LA-UR-97- 3920

CONF-980121--

Approved for public release; distribution is unlimited.

Title: FIRETEC: A TRANSPORT DESCRIPTION FOR WILDFIRE BEHAVIOR

Author(s): RODMAN R. LINN, EES-5
FRANCIS H. HARLOW, T-3

Submitted to: AMS SECOND SYMPOSIUM ON FIRE AND FOREST METEOROLOGY

PHOENIX, AZ
JANUARY 1998

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

CONF-980121-

FIRETEC: A TRANSPORT DESCRIPTION OF WILDFIRE BEHAVIOR

Rodman R. Linn*
Earth and Environmental Sciences Division

Francis H. Harlow
Theoretical Division
Los Alamos National Laboratory, Los Alamos, New Mexico

January 1988

1 INTRODUCTION

Wildfires are a threat to human life and property, yet they are an unavoidable part of nature and in some instances they are necessary for the natural maintenance and evolution of forests. Investigators have attempted to describe the behavior (speed, direction, modes of spread) of wildfires for over fifty years. Current models for numerical description are mainly algebraic and based on statistical or empirical ideas. We describe, in contrast, a transport model called FIRETEC, which is a self-determining fire behavior model (Linn , 1997). The use of transport formulations connects the propagation rates to the full conservation equations for energy, momentum, species concentrations, mass, and turbulence. In this text, highlights of the model formulation and results are described, whereas the details of this work are described in other papers (Linn , 1997), (Linn and Harlow , 1997), (Linn and Harlow , 1997).

The goal of the FIRETEC model is to describe average behavior of the gases and fuels. It represents the essence of the combination of many small-scale processes without resolving each process in complete detail.

The FIRETEC model is implemented into a computer code that examines line-fire propagation in a vertical spatial cut parallel to the direction of advancement. With this code we are able to examine wind effects, slope effects, and the effects of nonhomogeneous fuel distribution.

*Corresponding author address. Rodman R. LInn, MS-D401, Los Alamos National Laboratory, Los Alamos, NM 87545; e-mail rrl@lanl.gov. LA-UR-97-****

2 FORMULATION

We envision three different relevant size scales for the representation of the physics involved in the wildfire. The largest of the relevant size scales, A scales, is the size of the largest fuel structures. The next largest scales are the B scales, which are associated with the distance between branches. C scales are the smallest and are associated with scales at the size of the small structures of the fuel, such as leaves or pine needles.

A critical temperature is associated with each reaction (pyrolysis of wood, evaporation of pitch or water, oxidation of carbon, combustion of hydrocarbons, etc.). It signifies the point at which there is enough heat in the reactants for the reaction to commence. We assume that the reaction rates are mixing-limited and that the chemical kinetics are instantaneous.

The average temperature in a resolved volume is related to the extremes of temperature by means of a probability distribution function that enables an estimation of the fraction of a given volume that is over the critical temperature for ignition.

There is much complex chemistry involved in the combustion of wood, which we represent with a few simplified reaction models, including descriptions of pyrolysis, char burning and the combustion of hydrocarbons and soot, in the presence of transported oxygen and inert gases.

Individual gaseous species are transported with the following transport equation for species d.

$$\frac{\partial \rho_d}{\partial t} + \frac{\partial \rho_d u_i}{\partial x_i} = \frac{\partial}{\partial x_i}\left[(\sigma_{b,ij} + \sigma_{c,ij} + \delta_{ij}\sigma_m)\frac{\partial \frac{\rho_d}{\rho}}{\partial x_j}\right] + (\text{net species sources}_d) \quad (1)$$

In this equation the densities and velocities are appropriate averages and the σs are diffusion coefficients associated with the turbulent structures at the B and C scales.

The conservation of momentum equation is of the form

$$\frac{\partial u_i \rho}{\partial t} + \frac{\partial \left(\rho u_i u_j + R_{ij}\right)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \rho g_i - D\rho u_i \ . \quad (2)$$

where we have introduced R_{ij} and $D\rho u_i$ to represent the Reynolds-stress tensor and the drag term respectively.

The internal energy of the gas is also computed with a transport equation, including the effects of radiation loss, convective heat exchange, and the heat lost or gained from chemical reactions.

Turbulence is described at the three separate scales, A, B, and C. For simplicity we use transport equation for the Reynolds-stress trace at A and B scales, with a Boussinesq approximation to extract the full Reynolds stress components.

For the turbulence energy density at the A scale we write

$$\begin{aligned} \frac{\partial \rho K_A}{\partial t} &+ \frac{\partial u_i \rho K_A}{\partial x_i} = -R_{il_A}\frac{\partial u_i}{\partial x_l} \\ &+ \frac{2}{3}C_{DR}\frac{\partial}{\partial x_l}\left[s_A \frac{R_{lk}}{\sqrt{K}}\frac{\partial K_A}{\partial x_k}\right] - \frac{\rho_g}{T_o} g_i \overline{u_i' T'} \\ &- \frac{\sqrt{K}}{s_A}K_A - \frac{3}{8}C_D \frac{\rho\, K_A \sqrt{K}\alpha_s}{s_B} \end{aligned} \quad (3)$$

The second term on the left side of the equation represents the mean-flow advective transport of turbulence kinetic energy while the second term on the right side represents the random walk advection of the turbulence caused by turbulent velocity fluctuations (self diffusion). The first term on the right side of the equation represents the creation of turbulence in the presence of a mean flow shear gradient. This term is especially important at the locations where the mean flow shears across the canopy. The third term represents the creation of turbulence in the presence of temperature-driven bouyancy. The fourth term represents the cascade of turbulence energy to fine scales. The last term describes the removal of turbulence energy from the A scales due to the drag in the forest.

For the transport of K_B there are two additional drivers that describe the creation of turbulence at the B scale, due to the break up of turbulence at the A scale and to the mean flow in the vegetation. These source terms are

$$\frac{\partial \rho K_B}{\partial t} = \ldots + \frac{3}{8}C_D \frac{\overline{\rho}_g \sqrt{K} K_A \alpha_s}{s_B} + \frac{3}{8}C_D \frac{\overline{\rho}_g |\tilde{u}|^3 \alpha_s}{s_B} \quad (4)$$

We could also write a transport equation for the turbulence energy at the C scales, but for our present model we approximate the C-scale Reynolds stress by setting it proportional to that of the B-scale Reynolds stress.

The overall chemistry is extremely complicated. At this stage, we have examined three idealized limiting cases for guidance in the formulation of our burn model. These are

1. gas-gas, with two reactants forming a single final product, with no intermediate species,
2. gas-solid, representing the burning of char in the presence of oxygen,
3. single reactant, for pyrolysis of wood.

The essential features of the three results are remarkably similar, leading us to propose a simplified burn model that contains much of the essential physics and test its adequacy for representing the essence of fire propagation. Our principal postulate is contained by the "universal" reaction rate

$$F = c_F \frac{\rho_f \rho_o \sigma_{cm} \Psi}{\rho_{ref} s^2}\lambda \quad (5)$$

in which s is the scale of the smallest fuel elements. Numerical experiments show that $c_F = .07$ is consistent with the expectation that a fire in a 1 m/s wind can barely sustain itself.

The form of λ is

$$\lambda = \frac{\rho_f \rho_o}{\left(\frac{1}{N_f}\rho_f + \frac{1}{N_o}\rho_o\right)^2} \quad (6)$$

3 RESULTS

This burn description has been inserted into the FIRETEC model for testing with a variety of configurations. Simulations were run out to 250 seconds after ignition. Figures 1 through 6 depict the gas temperatures for these simulations at 250 seconds after ignition.

Figure 1 shows the temperature contours with ambient wind of 2 m/s and Fig. 2 is for a wind speed of 3 m/s from the left, each with a fuel bed that is distributed to a height of 10 m from the ground. These two pictures show the effects of different windspeeds on the behavior of the fire. Notice the difference in the fire spread rate as well as the difference in plume angle above the fire. The effects of mean wind on plume angle in FIRETEC simulations agrees well with previous observations, (Weise, 1993).

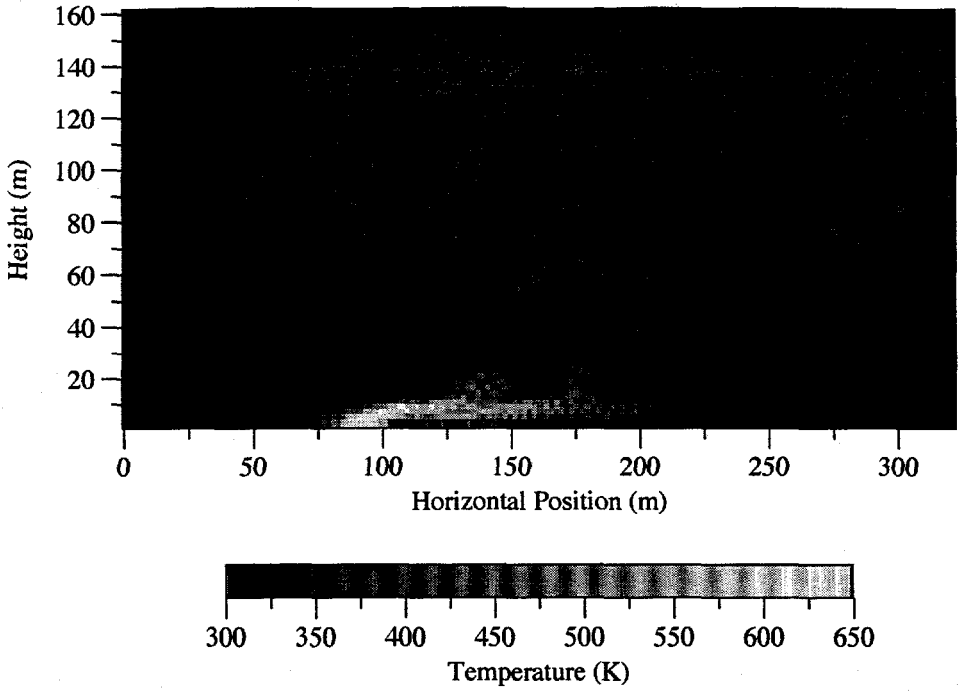

Figure 1: Temperature contour images with 2 m/s crosswind 250 s after ignition

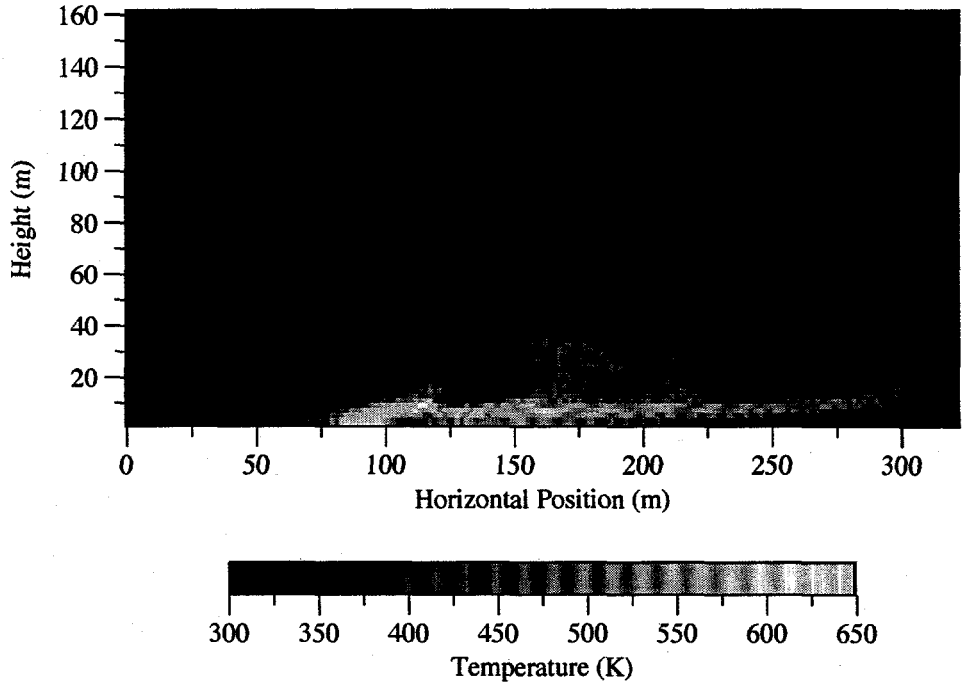

Figure 2: Temperature contour images with 3 m/s crosswind 250 s after ignition

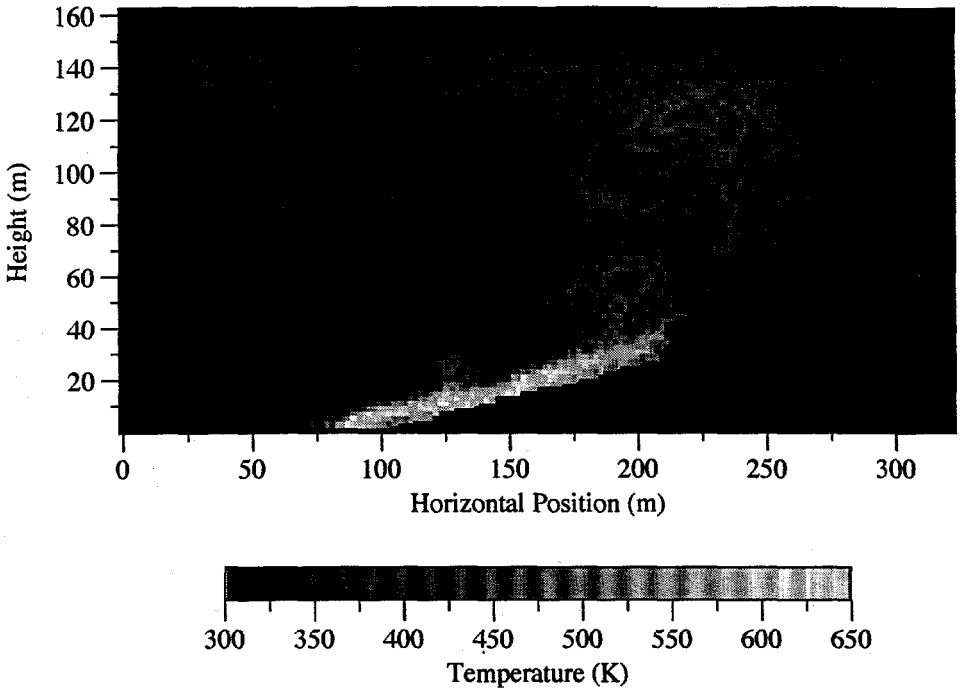

Figure 3: Temperature contour images for upslope terrain 250 s after ignition

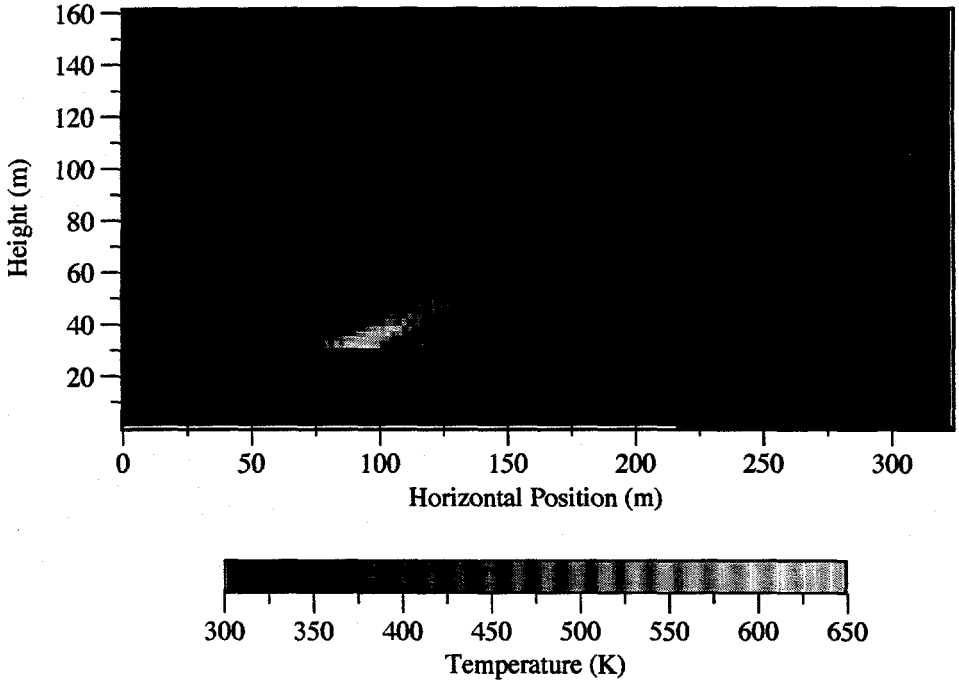

Figure 4: Temperature contour images for downslope terrain 250 s after ignition

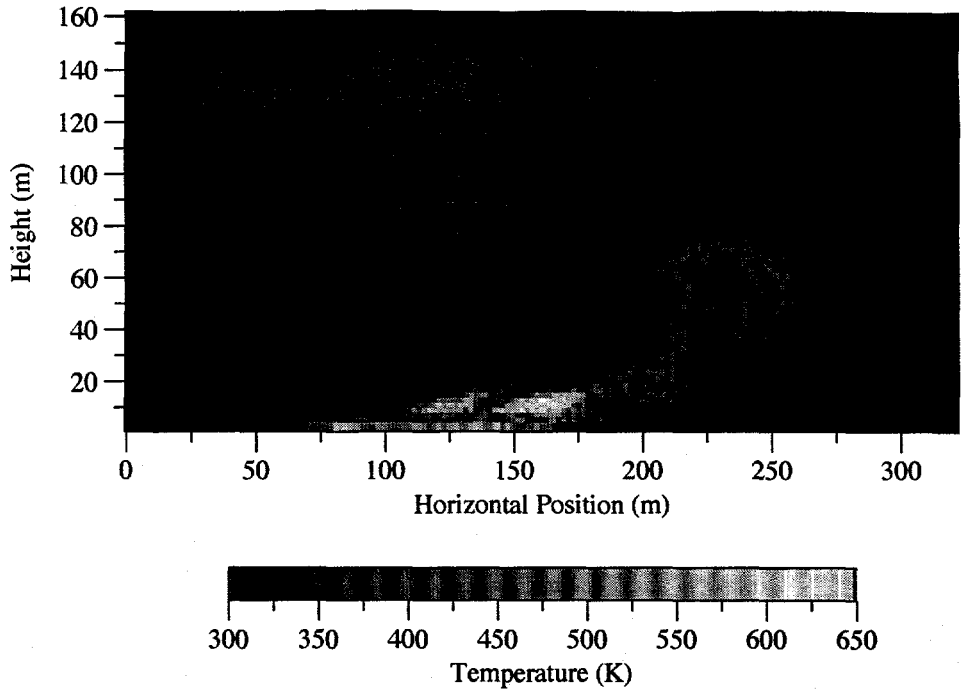

Figure 5: Temperature contour images for simulation with separated canopy and understory

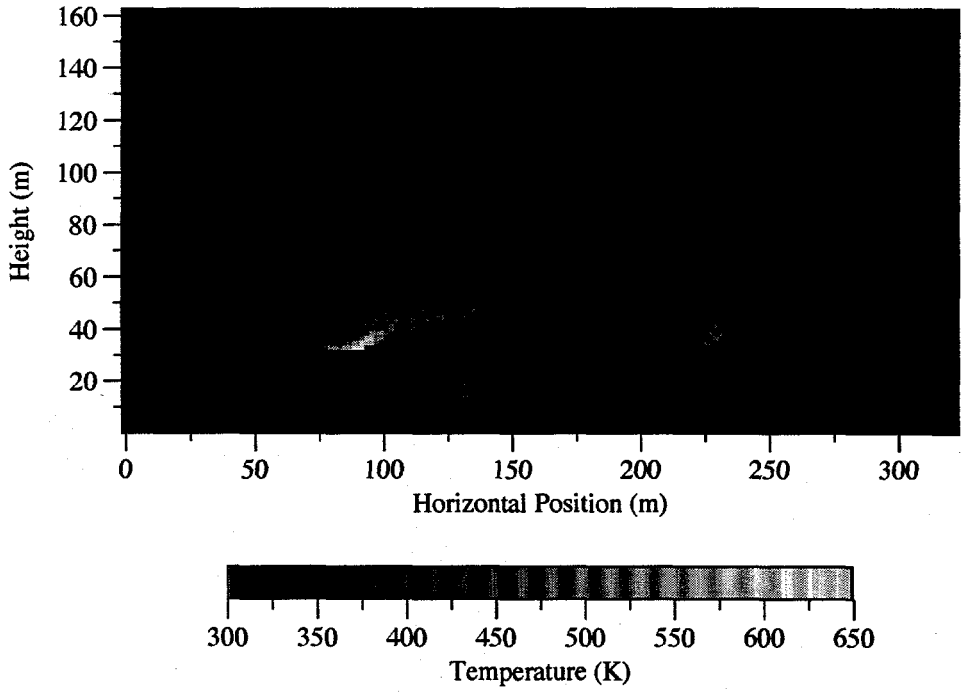

Figure 6: Temperature contour images for canyon simulation

Figures 3 4 illustrate fires driven by 2 m/s cross wind in the same conditions except that the terrain has been modified to an upslope in the first picture and a downslope in the second picture, showing, in particular, the accelerated spread rate on the upslope and the decelerated spread on the downslope.

Figure 5 depicts a fire that is being driven by a 2 m/s crosswind through a fuel bed that has the same total fuel load as the fuel beds used in previous calculations but the canopy is separated from the understory by a gap that has negligible vegitation in it. This gap allows a different fire behavior because the air can flow in between the two layers of vegitation and feed the fire in the understory.

Figure 6 illustrates especially well the capability of a transport representation to describe history dependent nonlocal processes. A canyon, 120 m wide is approached by a fire burning in a 2 m/s crosswind. The fire was ignited well back from the edge of the canyon. Complex wind patterns result from bouyancy and the induced circulation within the canyon. The plume touches the fuel at the far edge of the canyon resulting in the ignition. This representations is possible because the probability-distribution-function approach for temperatures describes the probable fraction of mass in the debris-laden plume that lies above the critical temperature for ignition. This formulation thus describes the presence of ignited firebrands and therefore makes the simulation of touchdown spotting possible.

References

Linn, R. R., 1997: A Transport Model for Prediction of Wildfire Behavior. PhD dissertation, New Mexico State University, Dept. of Mechanical Engineering, Las Cruces, New Mexico; also published as Los Alamos National Laboratory Report number LA-13334-T.

Linn, R. R., and F. H. Harlow, 1997: Self-Determining Transport Model for Wildfire Propagation, I Theory and Derivations, Paper in Preparation.

Linn, R. R., and F. H. Harlow, 1997: Self-Determining Transport Model for Wildfire Propagation, II Application and Validation, Paper in Preparation.

Weise, D. R., 1993: Modelling Wind and Slope-Induced Wildland Fire Behavior. PhD dissertation, University of California at Berkley, Berkley, California.