A MODEL FOR PREDICTING LIGHTNING-FIRE IGNITION IN WILDLAND FUELS

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PREFACE

This report is the second in a planned series describing the concepts, development, and application of lightning-fire models. These reports are:

1. A Conceptual Model for Lightning-Fire Prediction
   (Donald M. Fuquay)

The first report in the series will describe a conceptual model that tells the probability of forest fuel ignition by lightning. Fire ignition potential is described in terms of characteristics of summer storms and individual lightning flashes, fuel bed, and fuel moisture.

2. A Model for Predicting Lightning-Fire Ignition in Wildland Fuels
   (Donald M. Fuquay, Robert G. Baughman, and Don J. Latham)

This report describes a model for predicting the number of lightning-caused ignitions in forest fuels. The model is based on the physical processes involved in ignition of fine woody fuels by lightning and the chance occurrence of the simultaneous events required for fire ignition. Input information includes lightning activity, storm movement, fuel moisture and fuel bulk density.

3. Forecasting Lightning Activity and Associated Weather
   (Donald M. Fuquay)

The third report will present guidelines for forecasting Lightning Activity Levels required for the 1978 version of the National Fire-Danger Rating System (NFDRS). The concepts, organization, and data base for the Lightning Activity Level (LAL) Guide plus a forecast and verification guide will be described.

RESEARCH SUMMARY

A model has been developed for predicting the number of lightning-fire ignitions in wildland fuels. The model is based on both stochastic and physical processes. Stochastic methods are used to generalize the lightning storm characteristics and site conditions that affect the potential for ignition. Physical processes are involved in determining the ignition probability of woody fuels by individual lightning events. Input required to operate the model includes lightning activity, upper air windspeed (storm movement), fuel moisture, and fuel bulk density. The model can be used either to predict ignitions at some future time by using forecast data or to estimate the number of fire ignitions actually occurring by using current data.

A lightning activity level (LAL) guide has been provided as a means for field personnel to interact with the model. Although the predicted LAL and upper air windspeed are provided by the National Weather Service, the LAL guide can be used in the field to determine the actual lightning activity level. The LAL guide is given in terms of an index that describes the cloud and storm development and expected amount of cloud-to-ground (CG) lightning. For example, an LAL index of 1 describes the condition of no thunderstorms, while an LAL of 5 describes a very active thunderstorm development with over three CG discharges per minute. By referring to the LAL guide, field personnel can use cloud descriptions, rate and amount of CG lightning, and area coverage of storms to confirm lightning activity level forecasts.

The lightning-fire ignition model estimates the maximum number of ignitions to be expected under specified conditions. The probability of these ignitions becoming reported fires is not covered in this model development, but is the subject of further work.

CONTENTS

INTRODUCTION

This report, the second of several planned on the topic of lightning-caused fires (see Preface), describes the development and structure of a model for predicting the ignition of wildland fuels by lightning. The model is both physical and stochastic in structure. The physical processes for ignition of fine woody fuels by lightning are the basis for the model. Stochastic processes are used to generalize site conditions for a large area and the chance occurrence of simultaneous events required for ignition.

The updated National Fire-Danger Rating System (1978 version) uses a lightning-fire occurrence index as a measure of lightning-fire risk. We have developed a lightning ignition model that could provide the basis for a lightning-caused fire occurrence index within the context and limitations of the National Fire-Danger Rating System (NFDRS). In keeping with the NFDRS, an *occurrence index* is a number on a relative scale, usually 0-100, relating to the potential fire incidence within a protection unit. The *model*, as discussed here, provides a systematic means of producing a lightning-fire occurrence index.

The ignition of forest fuel by lightning depends on a large number of variables and chance factors. The development of this lightning-fire ignition model assumes that the probability of ignitions resulting from lightning discharges can be estimated from a very limited amount of physical data, particularly on fuel and storm characteristics. The utility of the model will depend, for the most part, on our ability to generalize those conditions within the wildland environment that most influence the ignition processes.

The following general guidelines were used to develop the lightning-fire ignition model:

1. The model had to be compatible with the philosophy of the NFDRS; it should evaluate the "worst" conditions within a rating area.

2. The model had to provide an estimate of the *maximum* expected number of ignitions, using either forecasted or observed values of the critical variables.

3. Guidelines were needed for forecasting the essential variables and for verifying that the forecast events occurred.

"A Conceptual Model for Lightning-Fire Prediction" (Fuquay 1974[1]), summarized our first attempt to develop a lightning-fire prediction model. This earlier model generates a probability of forest fuel ignition by lightning. Fire ignition potential is described in terms of characteristics of summer storms and individual lightning flashes, fuel bed descriptors, and fuel moisture. The ignition generator in the earlier model, corresponding to the Lightning Risk (LR) factor in the present NFDRS, is based on historical probabilities of storm occurrence and flash characteristics, and on lightning forecasts. Prediction, or estimate, of reported fires depends on the area distribution of specified fuels, state of the fuel, ambient meteorological factors, and a probability of sustained ignition based on fire spread models. Some features of this earlier model were used in developing the model described here.

The lightning-fire ignition model estimates the maximum number of *ignitions* to be expected under specified conditions. The probability of these ignitions becoming *reported* or *statistical* fires is not covered in this report.

The large array of variables influencing the ignition of forest fuels by lightning is illustrated in figure 1. We feel that a useful estimate of the number of expected ignitions can be derived from a model which considers only the following:

1. Area density of cloud-to-ground (CG) lightning
2. Storm movement (steering level winds)
3. Precipitation duration
4. Fine fuel moisture
5. Lightning flash characteristics
6. Effective bulk density of fine fuels.

In the following section, we group these variables into components or building blocks to form the structure of a lightning-fire ignition model.

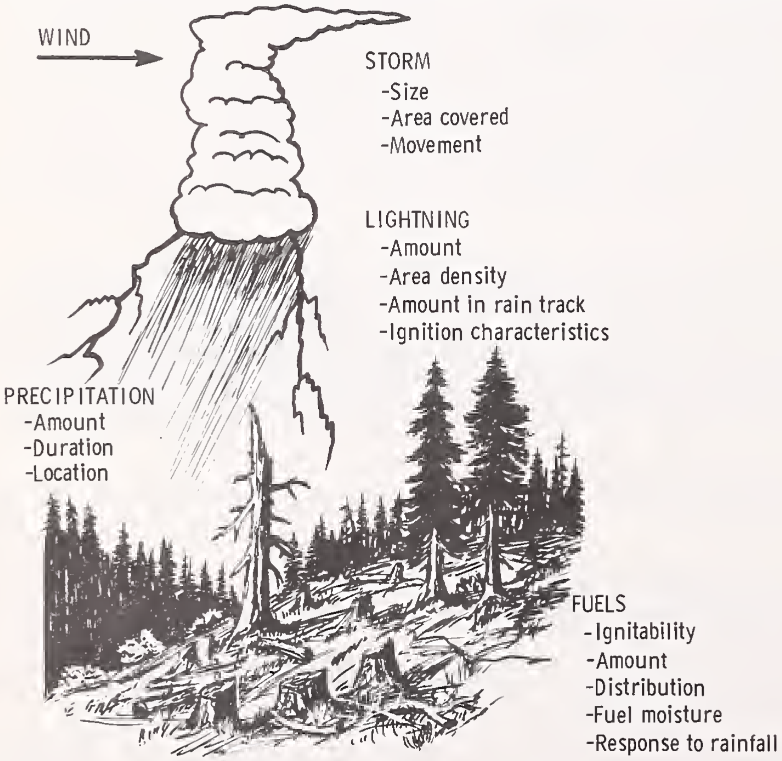

Figure 1.--The lightning fire ignitions environment.

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[1] A conceptual model for lightning-fire prediction. Unpublished report on file at Northern Forest Fire Laboratory, Missoula, Mont.

COMPONENTS OF THE LIGHTNING-FIRE IGNITION MODEL

Lightning Activity Level

The Lightning Activity Level (LAL) is an index of thunderstorm activity on a basic scale of 1 to 5 (see "How the Model Works, LAL Guide"). The LAL scale and narrative description format are similar to those given by Deeming and others (1972). We assume that the lightning activity and accompanying meteorological conditions occurring within a forecast area of approximately 2,500 mi^2 (6,500 km^2) can be adequately represented by a single index value. The LAL index enables a forecaster to predict the general conditions expected within the forecast area. The LAL descriptors can be used on the ground to identify and label what actually occurs and to convey the information back to the forecaster.

The information content of the LAL index is summarized in the LAL Guide (table 1). A lightning activity level forecast assigns predetermined values to the following:

1. Number of cloud-to-ground discharges (CG) per 2,500 mi^2 (6,500 km^2)
2. Area covered by radar echoes
3. Area intensity of rainfall
4. Storm size and duration.

Each of the activity levels in the guide provides the forecaster with information to describe the conditions expected in the forecast area (lightning, cloud development, precipitation) and for use by the observer in the field to determine the LAL that actually occurred (cloud description, amount and rate of lightning occurrence).

Meteorological Considerations

Fine fuels are highly susceptible to wetting by rainfall. The rainfall accompanying lightning increases fuel moisture and decreases the probability of ignition. Theory predicts that water uptake by fuel is affected more by duration of precipitation than by amount or rate (Fosberg 1972). This concept is used in our model. Calculation of the rainfall duration and fuel moisture requires knowledge of the storm size, speed, and duration ("How the Model Works"). Windspeed at cloud level (upper windspeed) is used to represent storm speed. Other meteorological elements such as air temperature, humidity, stability, and surface wind are not considered to play an important part in this ignition model.

Table 1.--*Lightning activity level guide*

Lightning activity level	Cloud and storm development	Rel. freq. on T/S days (percent)	Fraction of area covered by radar echoes of indicated strength				Percent of area receiving less than the amount of rain indicated			
			Very light	Light	Moderate	Heavy	0-T	<0.1"	<0.3"	<0.9"
TYPICAL CLOUD AND PRECIPITATION CONDITIONS (2,500 mi^2 or 6,500 km^2 area)										
1	No thunderstorms[1]		No radar echoes				No precipitation			
2	Few building cumulus only occasionally reaching cumulus congestus stage; single CB in forecast area. Visual tops: <30,000 ft (9,100 m) m.s.l.	10	0.1	<0.1			90	91	100	
3	Scattered cumulus to cumulus congestus; widely scattered CB's; cloud-to-ground lightning averaging 1 to 2 per min. max.	35	.2	.1	0.05		70	90	98	100
4	Growing cumulus and cumulus congestus stage over 1/10 to 3/10 of the area; scattered cloud-to-ground lightning in area averaging 2 to 3 per min. max.	35	.2	.1	.05		65	80	95	100
5	Cumulus congestus common over area, occasionally obscuring the sky; moderate to heavy rain associated with CB's; light to moderate rain preceding and following lightning activity. Lightning flashes occurring steadily at some place in or during storm period; maximum CG flash rate greater than 3 per min.	18	.3	.1	.05	0.02	50	75	85	100
6	Scattered towering cumulus with a few at thunderstorm stage; very limited horizontal extent; high bases (15,000 to 17,000 ft m.s.l.). Virga in most prominent hydrometeor form. Lightning flash rate is low, averaging less than 1 to 3 per 5 min. period each storm.[2]	<2								

Lightning activity	Maximum radar echo height, m.s.l.		Cloud-to-ground lightning per 2,500 mi^2 (6,500 km^2)	Occurrence rates, maximum		
	Feet	Meters		CG/5 min.	CG/15 min.	Aver. rate/min.
LIGHTNING - AMOUNT AND RATE						
2	<28,000	<8,500	20	--	--	--
3	26,000 - 32,000	7,900 - 9,700	40	0-10	0-17	1-2
4	30.000 - 36,000	9,100 - 11,000	80	4-19	6-32	2-3
5	>36,000	>11,000	160	9-32	19-77	3
6 (See text for explanation)						

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[1] In most general terms, 2 days out of 3 will not be thunderstorm days during a typical fire season in the mountainous areas of the western continental United States.

[2] Used with red-flag warnings of extreme fire activity.

Ignition

Lightning-caused fires originate almost exclusively in fine fuels, particularly in conifer duff and litter under trees, and in so-called "punky wood" found in snags and in crowns of some living trees (Taylor 1969). These fuels fall into the 1-hour timelag category of the NFDRS, and can be assigned a heat of ignition that depends on the fuel and the amount of water (fuel moisture) present. As the fuel is heated during the ignition process, this water must be evaporated (at least from the surface layers) before ignition can take place. The quantity of heat required to ignite a unit volume of fuel depends on the heat of ignition of the fuel per unit mass, the amount of fuel per unit volume (bulk density), and the fuel moisture. Bulk densities of the fine woody fuels used in the model calculations have values ranging from 2 to 12 lb/ft^3 (0.032 to 0.192 g/cm^3). These are much higher fine fuel bulk densities than those used for fuel loading in fire spread models where densities are averaged over a large area (see table 5).

A lightning flash to ground (CG) consists of several sequential events; among these are the "return strokes." The return strokes, surges of current in the channel, cause the flash of light and thunder. In about 20 percent of these CG flashes, an event called the "long continuing current" (LCC) will be present. The LCC has been shown to be highly likely to ignite most lightning-caused forest fires (Fuquay and others 1967, 1972). Thus, the LCC event is included as an important part of our model ("How the Model Works, Ignition Probability").

We now have the fuel, litter and duff, and the "match," the LCC event. The LCC has a wide range of energies, and all will not supply sufficient energy to ignite the fuel. We must, therefore, have an ignition criterion--a way to designate if ignition has taken place. Our model uses a very simple approach. If the energy supplied by an LCC is greater than the amount required to ignite the fuel, an ignition occurs. The model relates this ignition criterion to storm, lightning, and fuel characteristics.

Model Structure

Figure 2 is a simplified diagram of the model. The inputs are:

- LAL, giving the number of expected discharges, the storm size, and the duration of the lightning activity
- speed of the storm
- initial fine fuel moisture
- fuel bulk density.

We use these inputs, together with what we know about the wetting of fuels and the nature of the LCC, to predict the probability that a discharge will cause ignition. This probability is combined with the total number of discharges expected in a given area to give the number of expected fire ignitions in that area. The following section covers the calculations in detail.

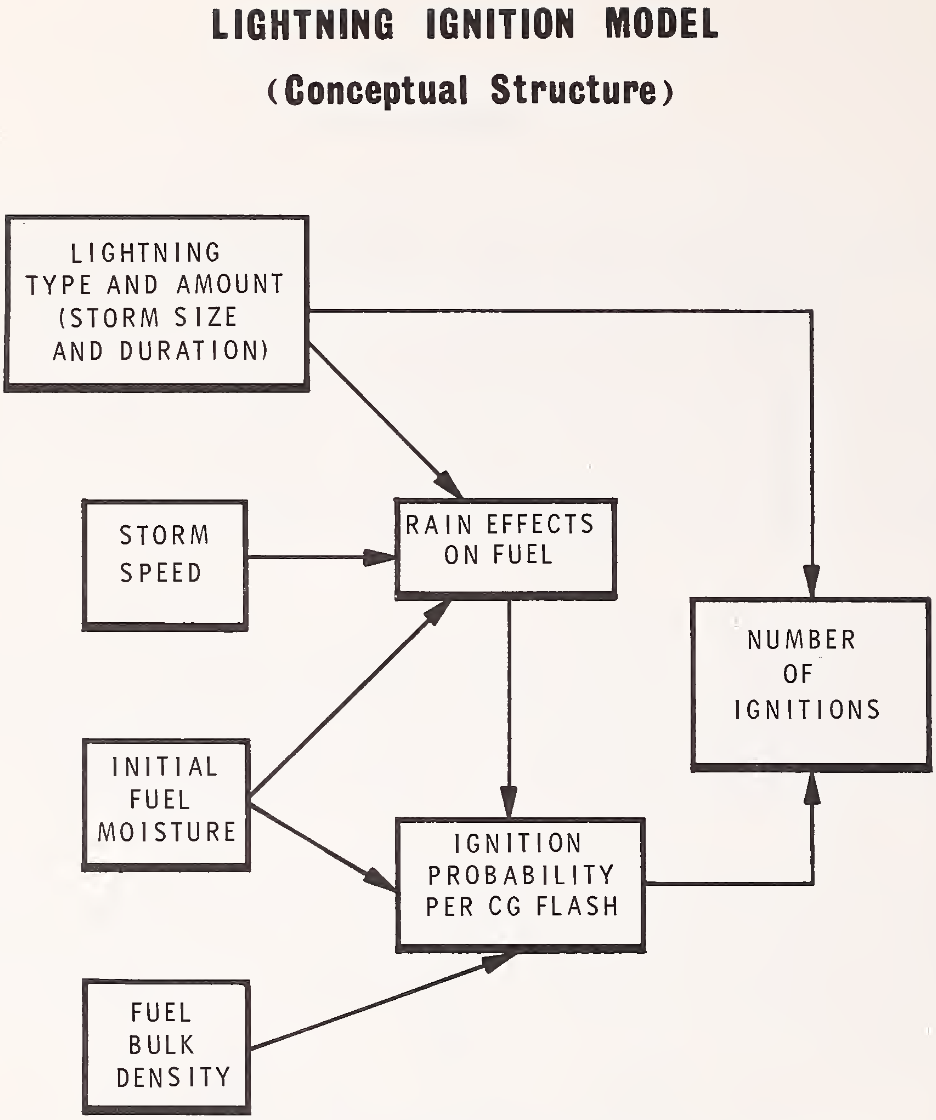

Figure 2.--Lightning-fire ignition model (conceptual structure).

HOW THE MODEL WORKS

Lightning Activity Level Guide

The LAL is an index, ranging in steps from 1 to 5, used to describe a generalized daytime thunderstorm condition within a specified forecast area (LAL 6, a special case, is covered under "Precipitation Amount and Area Coverage"). In most cases, the forecast areas are designated by the National Weather Service Fire-Weather Forecast Office in their annual operating plan. Forecast areas vary considerably in size and shape.

The basic and smallest area for which a forecast is made is 2,500 mi^2, a square 50 miles on a side (about 6,500 km^2). The values given in the LAL Guide are for each 2,500 mi^2 unit within a forecast area. When lightning occurrence or storm coverage is observed in the field, the observed values should be adjusted to this same area. Lightning observed over about a 28-mile radius (45 km) would correspond to the 2,500 mi^2 forecast unit.

In general practice, the forecast LAL is used to calculate the maximum number of *new* ignitions to be expected in the forecast area for the period of the forecast. In the NFDRS, the number of holdover or "sleeper" fires is based on the LAL's that actually occurred on previous days. For this reason, an LAL forecast should always be regarded as conditional. It must be confirmed or corrected before being used for holdover fire calculations on subsequent days.

For example, a forecast of LAL 4 for a given forecast area means that *if* LAL 4 actually occurs, the descriptions within the LAL Guide should be representative of conditions within the forecast area. The descriptors and calculation of ignition occurrence are valid only *if* that LAL actually occurs. Thus, there must be field confirmation of the occurrence of the forecast events.

The LAL Guide has been developed with both forecasting and confirmation in mind. Confirmation can be accomplished by both the forecast office and field personnel. The forecaster can confirm using available radar data (maximum radar height of storms, precipitation coverage and duration), pilot reports, satellite data, and network meteorological data. Field personnel can use cloud descriptions, rate and amount of observed CG lightning, and area coverage of storms to confirm the LAL.

Now let's look at the LAL Guide and review its structure and the sources of data. The following is an outline of the LAL Guide (table 1):

a. Typical cloud and precipitation conditions

    1. Cloud and storm development

    2. Area coverage of radar echoes

    3. Area amount of precipitation.

b. Lightning - amount and rate

    1. Maximum radar height vs. lightning

    2. Lightning occurrence rates.

The basic data set for the LAL Guide consisted of measured lightning and associated meteorological events during the summer months of 1965, 1966, and 1967 near Missoula, Montana. The 3-year period included seasons of high and low lightning occurrence.

Amount of lightning.--The first step was to estimate the number of CG discharges associated with each LAL. To do this, we first found the distribution of CG lightning per storm day vs. maximum radar echo height. (The visual top of a cloud or thunderstorm system, as might be reported by a pilot, generally exceeds the radar echo height by about 2,000 ft (600 m). Fuquay (1967) showed that a strong relationship exists between maximum radar echo height and the frequency of lightning. Then, LAL's were assigned by height classes, with the aid of relative frequency of occurrence data for each radar echo height. In assigning the maximum heights to an LAL index, it was recognized that a forecast will include a range of values to be expected over the forecast area. Thus, LAL 3 implies that we can expect maximum radar heights to generally fall in the range 26,000 to 32,000 ft m.s.l. (7,900 to 9,700 m) over the forecast zone. Finally, using radar and lightning data, we developed an estimate of the amount of CG lightning that could reasonably be assigned to each LAL class (table 1).

Maximum lightning occurrence rates.--Lightning occurs from coherent groups of clouds or a storm. Usually, the storm will cover less than 500 mi^2. We call this an individual storm. A storm may be made up of one to several cells each in a different stage of development. Two or more individual storms may occur within the forecast area. We can use the *maximum* lightning occurrence rate from one of these storms to estimate the LAL. In general, the maximum rate will occur during the middle one-third of the storm period. Table 1 gives the expected flash rates for each LAL class.

Area-intensity of radar echoes.--An estimate of the fraction of the forecast area covered by radar echo intensities of very light, light, moderate, and heavy for each LAL class was determined (table 2). Some judgment will be required in applying these data. The lightning-fire ignition model is designed for the midseason storms when an appreciable number of fire starts can present a management problem. The preseason and postseason storms do not usually result in large number of lightning fires. In the Northern Rockies, the onset of the midseason storm period is early in July. Further south, the season will often begin in late May and early June. The onset of the postseason storms, the fall regime, usually marks the end of the summer fire season.

Table 2.--*Radar echo intensity and coverage, as a fraction of the forecast area covered by radar echoes*

LAL index	Season	Frontal (F)				Non-frontal (AU, U)			
		VL	L	M	H	VL	L	M	H
2	Preseason	0.7	0.5	-	-	-	-	-	-
	Midseason	.1	>.1	-	-	0.1	>0.1	-	-
	Postseason	-	-	-	-	-	-	-	-
3	Preseason	.7	.5	-	-	.2	.1	-	-
	Midseason	.3	.1	.05	-	.2	.1	.05	-
	Postseason	.5	.1	.05	-	.5	.1	.05	-
4	Preseason	.7	.5	.1	-	-	-	-	-
	Midseason	.4	.2	.1	-	.2	.1	.05	-
	Postseason	.5	.2	.1	-	.5	.1	.05	-
5	Preseason	.7	.5	.1	-	-	-	-	-
	Midseason	.4	.2	.1	.05	.3	.1	.05	.02
	Postseason	.5	.2	.1	.05	.4	.2	.1	.05

VL = Very light
L = Light
M = Medium
H = Heavy

Precipitation amount and area coverage.--Precipitation from midseason summer thunderstorms is usually very spotty. An analysis of radar data (table 3) gives an estimate of how much of a forecast area will receive precipitation and the expected amount. These values should be interpreted as follows: For an LAL 3, 72 percent of the forecast area will have 0 or a trace of precipitation. About 20 percent of the area will receive from 0.01 to 0.09 inch (0.2 to 2.3 mm) of rain. Perhaps only 2 percent of the area will receive from 0.2 to 0.5 inch (5 to 13 mm). The actual values have been rounded off for use in the LAL Guide.

Table 3.--*Precipitation amount (inch) and area coverage (percent) for LAL's 1-5.*

Precipitation amount	Rainfall area coverage LAL 1	2	3	4	5
(inch)		*(percent)*			
0.9 -0.99					
.8 - .89					1
.7 - .79				1	1
.6 - .69				1	1
.5 - .59				1	4
.4 - .49			1	1	6
.3 - .39			1	1	3
.2 - .29			1	3	5
.1 - .19			5	10	5
.01- .09		9	21	19	27
Trace		12	14	10	14
0		79	58	54	34

The high-level thunderstorm (LAL 6).--The high-level dry thunderstorm (LAL 6) is a special situation not fully covered by this report. We know that this type of storm, while relatively rare, can present a severe fire problem. Also, at the present time, the forecast of such storms is always accompanied by a red flag warning issued by the forecaster. The determination of the appropriate values for calculating the fire load associated with these storms will require additional study and development. In the interim, the lightning activity for LAL 3 of 40 CG discharges should be forecast. The lack of precipitation associated with LAL 6 is handled within the model structure.

The term "high-level thunderstorm" should be reserved for the situation where sufficient moisture and instability for thunderstorm initiation are found in the upper levels only. Cloud bases in the Northern Rockies will be at the 15,000 to 17,000 ft (about 4,600 to 5,200 m) levels. The thunderstorm activity is generally triggered by the advection of cold air aloft, an upper cold front passage, or widespread vertical motion. This situation is often preceded by *altocumulus castellanus* in the early to midmorning hours. The actual speed of storm movement varies considerably, from near stagnant conditions to rapidly moving systems. The local cells may show considerable precipitation in the form of virga, but virtually no precipitation reaches the ground from the high bases. Strong downdrafts may develop as the rain evaporates below cloud base. If the downdraft reaches the ground, strong erratic surface winds may result.

In situations with relatively high moisture content at all levels, storms may be triggered by the same mechanisms. However, bases will be generally lower and considerably more moisture will reach the ground. This situation would be better described by LAL's 2 or 3.

Rainfall Effect on Fuel Moisture

Rainfall has a major influence on lightning-fire ignition because it occurs along with lightning and immediately affects the moisture content of fine forest fuels. Fine fuel moisture is a predominant factor in the ignition of fire and was therefore made a component of the model. Although other meteorological elements such as temperature, humidity, and wind are also involved, they are only briefly considered here.

How rainfall produces a rapid, predictable increase in fine fuel moisture is described in a recent theory by Fosberg (1972). It states that water uptake by wood is limited by the rate that moisture can be transferred from the surface to internal layers of the fuel. Therefore, the final fuel moisture depends on the *time* that the fuel surface is exposed to precipitation rather than the rate or total amount of precipitation. Also, moisture loss is quite rapid following the end of precipitation. Following this theory, we use rainfall *duration* in our model, instead of rainfall amount or rate, and disregard any day-to-day carryover effect of rain on fuel moisture. The duration of precipitation, as used in the model, corresponds to periods of continuous lightning activity. Even though lightning strikes at random times during a rainfall, we are assuming that the fuel has reached its final moisture value before "allowing" it to be struck. This may mean a very slight underestimate of the total ignition probability.

Rainfall duration.--An estimate of rainfall duration at a point on the ground can be obtained by finding the ratio of storm size to storm speed. Storm size refers to the core of the cloud (radar echo) that produces lightning and precipitation, and not to the overall visible extent of clouds making up the storm. Our model relates a storm size to each of the LAL's. This was done by using data where the horizontal storm dimension and corresponding maximum radar echo heights were given for North Dakota (Miller and others 1975) and Montana (unpublished data[2]). These maximum heights were then matched with the maximum radar echo heights for each LAL class to give us an LAL-to-horizontal storm dimension relationship. Thus, a prediction or declaration of an LAL automatically selects a maximum storm dimension in the model.

It is known that lightning strikes the ground both inside and outside of the rain area (or track) on the ground, and observations indicate that a total lightning strike zone 4 miles wider than the corresponding storm width is appropriate for model use. The storm size (rainfall track width) and lightning zone width corresponding to each LAL class are given in table 4.

Table 4.--*Storm size and lightning zone size as defined in figure 3*

LAL	Storm size		Lightning zone size	
	Miles	Kilometers	Miles	Kilometers
2	3	4.8	7	11.2
3	4	6.4	8	12.8
4	5	8.0	9	14.4
5	7	11.2	11	17.6

We also need to know the speed of a storm to calculate rain duration. There exists an upper air level (steering level) where the velocity of the basic flow bears a direct relationship to the velocity of clouds embedded in the flow. For example, the best steering level over the Northern Rockies is the 14,000 ft (4,300 km) level (Osborne and others 1953). For the 49 cases tested (radar echo movement), the 14,000 ft (4,300 km) echo speed was within 10 knots of the windspeed 90 percent of the time. Upper windspeed data available from the National Weather Service can be used to calculate windspeed at this level. Rain duration can then be computed as the ratio of storm size to storm speed.

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[2] Unpublished data on file at the Northern Forest Fire Laboratory, Missoula, Mont.

Rainfall effect on fine fuel moisture.--The effect of precipitation on the fine fuel moisture content can be determined by the following equation (Fosberg 1972):

$$\delta m/\Delta m = 1 - \zeta e^{-t/\tau m}$$

where:

δm is the actual moisture content change

Δm is the potential change

ζ is a varying parameter, depending on t/τ_m

t is the time period involved (rainfall duration)

τ_m is the particle moisture timelag.

$\delta m/\Delta m$ can be given as:

$$\delta m/\Delta m = \frac{FMF - FMI}{FMS - FMI}$$

where:

FMF is the final fuel moisture content

FMI is the initial moisture content

FMS is the moisture content at the wetted surface of the fuel, thus:

$$FMF = FMI + (FMS - FMI) (1 - \zeta e^{-t/\tau_m}).$$

Fosberg's theory was developed for dead cylindrical fuel such as logs, stems, and twigs. We apply the theory to any fine fuel that may be ignited by lightning, including fuel on trees and snags, or in duff and litter layers. Also, since we are dealing only with fine fuels, we limit the values of FMF to those fuels with timelag periods of 1 hour or less. This means that we can use a 1-hour moisture timelag value for τ_m, set ζ equal to 1, and assign FMS a value of 76 percent (after Fosberg 1972). The initial fuel moisture (FMI) can be obtained from current observations (Deeming and others 1972) while the rainfall duration (t) is obtained as given above.

Rainfall area.--We have shown (fig. 3) that we consider two areas within each storm: a rainfall area and a lightning area. We included two areas in the model because lightning hits both inside and outside of the storm rainfall area. Obviously, the ignition probability inside the rainfall area is less than that outside the rainfall area.

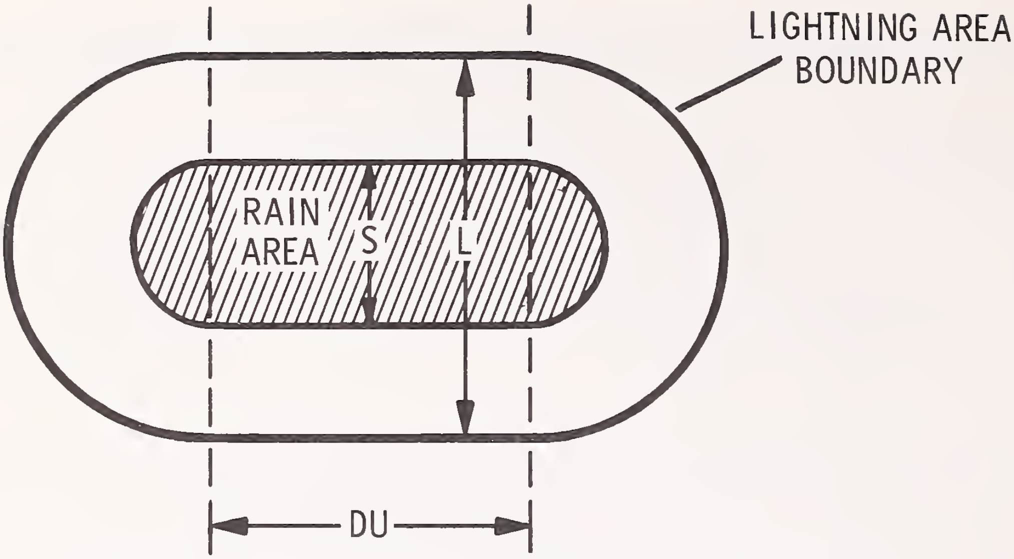


Figure 3.--Idealized shape of lightning and rain area.

D = Lightning activity duration
U = upper windspeed
S = storm size (rainfall area)
L = lightning area

In order to calculate the different ignition probabilities, we need to know the lightning activity duration and the relative size of the area with rainfall and of the dry zone outside. (Lightning activity duration refers to the continuous periods of lightning activity in a general area.) For modeling purposes, information was taken from data obtained in western Montana (Fuquay and Baughman 1969). The following tabulation gives a representative storm duration from each LAL:

LAL	*Lightning Activity Duration (Minutes)*
2	150
3	174
4	200
5	230

The idealized shape of an electrically active storm (considering a circular storm moving along with the wind) is that of a racetrack with an infield. Lightning hits the total area (racetrack plus infield) while rain falls only in the infield. Figure 3 shows the racetrack concept.

The fractions of the area with rain (FI) and without rain (FO) are computed as follows:

$$FI = \frac{4DUS + \pi S^2}{4DUL + \pi L^2}$$

$$FO = 1 - FI.$$

A flow diagram (fig. 4) shows the steps necessary to obtain a final fuel moisture (FMF) due to rainfall and the fractional size of the area with (FI) and without (FO) rain. This information will be combined later with ignition probabilities to calculate an overall average probability.

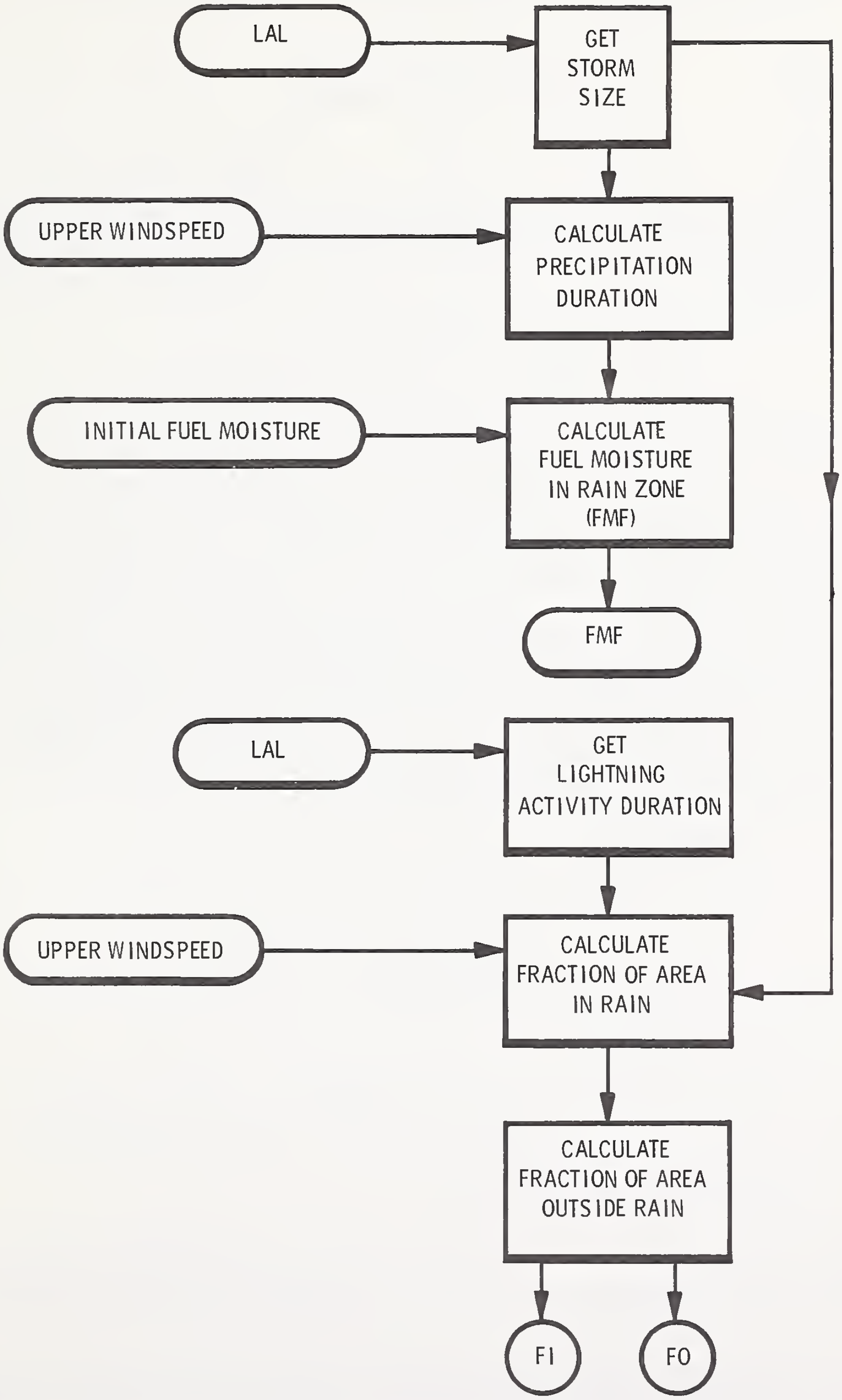


Figure 4.--Final fuel moisture and rain fraction determination.

Other meteorological elements.--Other meteorological elements such as temperature, humidity, and wind are also part of the lightning-fire problem. Air temperature and humidity are included indirectly in our model through the use of an initial fuel moisture content. The model is presently set up to use the 1 hour fine fuel moisture as an initial condition. The surface wind is not now included as a factor in ignition. We may need to change our model with regard to these elements later on.

Ignition Probability

We need to know the probability that a CG discharge will ignite the fuel through which it passes. We have shown that ignition depends on the characteristics of the fuel, its moisture content, and the nature of the lightning flash. The basic criterion for ignition is that

$$E_c > E_{ig}$$

where:

E_c = the energy density of the lightning channel

E_{ig} = the energy density required to ignite a volume of fine fuel.

Here, we shall develop an expression for the probability that a CG discharge will have an energy density $E_c > E_{ig}$.

First we consider E_{ig} for fine fuels. The energy density necessary to ignite a volume of fuel is taken from Anderson (1969), as well as Frandsen (1973), Stockstad (1975), and Rothermel (1972), and can be expressed as:

$$E_{ig} = (\varepsilon)\ (RHOB)\ (Q_{ig}) \qquad (1)$$

where:

Q_{ig} = ignition energy per unit mass of fuel

RHOB = the fuel bulk density

ε = an efficiency factor, $\simeq 1$ for fine fuels.

This expression can be put in terms of fuel moisture (FM) and bulk density (RHOB):

$$E_{ig} = RHOB\ (170 + 6.20\ FM)\ cal/cm^3 \qquad (2)$$

RHOB, as used in our model, refers to concentrations of fine fuels such as duff and litter, standing punky wood, etc. It is not the average fine fuel bulk density as used in the NFDRS.

These "spot" bulk densities of various fine fuels can be obtained from Brown (1970) and Mader (1953). Typical values for those fuels likely to be struck are given in table 5. The model treats RHOB as a continuous variable.

Table 5.--*Bulk densities for some of the NFDRS fuel models. After Brown (1970, private communications); Mader (1953)*

Forest fuel type	NFDRS fuel model	RHOB lb/ft^3	RHOB g/cm^3
Tundra	S	2	0.032
Western annual grass	A	2	.032
Pine-grass	C	4	.064
Western long-needled conifer	U	4	.064
Short-needle (normal dead)	H	8	.128
Short-needle (heavy dead)	G	8	.128
Alaskan black spruce	Q	8	.128
Sagebrush-grass	T	2	.032
Eastern pine (plantation)	P	4	.064

We next need to know the probability of the energy density in an LCC discharge being sufficient to cause ignition or:

$$p(\text{Ignition}/\text{LCC}) = p(E_c \geq E_{ig}). \tag{3}$$

The energy density (E_c) in the lightning channel must be calculated from the electrical heating in the channel, the channel radius, and the duration of the discharge, or:

$$E_c = \frac{Q_c d}{\pi r^2} \times 10^{-3} \quad \text{cal/cm}^2 \tag{4}$$

where:

Q_c = channel power dissipation per unit length

d = duration of the discharge, milliseconds

r = radius of the channel, cm.

To find the channel power, we have:

$$Q_c = FI \text{ watt/cm} \tag{5}$$

where:

F = the electric field

I = the current.

King (1962) found a constant electric field along long vertical arcs of 10 V/cm (Volts per centimeter).

Brook and others (1962) and Williams and Brook (1963) have measured continuing currents and their duration. A good fit to these data was:

$$I = 44.7d^{0.1787}. \tag{6}$$

The range of currents was from 50 to 500 A.

From (5) and (6), and King's value for F:

$$Q_c = 107d^{0.1787} \text{ cal/cm-s}. \tag{7}$$

The total energy release per cm of channel is Q_c $(d \times 10^{-3})$.

A channel radius value has been calculated from considerations by Cobine (1958) and Finkelnburg and Maecker (1956); this value is approximately 1 cm, hence (4) becomes:

$$E_c = 0.034d^{1.1787} \text{ cal/cm}^3. \tag{8}$$

Statistics on LCC durations are available from measurements in western Montana (Fuquay 1974). Using these, we have applied a Beta P probability distribution (Mielke and Johnson 1974) which gives the fraction of continuing currents which can be expected to yield an energy exceeding E_{ig}:

$$p(E_c > E_{ig}) = (1 + (E_{ig}/\beta)^{\theta})^{-\alpha} \tag{9}$$

where:

$\alpha = 1401.647$

$\beta = 2822.164$

$\theta = 1.442.$

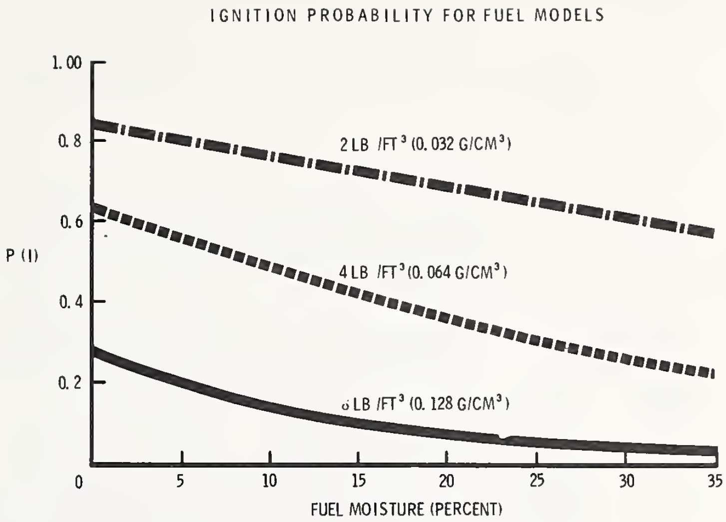
The ignition criterion is that the available energy from a given LCC event be greater than that required by the fuel for ignition, assuming that all LCC energy is transferred to the fuel. Since the available energy density has a probability, so must the ignition. We call this the ignition probability per LCC event. It is a function of fuel moisture and bulk density, and can be obtained from (2) and (9):

$$P_{ig} = \left[1 + \left(\frac{\text{RHOB } 170 + 6.20 \text{ FM}}{\beta}\right)^{\theta}\right]^{-\alpha}. \tag{10}$$

Figure 5 gives curves of (10) as a function of fuel moisture for values of bulk density from table 5.

Because the LAL gives the number of CG discharges without regard to the presence of an LCC event, we must modify the probability from "per LCC" to "per CG"; this is done by multiplying by the LCC/CG ratio. For Rocky Mountain thunderstorms this ratio is about 1 in 5. The flow chart for the entire ignition probability calculation is shown in figure 6.

Figure 5.--Ignition probability vs. fuel moisture for the bulk densities of table 5.



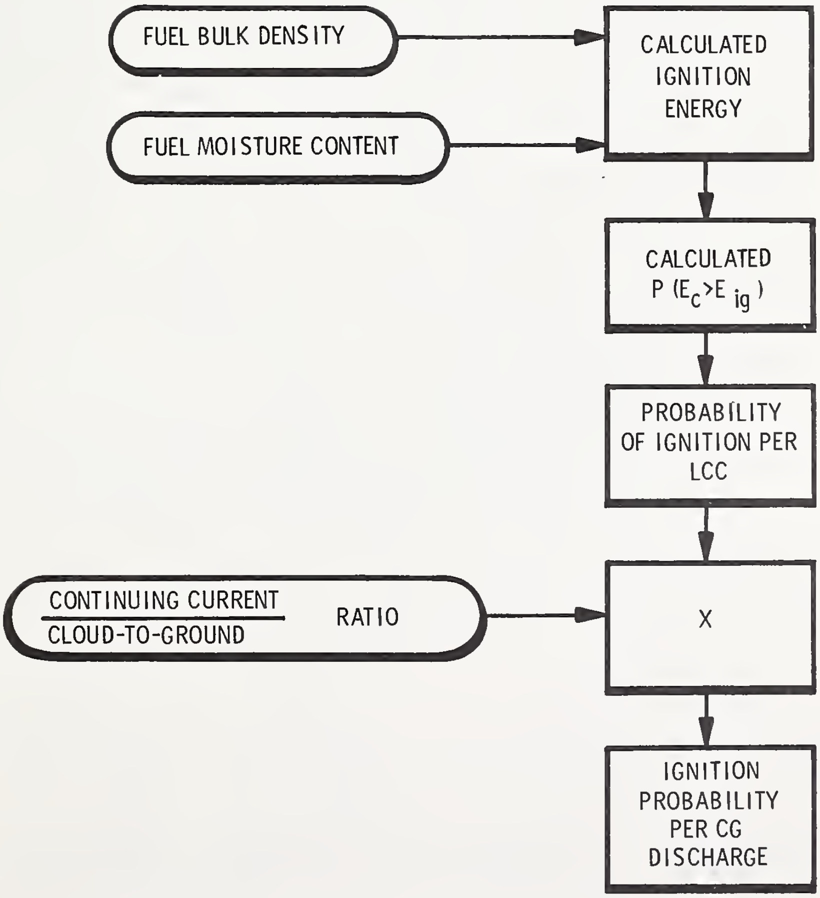


Figure 6.--Ignition efficiency flow chart.

The Model

In the previous sections, we discussed the lightning activity level, behavior of fine fuels with rainfall, and ignition probability per CG discharge. These will now be combined to yield a probable number of ignitions in a given area. Figure 7 is a flow chart expressing this combination.

Each block is numbered; we shall discuss the flow chart in terms of the functions of these blocks (note that there are four input blocks, 1, 2, 3, 4, and one output block, 15):

1. LAL--Lightning Activity Level; forecast or determined by direct observations,
2. Upper Wind--the steering level wind,
3. FMI--the initial one hour timelag fuel moisture,
4. RHOB--the bulk density of litter, duff, grass, or other fine fuels into which the discharge may take place; again, not the average fine fuel bulk density as used for loading calculations, but rather the "spot" bulk density under trees,
5. Storm Size--an empirically determined effective rain track width,
6. Rain Duration--the storm size (5) divided by the upper wind (2) giving the rainfall duration at a spot on the ground,
7. FMF--final fuel moisture,
8. Lightning Activity Duration--the empirically determined time during which lightning and rain occur,
9. Lightning Area--the total area where lightning may strike,
10. $P(I)_i$--probability of ignition in rain,
11. $P(I)_o$--probability of ignition outside of rain,
12. FI--the fraction of the total area covered by rain,
13. FO--the fraction of total area covered by lightning outside the rain track.
14. A combinatorial block--(fraction inside rain) × (probability of ignition inside rain) + (fraction outside rain) × (probability of ignition outside rain) = ignition probability per LCC,
15. Fire ignitions per 2,500 mi^2 (6,500 km^2)--the expected number of CG discharges per 2,500 mi^2 (6,500 km^2) (obtained from the LAL) is multiplied by 0.2 (to get expected number of continuing current discharges); then multiplied by the probability that any given LCC discharge will ignite the fuel; the resulting number is the number of expected ignitions per 2,500 mi^2 (6,500 km^2) (figure 7).

Note: For the high-level thunderstorm (LAL 6), we use the LAL 3 lightning activity of 40 CG, set FI = 0 and FO = 1, and LCC/CG = 1.

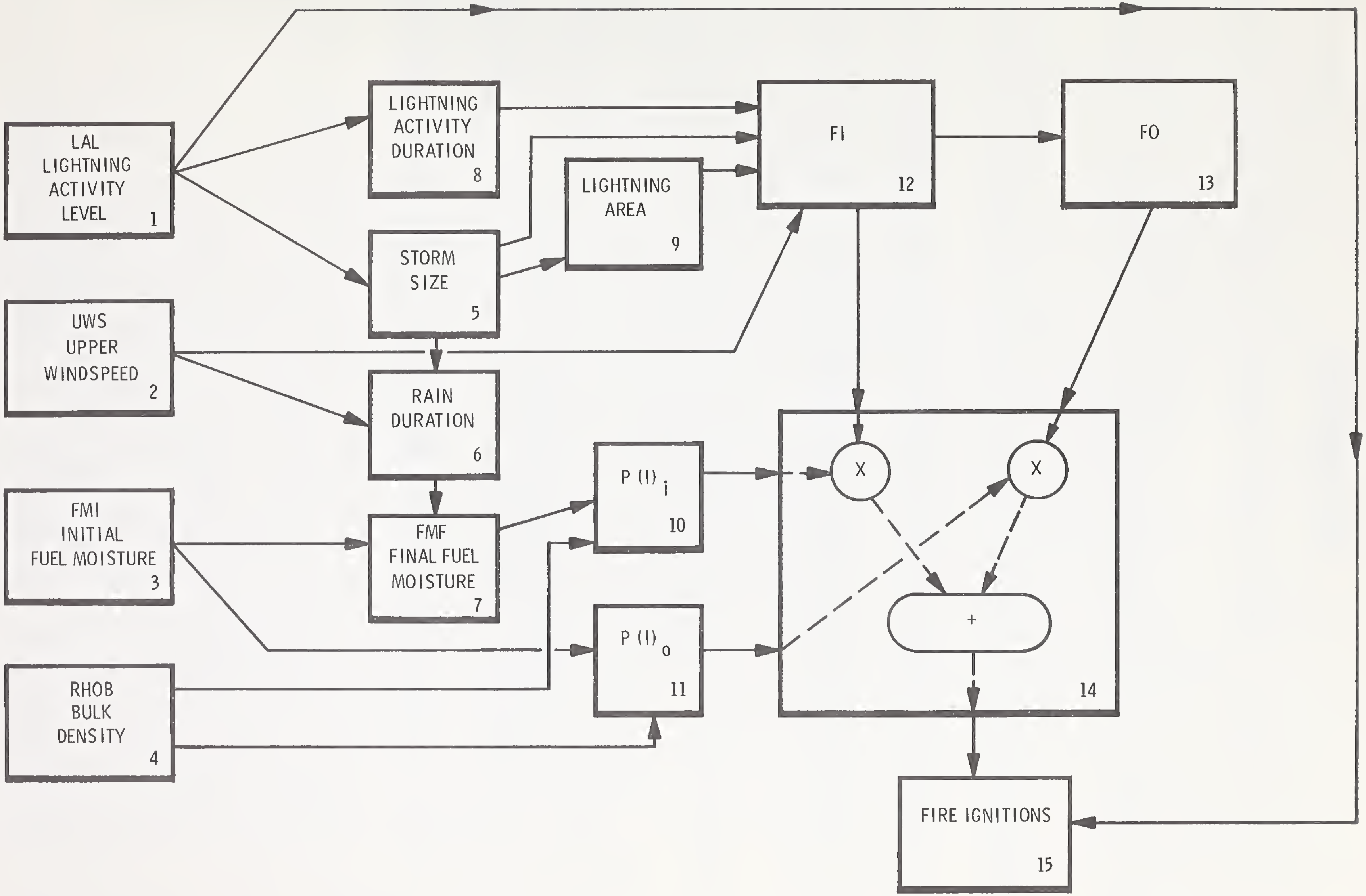


Figure 7.--Flow chart for the ignition model.

REMARKS

We have described a model for predicting lightning-fire ignition based on physical processes of woody fuel ignition; however, the strong influence of chance events is an integral part of the model.

The model is rudimentary. Little information is available on ignition of woody fuel by arc discharge. Further, several characteristics of lightning discharges had to be estimated. Little is known about the spatial distribution of fine fuel characteristics, such as bulk density and moisture content.

Much of the information on thunderstorms and lightning used in developing this model was gathered in the Northern Rocky Mountain region. However, comparison with other areas gives us confidence that the basic model can be adapted for use in the western United States, western Canada, and parts of Alaska.

In describing the model, we have emphasized use of a 24-hour prognosis of weather events. The model also applies in real time when used with current fine fuel and lightning storm data.

The complete program for the model in Fortran IV computer language is available from the authors at the Northern Forest Fire Laboratory.

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GLOSSARY

CG	Cloud-to-ground lightning discharge or flash consisting of one or more strokes
LCC	(long) continuing current - an arc-like discharge sometimes accompanying one stroke in a flash
D	Duration of lightning activity (during a given storm)
FM	Fuel moisture
FMI	Initial fuel moisture
FMF	Fuel moisture after rainfall
FMS	Moisture content at wetted surface of the fuel
RHOB	Fine fuel bulk density (ρ_b)
U	Storm speed (windspeed at 14,000 feet or about 4,300 meters)
S	Width of rainfall track on the ground
L	Width of zone in which lightning strikes
FI	Fraction of total lightning struck zone which also has rainfall
FO	Fraction of total lightning struck zone with no rainfall
E_c	Energy density in LCC channel
E_{ig}	Energy density required for fuel ignition
Q_{ig}	Ignition energy per unit mass of fuel
Q_c	LCC channel power dissipation per unit length
d	Duration of LCC discharge
r	LCC channel radius
F	Electric field in LCC channel
I	Current in LCC arc
P_{ig}	Ignition probability per LCC

Fuquay, Donald M., Robert G. Baughman, and Don J. Latham.
1979. A model for predicting lightning fire ignition in wildlands fuels. USDA For. Serv. Res. Pap. INT-217, 21 p. Intermt. For. and Range Exp. Stn., Ogden, Utah 84401.

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KEYWORDS: lightning-fire model, fire danger, thunderstorm-fire, meteorology.

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