A Foundation for Initial Attack Simulation: The Fried and Fried Fire Containment Model

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Why Simulate Initial Attack?

Fire protection planners have long sought analytic approaches for evaluating the effectiveness and efficiency of fire protection organizations. A reasonably faithful representation of initial attack is a key requirement for almost any analysis in exploring alternative configurations of initial attack.

Early Efforts

Simplistic simulations of initial attack date to the 1970s: for example, in the Forest Service National Fire Management Analysis System's Initial Action Assessment (NFMAS-IAA) model and the U.S. Department of the Interior's Airpro model. In the NFMAS-IAA model, which sought to identify the configuration of initial attack resources that would minimize firefighting costs and the net change in resource values resulting from fires, the fire containment process was represented in caricature—in other words, as a highly simplified version of the real world. The model tracked two numbers separately as the simulation of initial attack progressed: 1) the perimeter of a growing, 2:1 length-to-width ratio ellipse representing a freely burning, uncontained fire and 2) the length of fireline that could be constructed as modeled firefighting resources "arrived" at the fire. If the two values, perimeter length and constructed fireline length, converged, the fire was declared contained. If this did not occur within a specified time or before the fire had grown to a specific size, an escape event was declared. Although computationally simple, this convention (or algorithm) produced overestimates of fire size—sometimes by a factor of 10 or more—because no "credit" was given for the effects of line-building efforts by early-arriving resources in slowing in the growth of the fire.

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Scaling Up, Enhancing Realism

Capturing the essence of fire management in a simulation context typically requires simulating initial attack for thousands of simulated fires in any given scenario due to the considerable local, spatial, and temporal, real-world variability in fire occurrence, fire behavior, firefighting capacity, and firefighting challenge (as manifest in fireline productivity). Modelers often simulate containment of fire events from multiple fire seasons (either by running event data from actual fire seasons or from "synthetic" seasons simulated so as to be consistent with the distributions of fire occurrence, behavior, etc. from actual fire seasons). While one could attempt to simulate the growth and containment of each wildfire in a spatially explicit modeling environment such as FARSITE, this approach is time-intensive, and it is not clear if there are advantages to using this technique over modeling a broad range of fire behaviors with response times and fireline productivities based on representative geographic information system data. Instead, contemporary initial attack models, such as the California Fire Economics Simulator (CFES) version 2 and the Interagency Fire Program Analysis' Initial Response Simulator (FPA-IRS), simulate containment on thousands of such quasi-spatially represented fires. Both of these models rely on the Fried and Fried containment algorithm (Fried and Fried 1996), which models the effect of suppression efforts on fire growth, allows simulation of any mathematically representable fire shape, provides for "head" and "tail" attack tactics as well as parallel attack (building fireline parallel to but at some offset distance from the free-burning fire perimeter, alone and in combination with "firing out"), and supports dynamic (variable) forward rates of spread and fireline productivity over the course of initial attack (fig. 1).

How It Works

The following scenario illustrates how the simulation works:
A single firefighting unit arrives at the scene of a fire. The fire spreads at a constant forward rate of spread, calculated from slope, fuels, and weather data for the location (extracted from enterprise data). The unit anchors at the tail (heel) and begins line construction. The unit works its way around the fire perimeter (fig. 2). If the line holds and the unit is catching the fire, there will be a net decrease in overall fire spread. No further spread will occur where the perimeter is contained, but the fire's rate of spread at the front of the linebuilding effort will be continually increasing as the unit moves closer to the head of the fire, where fire spread rate is maximum.

Note that, in a head attack, the opposite is true: even if fireline production is declining—for example, due to engines running out of water or crews becoming exhausted—there will still be a chance of containing the fire as linebuilding efforts approach the tail.

The algorithm represents one flank of the contained fire perimeter as a differential equation in which location of the constructed containment line is a function of the ratio of fireline productivity to forward rate of spread. For simplicity and computational tractability, the second flank is assumed to be a mirror image of the first flank.

If, in the above example, the unit is unable to make net progress toward the head of the fire, for example, because the aggregate linebuilding rate is dwarfed by the rate of perimeter expansion, linebuilding resources become inadequate for the task, engines run out of water, or hand crews become exhausted, the fire would "outrun" the suppression resources and exceed simulation limits.

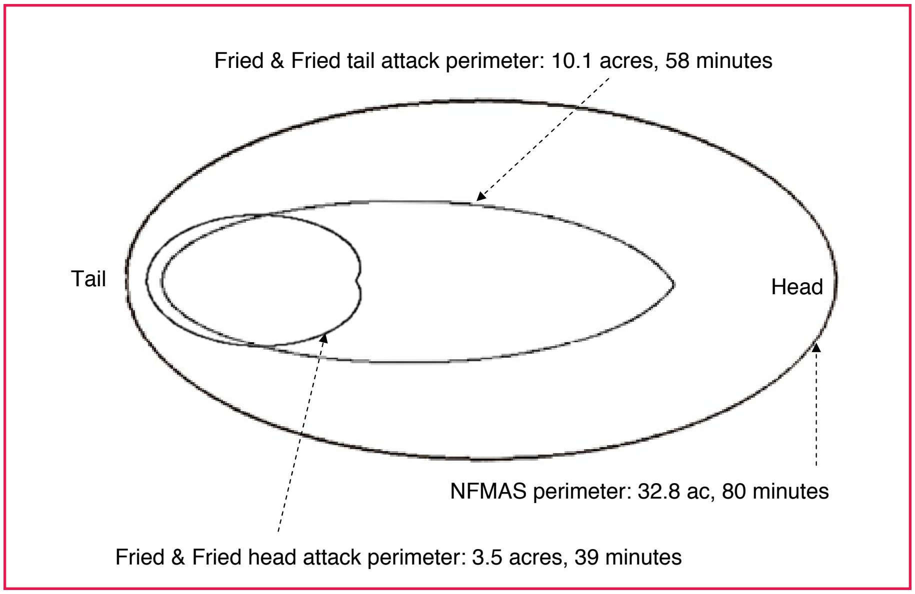


Figure 1—*Final simulated perimeters, sizes, and containment times of a fire that is 0.01 acres at report time, has a forward rate of spread of 20 chains/hour, is assumed to have a 2:1 length-to-width ratio elliptical shape when free-burning (not suppressed), and is attacked on two flanks 20 minutes after reporting by two resources, each producing fireline at 35 chains per hour, using the NFMAS algorithm and the Fried and Fried algorithm with tail and head attack options.*

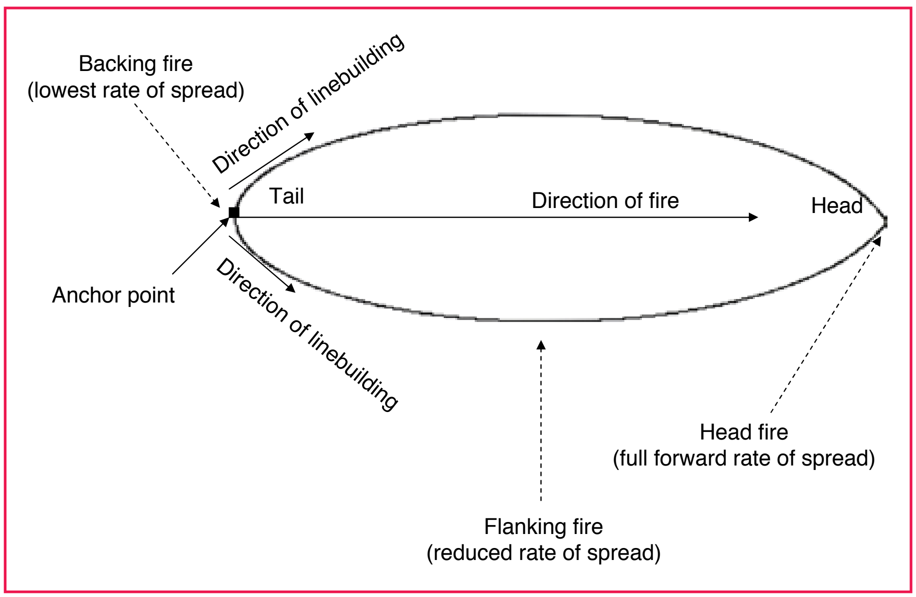


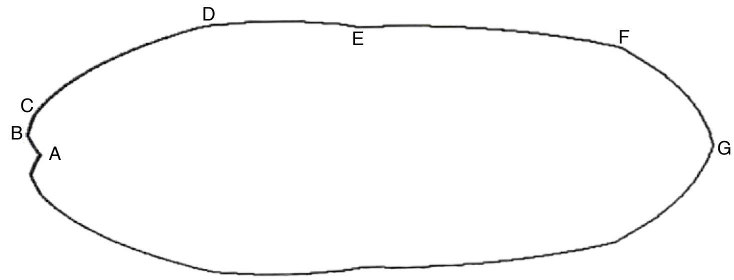
Figure 2—*Schematic representation of a tail attack on an elliptical fire that would have a 2:1 length to width ratio if free-burning. Rate of spread at the point of linebuilding increases steadily as firefighters get closer to the head.*

Inputs to the Algorithm

For each fire to be modeled, the Fried and Fried algorithm requires the following inputs: (1) reporting time, (2) fire size at reporting time, (3) forward rate of spread, (4) length-to-width ratio of the ellipse, (5) type of attack (head, tail, or parallel), (6) offset distance (if parallel), and (7) simulation size and time limits. In addition, for each ground-based line-building resource dispatched to the fire (for example, fire engines, bulldozers, or hand crews), the algorithm requires the following inputs: (1) time of arrival; (2) initial productivity (in chains per hour); (3) time at which productivity drops from an initial, high rate to a lower, more sustainable rate; and (4) the associated sustainable production rate. Air tanker and helicopter drops of water and retardant are represented somewhat differently. The length of containment line corresponding to a drop is a required input, but the algorithm translates this distance to a rate of line production that will continue for 1 minute, resulting in the specified length of containment line. Thus, a drop that produced 10 chains (200 m) of fire line would be represented by the algorithm as 600 chains (12,070 m) per hour for 1 minute (600 chains per hour x 1 hour/60 minutes = 10 chains per minute). Such drops can generate rapid linebuilding progress that is quite noticeable on a plot of the fire perimeter (fig. 3).

Will the Fire Be Contained?

The algorithm outputs whether or not the fire could be contained with the available resources and, if so, the containment time and final size of the fire in perimeter and area. Using all of the input data provided, the Fried and Fried algorithm represents the one-flank containment boundary as a differential equation and then attempts to solve it using numerical integration. Solution of the equation is successful if the resources are sufficient to contain the fire and fails if the resources are not.



Label Point	Arriving resource	Arrival Time minutes	Change in Production Rate chains per hour
A	Small crew	5	+2
B	Small engine	25	+6
C	Large crew	30	+25
D	Air tanker	40	+240
E	Air tanker	41	-240
F	Bulldozer	55	+45
G	#N/A	62	Fire contained

Figure 3—Perimeter of a fire attacked from the tail by five resources. Note that 1) as production rate changes with the arrival of resources, forward progress in containing the fire adjusts accordingly, 2) the air tanker drop is modeled as a one minute long burst of high productivity between points D and E, 3) production rates are halved by the model to fulfill the assumption of symmetry between the two fire flanks, and 4) the final fire shape is more elongated than the assumed 2:1 free-burning elliptical shape because attack was from the tail. (Successful head attacks result in less elongated fire shapes.)

The differential equation can fail mathematically if the linebuilding rate is less than the spread rate of the fire and firefighters would be overcome by the fire unless they abandon the attack. In this situation, the algorithm attempts to "re-run" the simulation, delaying the initiation of attack until the arrival of the next firefighting resource or until the simulation time limit is exceeded. If re-runs are unsuccessful in achieving containment, the fire is labeled "outrun" and classified as having exceeded simulation limits.

If the solution of the differential equation does not fail mathematically, then the simulated fire may be contained. Because the one-flank containment line is fully represented in the model following solution of a differential equation, it is computationally straightforward to calculate the area "under" that flank using numerical approximations and then double the result to get the full area of the contained fire. If this area exceeds the simulation size limit or the containment time exceeds the simulation time limit, the fire is classified as exceeding simulation limits; otherwise, it is classified as contained.

What We Can Learn

We can learn much in analyzing the parameters of fires that exceed simulation limits. Some fires could have been contained by initial attack resources but not within the specified size or time limits. These limits are typically set at the point at which a fire would transition from an initial attack fire to an extended attack fire or when the shape for a free-burning fire changes from a shape easily represented by an algebraic function, such as an ellipse, to a more complex, irregular shape in response to geographical or environmental conditions (for example, when the fire has become large enough to extend fingers up adjacent canyons or when wind direction has changed significantly since fire ignition). For other fires, there is little hope of ever achieving containment with initial attack because the production rates of firefighting resources are no match for a rapid forward rate of spread.

Some fires fall in a middle ground, in which containment is possible but risky. On such fires, containment involving airdrops would be possible except that a retardant or water drop could push the containment efforts on the ground toward the head of the fire, where the local spread rate is closer to the full forward rate of spread; working where the spread rate is high may overwhelm ground-based firefighting resources, triggering a provisional "exceeds simulation limits" classification. In other instances, a drop-off in the fireline production rate of ground forces can trigger an outrun condition and represent a provisional "exceeds simulation limits" status. In still others, an upward, diurnal adjustment to the forward rate of spread as a fire burns from morning into afternoon may trigger the "outrun" condition. In all three scenarios, the fire can be rerun by the algorithm with a delayed initiation of containment effort, but only a subset of such fires will ultimately be classified as "contained."

We can learn something about the efficacy of our dispatch rules from patterns in modeled fires that exceed simulation limits, identify areas where availability of resources is an issue, and provide guidance on prioritizing areas for fuels management. Because the resource arrival times are known from the inputs and the containment time is known from the outputs, it is also possible to use models built on this algorithm to examine resource utilization—the specific resources assigned to fight the fire—both for specific fires and for all fires in a fire season. If costs are assigned to modeled resource utilization according to initial attack parameters, then it is also possible to assess some components of firefighting costs through the model.

Algorithm realism and flexibility have proven instrumental in facilitating simulation of a wide range of scenarios, including alternative budgets, initial attack configurations, fuels, and changing climates.

Caveats and Applications

The Fried and Fried containment algorithm was designed to represent initial attack scenarios only. It does not address extended attack fires for which (1) an elliptical fire shape assumption is likely unrealistic, (2) quite different containment tactics may be deployed, (3) fuel types (and thus both forward rate of spread and fireline production rates) may vary over the containment boundary, and (4) spot fires may figure prominently in the firefighting challenge. Moreover, simplified assumptions—such as airdrop-created fireline being "permanent," at least over the time-scale of initial attack—make them less useful for modeling multiday fires. However, the comparatively short but critically important period of initial attack imposes no artificial limitation on the usefulness of the algorithm in a strategic planning and budgeting system.

Models such as CFES and FPA-IRS, both of which employ this algorithm as the initial attack simulation engine, are well-suited to marginal analysis—examining the effects of incremental changes to budgets and, ultimately, the configuration of initial attack on fire suppression effectiveness. CFES has been used by the State of California to help ensure consistency in fire response across the State. FPA-IRS generates lists of fire scenarios that exceed simulation limits and passes them to FPA's large-fire module, a modeling system that accounts for landscape-scale fuel management and firefighting organization in addressing large wildland fires and defining final fire areas.

This containment algorithm is also integrated into the BEHAVE fire modeling system so that outcomes for specific fires can be easily analyzed. Algorithm realism and flexibility have proven instrumental in facilitating simulation of a wide range of scenarios, including alternative budgets, initial attack configurations, fuels, and changing climates. These attributes have contributed to acceptance of simulation results by managers and firefighters alike.

Reference

Fried, J.S.; Fried, B.D. 1996. Simulating wildfire containment with realistic tactics. Forest Science. 42:267-281.