A Scientific Method for Determining Point of Origin in Arson Investigation

By

Quon Yin Kwan

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Approved:

M. Edwin O'Neill

Paul Casamajor

Patrick J. Perry

Committee in Charge

Degree conferred ....
Date

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Abstract

A need to solve the problems of arson investigation arises from the high incidence and gravity of incendiarism. This thesis represents a preliminary attempt to solve some of the technical problems encountered in arson investigation beginning with the most fundamental, the determination of the point of origin. A scientific approach to solving the problem of determining the point of origin is proposed applying mathematical modeling concepts from fire science to criminalistics.

What is specifically formulated in this thesis is a computer method for quantitatively determining the point of origin and for ascertaining the time of ignition of a fire. The method of solution relies on a computer program which regressively constructs the location of the previous fire perimeter which occurred an arbitrarily chosen time unit prior to the one observed. This procedure is repeated obtaining a series of concentric burn perimeters. The program terminates when the burn perimeter converges to a suitable working area for the investigator. Future advancements can be made to take into account heterogeneous and time-varying conditions.

The significance of a scientific method for determining point of origin in urban arson investigation is forseeable. Such a method for use in investigating structural fires would be most beneficial to ascertaining cause and locating physical evidence. The long range implications of such a method encompasses increasing the reliance upon physical evidence in both crime investigation and in criminal trials and improving objectivity of criminalistics and the administration of justice.

Table of Contents

I. Introduction: The Arson Problem

Arson poses a problem of such magnitude and gravity that it should be called the crime of all crimes. The conception that arson is the mere destruction of property is pretentious for arson is more heinous than murder because of the unrecognized danger to life. The act of arson jeopardizes the lives of occupants, neighbors, firemen, and others that come to the rescue of innocent victims.

Fire statistics demonstrate the magnitude or the high incidence of arson. Nationwide, incendiary and suspicious fires account for approximately six percent of the total number of urban fires.[1] This does not include that portion of fires of undetermined origin that are incendiary nor the fact that arson increases in periods of economic recession. With respect to the realm of wildland or rural fires, the incendiary cause accounts for the greatest number of fires and the greatest number of acres burned.[2] The arson problem in the South of the United States is the major factor influencing the nationwide arson statistics[3,4]. In California, approximately one-fifth of the total number of wildfires are attributable to incendiary cause.[5]

In addition, there is the gravity of the arson problem which is not represented by statistics. Generally, incendiary fires are apt to be the most dangerous for several reasons. They tend to concentrate in foothills where a greater potential for upward spread exists. Show and Kotok's analytical study of California forest fires[6] showed a prominence of incendiarism during critical fire weather and in heavy brush making them certainly dangerous to suppress. Because arson is deliberate, such fires are set at the time and place where they will do the most damage and have the least chance of discovery.

A. The Essence of Investigating Arson

The human elements of desire and opportunity to perpetrate arson cannot be predicted nor eliminated. However, this felonious behavior can be deterred by enforcement of laws proscribing malicious firesetting implemented through effective investigation and apprehension. Thus, investigating arson is an essential and necessary form of fire prevention directed at regulating the human factors that govern ignition rather than fuel factors [7,8,9,10,11]. This approach to fire prevention is what Davis considers "the compulsion approach."[12] Reynolds asserts that the legal approach is the principal key in lowering fire occurrence and severity.[13] The value of arson investigation is manifest in deterring incendiarism even where it comes short of a criminal conviction. Deterrence as a result of investigation is effected through civil as well as criminal adjudications and the pyschological impact of being suspected or apprehended for arson.

In view of the high incidence of incendiarism and its gravity and the deterrence value of arson investigation, the investigation of all fires for arson cannot be overemphasized. In practice, the investigation of arson should be given the highest priority next to life safety in the handling of a fire situation.[14] Furthermore, the phases of determining the origin and cause must be done as quickly as possible so as to preclude loss or contamination of the physical eivdence by changes in the natural elements, curiosity seekers, or even removal by the arsonist.

B. The Need for Determining the Point of Origin

The investigation of arson generally proceeds by first tracing the point of origin, then determining the cause, and finally establishing the causal agent of the fire. This is the logical order for the investigation in the absence of verbal or other information. The rationale for this procedure is that the point of origin is generally where the clues to the cause of the fire is located. It then follows that the determination of cause and the collection of associative physical evidence would lead the investigator to the causal agent, that is the person(s) responsible for the fire.

The procedure of tracing back to the fire origin is also pre-requisite to reconstructing the crime. It is from the physical evidence located at the origin that inferences of the motive and modus operandi and other circumstances of the crime can be made. Wakefield[15] emphasizes the concept of reconstruction to piece together the events that occurred in the perpetration. Thus, the process of determining point of origin is necessary to the investigation by virtue of the fact that it leads to location of evidence of the causal agent and that it is intrinsic to the reconstruction of the crime.

C. The Problem of Determining Point of Origin

At the present time, there are several ways of going about tracking down the point of origin. One is to rely on eyewitnesses. For example, the investigator, after being told that hunters were seen in the area, may deduce that searching for good hunting "stands" would lead him to a point of origin. Unlike urban areas, there is a lack of eyewitnesses in rural areas due to the low population density frequently leaving the arsonist undetected.[16] Another method is to make some educated guesses; this is not difficult in investigating accidental fires because the more common locations are known, e.g. roadsides, campsites, trails, etc. Investigating an incendiary fire is more difficult because there are no such similar clues, especially since the arsonist takes advantage of deliberately where and when to set the fire.

In the most general case where the arson investigator must commence with the absence of any information, he relies on the interpretation of burn "indicators" or "pointers," in order to back-track his way to the point of origin. The effects left by the passage of a fire on the vegetation and terrain constitute these so-called "indicators" or "pointers." From these effects, the intensity, persistance, and the direction of fire can be inferred. Ford, of the California Division of Forestry, is the author of this technique.[17,18.] The general principle that is applied is that the vegetation and objects still standing after a fire has passed will show more intense heat effects, such as charring, on the face that was originally exposed to the oncoming fire. A few terse examples illustrate this technique: Brushing the back of the hand or some sensitive part of the skin against the burned top stubs of some plants will indicate fire direction. A movement toward the fire origin will be perceived as a rough texture because of going against the grain or char direction set by the passing fire. A movement away from the origin is velvety or smooth; movements in any other direction reveal no information. Another "indicator" is burned stubs of brush which remain and do not fall after a fire has passed. They will be cupped with the tip of the cup pointing toward the fire origin. It is noted here that urban arson investigators abide by the same principles in tracing origin in structures: The depth of char, the intensity of soot, characterization of alligatoring, etc. are used to interpret fire direction. The only differences from rural arson investigation is in the type of objects burning and confinement.

After back-tracking towards the fire origin, the rural arson investigator verifies his closeness to the origin by being in the vicinity of the "area of confusion," so-called because the burn "indicators" no longer demonstrate a prominent burning direction but contradict each other and thus confuse the interpretation. Once at this area, the most efficient manner to examine the area is to spiral or semi-spiral about in the mode that is described by O'Hara.[19]

There are a number of criticisms associated with determining the point of origin using the prescribed method of interpreting burn "indicators." One is the extensiveness of the area with which the investigator must work.[20] In contrast to a structural fire, the wildland burn area is not confined, and thus, a wide variation in combustible materials and burning conditions exist. Because the difficulty of locating the fire origin exponentially increases with the size of the burn area, considerable amounts of time and manpower must be expended. Another criticism is the fact that these burning "indicators" have not proven to be infallible. Some investigators have rejected the use of some of the burning "indicators" and Ford has recognized some of the controversies such as heliotropism "indicator."[21] For these reasons, there is a need for ameliorating the method for determining the point of origin.

D. The Problem of Ascertaining the Time of Inception

A problem akin to the point of origin determination is that of ascertaining the time of inception of the fire. Often, a great deal of time will elapse before the fire is discovered and still a longer time before the arrival of fire crews. The problem is aggravated in rural areas because of the low population density meaning less likelihood of detection and great dispatching distances. A consequence of this procrastination is the greater opportunity for obliteration of materials of evidentiary value as well as a delay in the commencement of the investigation. Albeit that the investigator has no control over these factors, he must have knowledge of the time of inception of the fire or the relative time lapse. This fact is needed to reconstruct the crime by establishing the opportunity for a particular suspect to set the fire and his whereabouts at that time. In interrogation, this fact is desired in order to test alibis and to detect anachronisms in a suspect's story.

It is upon these two specific questions: the point of origin and time of inception determinations, that the remainder of this thesis will concentrate. Some light can be shed on a potential method of solving these two problems by examination of modeling principles.

E. Plausibility of Applying Fire Modeling Principles

Experience in interpreting burn "indicators" by using the current method to determine the point of origin cannot be gained without a good qualitative comprehension of fire behavior. Ford indicates that the investigator must carefully take into account the effects of wind, slope, and moisture on fire spread and their relative orders of magnitude of effect.[22] According to Ford[23],

> "...let's examine...burning behavior to 'crank' this element into the analysis of visual signs (of direction of fire spread)..."

The point made is that the similarities between what knowledge of fire behavior that the investigator uses in order to determine fire origin and what principles that a combustion scientist uses to determine horizontal flame spread instigated an idea as to whether or not more exact and quantitative principles of the latter could be applied to assist the investigator. Certainly, a scientific approach to this phase of arson investigation would be a significant improvement.

It is the intention of this thesis to demonstrate the application of fire science modeling principles to arson investigation and specifically use these to attack the fundamental problems of determining the point of origin and the time of inception of fire. The wildland case, in contradistinction to the urban case, will be used to exemplify the proposed method in this thesis. The wildland case is the preferred example because of its greater simplicity and the greater utility and application to the wildland situation.

II. Solving the Problem of Determining the Point of Origin by Application of a Mathematical Model for Prediciting Fire Spread

A. Mathematical Models for Prediction of Fire Spread Rate

The kind of fire science modeling that is applicable to the problems of determining the point of origin and time of inception of fire in arson investigation is mathematical modeling. Although experimental or laboratory modeling has potential utility[24,25], it will not be discussed here. Mathematical modeling is quantitatively describing the behavior of a physical process occurring in a system under defined conditions.[26] In the realm of wildland fires, analytical mathematical models have been formulated to predict the rate of horizontal fire spread through a porous fuel bed. Such models predict the rate of spread based upon given input values of fuel bed parameters, topographic, and atmospheric data. A mathematical model that is worked up from first principles of heat transfer, fluid mechanics, kinetics, etc. is an analytical model. Empirical mathematical models are those that are formulated from empirical studies in which the different macroscopic effects controlling the rate of spread are investigated and correlated. The justification for development of mathematical models which predict fire spread rates lie in the needs to solve technical fire suppression and prevention problems, e.g. prediction of wildland fire danger ratings, location of fire breaks, etc. Yet, the potential of mathematical models and fire science concepts in arson investigation have not been mentioned in the literature. The first serious attention was given to fire modeling in 1959 in the symposium of the National Academy of Sciences—National Research Council.[27,28] Since then several avenues of modeling research have been persued.

The first mathematical model predicting the rate of fire spread was attempted by Fons in 1940.[29] He completed a more thorough analysis of the model in 1946[30]; in this model, the underlying thesis is the idealization of flame propagation as a series of successive ignitions. Hottel, Williams, and Steward contributed a rigorous study of the effect of flame radiation and pre-heating on flame propagation using thick and thin fuel bed approximations.[31] De Ris formulated a model that treats flame spread as a gas phase laminar diffusion flame through two types of cases: a thin fuel bed and a semi-infinite fuel bed.[32] Atallah presents a highly simplified theoretical model for a fire spreading through a forest fuel bed in terms of an energy balance on an element at the base of the flame.[33] Albini presents a model for fire spread in brush in terms of a set of iterative scheme of equations showing the spread rate, flame length, and burning zone depth as functions of fuel bed height, moisture content, and fuel loading.[34] Peterson and Pagni[35] have finalized an analytical fire spread model which desscribes energy conservation on an element of fuel taking into account moisture effects, pre-ignition, pyrolysis, forced and free convection. This is the most recent model which approaches the most general and realistic of all the analytical models.

Most of the analytic models are still in the developing stages for not all of the phenomena underlying fire behavior have been unraveled and understood. Until a working analytical model is completed, empirical models will have to suffice. Probably the most accurate contemporary model that would be suitable for application in arson investigation is one recently developed by Rothermel.[36] Rothermel's model is tailored to field application in that all input parameters such as fuel conditions, wind, slope, moisture, etc. are measurable. The theoretical antecedent to Rothermel's model is Frandsen's conception of fire spread as a quasi-steady state where the heat absorption required to ignite the fuel and heat flux within the potential fuel are sufficient to develop a solution.[37]

An elaboration of Rothermel's model is pre-requisite to the discussion of its application to the determination of origin. His model assumes one-dimensional spread, stabilization of fire into a quasi-steady state, continuity in the fuel strata, a non-crowning fire, i.e. fire propagation only on the ground, negligence of fire brand activity, and uniform distribution of fuel size classes. The model also excludes fire blow-ups, fire whirls, and fire storms. Of course, these assumptions restrict its application because of the few fuel beds and fires found in nature with these characteristics; nonetheless, the problem statement for determining the point of origin will have to be adapted to take these into consideration.

The input parameters that are required for inserting into the equations of Rothermel's mathematical model are listed in Appendix I. The values of these parameters have to be known, of course, before the occurrence of the fire, and can be obtained through the use of keys[38] for appraising forest fuels or fuel maps of vegetation maintained by forestry districts. The mathematical equations of Rothermel's model are provided in Appendix II.

B. Method of Solution

A definition of the problem statement of determining the point of origin and a delineation of the assumptions is in order: the unknowns to be determined are the point of origin or the approximate "area of confusion" in which the point of origin lies, and secondly, the time lapse between the fire's inception and outermost perimeter. The information that must be given are the burn pattern perimeter and its mapping at some specified time, preferably at the first arrival of the fire. The fuel conditions and parameters, the topographic, and atmospheric parameters needed to satisfy Rothermel's equations must be procured. The assumptions inherent in the method proposed here for scientific determination of the fire origin are intrinsically the same as that stated in the mathematical model being used which is Rothermel's model. To repeat these, these are assumptions of steady-state conditions, absence of fire whirls, blow-ups, storms, fire spotting, fire crowning, i.e. fire propagation only along the ground, uniformity of fuel size classes, and continuity of fuel strata. In addition to these assumptions, are (1) two-dimensional fire spread can be decoupled or separated into two one-dimensional cases, (2) the fire direction is normal to the fire front or instantaneous fire perimeter, (3) the ignition source is a single point, (4) the ignition source is located within the burned area, and (5) the outermost fire perimeter has been not tampered with by any suppressing action before it is recorded or used for the proposed method.

In consideration of a number of alternative solutions, it appeared that the most suitable to that of determining the point of origin for the most general conditions of non-uniform, heterogeneous fuel and terrain, was best achieved by computer programming involving a numerical approach. This was evinced in view of the necessity for instantaneously calculating the rate of fire spread (rather than taking an average for each parcel considered), the repetition or re-iteration of the same calculations, the speed and accuracy derived from digital computation, and the facilities available for graphically displaying the results.

In brief, only the most general notions about the computer program proposed as the solution to the determination of point of origin problem will be discussed. The computer solution originally designed by the author is best summarized in terms of the main and subprograms leaving the mathematical derivations and equations in Appendices II, III, and IV. The source deck is written in FORTRAN IV, consists of approximately 500 cards, and is broken down as follows: main program POOD and four subprograms, CALANG, ROS, INTCHK, and PLOTT. The relationships and interaction between the main program and subprograms are shown in Chart 1.

The main program, POOD, acronym for Point of Origin Determination, constructs the fire perimeter regressively from the given outermost perimeter. This outermost fire perimeter is obtained directly from the field or by aerial photogrammetry at preferably first sight of the fire. The outermost fire perimeter is transposed from its amoebic shape on a map into a workable medium for a computer with the use of a digitizer by transcribing the curve in terms of a suitably large number of coordinates of points on a set of Cartesian axes. For the sake of simplicity, all coordinates are converted into non-di-

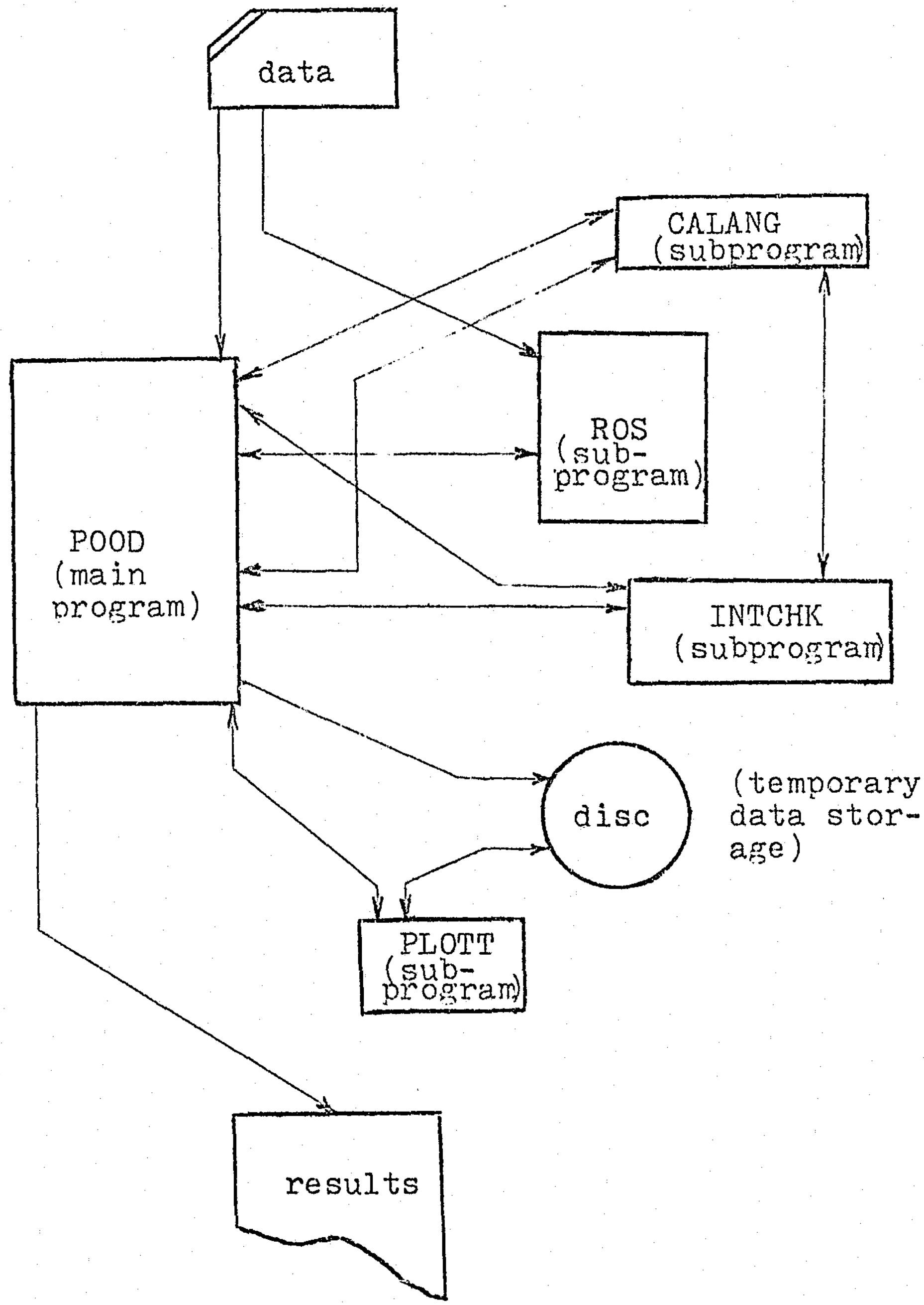


Chart 1. Computer flow chart showing relationships between main program and subprograms in proposed method for point of origin determination.

mensional units and translated such that all fit into the first quadrant and lie in the range and domain of positive 0 to 100. All directions: wind, fire direction, aspect are measured in radians using polar coordinates as the frame of reference with east and 0^{o} coincident with the positive x-axis.

Given the outermost fire perimeter, the fire perimeter as it actually occurred at some interval of time earlier is constructed. The next earlier fire perimeter is constructed from this and continued in this fashion. Each one falls inside of the previous contour. By reiterating this procedure, the concentric contours finally converge to an "area of confusion" in which the point of origin lies. This area is pre-defined so that it is sufficiently small that an investigator can go in to search for evidence.

The concept of regressively constructing fire perimeters at equally spaced time intervals until the concentric contours converge to the origin is analogous to a "reverse" Huygen's principle of wave propagation through a material medium in physics. By analogy, if the fire perimeter is approximated by a series of infinitesimal line fires juxtaposed to each other, then each line fire can be treated like a reaction wave with the entire fire perimeter treated as a wave surface. By reconstructing the previous tangent secondary reaction waves, their emitting source can be tracked back along the route of propagation. Although the concept appears simple, by no means was it easy to program the algorithms to perform these iterations. The algorithm for constructing the fire perimeter occurring earlier is the consequence of satisfying two equations which is detailed in Appendix III. One, a linear equation, describes that the coordinates of the point on the new contour lie on the normal to the given fire perimeter. The other equation gives the distance the fire traversed as a product of the rate of fire spread in the immediate vicinity times the arbitrarily chosen time interval; this equation is a quadratic since it appears in the form of a distance formula. The value of the rate of spread used is called from subprogram ROS. The solutions common to these two equations give the coordinates of the points of the next contour. Since there are two pairs of solutions, one physically corresponding to the contour outside of the burn perimeter and the other on the inside, an algorithm had to be devised to select the proper solution. Depending on the instantaneous slope of the fire perimeter, the appropriate solution can be consistently obtained; this algorithm is detailed in Appendix IV. A consequence of this algorithm was the necessity to order the numbering of the coordinates at the initial stage of digitizing; and this was chosen arbitrarily to be counterclockwise. This pair of algorithms is repeated for every point on the given fire perimeter and then reiterated for each fire contour.

After the points of each contour are generated, the distance between each pair of points in the contour array is compared to determine whether there are an inordinate or insufficient number of points representing the contour. If there is an excess, the total number of points describing the contour is dynamically reduced during each iteration. On the other hand, if there is an insufficient number, points are added midsection between pairs of contour points in order to maintain consistent accuracy and without distortion of the already constructed array. The coordinates of points comprising the contour array are stored temporarily on magnetic disc after they have been scanned by subprogram INTCHK and until ready to be used by subprogram PLOTT.

The algorithm for terminating the program, that is, for determining that the contours have converged into the fire origin consists of testing the area of the fire perimeter. The formulation of the test for convergence is derived from the classic trapezoid method of integrating under a curve. The program terminates when the area is less than or equal to a conveniently chosen "area of confusion."

Subsequent to the termination of the convergence, the main program calls subprogram PLOTT to graphically plot all of the fire perimeters and to show the last contour as that containing the point of origin lying in the "area of confusion." The results of the program are printed with the approximate time lapse between the time of inception and the outermost perimeter and with the location of the coordinates of the "area of confusion." The time lapse is computed from accumulative addition of the time increments between each of the fire contours from the outermost to the origin. Subtraction of the computer calculated time lapse from the absolute time of day that the given original fire perimeter was observed will give the absolute time of inception of the fire.

The subprograms are auxiliary to the main program in that they perform calculations for the main program and when called by other subprograms. Subprogram CALANG, acronym for CALculating ANGles, calculates the instantaneous fire direction normal to the instantaneous fire perimeter. The fire direction normal is needed for calculating the instantaneous rate of spread where the wind and ground slope aspect do not coincide with the fire direction for subprogram ROS. The second use for the fire direction normal is in checking the progress of the fire perimeter, that is, to verify inconsistencies in the newly constructed fire perimeter so that they can be corrected or eliminated in subprogram INTCHK.

Subprogram ROS, acronym for Rate Of Spread, calculates the instantaneous rate of spread of fire based upon the input values for the fuel, atmospheric, and topographic conditions in the particular vicinity. Because the calculations of the instantaneous rate of spread are placed independently into the subprogram, the computer program is versatile such that any mathematical model that calculates the rate of fire spread from easily measurable input field parameters can be substituted. The data is transmitted from the main program to ROS for calculating rate of spread via several common blocks.

Since a natural fuel bed is composed of particles varying in size, shape, density, specific heat, fuel composition, and moisture, the heterogeneous fuel bed is the more typical case. In the literature, only Fons[39] and Rothermel[40] have taken heterogeneity into account. In essence, what each one has done was to weight average all of the varying physical characteristics of the different fuel types and fuel size classes. This, in effect, is the same as homogenizing diverse fuel conditions before applying the same fire spread model. Heterogeneous fuel conditions can be approached by either a grid mapping or an irregular-polygonal mapping in respect to computer programming; the grid approach is far simpler and time-saving while the irregular-polygonal mapping is more realistic and flexible. However, for the sake of simplicity, the subject matter exemplified in this thesis will be restricted to homogeneous fuel conditions.

In applying Rothermel's equations for fire spread to this computer method of determining origin, several adaptations had to be incorporated into subprogram ROS. The adaptations are for situations where wind direction and/or topographic aspect are not concurrent with the direction of fire normal. Where the difference in the directions is either between 0^{o} & 90^{o} or between 270^{o} & 360^{o}, a factor of the cosine of the absolute value of the difference in directions must be applied. However, according to Rothermel's data, in other cases as where the fire may be going against the wind, he suggests no effect on the rate of spread[41]. Although some fire modelers might contest this point, no data has been presented to substantiate their negation at this time. With these modifications, the rate of spread can be calculated instantaneously for each parcel of the burned area. The value of the rate of spread is returned to the main program in which it is used to construct the location of the preceding fire contour.

Subprogram INTCHK, acronym for INTernal CHecKing, scans the array of points constituting the newly constructed fire contour and also the originally given contour for inconsistencies such as spikes, loops, reversals, and cross-overs. This is necessary since fire perimeters do not realistically cross over themselves or make sudden reversals. Possible errors are detected by scanning the array of fire direction normals, which was calculated by CALANG, for abrupt changes in the instantaneous path of the fire. An abrupt change is encountered when the difference in successive fire normal directions exceeds 90°. An algorithm verifies the inconsistency by solving for the point of intersection of the segments representing instantaneous portions of the fire perimeter in question. Cramer's rule is applied to solving the two equations describing the line segments involved simultaneously. If the common solution which gives the point of intersection lies within the extrema formed by the endpoints of both line segments, the cross-over is eliminated by re-numbering the array so as to exclude the inconsistent points. Similarly, separate algorithms had to be devised for removing inconsistencies from the very beginning or very end of an array, for removing spikes, for interfacing all of these algorithms so that all possible situations would be taken care of. Because of the time-consuming nature of this particular subprogram, the scanning for inconsistencies was limited to approximately twenty points adjacent to the one being tested.

The final subprogram, PLOTT, constructs the singly dimensioned arrays from doubly dimensioned arrays containing the coordinates of contour points so that use of the Graphical Display System library of plotting subroutines can be made to display the results visually. The Graphical Display System and Calcomp 663 plotter used in this program are part of the University of California, Berkeley Computer Center's facilities . The entire program is run here on CDC-6400 hardware and consumes approximately twenty seconds central pocessing time.

In summary, the method that has been presented in this thesis is a computer program which applies Rothermel's mathematical model for predicting fire spread rate to the solution of the problem of scientifically determining the point of origin and time of inception. Conditions of the fuel, wind, ground, and outermost fire perimeter must be specified; the results of the computer program are the "area of confusion" in which lies the point of origin and time lapse between origin and outermost perimeter.

C. Attempts to Procure Data

Several attempts were made to acquire data to test the proposed method of origin determination. Data from actual fires from the standard fire report form, F.C.-18, and preliminary fire investigation report form were obtained from the Law Enforcement Coordinator's Office at the California Division of Forestry in Sacramento. A 400 sample studied consisted of mostly 1971 class "A" fires (less than one acre) occurring in the Lake-Napa County area. Upon meticulous study of the reports, it was revealed that the data needed was not sufficiently precise nor accurate for purposes of corroboration.

Among the California Division of Forestry fire reports studied, the most significant item to which inaccuracy was attributed was wind data. Recorded wind data are gross estimates of ranges of wind speeds and directions; occasionally, these were not taken at the fire scene and almost always without a calibrated instrument. Comparison of the data from reports also revealed a consistent underestimation of the actual wind present. Wind is quite critical to the prediction of the fire spread rate as can be seen in Rothermel's equation in Appendix II. According to Anderson et al[42],

> "...most deviations from the predicted rate of spread are attributed to changes in wind velocity..."

Hence, the inadequacy of the fire reports would not render it appropriate to use the data at this time.

Evidently, the problem of the lack of data is not just peculiar to the present situation in this thesis but is the most classic fundamental problem to fire science that must be overcome. The literature also evinces a lack of data on fuel input parameters such as density, surface area/volume ratio, heat content, etc. Only recently has mensuration of such parameters commenced.[43] In spite of the disappointing lack of reliable data, a quote from Emmons[44], should provoke some hopeful alternatives,

> "...with such profound ignorance of essential quantitative knowledge, we might stop here pending correction of the deficiency...Instead of terminating, let us proceed to do what we can to identify the nature of the problem..."

With this in mind, some hypothetical tests and results can be elaborated and future areas of research sketched.

D. Hypothetical Tests and Results

A number of hypothetical situations can be presented to the computer method for origin determination to show the possible results. The first hypothetical test of the method was against a given circular burn pattern which is the most simple case. Fons[45] and Ford[46] both document that a fire that has just started will burn radially from its source resulting in a circular burn pattern when all fuel conditions are homogeneous and wind and slope are both absent. Fons, in fact, bases his model for fire spread on this fact and takes advantage of radial symmetry to construct the frame of reference for his model. Hence, in using a circular burn pattern to test the hypothetical method of origin determination, the computer should give the fire origin as the center of the circle. This indeed was verified as the computer correctly gave the result that the fire origin was at the center of the circle as shown in Fig. 1. Pertinent data to the Fig. 1 are as follows: time interval between contours: 10 time units, rate of spread: .5 length/time units, and radius of originally given fire perimeter is 50 length units.

In order to demonstrate how the proposed computer method would work for some other cases, the program was run for a number of simple conditions associated with an oval or elliptical burn pattern. All of these are for homogeneous fuel and uniform slope conditions. Since experience has shown that burn perimeters bear oval or elliptical shapes elongated in the direction most favorable to spread, the computer program was tested on several of these cases. The slope angles were selected arbitrarily; these were 8°, 14°, 22°, and 24° as shown respectively in Figs. 2,3,4, and 5. The aspect or direction of rising slope is east or 0° (polar coordinates) in each case. The arbitrary time increment between contours was 2.5 time units in the first two figures and changed to 1.0 time units in the latter two figures. The outermost oval fire perimeter is the same used in all cases and was constructed from a point generation program consisting of 250 points. The "area of confusion" containing the point of origin is marked. Although the same initial burn perimeter was given in each plot, it is not necessarily true that the same burn pattern would occur for different angles of slope. Nevertheless, instead of changing the burn pattern the same one was used for the sake of convenience. It can be seen from each of the plot results that by keeping the burn pattern constant, the point of origin is removed further back from the rightmost fire front in direct proportion with the with increase in slope. This is equivalent to having cases with the same point of origin but with the fire front moved further forward from the origin in direct relationship with increase in slope. Although the arbitrary time interval between fire perimeters was varied, this did not affect the outcome of the determination of the point of origin. However, a smaller time interval between successive contours improves the accuracy of the origin determination.

The more general burn pattern is irregular amoebic shaped; attempts were made to apply the computer method to such hypothetically conceived burn patterns. Because the extreme irregularity presented a most rigorous test, it was through computer runs on this pattern that the most "bugs" were discovered and corrected, especially in the design of subprogram INTCHK. Comparison of Figs. 6 and 7 illustrate how subprogram INTCHK corrects cross-overs and inconsistencies in the fire perimeter; Fig. 6 includes INTCHK and Fig. 7 shows the same situation without subprogram INTCHK although slightly terminated early for sake of convenience. Fig. 6 simultaneously shows how the computer program would determine point of origin for the amoebic hypothetical burn pattern for an homogeneous fuel in absence of slope and wind. The outermost fire perimeter is constructed from 540 points using a digitizer to trace the contour from a hand-drawn hypothetical map; this same hypothetical outermost burn pattern is used in Figs. 8-14.

Figures 8 through 14 show how the computer would determine fire origin given homogeneous fuel conditions with a steady uni-directional wind and in absence of slope. The wind speeds were selected arbitrarily to be 58, 120, 150, 175, 220, 260, and 300 length/time units as respectively shown in Figs. 8, 9, 10, 11, 12, 13, and 14. In each case the wind was blowing from the southeast or at 2.271 radians (polar coordinates.) More specific data and values of parameters, rate of spread, arbitrary time increments between contours are explained in the Figures.

The computer method presented for the determination of point of origin should not be hastily accepted until a comparison with actual fires is made. Improvement in the acquisition of fire information and fire reporting will make data available from the field. The most suitable means of verification by experimental data is perhaps to conduct a controlled burn. In corroboration, one should look for agreement or discrepancy in the time and position of origin with particular attention paid to the validity of the assumptions made in the computer method and to factors that may not have been accounted for in this thesis. It is anticipated that such factors might include eddies and edge effects of the fire perimeter.

There are five major facets that are worthy of additional investigation beyond this thesis. First is that the limits of accuracy and precision have not been worked out yet awaiting comparison with actual data. Nevertheless, the accuracy is dependent upon the number of points used to represent the originally given outermost fire perimeter, the number of iterations used to reach the point of origin, and the arbitrary time interval between each contour. Of course, the computer method is also dependent upon the accuracy of the input parameters for fuel, slope, and wind that are inserted into the equations of Rothermel for calculating the rate of spread.

Second, the method proposed is as only good as the mathematical model that is relied upon to calculate the rate of fire spread. All of the assumptions and restrictions inherent in the model being used extend to the computer method of determining point of origin. The fact that Rothermel's model is being used here subjects this computer method to several limitations. One is the model's inability to account for the effect of living fuels on fire spread rate and intensity.[47] Also, the effect of moisture is not well understood nor is the seasonal variation of extractive content in living fuels. Another unaccounted for effect is clumpiness in fuels such as brush.[48] It is optimistic that future fire spread models will take into account all of the aforementioned limitations, and in addition, vertical flame spread or crowning, fire spotting, fire whirls, persistence, etc. Future models derived from first principles look promising in that they will greatly expand the number of situations and the accuracy to which this method of origin determination can be applied.

Third is a careful study of the effect of wind movements. There is a need to derive local wind conditions such as that in valleys, canyons, etc. from macroscopic weather data. Schroeder et al at the Pacific Southwest Forest & Range Experiment Station, Riverside, California are tackling with the complexities of linking the two meteorological phenomena. There is also a need to undertake a careful study of the effect of wind moving in opposite or non-concurrent directions with the fire. The issue of wind moving in opposite direction to the fire must be definitely clarified in order to refine the proposed computer method. In addition, interaction and effects of combining slope and wind conditions, also in non-concurrent directions, should also be looked into.

The fourth that should be investigated is adaptation of the computer method to heterogeneous fuel conditions followed by heterogeneous topographic conditions. Only a superficial allusion to this topic was made with respect to subprogram ROS; notwithstanding, optimal grid sizes and data storage set-ups for each fuel type region need to be worked out subject to the field length capacity of the computer. A means of automatically converting topographic maps into slope and aspect data will also be desirable.

The fifth facet is probably the most complicated. This is adapting the computer method of origin determination to time variant and dynamic weather and fuel conditions. In actuality, wind velocities are far from being static for long durations of time in a good sized fire; and wind data should be incorporated into the computer method as time dependent in character. The rate of spread varies with time by itself under constant conditions even where wind is absent; for there is a slow down in fire spread subsequent to the initial stages of the fire. Also, in the initial stages of the fire, each segment of the perimeter cannot be treated as a line fire but interdependently. Thus, all of these factors will have to be considered in the future. Again, core or field length restrictions of the computer limit the extent to which time dependency can be taken into account.

Although only five major facets of areas warranting further study have been discussed, by no means is the list complete. At this point, it is best perhaps to leave these areas of additional investigation with the forestry or fire scientist since they are beyond the scope of criminalistics. It is the intention of this thesis to demonstrate only that fire science modeling principles can be applied to investigating arson. After additional pure research has been done in unraveling the mysteries of fire, the knowledge learned can be of use to criminalistics.

III. Significance of A Scientific Method for Point of Origin Determination

A. Implications for Urban Arson Investigation: Cause Determination

A problematic area of urban arson investigation is the great number of misclassifications of fire cause.[49] This could be clarified by a scientific method of origin determination. One of the earliest fact-finding reports which seriously challenged the statistics of arson investigation was the 1954 Tennessee Valley Authority report.[50] Urban as well as rural arson investigators have a tendency to throw most guesses of fire cause into the category of "smoker" without justification. Folweiler in 1937 had raised the issue,[51]

> "...why in a five-year average 44% of the known fires in Pennsylvania was said to be caused by smokers when across the Delaware River under similar conditions of topography, climate, soil, vegetation, social pattern, and industrial activity in New Jersey, was there reported only 2%?..."

On the basis of statistical documentation, Chandler also concluded that the most guesses of fire cause were being thrown into the smoker-cause classification from a chi-square analysis.[52]

This problem of misclassifying fire cause is directly related to that of determining the point of origin. After an object has undergone combustion, it leaves some residue or ash that would characterize its original form. To presume always that the evidence has been destroyed in a fire is a misconception.[53] It follows that the fault is not ascertaining the cause when the evidence of cause is there; but the fault is in determining the point of origin. This is because the point of origin, where the evidence of cause is to be found, is not discovered. For illustration, in the aforementioned examples of where cigarette smoking was alleged cause of fire, the finding of a cylinder of ash and/or a cigarette butt would confirm the allegation. Thus, the crux of the matter comes back to locating the evidence by determining the point of origin. It can be seen that the materialization of a scientific method for origin determination would tremendously enhance the investigation of arson, especially in the urban sector of ascertaining the proper cause of fire.

B. Long Range Implications of A Scientific Method for Point of Origin Determination

It must be stressed that the highest priority should be given to determining the point of origin to locate physical evidence. As well as the advantage of physical evidence in providing investigative leads, it has extreme significance in proving the guilt or innocence of a suspect. Recent U.S. Supreme Court rulings have placed greater emphasis on the utilization of physical evidence in the administration of justice both directly[54] and indirectly[55,56]. Physical evidence has vastly greater reliability and objectivity[57] as opposed to eyewitness testimony. Physical evidence is not subject to human frailties whereas eyewitness evidence can be perjured, distorted, intimidated, or tricked. Physical evidence surpasses all of these weaknesses. Thus, the value in a scientific method of origin determination because it locates physical evidence and consequently provides facts for investigative and judicial proceedings is in its long range improvement of the objectivity of criminal justice system.

The same can be said about a scientific method of origin determination and the enhancement of objectivity of criminalistics. The problem of subjective interpretation in the methodology of criminalistics is summed up by Osterburg[58],

> "...opinions (of criminalists) are based on experience, education, and training of the criminalist or 'expert.' It is self-evident that an important task in criminalistics is the transposition of the interpretative aspect of the work from a subjective to an objective basis..."

In the aspect of origin determination, the direction of fire spread and tracing of the fire path is made by subjective interpretation of previously discussed burn "indicators." What in effect mathematical modeling application renders that is significant to the overall methodology of criminalistics is removing much of the subjectivity in the area of arson investigation. In other words, the point of origin can be obtained directly from primary data parameters through the use of mathematical modeling without the need for subjective evaluation. In so doing, it transposes the interpretative decision from a qualitative to a quantitative basis. It is primarily this quantitative basis that capsulates science enabling Western civilization to surpass the ancient Greeks in deductive inquiry. Lord Kelvin once said,

> "...when you can measure what you are talking about and express it in numbers, you know something about it, and when you cannot measure it, when you cannot express it in numbers, your knowledge is a meager and unsatisfactory kind...It may be the beginning of knowledge, but you have scarcely in your thought advanced to the stage of science..."

C. A Scientific Method for Determination of Origin in Structural Fires in Urban Arson Investigation

In continuing the theme of the implications and significance of a method of origin determination to urban arson investigation, it would be exciting to lurch into future prospectives of the method.

An article by Rockett points to the plausibility of predicting the course of a fire through a building with the use of the National Bureau of Standards computer in Washington, D.C.[59] Although the article was intended for fire sprinkler planning, the potential modification of this method to synthesize fire history for investigating structural fires is highly conceivable. Rockett utilizes Phung and Willoughby's model of fire spread[60] and follows it in dividing up the building under consideration into pseudo rooms and cubicles analogous to parcels in the wildland case and establishes a number of burning states ranging from spread to no-spread in each cubicle. At the moment only gross effects and allowable transitions of fire conditions are defined. The requirements for data in this method are very similar to the input parameters presented in the method proposed in this thesis for the wildland case. The desired data consists of the loading of each room, i.e. its contents, and the room geometry, i.e., influence coefficients of walls, partitions, ceilings, floors, etc. Similar problems that were encountered in this thesis confront Rockett—simply that needed data is not yet available.

A part of Rockett's method which is troublesome is that of describing air movement through the building, a perplexity paralleling that of wildland wind. Knowledge of the positions of doors, transoms, vents, and other ventilation controls, i.e. whether they are open or closed, is required as input data. Whereas this fact would not be known before a fire started, this fact could almost always be obtained after a fire; Rockett's method is more useful as a fire historiographer than as a fire prediction tool. The investigator can supply data regarding the positions of ventilation controls by verifying the manner in which the object was covered by soot.

The prospects of using an advanced form of the method of origin determination as proposed in this thesis for investigating arson in structures appears very fascinating. What will probably have to be done is to collect the needed data and develop computer routines for reducing it. Rockett's program will have to be modified to give a regressive analysis similar to the method proposed in this thesis. The idea of collecting data on each building is not far-fetched as it may seem. Fire stations already maintain blueprints of buildings where there may be a high life-safety priority in an exigency. Furthermore, fire departments already inspect plan of structures for compliance with local fire codes. If blueprints and plans could be maintained with time-to-time inspection reports of occupancy, storage, and improvements, data banks could be established that could be applied that would not only assist in fire protection planning but also in tracing fire history and origin for arson investigators. It is only a matter of time when an arson investigative team in the field is linked to a computer at headquarters through which members could request determination of point of origin and listing of possible causes under the given circumstances.

IV. Conclusion

In conclusion, the fundamental problem of arson investigation--determining the point of origin has been discussed. Its extreme significance in providing information in reconstructing the crime and locating physical evidence warrants a need for a scientific method of origin determination.

It has been found that a method for ascertaining the point of origin and time of inception using a computer approach of retroceding analysis can be formulated. Its application has been shown in several simple examples of wildland cases of homogeneous fuel and steady-state conditions. Additional work is needed to refine the proposed method of origin determination to take into account heterogeneous and unsteady considerations before a working method can be established. A major significance of this work is the demonstration of the usefulness of mathematical modeling principles of fire science to solving technical arson investigation problems. Much potential lies in the application of other untouched areas of fire science to criminalistics. A potential model for urban investigation of structural fires similar to that proposed in this thesis is highly plausible.

The values in scientific determination of origin lie in improving the cause classification of fires in urban sectors, increasing objectivity of criminal justice administration, and transposing arson investigation from an art to a science.

Appendix I: Input Parameters for Rate of Spread Model Calculations

FUEL PARAMETERS

symbol	dimensional units	physical meaning	typical values
MX	lbs moisture/lbs oven dry wood	fuel particle moisture extinction coef.	.30-2.0
MF	"	fuel particle moisture content	.05-.70
SE	lbs silica free mat'l/lbs oven dry wood	fuel effective mineral content	.02
ST	lbs mineral/lbs oven dry wood	fuel total mineral content	.05
SIG	1/feet	surface area-to-volume ratio of fuel	2000-4000
PP	lbs/cubic feet	fuel particle density	20-40
WO	lbs/square feet	oven dry fuel loading	.01-.10
DEL	feet	fuel depth	.1-5.0
H	B.T.U./lb	fuel particle low heat content	1000-10000

TOPOGRAPHIC PARAMETERS

symbol	dimensional units	physical meaning	typical values
ASPECT	radians (polar coordinates)	direction of slope	.00-6.28
TANPHI	dimensionless	tangent of angle of slope	.00-1.5

ATMOSPHERIC PARAMTERS

symbol	dimensional units	physical meaning	typical values
U	feet per minute	wind velocity	0-440000
DWIND	radians (polar coordinate)	wind direction	0-6.28

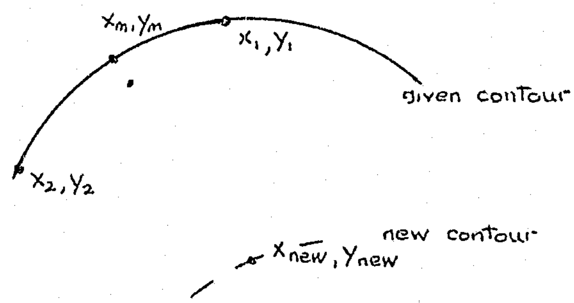
OUTPUT PARAMETERS FROM ROTHERMEL'S RATE OF SPREAD EQUATIONS

symbol	dimensional units	physical meaning
FUL	feet / minute	rate of spread due only to fuel conditions
S (or SO)	dimensionless	rate of spread correction factor due to slope
W	dimensionless	rate of spread correction factor due to wind

Appendix II: Rothermel's Rate of Spread Equations

formulation	physical significance
PB=WO/DEL	oven dry bulk density
B=PB/PP	packing ratio
C=7.47/exp(.133*(SIG**.55))	(intermediate variable)
F=.715*exp99-3.59*10^{-4})*SIG	(intermediate variable)
D=.02526*(SIG**.54)	(intermediate variable)
BOP=3.348/(SIG**.8189)	optimum packing ratio
E=(1./(192.+.259*SIG)*exp((.792+.681*$\sqrt{(SIG*(B + .11))}$	propagating flux ratio
NS=.174/(SE**.19)	mineral damping coefficient
NM=1.-2.59*MF/MX + 5.11*((MF/MX)**2.) - 3.52*((MF/MX)**3.)	moisture damping coefficient
QIG=250. + 1116.*MF	heat of pre-ignition
A=1./(4.774*(SIG**.1)-7.270)	(intermediate variable)
WN=WO/(1. + ST)	net fuel loading
GAMM=(SIG**1.5)/(495.+(.0594)*(SIG**1.5))	maximum reaction velocity
GAM=GAMM*((B/BOP)**A)*exp(A*(1.-(B/BOP)))	reaction velocity
NR=WN*H*GAM*NM*NS	reaction intensity
NO=NR*E	(intermediate variable)
PBE=PB/exp(138./SIG)	effective bulk density
FUL=NR*E/(PBE*QIG)	rate of spread dependent only on fuel
W=C*(U**D)*((BOP/B)**F)	wind coefficient
SO=(5.275/B**.3)*(TANPHI**2.)	slope coefficient
R=FUL*(1. + W + SO)	rate of spread

Appendix III: Program POOD— Derivation of Equations for Contour Construction Algorithm



slope of line joining x_1,y_1 to x_2,y_2 is $\frac{y_2 - y_1}{x_2 - x_1}$

slope of normal through x_m,y_m which is the mid-point of the chord between x_1,y_1 and x_2,y_2 is

$$\frac{x_1 - x_2}{y_2 - y_1}$$

equation of the normal through x_m,y_m is then

$$y = \frac{x_1 - x_2}{y_2 - y_1} * x + \text{const.}$$

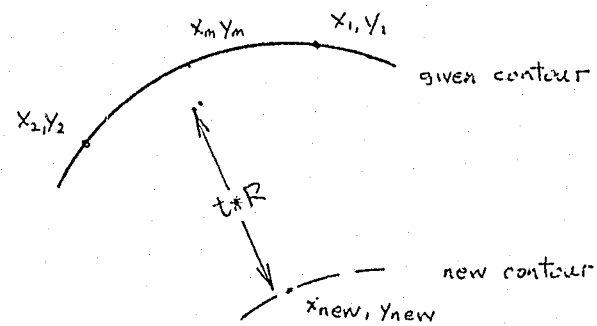
where the const. is evaluated by use of the given points x_1,y_1 , x_2,y_2 , and x_m,y_m which is easily obtainable from the first two:

$$y - y_m = \frac{x_1 - x_2}{y_2 - y_1} * (x - x_m)$$

or

$$y = \frac{x_1 - x_2}{y_2 - y_1} * x + (y_m - x_m * \frac{x_1 - x_2}{y_2 - y_1})$$

since the coordinates x_{new},y_{new} of the point to form the new contour are to lie on this normal, x_{new},y_{new} are substituted for x,y in the above equation. This equation is to be combined with one other condition and then to be solved for x_{new},y_{new}. The physical significance of this equation is that the coordinates of the point on the preceding fire perimeter to be constructed lies on the fire direction normal. The equation incorporates the assumption that the fire direction is normal to the chord between two adjacent points on the perimeter. The distance between these two points is optimally chosen such that the fire perimeter can be approximated by a multitude of line segments joined together.



let t = an arbitrarily chosen time interval between successive fire contours

R = rate of spread given by the modified Rothermel equations

then t*R = the distance between successive fire perimeters or the distance from the current contour at point x_m, y_m to the newly constructed contour formed from point x_{new}, y_{new}. In other words, t*R expresses how far back the preceding fire perimeter was for an elasped time, t.

also, $t*R = \sqrt{(x_m - x_{new})^2 + (y_m - y_{new})^2}$ (2)

The above equation is a quadratic prescribing a circle with radius, t*R, and center x_m, y_m. These two equations (1) and (2) must be solved simultaneously in order to obtain x_{new}, y_{new} to construct the preceding fire contour. It is mathematically apparent that the simultaneous solving of equation (1) which is a line with (2) which is a circle yields two solutions. The algebraic conclusion of the solving of these two equations are:

$$x_{new} = x_m \pm (y_2 - y_1)\sqrt{(t*R)^2/((x_1-x_2)^2 + (y_2-y_1)^2)}$$

$$y_{new} = y_m \pm (x_1 - x_2)\sqrt{(t*R)^2/((x_1-x_2)^2 + (y_2-y_1)^2)}$$

Note that the plus sign between the two right-hand side terms appears in one pair of solutions and the minus sign appears in the other pair of solutions. In the actual program, the terms were simplified by substitution of:

$$(x_1 + x_2)/2 = x_m$$
$$(y_1 + y_2)/2 = y_m$$
$$S = x_2 - x_1$$
$$T = y_2 - y_1$$

and $ARQ = \sqrt{(t*R)^2/((x_1-x_2)^2 + (y_2-y_1)^2)}$

Hence, the equations expressing the solutions for the point forming the new contour appears in program POOD as:

$$XI = (x_1 + x_2)/2 + T*ARQ$$
$$YI = (y_1 + y_2)/2 - S*ARQ$$
$$XII = (x_1 + x_2)/2 - T*ARQ$$
$$YII = (y_1 + y_2)/2 + S*ARQ$$

Physically, this corresponds to one set of coordinates of a point external to the fire perimeter given and the other set to a point internal to the fire perimeter. Hence, an algorithm was needed to choose the appropriate solution. This is explained in the next section under Appendix IV.

Appendix IV: Program POOD—Derivation of the Algorithm for Selection of the Appropriate Solution

Of the two solutions rendered by the equations obtained in Appendix III, the one which forms the preceding fire contour or which lies inside the burned area is the appropriate solution. The algorithm for selecting this solution appeared at first to be deceptively simple but required some ingenuity. What was realized was that the correct solution was not always the maximum nor minimum of the two possible solutions. The construction of this algorithm necessitated an orderly numbering of the points in addition to that out of convenience. This was chosen arbitrarily to be counterclockwise. What was observed to be be characteristic of the appropriate solution was the relationship between the maxima of the two solutions and the slope,i.e. the slope of the line segment joining the two points on the given contour from which the points for the new contour were to be constructed. For example, if the angle of the slope between two points were 3.14 radians, then the correct solution was given by the lesser of the y values of the two solutions and the x value associated with that particular y value. If the angle of the slope were 5.0 radians then the correct solution were given by the higher of the x values and the corresponding y value associated with that particular x value. This relationship was studied for all possible angles of slopes of the fire perimeter resultting in the table given on the next page.

Value of S	Value of T	Angle of slope on fire perimeter	Angle of fire direction normal to perimeter	Correct Solution is determined by
.EQ. 0	.GT. 0	1.57	0.00	XMIN,YMIN
.LT. 0	.GT. 0	1.58-3.13	.01-1.56	XMIN,YMIN or YLOWH,XLOWH
.LT. 0	.EQ. 0	3.14	1.57	YLOWH,XLOWH
.LT. 0	.LT. 0	3.15-4.70	1.58-3.13	XMAX,YMAX or YLOWH,XLOWH
.EQ. 0	.LT. 0	4.71	3.14	XMAX,YMAX
.GT. 0	.LT. 0	4.72-6.27	3.15-4.70	XMAX,YMAX or YHIGH,XHIGH
.GT. 0	.EQ. 0	0.00	4.71	YHIGH,XHIGH
.GT. 0	.GT. 0	.01-1.56	4.72-6.27	XMIN,YMIN or YHIGH,XHIGH

where $S = x_2 - x_1$

$T = y_2 - y_1$

slope of fire perimeter is T/S and the angle of the slope of fire perimeter is the arc tan (T/S)

slope of fire direction normal is -S/T and the angle of the fire direction normal is the arc tan (-S/T)

$\left\{\begin{matrix}XMAX\\XMIN\end{matrix}\right\}$ refer to the $\left\{\begin{matrix}\text{greater}\\\text{lesser}\end{matrix}\right\}$ of the two x values given as solutions, and the x value is the criterion for selection of the appropriate solution.

$\left\{\begin{matrix}YMAX\\YMIN\end{matrix}\right\}$ refer to the corresponding y value associated with the $\left\{\begin{matrix}\text{greater}\\\text{lesser}\end{matrix}\right\}$ of the two x values

$\left\{\begin{matrix}YHIGH\\YLOWH\end{matrix}\right\}$ refer to the $\left\{\begin{matrix}\text{greater}\\\text{lesser}\end{matrix}\right\}$ of the two y values given as solutions, and the y value is the criterion for selection of the appropriate solution.

$\left\{\begin{matrix}XHIGH\\XLOWH\end{matrix}\right\}$ refer to the corresponding x value associated with the $\left\{\begin{matrix}\text{greater}\\\text{lesser}\end{matrix}\right\}$ of the two y values.

List of Figures

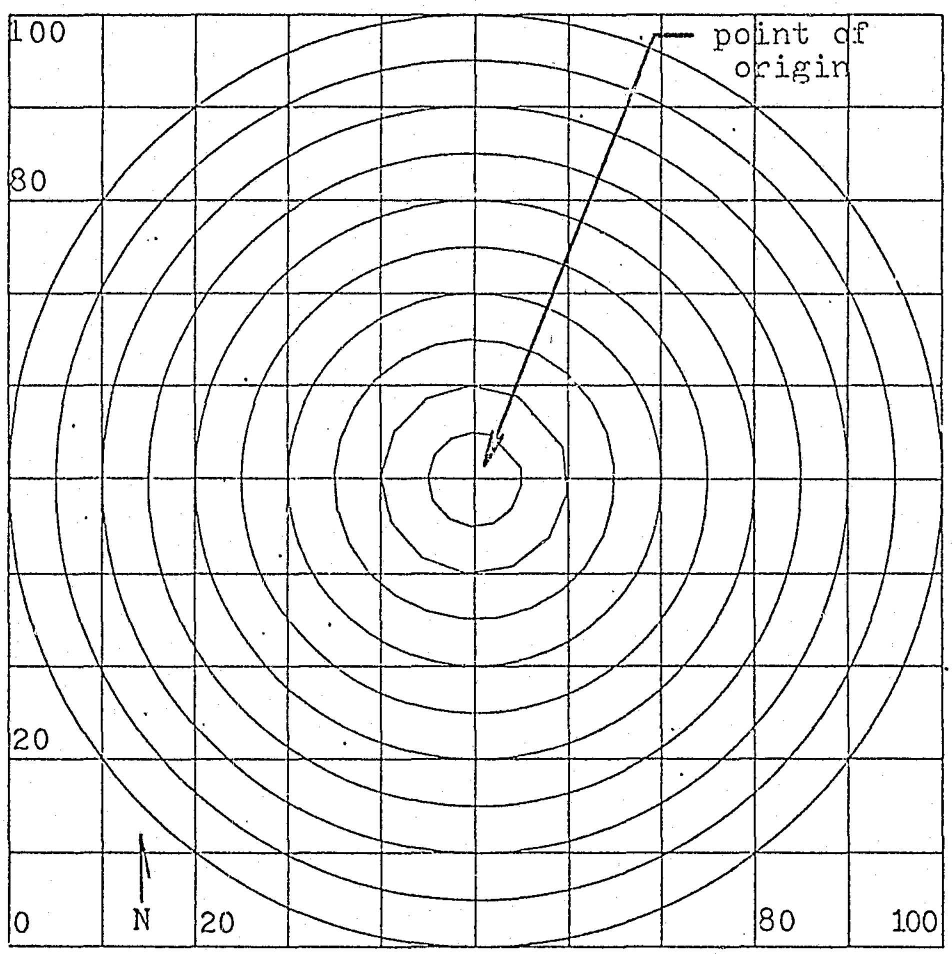


Figure 1. Circular Burn Pattern. Outermost fire perimeter is given. Point of origin is determined as the fire contours converge into innermost contour, ninth from outside. Wind and slope are absent. Time interval between contours is 10 temporal units. Fire started at least 90 time units prior to reaching outermost perimeter.

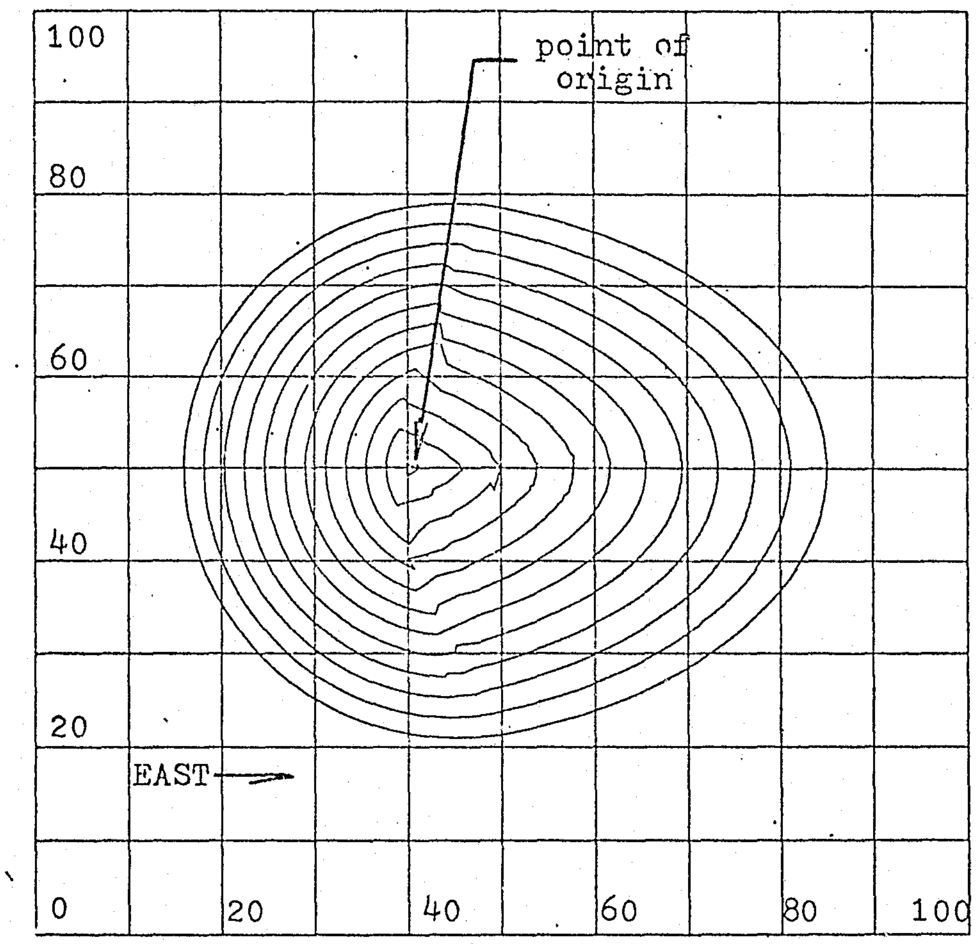


Figure 2. Oval Burn Pattern W/ Slope 8°
This is an oval burn pattern on a slope of 8° and 0° aspect. Spread rate is calculated from Rothermel's equations for typical cheatgrass with .2 moisture content. Fuel bed is homogeneous, and wind is absent. Time interval between contours is 5.0 time units. Fire started in loci of contour 12, fifty-five time units priorto reaching outermost contour.

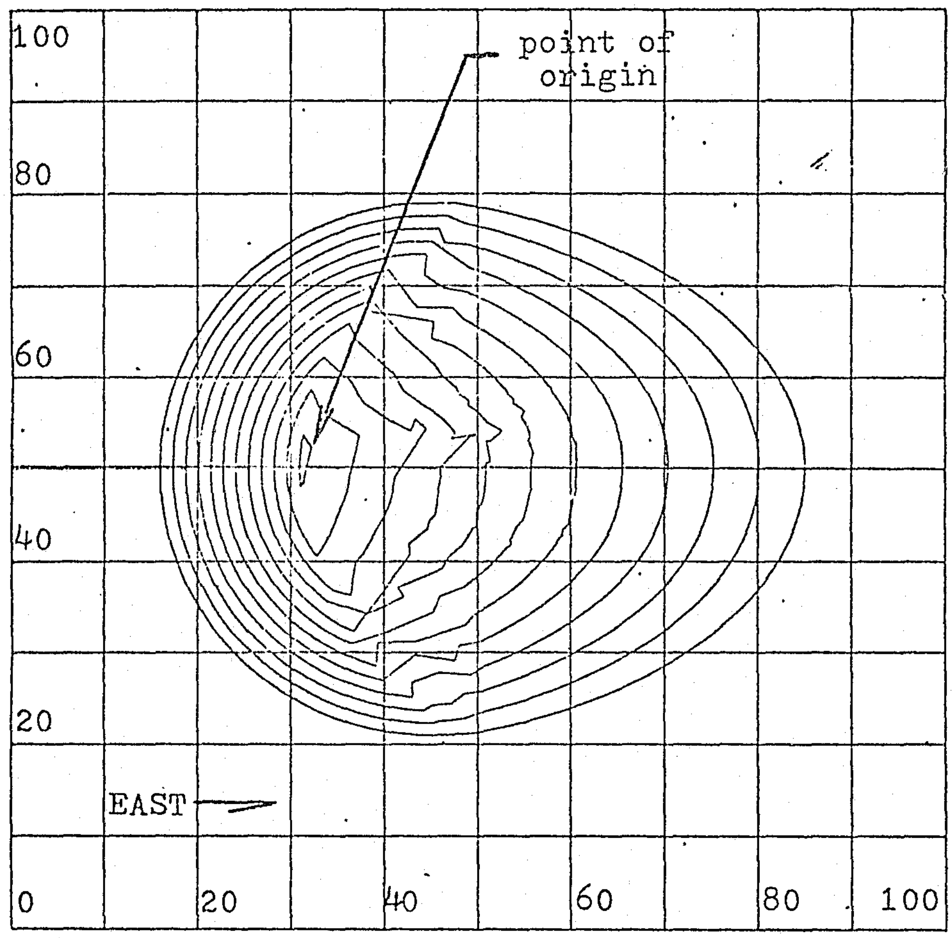


Figure 3. Oval Burn Pattern W/ Slope 14°
This is same burn pattern as Fig.2 but on slope 14° and aspect of 0°. Same fuel conditions. Time interval between contours is 2.5 time units. Fire started within loci of innermost contour, twelfth from outside, 28 time units prior to reaching outside perimeter. Also, same rate of spread.

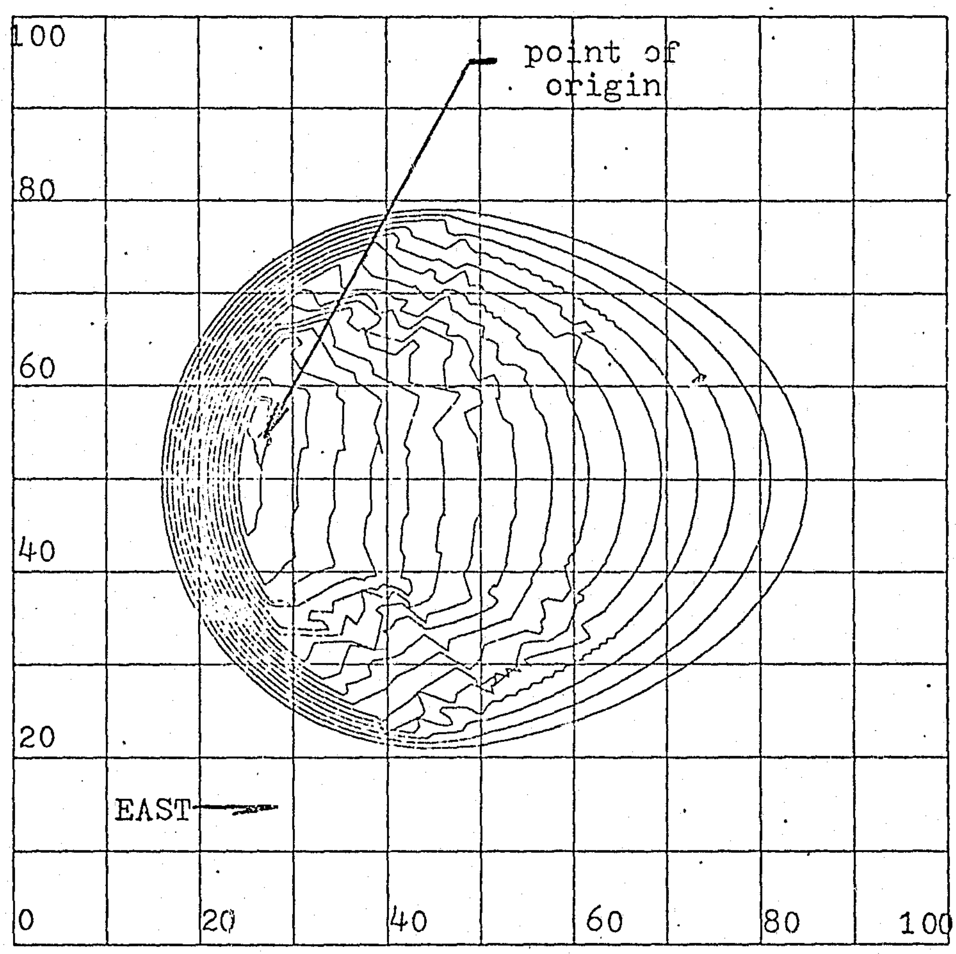


Figure 4. Oval Burn Pattern W/ Slope 22°
This is an oval burn pattern on a slope of 22° and 0° aspect. Same fuel conditions and unmodified rate of spread value of 5.4144 length/time units as in Figs. 2,3, and 5. Time interval between contours is changed to 1.0 time units to increase number of iterative contours. The increase buffers out irregularities exaggerated by the wide range in modified rate of spread with slope factors. Fire started 16 time units prior to attaining outermost perimeter.

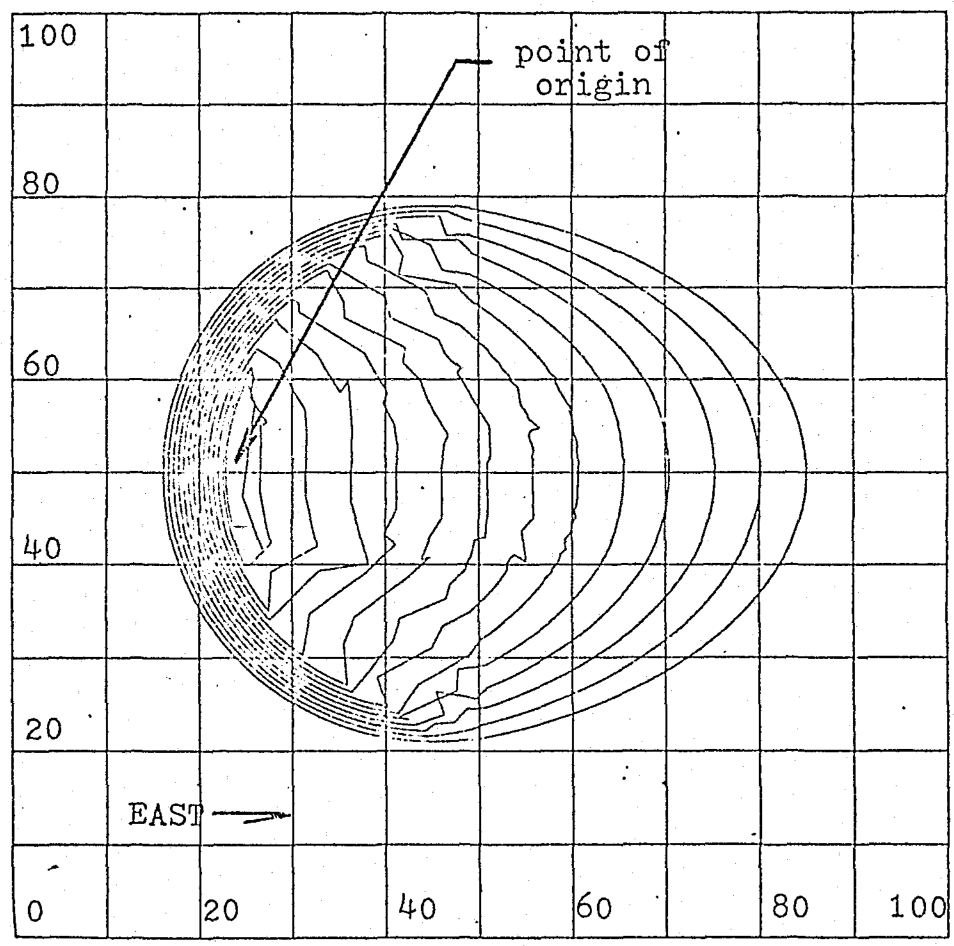


Figure 5. Oval Burn Pattern W/ Slope 24°
Slope is 24° and aspect is 0°. The range of rate of spreads varies from the unmodified 5.4144 to 48.7296 when fire direction and slope direction concur. Time interval between contours remains as 1.0. Fire started 12.5 time units prior to attainment of outermost perimeter.

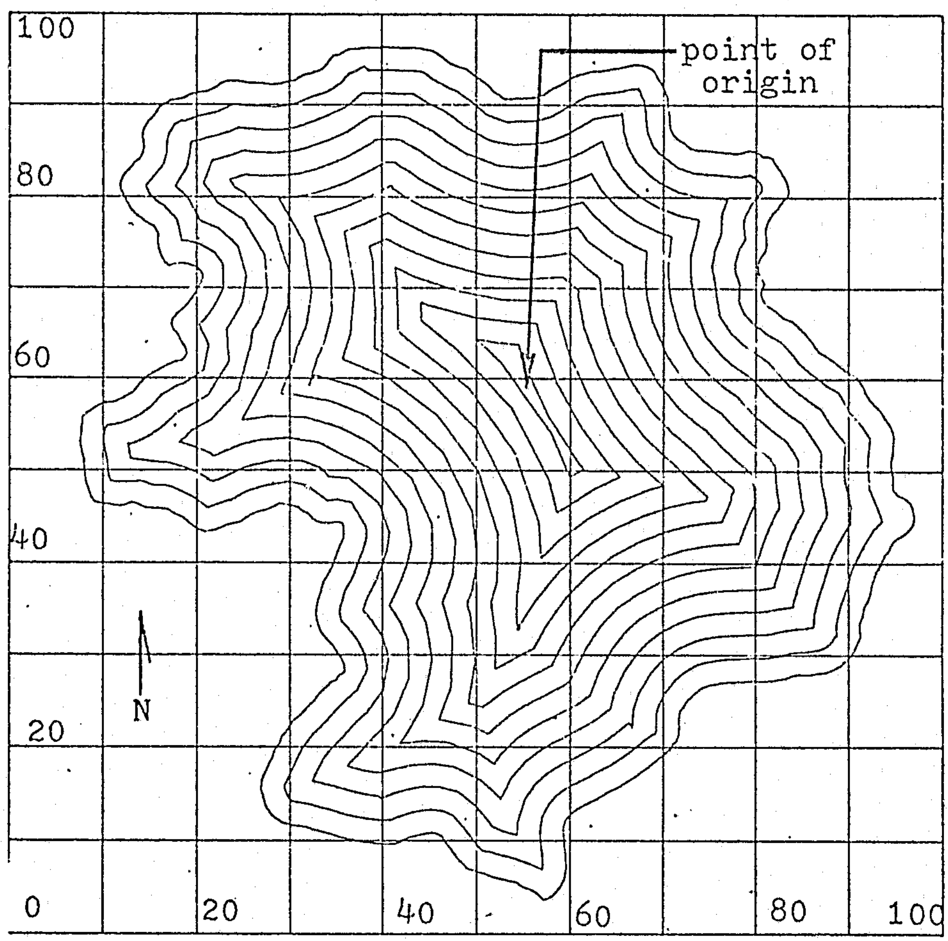


Figure 6. Hypothetical Burn Pattern in Absence of Wind and Slope. Fuel is homogeneous having a spread rate of 2.50 length/time units. Time interval between contours is 10. time units. Fire started approximately 111 time units prior to attaining outermost perimeter.

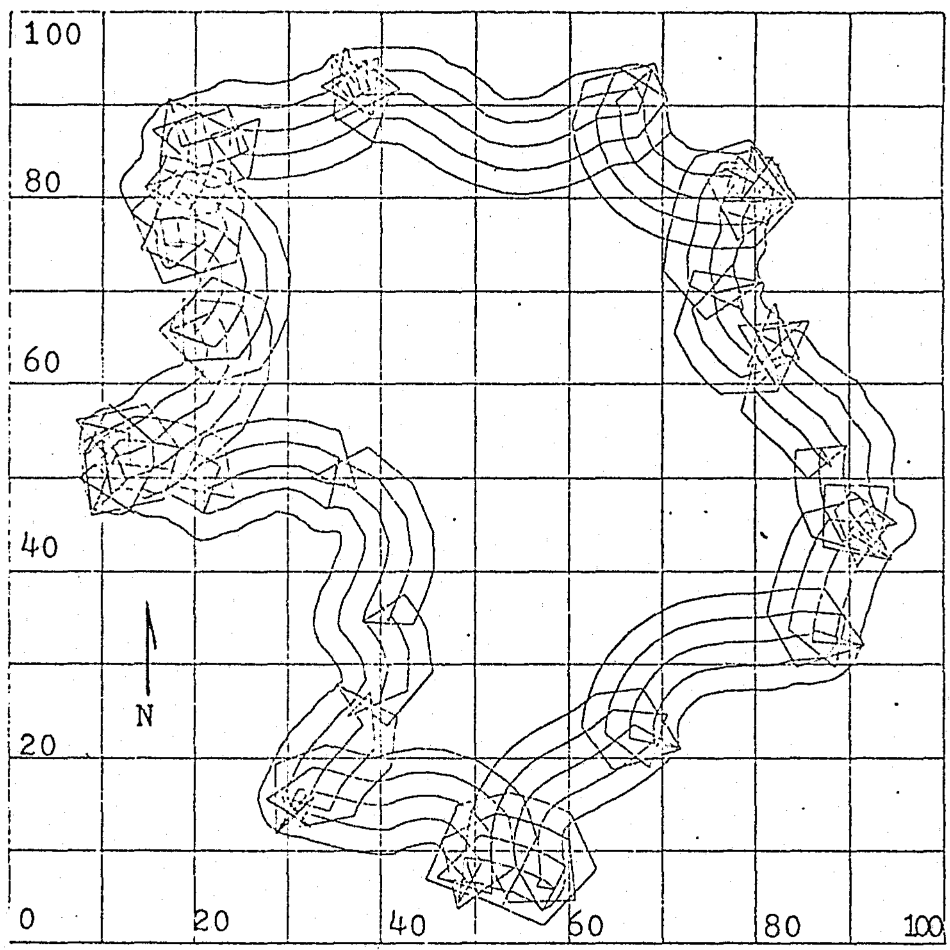


Figure 7. Hypothetical Burn Pattern Without INTCHK. This is the same hypothetical burn pattern with same fuel conditions as previous fig.6, but run without subprogram INTCHK in order to demonstrate purpose of INTCHK. The iterations were stopped prematurely since it is only intended for exemplary purposes.

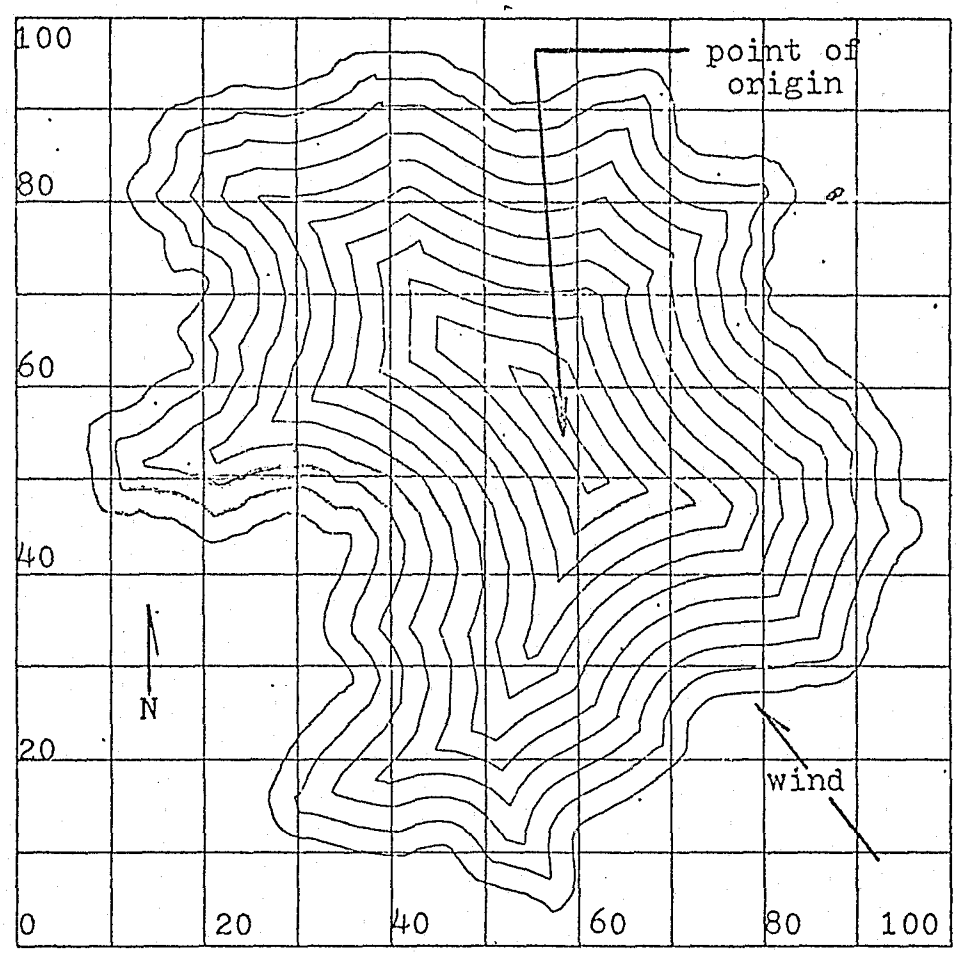


Figure 8. Hypothetical Burn Pattern W/ Wind Speed of 58. Hypothetical burn pattern same as fig. 6, but with wind blowing at 58 length/time units steadily. Fuel is homogeneous and slope is absent; these two specifications apply to remaining figs. 9-14. Also, all have unmodified rate of spread of 6.484 length/time units from Rothermel's equations for typical cheatgrass having .15 moisture content. Time interval between contours is 4.00 time units. Point of origin lies in innermost contour, eleventh from outside, and time of inception is 40 time units prior to reaching outermost contour. Wind is blowing from southeast at a direction of 2.271 radians.

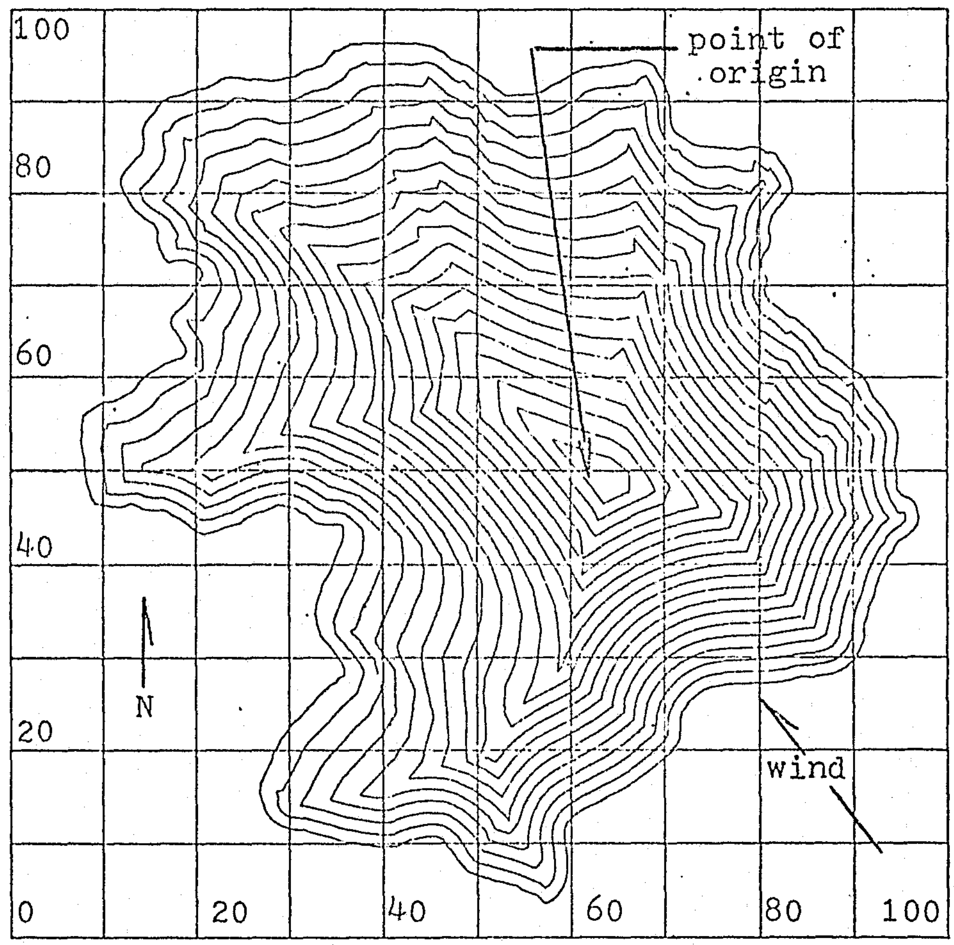


Figure 9. Hypothetical Burn Pattern W/ Wind Speed of 120. Same burn pattern with wind blowing from southeast at direction of 2.271 radians an 120 length/time units. All fuel and slope conditions remain constant and identical with fig.8. Time interval between contours is 2.00 Point of origin is in 19th contour from outermost and started 36 time units prior to attaining outermost perimeter.

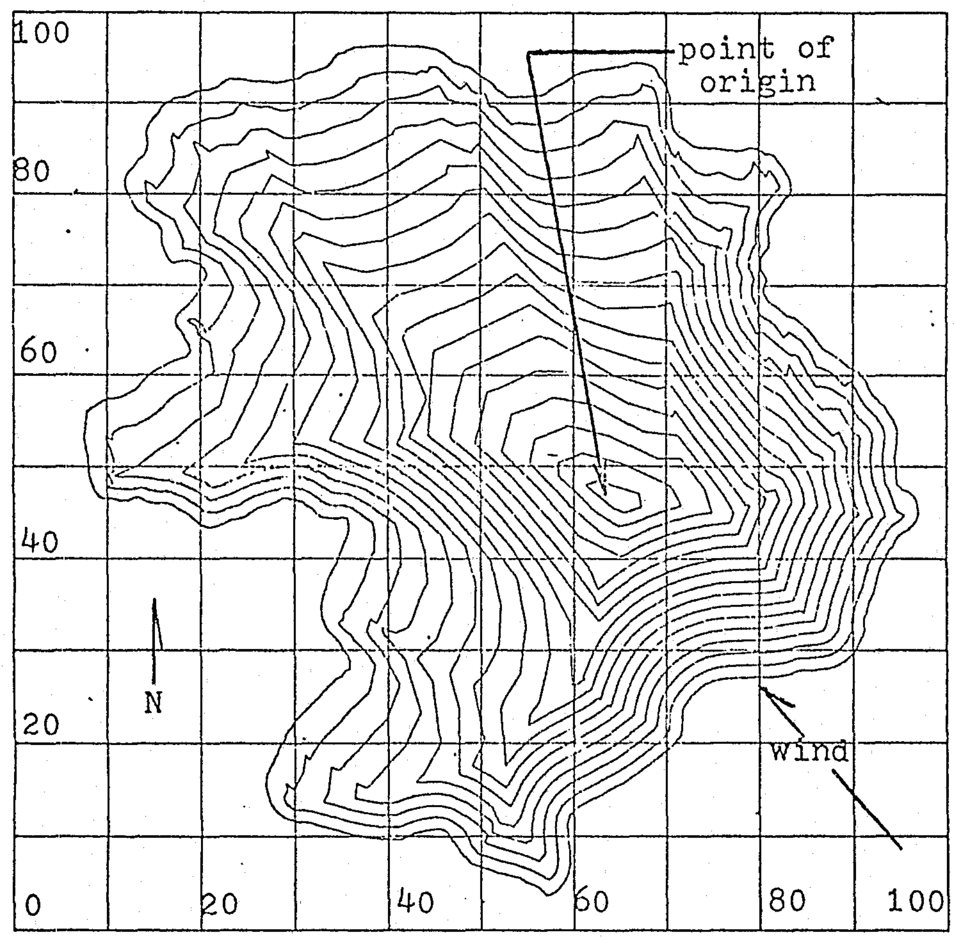


Figure 10. Hypothetical Burn Pattern W/ Wind Speed of 150. Wind is blowing at 150 length/ time units at a direction of 2.271 radians. Same burn pattern, fuel conditions as fig. 9. Time interval between contours is 2.00. Point of origin lies is innermost contour, seventeenth from outside. Fire's time of inception is 32 time units prior to reaching outermost perimeter.

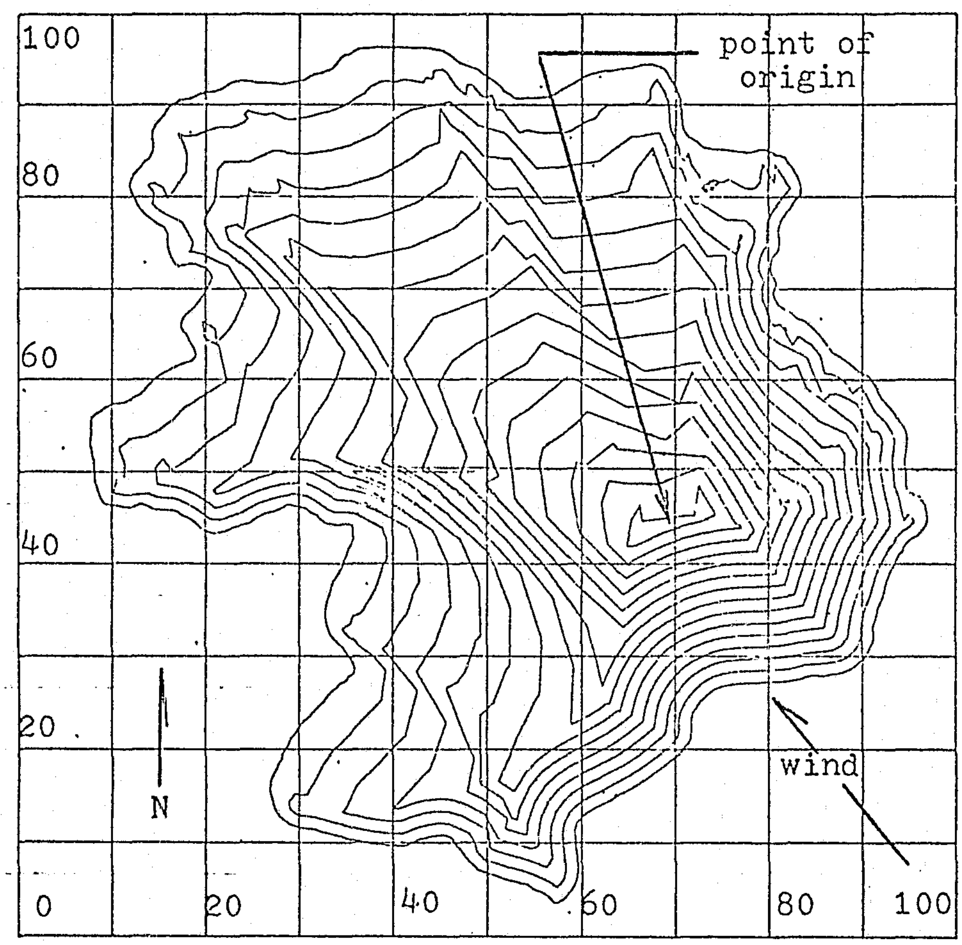


Figure 11. Hypothetical Burn Pattern W/ Wind Speed of 175. Wind is blowing steadily at 175 length/time units from southeast at a direction of 2.271 radians. All fuel conditions and unmodified rate of spread remain constant and identical with fig.8. Time interval between contours is 2.00 time units. Point of origin lies in fifteenth contour from outermost perimeter. Fire started 28 time units prior to attainment of final outermost perimeter.

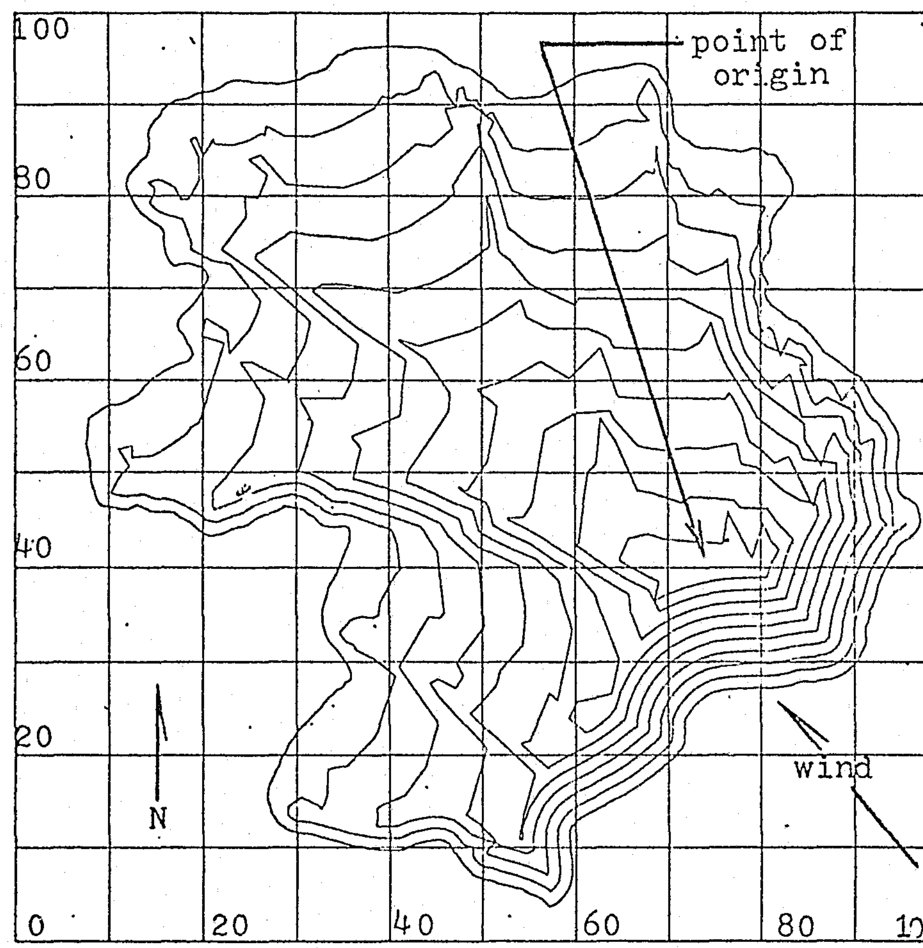


Figure 12. Hypothetical Burn Pattern W/ Wind Speed of 220. Steady wind of 220 length/time units is blowing from southeast at a direction of 2.271 radians. Fuel conditions and unmodified rate of spread reamins identical with fig.8. Time interval between contours is 2.00 time units. Point of origin lies in tenth contour from outside. Fire started 18 time units prior to attaining outermost contour.

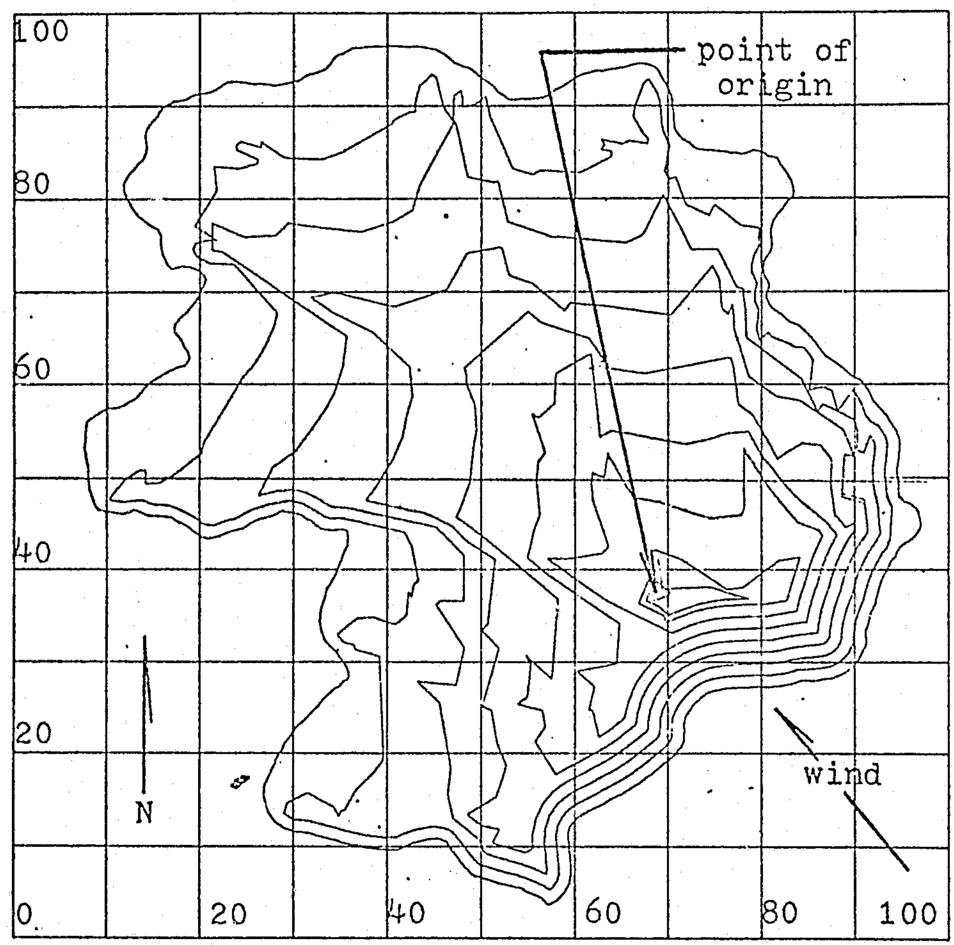


Figure 13. Hypothetical Burn Pattern W/ Wind Speed of 260. Steady wind of 260 length/time units is blowing from southeast at direction of 2.271 radians. All fuel conditions and unmodified rate of spread remain identical with fig.8. Time interval between contours is 2.00. Fire originated in tenth contour from outermost perimeter and 15.5 time units prior.

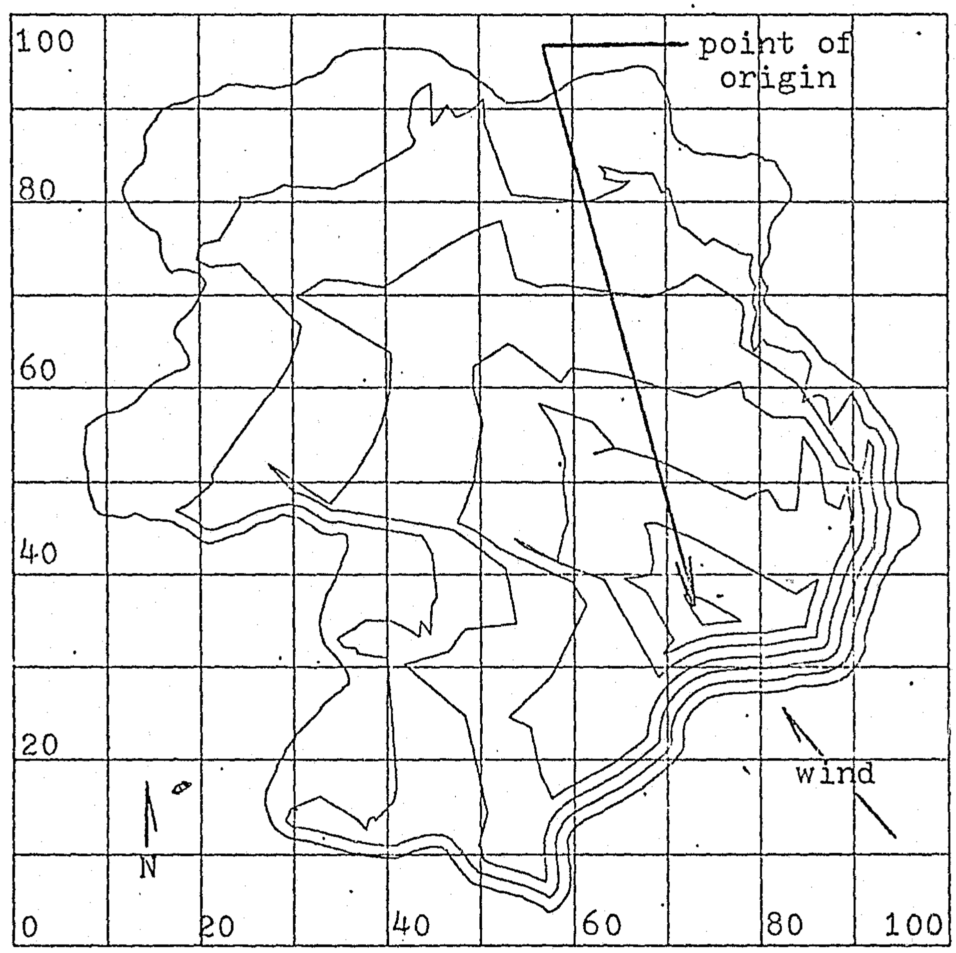


Figure 14. Hypothetical Burn Pattern W/ Wind Speed of 300. Steady wind of 300 length/time units is blowing from southeast at a direction of 2.271 radians. Fuel conditions and unmodified rate of spread remain same as previous figures. Point of origin lies in innermost contour, seventh from outside. Fire started 12 time units prior to attaining outermost perimeter.

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