A HEAT CONDUCTION ANALOG MODEL OF URBAN FIRE SPREAD

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Introduction

In the development of computational models for use in civil defense planning, one must always be conscious that the goal is a practical tool. The product must not be prohibitively expensive in time or money.

It was in this spirit that the heat conduction analog model of urban fire spread was conceived and investigated. This work proceeded from the observation that many fire spread phenomena have at least a superficial similarity to transient heat conduction phenomena, and from the recognition that well-developed and maintained heat conduction codes and associated graphics are available.

The intent of this preliminary investigation was to get some idea of the virtues and limitations of the model by developing it sufficiently for use on simple test problems. The practical problem of ultimate interest is the estimation of the rate and extent of fire spread across fuel distributions that are continuous (debris fields) or discontinuous (standing buildings with various amounts of damage), or a combination of both types.

Previous models of fire spread have been of two basic types. One type is completely stochastic.[1,2] The second type of fire spread model may be described as deterministic on a microscale and statistical on a macroscale.[3]

There are so many variables, even for the limited case of fire spread among similar buildings, that many compromises have to be made. With this in mind, it does not appear unreasonable to circumvent the detailed modeling by use of a few parameters that can be adjusted to agree with experiment or fire experience.

Concept of the Heat Conduction Analog Model

Consider an array of buildings of various types of construction, occupancies, and physical condition. Wind is negligible, separations are such that fire spread by radiation across the streets is possible in some cases. At t=0, some of the buildings suffer ignition of sustained fires. Following an induction period during which fire spreads within the affected buildings, the burning buildings become intense heat sources as the fires reach their peak burning intensity, with flames shooting out of windows and over the roofs. If the configuration and obscuration factors, fire susceptibilities, etc. are appropriate, neighboring buildings may be ignited, creating new heat sources while the original ones are dying out.

If one thinks of the burning buildings as heat sources releasing a prescribed amount of energy in some prescribed fashion, and the non-burning buildings are seen as potential heat sources separated by regions of various heat capacities and temperature-dependent thermal conductivities, one can imagine representing the spread of fire by the spread of heat in a transient heat conduction problem. Thermal conductivities can be modified to give expected fire spread rates and to favor spread in expected directions. We would expect that a building very susceptible to ignition would light faster than a less susceptible neighbor. This can be reflected in the specific heats assigned to the buildings. We would also expect a building exposed to several burning buildings to ignite faster than a building exposed to only one. Heat conduction automatically provides for this effect, at least qualitatively.

It should be clear already that we are no longer dealing with actual physical properties. One starts with plausible base values, then adjusts some parameters to get agreement with experiment and physical expectations. The only parameters not subject to change are: geometrical layout of the urban area, the fuel values and burn characteristics of the buildings, and the (approximate) time for fire spread between neighboring similar structures.

Implementation of the Model

The code used to test the model is the 2-dimensional version of TACO, a finite element, transient heat conduction code that has been developed over several years and is in general use at LLNL.

Each element in TACO has an associated material, which in turn has a specified density, specific heat, thermal conductivities (the conductivity may be orthotropic), and heat generation rate. The specific heats, conductivities, and heat generation rates may be time or temperature dependent. The timestep in transient problems may be varied according to the rate of temperature change, or interactively between timesteps.

While conduction is usually not important in fire spread between buildings, the model is in the bizarre position of using conduction to model radiative and convective heat transfer. A more difficult incongruity in the model is the use of a continuous process (heat conduction) to represent a spatially discontinuous one (fire spread between buildings). Spread across debris fields is a much better match to the model. It has not been studied for lack of data, and because it was recognized that the model had to be able to do the discontinuous problem to justify its development. The procedure is as outlined below.

1. For each "material" in the problem, choose densities, specific heats, and thermal conductivities typical of non-conductors (e.g., wood, asphalt, soil). Modify c_p and k as necessary to get physically plausible results.
2. Choose heat generation rates to approximate expected values for corresponding building types and occupancies; modify to simulate effects of damage.
3. Get approximate value for threshold ignition temperature for each building type by calculating its adiabatic temperature, the temperature it would reach if all the heat generated by its burning went into self-heating. Divide this by four to get an idea of the maximum temperature that a burning building can give any of its neighbors. Lower this by 15-20% to account for some conduction.

4. Allow random fluctuations in threshold temperatures about the mean value for each finite element of the type. (I.e., assign each building element a threshold temperature in the range $[\theta-\delta\theta, \theta+\delta\theta]$). This is to reflect differences in building conditions and contents, obstructions, and the heat generation rates of neighboring buildings.
5. Give material between buildings temperature-dependent thermal conductivity of form $k = k_o(1+\alpha T^3)$, where k_o is the intrinsic conductivity. This form is chosen in analogy with the radiation heat transfer coefficient and to force fire spread to occur near peak burning rates. Make materials between buildings orthotropic, with temperature-dependent conductivity in the direction normal to buildings to account for the rapid decrease of radiation configuration factors laterally.
6. Run test problems of homogeneous building types, modifying α's and the specific heats of materials between buildings and α's ,c_p,θ,$\delta\theta$ of building types to approximate expected rate of spread for given building separation. For maximum sensitivity, the separation should be about that for 50% spread probability.
7. Using parameters chosen in step 6, check spread probabilities at other separations (e.g., at 20% spread probability). Some iteration between steps 6 and 7 may be appropriate to make slight improvements.

Test Runs

Only very simple cases have been run. By running simple problems one has some idea of what is physically plausible. The uniform, square grid most commonly used is shown in Fig. 1. "Buildings" consisted of 4 elements. Only one building type was used. Floor area and the heat generation rate were chosen to approximate wooden barracks burned at Camp Parks[5]. (Fig. 2 shows the heat generation rate used). Building separations of one or two elements, corresponding to 12.9m or 25.8m, were chosen to ensure significant spread probabilities.[6,7] The building material was given an isotropic, temperature-dependent thermal conductivity so large that spread within a building generally occurred. No effort was made to approximate expected spread rates within a building. (In any problem of realistic size buildings would almost certainly be represented by a single element so this is not a major area of concern.) The material between the buildings consists of four types of "asphalt". They have the same density and nearly the same c_p, but different thermal conductivities. Most are strongly undirectional. Some, in corners or at misaligned buildings are temperature-dependent but isotropic. Some have a low, constant, isotropic conductivity reflecting their expected lack of participation in fire spread due to their location.

Within the parameter space for which any spread within or between buildings occurs, the results are sensitive to changes in c_p's, α's, θ, and $\delta\theta$. The values used for the examples are given in the Table. This is not necessarily an optimum set, as there was not enough time to investigate all possibilities. These parameters gave the desired spread probability across a 12.9m separation of about 45% (5 out of 11 chances) in a test configuration.

The effects of a constant ambient wind have been simulated in some runs by adding a term to the thermal conductivity of all elements. The wind is taken as the positive X-direction without loss of generality since the urban grid could be rotated by an appropriate amount if desired. Since thermal conductivity is bidirectional by nature, it is necessary to know the direction of the temperature gradient at each element in order to know the appropriate sign of the effective conductivity due to the wind. That is, if the temperature increases in the X-direction, the effect of the wind should be to retard heat flow Conversely, if the temperature decreases in the X-direction, the wind should augment the heat flow.

The appropriate form of k_w is not known, nor is there data available for calibration. The test problems were run with $k_w = BW$ for $W \leq W_o = 3.76$ m/s, and $k_w = BW_o (W/W_o)^\beta$ for $W \geq W_o$. B and β are viewed as empirical constants. The choice of W_o is to reflect the empirically-derived demarcation between stationary and moving mass fires. In the test problems, B = 500 and β = 1.25. If suitable data were available, B and β would be modified to give the appropriate downwind rate of spread, then compared with the upwind rate.

Results

For the test problems initial ignitions were chosen to see the effects of interactions, or 10% - 30% of the buildings or elements were chosen at random for initial ignition. Some of the results are shown in Fig. 3 and 4.

An important observation is that the spread of fire appears physically plausible in time and space. That is, fire spread events can be attributed to one or more neighboring burning buildings near or a little past peak burning intensity.

Even with only 10% building or element ignitions generally all buildings eventually ignite for the basic urban area used here. This basic urban area, however, has building separations of only 12.9 or 25.8 m and only one type of building--there are no fire resistive types which might stop fire spread. Not all burning buildings in the test problems cause spread. In some cases most of the spread can be traced back to one or two of the initially ignited buildings. Recall also that the parameters were chosen to give about 50% spread across a 12.9 m separation. It is known from Schmidt's work that with a spread probability of 50% or more there is generally unlimited spread.[2]

Some problems were run with a break of 38.7 m through the center of the problem area. Fire failed to cross this break in some cases or barely managed to cross it in others. More work is needed to ensure appropriate spread probabilities for various separation distances.

For one test problem (10% random element ignitions), the initially ignited elements were fixed but different sequences of random numberswere used to choose the threshold ignition temperatures. Qualitatively similar results were obtained for fraction of buildings burning vs. time.

A constant wind had plausible effects of speeding spread downwind and slowing or preventing upwind spread. Lack of data for adjusting empirical constants prevents any useful conclusions other than that the technique used appears promising.

Conclusions

While this preliminary effort has been very limited in scope, it has shown that the heat conduction analog model can produce plausible results for discontinuous fire spread. Given suitable information on fire spread in a constant wind or spread due to firebrands, it may be possible to incorporate these effects. Fire spread across debris fields should be simpler to treat than the discontinuous case. Modeling of fire-induced winds and related mass fire development appear to be beyond the range of the model.

Credibility is a more immediate problem. An important test would be to run an improved version of the model against other fire spread models. This would also provide a comparison of problem set-up and computation times. Such a comparison should indicate whether this model has advantages justifying further development.

References

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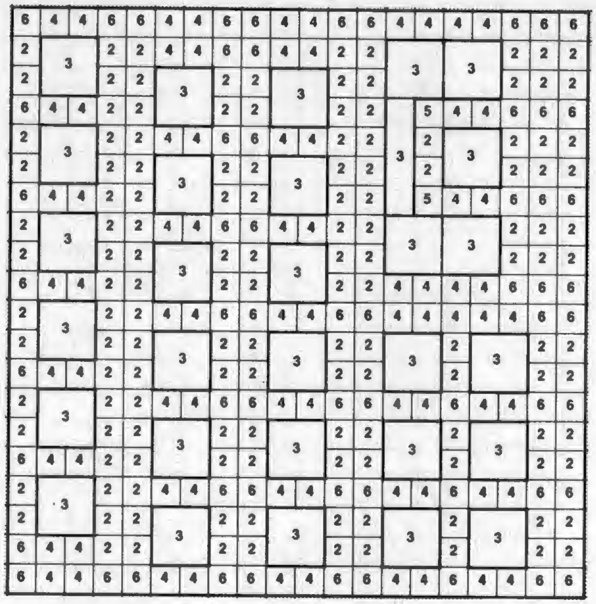

Fig. 1. Problem layout used for most problems.

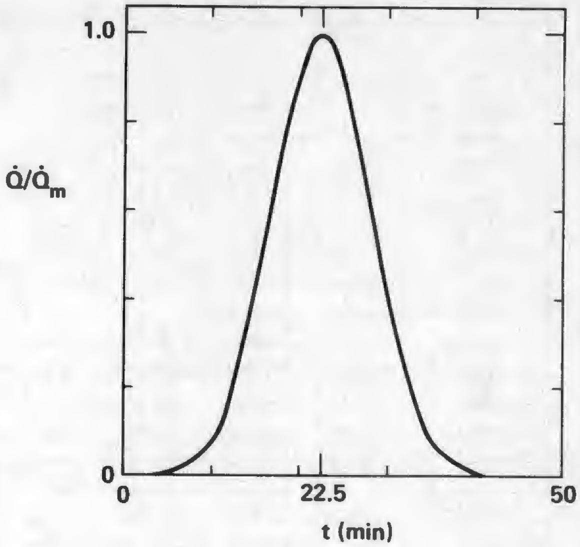

Fig. 2. Heat generation rate for buildings.

θ = 140, $\delta\theta$ = 40

Material No.	ρ	c_p	α_x	α_y
1	2500	1800	$1\cdot10^{-3}$	$1\cdot10^{-3}$
2	1900	60	$1\cdot10^{-3}$	0.0
3	720	850	$1.6\cdot10^{-2}$	$1.6\cdot10^{-2}$
4	1900	60	0.0	$1\cdot10^{-3}$
5	1900	60	$1\cdot10^{-3}$	$1\cdot10^{-3}$
6	1900	100	0.0	0.0

$k = k_0\ (1+\alpha T^3)$, k_0=0.6 for all materials
timestep = 2 minutes for problems without wind, variable otherwise.

Table of parameters used in test problems. (All units are S.I.)

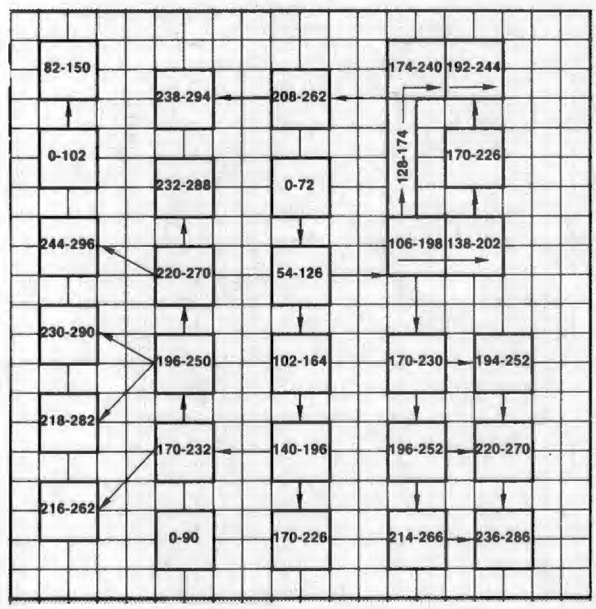

Fig. 3. 10% building ignitions. Here and in subsequent figures the numbers are the times (in minutes) during which the "buildings" burned.

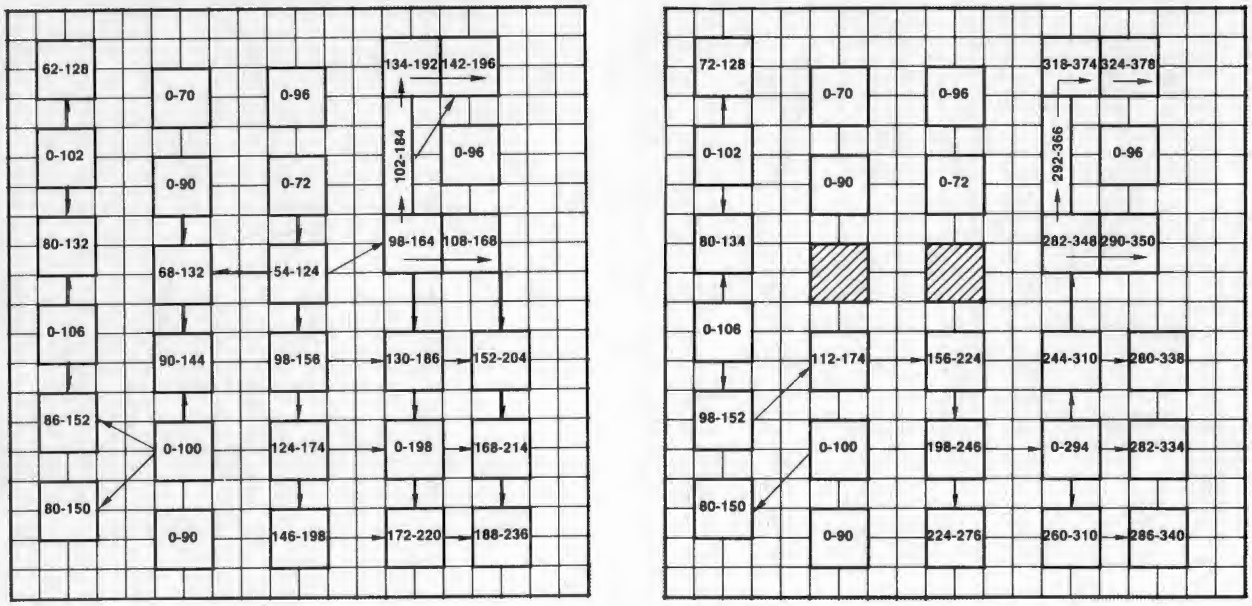

Fig. 4. 10% element (33% building) ignition. On left, all buildings have C_p = 850; on right, two hatched buildings have C_p = 8500. Note delay in fire spread caused by failure to ignite.

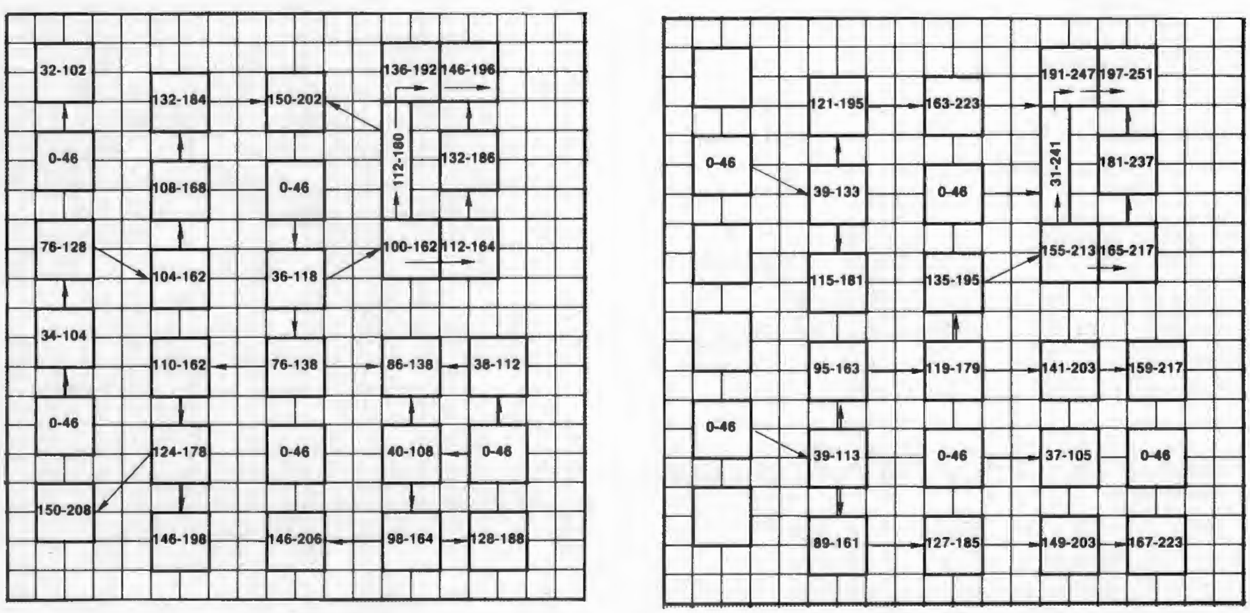

Fig. 5. Effects of a 9 m/s "wind" for 17% building ignition. (The parameters for the effective conductivity due to wind have not been fit to data.)