_{front}=k_1(k_2-1)(1+k_3U_m) \tag{23}$$

The algorithm for the approximation of new fire front $F_{t+\Delta t}$ is described as follows [33]. A local ellipse with parameters expressed by Eqs.(20)-(21) and focus located at some point $P_{t,i}$ on the old fire front F_t is constructed (Fig.3). Vector $\vec{V}$ is defined which could be $\vec{g}$ or $\vec{h}$, or any linear combination $\xi_1\vec{g}+\xi_2\vec{h}$, where ξ_1 and ξ_2 are non-negative and $\xi_1+\xi_2=1$.

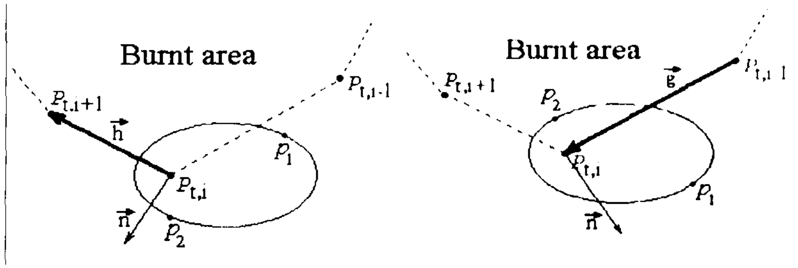

FIGURE 3. Approximation of the local ellipse.

Transformation from the global coordinate system to local one (x- coordinate coinciding with wind direction) yields

$$V_x=V_x^*\cos\theta+V_y^*\sin\theta \tag{24}$$

$$V_y=V_y^*\cos\theta-V_x^*\sin\theta \tag{25}$$

Searching the tangent points P_1 and P_2 where gradients of the ellipse and vector $\vec{V}$ are equal (Fig.3), the parametric angle is defined as

$$\varphi=\arctan(-bV_x/aV_y) \tag{26}$$

which results the coordinates of P_1 and P_2 in local

$$x_P=c+a\cdot\cos\varphi \tag{27}$$

$$y_P=b\cdot\sin\varphi \tag{28}$$

and global coordinate systems:

$$x_P^*=x_P\cos\theta-y_P\sin\theta \tag{29}$$

$$y_P^*=y_P\cos\theta+x_P\sin\theta \tag{30}$$

There are two solutions of Eq.(26) for each given vector $\vec{V}$, among which the points located outside of the old perimeter could be accepted as a points forming the new perimeter. The number and order of these points are chosen in dependence upon the old perimeter shape, actually, upon the angle between $\vec{g}$ and $\vec{h}$ vectors. Here, low curvature, moderately and sharply convex modes are distinguished [33]. In addition, optimization procedures [33] for overcome the possible complicated situations such a concave points, internal loops and overlapping of fire perimeters are employed.

FRAMEWORK OF COMPUTER CODE

The general scheme of developed computer code for the prediction of forest fire behavior is presented in Fig.4. The code is based on the geographic information system (GIS) which is created as a monitoring and operating tool for the management of forest resources. GIS considered here is arranged on the base of ArcTools and compatible softwares (such a GeoDraw and GeoGraph) as adopted by Russian Forest Service for Khabarovsk Territory. Two parts of GIS, the map layers and inventory database are inputs for ArcView graphical interface allowing to create a problem oriented maps by involving some data processing. The fuel types map is created by using the data analysis corresponding to fuels classification described above. As vector layers and fuels data are brought into ArcView interface the fuel types map containing the forest area of specific location and of appropriate scale is created.

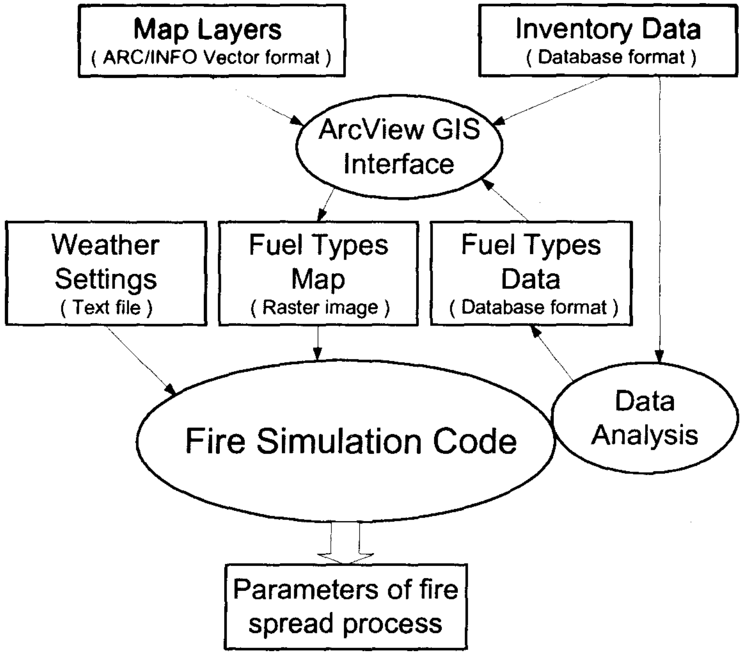

FIGURE 4. Framework of the computer code.

This map is transferred into fire simulation code in the form of raster layer where information on fuels characteristics, coefficients k_1 and k_1 of Eq. (17), are stored as pixel's colors corresponding to fuel types introduced in Table 2. The weather condition, another input for fire simulation code, provide the values of the coefficient k_2 (Fire Danger Index) and wind's velocity and direction.

EXAMPLE OF FIRE SPREAD SIMULATION

Figures 5-7 present the results of simulation of fire spread process and simultaneous construction of fire-break line. Analyzing the final location, one can estimate the tactics chosen for fire suppression (Fig.7). While the upper branch was built up properly, the lower one contradicts the safety regulations because of very close location of leading edge of fire front and acting facility.

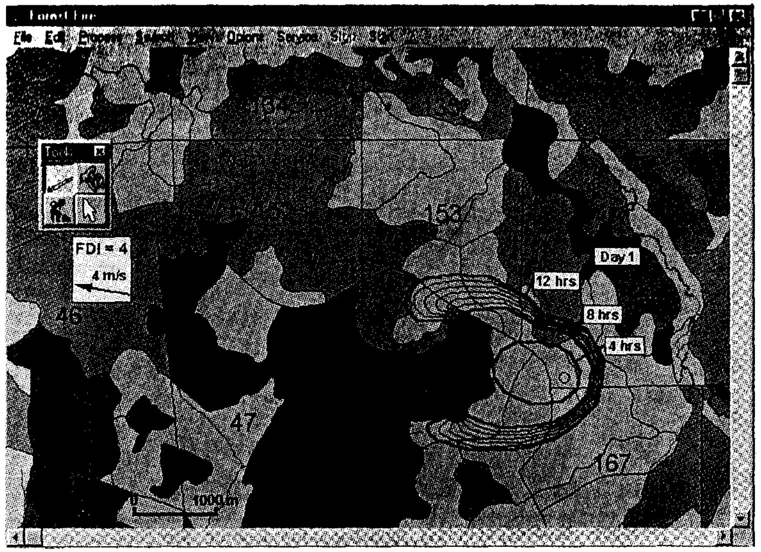

FIGURE 5. Fire perimeter distribution during the first day of propagation

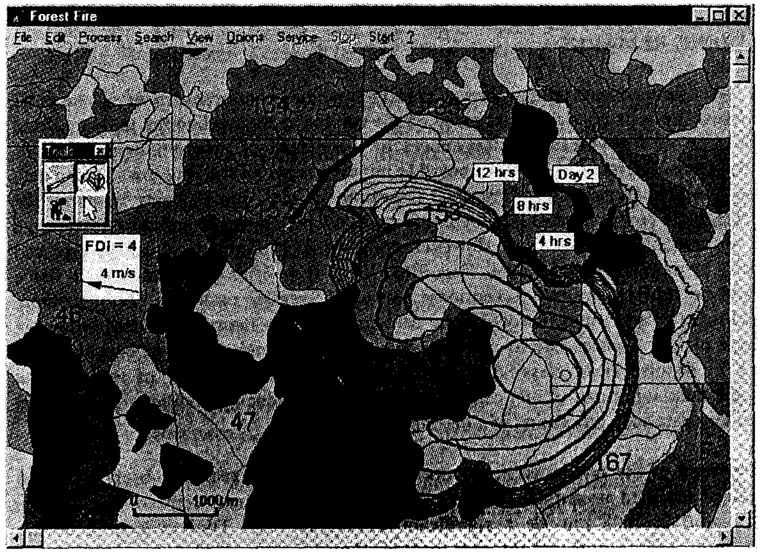

FIGURE 6. Fire perimeter distribution during the second day of propagation. The fire-break line is begun to build up.

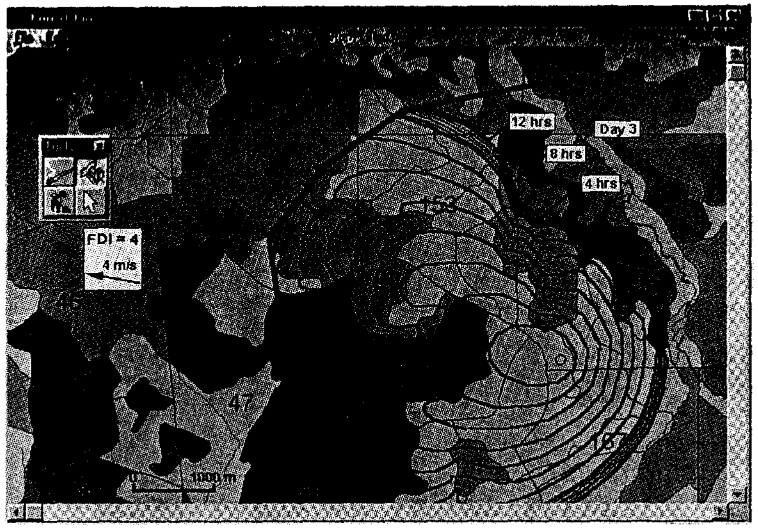

FIGURE 7. Fire perimeter distribution during third day of propagation. The construction of fire-break line is finished.

CONCLUDING REMARKS

As it has been pointed out, the purpose of presented study is an arrangement of computer code for forest fire behavior prediction based on the combined approach to the problem, from the formulation of fire spread physical model to the details of programming technique. Apparently, there is number of spots for possible improvements on the way toward the much comprehensive prediction system. Described fire spread model, despite being based on the physical approach, contains lot of empirical information which could be gained only through the field observation of forest fires. However, some of such correlations can be replaced rather easily by more advanced model. Thus, Eqs.(10)-(14) describing heat transfer in flame zone would be replaced by two-dimensional partial differential equations of momentum, energy and mass balance, which provides the velocity and temperature fields describing the mechanisms of heat transfer due to radiation and convection and effects of buoyancy and turbulence in details. Then, classification of forest fuel types (the kind of investigation requiring the substantial part of art) can be improved by introducing additional information from inventory data such processing of a descriptive 'forest type'.

Finally, the result of fire simulation needs much a comparison with real fire observations and verification of accepted assumptions. Eventually, massive forest fires occurred over Russian Far East region in 1998 provide a significant amount of data. Trial evaluation of fire perimeter propagation predicted by our system showed a reasonable agreement with observations as well as a wide area for future research. We did not present the comparison here, since primary goal of this study has been aimed on conceptual features of the elaboration of forest fire behavior prediction system. In fact, concerning such complicated phenomenon as forest fire, it is easy to draw good agreement between theory and reality, but it would be difficult to believe.

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