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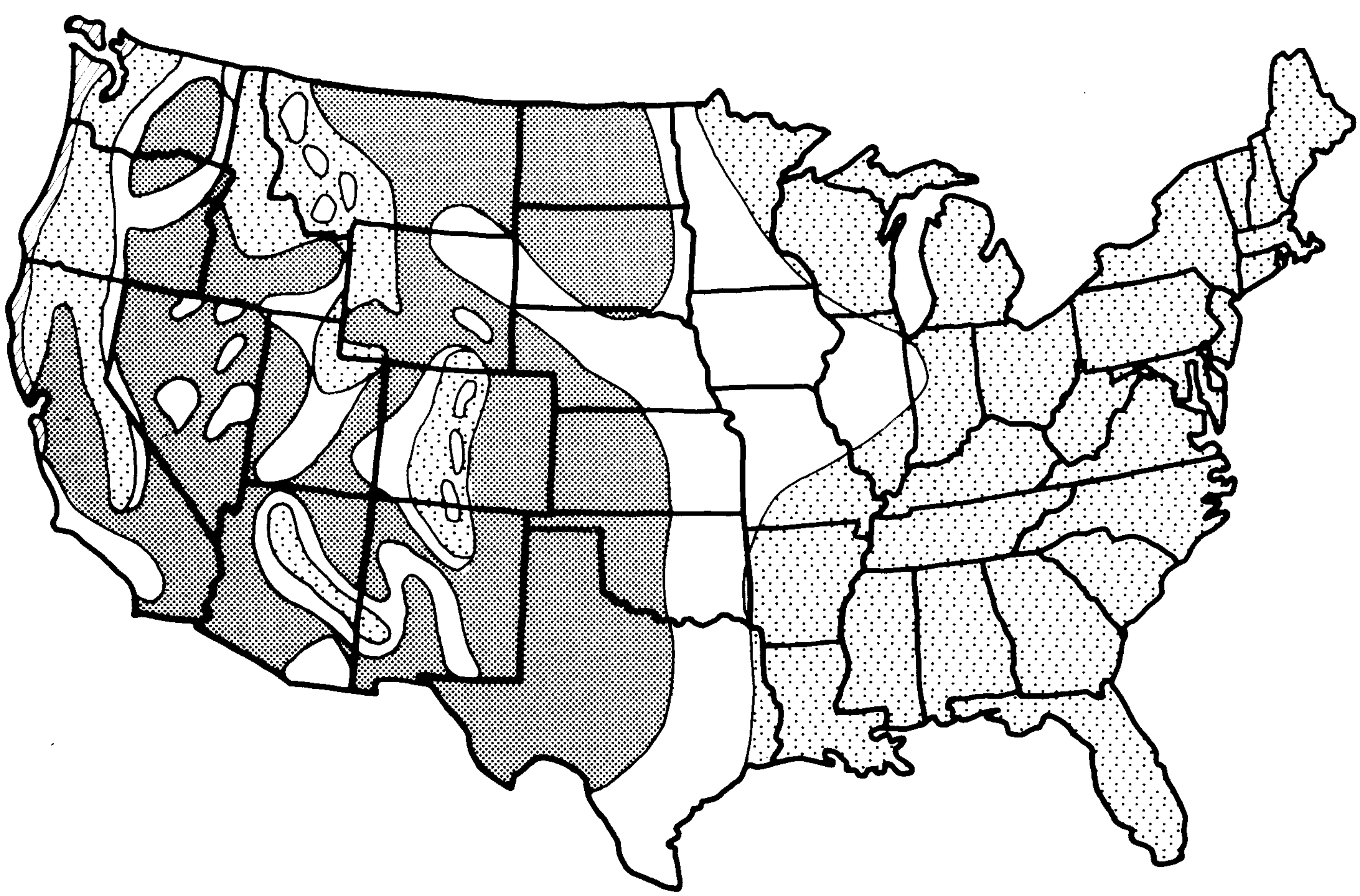
The National Fire-Danger Rating System: basic equations

Jack D. Cohen **John E. Deeming**



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Cover: Four climate classes in the United States are associated with different vegetation moisture contents, which affect fire spread and fire danger rating.

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GLOSSARY

AA: Intermediate variable in stick age correction equation.
AD: Exponent in surface area weighted optimum reaction velocity (GMAOP) equation.
ADE: Exponent in loading weighted optimum reaction velocity (GMAOPE) equation.
AGE: Number of days since fuel moisture sticks were set out.
AMBVP: Ambient vapor pressure.
ANNTA: Parameter in linear herbaceous moisture content equation that is used in transition period for annual vegetation.
ANNTB: Parameter in linear herbaceous moisture content equation that is used in transition period for annual vegetation.
ATAN: Trigonometric inverse tangent function of ().
B: Wind effect exponent in PHIWND equation.
BB: Intermediate variable in stick age correction equation.
BDYBAR: Seven-day running average of BNDRYT values for calculating MC1000.
BETBAR: Packing ratio.
BETOP: Optimum packing ratio, surface area weighted.
BETOPE: Optimum packing ratio, loading weighted.
BI: NFDRS Burning Index.
BNDRY1: Average boundary moisture condition of first 16 hours of 24-hour forecast period. Applies to predicted 10-hour timelag moisture content.
BNDRY2: Average boundary moisture condition of last 8 hours of 24-hour forecast period. Applies to predicted 10-hour timelag moisture content.
BNDRYH: Weighted 24-hour average moisture condition for 100-hour timelag moisture content calculation (MC100).
BNDRYT: Weighted 24-hour average moisture condition for 1000-hour timelag moisture content calculation (MC1000).
C: Intermediate variable in UFACT equation for calculating wind factor (PHIWND).
CC: Intermediate variable in stick age correction equation.
CELS: Temperature in degrees Celsius.
CGRATE: Cloud-to-ground lightning discharge rate.
CHI: Intermediate variable used in ignition probability (P(I)) equation.
CLIMAT: NFDRS climate class.
CORR: Calculated difference between wet bulb saturation vapor pressure (SATVPW) and ambient vapor pressure (AMBVP).
CURED: AFFIRMS user command to model herbaceous condition as cured.
D: Depth of flaming zone (ft).
DAYLIT: Hours between sunrise and sunset.
DELL: Daily solar zenith angle in radians.
DEDRT: Ratio (WTMCD/MXD) in calculation of ETAMD.
DEDRTE: Ratio (WTMCDE/ MXD) in calculation of ETAMDE.
DEPTH: Effective fuel-bed depth measured (ft).
DIFF: Twenty-four hour change in MC1000.
DWPT: Dewpoint temperature.
E: Wind effect exponent in UFACT equation used for calculating wind factor (PHIWND).
ELEV: Elevation of the observing station in feet.
EMC: Equilibrium moisture content.
EMCBAR: Average EMC, weighted by hours of day and night.
EMCBR1: EMC calculated using average temperature and relative humidity from first 16 hours of 24-hour forecast period.
EMCBR2: EMC calculated using average temperature and relative humidity from last 8 hours of 24-hour forecast period.
EMCMAX: EMC calculated from minimum temperature (TMPMIN) and maximum relative humidity (RHMAX).
EMCMIN: EMC calculated from maximum temperature (TMPMAX) and minimum relative humidity (RHMIN).
EMCOBS: EMC calculated from observation time temperature (TMPOBS) and relative humidity (RHOBS).
EMCPRM: EMC calculated using temperature and relative humidity at fuel-atmosphere interface (TMPPRM, RHPRM, respectively).
ERC: NFDRS energy release component.
ETAMD: Surface area weighted dead-fuel moisture damping coefficient.
ETAMDE: Loading weighted dead-fuel moisture damping coefficient.
ETAML: Surface area weighted live-fuel moisture damping coefficent.
ETAMLE: Loading weighted live-fuel moisture damping coefficient.
ETAMD: Dead-fuel mineral damping coefficient.
ETASL: Live-fuel mineral damping coefficient.
EXP: Exponential function of ( ).
FAHR: Temperature in degrees Fahrenheit.
F1: Proportion of dead-fuel surface area in 1-hour class, used as a weighting factor for ROS calculation.
F10: Proportion of dead-fuel surface area in 10-hour class, used as weighting factor for ROS calculation.
F100: Proportion of dead-fuel surface area in 100-hour class, used as weighting factor for ROS calculation.
F1E: Proportion of dead-fuel loading in 1-hour class, used as weighting factor for ERC calculation.
F10E: Proportion of dead-fuel loading in 10-hour class, used as weighting factor for ERC calculation.
F100E: Proportion of dead-fuel loading in 100-hour class, used as weighting factor for ERC calculation.
F1000E: Proportion of dead-fuel loading in 1000-hour class, used as weighting factor for ERC calculation.
FCTCUR: Fraction of fuel model herbaceous fuel loading transferred to 1-hour fuel class.
FDEAD: Proportion of total surface area in dead-fuel classes.
FDEADE: Proportion of total loading in dead-fuel classes.
FHERB: Proportion of live surface area in herbaceous class.
FHERBE: Proportion of live loading in herbaceous class.
FINSID: Fraction of total corridor (TOTWID) occupied by lightning-rain corridor.
FL: Byram's flame length (ft).
FLI: NFDRS fire-load index.
FLIVE: Proportion of total surface area in live-fuel classes.
FLIVEE: Proportion of total loading in live-fuel classes.
FMF: Moisture content of 1-hour fuels inside rain area.
FOTSID: Fraction of total corridor (TOTWID) occupied by lightning-rain corridor.
FREEZE: AFFIRMS user command to model herbaceous condition as cured and woody condition as dormant.
FWOOD: Proportion of live surface area in woody class.
FWOODE: Proportion of live loading in woody class.
GMAMX: Weighted maximum reaction velocity of surface area.
GMAMXE: Weighted maximum reaction velocity of loading.
GMAOP: Weighted optimum reaction velocity of surface area.
GMAOPE: Weighted optimum reaction velocity of loading.
GREEN: AFFIRMS user command to start modeled process of herbaceous greenup.
GREN: Fraction of greenup period that has elapsed in calculation of MCHERB.
GRNDAY: Number of days elapsed since greenup started.
HD: Specified dead-fuel heat of combustion of fuel model.

HERBGA: Parameter in equation for linear herbaceous moisture content in greenup period or when MCHERB is greater than 120 percent.

HERBGB: Parameter in equation for linear herbaceous moisture content used in greenup period or when MCHERB is greater than 120 percent.

HL: Specified live-fuel heat of combustion of fuel model.

HN1: Heating number of 1-hour class.

HN10: Heating number of 10-hour class.

HN100: Heating number of 100-hour class.

HNHERB: Heating number of herbaceous class.

HNWOOD: Heating number of woody class.

HTSINK: Heat sink term in ROS equation.

I: Byram's fireline intensity (Btu/ft/s).

IC: NFDRS ignition component.

ICBAR: Area-weighted average ignition component for storm corridor.

ICR: Ignition component calculated for inside rain corridor.

IR: Surface area weighted reaction intensity, used for calculating ROS (Spread Component -- SC).

IRE: Loading weighted reaction intensity, used for calculating energy release component (ERC).

IRND: Round-off function of ( ).

JDATE: Julian day of year, 1 to 366, derived from month and day.

KELVIN: Temperature in degrees Kelvin.

KTMP: Temperature factor in X1000 calculation.

KWET: Wetting factor in X1000 calculation.

LAL: NFDRS lightning activity level.

LAT: Station latitude in degrees.

LGTDUR: Duration of lightning at a point within affected area.

LIVRT: Ratio (WTMCL/MXL) in calculation of ETAML.

LIVRTE: Ratio (WTMCLE/ MXL) in calculation of ETAMLE.

LOL NFDRS lightning-caused fire occurrence index.

LRISK: NFDRS lightning risk.

LRSF: Lightning-risk scaling factor.

MC: Moisture content, expressed as percent dry weight.

MC1: Calculated 1-hour timelag percent fuel moisture content.

MC10: Percent moisture content of fuel stick (age corrected) or calculated percent moisture content for 10 - hour timelag.

MC100: Percent moisture content for 100 - hour timelag.

MC1000: Percent moisture content for 1000 - hour timelag.

MC10P1: Predicted MC10 as of next morning of forecast period.

MC10P2: Predicted MC10 for observation time of next day.

MCHERB: Calculated herbaceous percent moisture content.

MCHRBI: Maximum of 30 percent of MCHERB calculated day before greenup.

MCH RBP: Potential herbaceous moisture content during greenup period.

MCLFE: Dead-fuel moisture content, weighted by heating number, for calculation of live moisture of extinction (MXL).

MCOI: NFDRS human-caused index of fire occurrence.

MCWODI: Greater of PREGRN or MCWOOD calculated day before greenup.

MCWODP: Potential moisture content of woody fuel during modeled greenup period.

MCWOOD: Calculated moisture content of twigs and foliage of woody shrubs.

MRISK: NFDRS human-caused risk.

MXD: Specified dead-fuel moisture of extinction for fuel model.

MXL: Calculated live-fuel moisture of extinction.

P(I): Probability that a firebrand will produce a successful fire start in dead, fine fuels.

P(F/ I): Probability that ignition will result in a reportable fire.

PDUR1: Predicted rain duration for first 16 hours of 24-hour forecast period.

PDUR2: Predicted rain duration for last 8 hours of 24-hour forecast period.

PERTA: Parameter in equation for linear herbaceous moisture content used in transition period for perennial vegetation.

PERTB: Parameter in equation for linear herbaceous moisture content used in the transition period for perennial vegetation.

PHI: Station latitude in radians.

PHISLP: Multiplier for slope effect in ROS equation.

PHIWND: Multiplier for wind effect in ROS equation.

PM1000: MC1000 calculated for previous 7th day.

PNORM1: PNORM2 PNORM3 Scaling factors in P(I) calculation that cause P(I) to equal 100 when MC1 is 1.5 percent and zero when MC1 is 25 percent.

PPTAMT: Amount of precipitation.

PPTDUR: Duration of precipitation.

PREGRN: Modeled moisture content of woody shrubs when dormant.

QIGN: Calculated heat of ignition used for calculating P(I).

RAIDUR: Duration of rain at a point within lightning-rain corridor.

RH: Relative humidity.

RHMAX: Maximum relative humidity for 24-hours.

RHMIN: Minimum relative humidity for 24-hours.

RHOBAR: Particle density of weighted fuel.

RHOBED: Bulk density of fuel bed.

RHOBS: Relative humidity of afternoon observation time.

RHOD: Particle density of dead-fuel.

RHOL: Particle density of live-fuel.

RHPRM: Relative humidity estimated for fuel-atmosphere interface.

ROS: Forward rate of spread of flaming front (ft/min).

SA1: Surface area of 1-hour class fuels.

SA10: Surface area of 10-hour class fuels.

SA100: Surface area of 100-hour class fuels.

SADEAD: Surface area of dead-fuel classes.

SAHERB: Surface area of herbaceous fuel class.

SALIVE: Surface area of live-fuel classes.

SATVPD: Saturation vapor pressure for dry bulb temperature (TMPOBS).

SATVPN: Saturation vapor pressure for minimum temperature (TMPMIN).

SATVPW: Saturation vapor pressure for wet bulb temperature (TMPWET).

SATVPX: Saturation vapor pressure for maximum temperature (TMPMAX).

SAWOOD: Surface area of woody fuel class.

SC: NFDRS spread component.

SCM: Specified spread component (SC) of fuel model when all fire starts become reportable fires.

SCN: Percent actual SC is to specified SCM (SC/SCM*100).

SD: Silica-free mineral content of dead fuels.

SG1: Specified surface area-to-volume ratio for 1-hour class of fuel model.

SG10: Specified surface area-to-volume ratio for 10-hour class of fuel model.

SG100: Specified surface area-to-volume ratio for 100-hour class of fuel model.

SGBRD: Characteristic surface area-to-volume ratio of dead fuel, surface area weighted.

SGBRDE: Characteristic surface area-to-volume ratio of dead fuel, loading weighted.

SGBRL: Characteristic surface area-to-volume ratio of live fuel, surface area weighted.

SGBRLE: Characteristic surface area-to-volume ratio of live fuel, loading weighted.
SGBRT: Characteristic surface area-to-volume ratio of fuel bed, surface area weighted.
SGBRTE: Characteristic surface area-to-volume ratio of fuel bed, loading weighted.
SGHERB: Specified surface area-to-volume ratio for herbaceous class of fuel model.
SGWOOD: Specified surface area-to-volume ratio for woody class of fuel model.
SIN: Trigonometric sine function of ( ).
SL: Proportion of silica-free mineral content of live fuels.
SLPFCT: Coefficient in PHISLP equation.
SQRT: Square-root function of ( ).
STD: Proportion of inert mineral content of dead fuels.
STL: Proportion of inert mineral content of live fuels.
STMDIA: Width of corridor affected by rain-lightning.
STMSPD: Translational speed of storm in miles per hour.
TAN: Trigonometric tangent function of ( ).
TAU: Calculated residence time of flaming front (min).
TEMP: Dry-bulb temperature.
TLA: Intermediate value in daylength calculation.
TLA1: Intermediate value in daylength calculation.
TMPMAX: Twenty-four hour maximum dry-bulb temperature.
TMPMIN: Twenty-four hour minimum dry-bulb temperature.
TMPOBS: Dry-bulb temperature of afternoon observation time.
TMPPRM: Temperature estimated for fuel-atmosphere interface.
TMPWET: Wet-bulb temperature.
TOTWID: Total width of lightning-only and lightning-rain corridor.
UFACT: Wind-effect multiplier in PHIWND equation.
W1: Fuel model specified 1-hour class fuel loading.
W10: Fuel model specified 10-hour class fuel loading.
W100: Fuel model specified 100-hour class fuel loading.
W1000: Fuel model specified 1000-hour class fuel loading.
W1N: Net fuel loading of 1-hour class.
W10N: Net fuel loading of 10-hour class.
W100N: Net fuel loading of 100-hour class.
W1P: One-hour fuel loading and transferred herbaceous loading (WHERBC).
WDEADN: Net loading of dead fuels, surface-area weighted.
WDEDNE: Net dead fuel loading.
WETRAT: Rainfall rate set by climate class (CLIMAT).
WHERB: Herbaceous fuel loading of fuel model.
WHERBC: Amount of herbaceous loading transferred to 1-hour class.
WHERBN: Net fuel loading of herbaceous class.
WHERBP: Amount of herbaceous loading left after transfer to 1-hour fuel loading.
WLIVEN: Surface area weighted net loading of live fuels.
WLIVNE: Net live-fuel loading.
WNDFC: Fuel model specified wind reduction factor. WNDFC is calculated under certain conditions.
WOODGA: Parameter in linear woody moisture content equation used for calculating MCWODP and MCWOOD.
WOODGB: Parameter in linear woody moisture content equation used for calculating MCWODP and MCWOOD.
WRAT: Ratio of dead-to-live heating numbers for calculation of live moisture of extinction (MXL).
WS: Ten-minute average 20 ft windspeed for 10 minutes in miles per hour.
WT: Weight of fuel sticks in grams.
WTMCD: Surface area weighted dead-fuel moisture content.
WTMCDE: Loading weighted dead-fuel moisture content.
WTMCL: Surface area weighted live-fuel moisture content.
WTMCLE: Loading weighted live-fuel moisture content.
WTOT: Total fuel loading.
WTOTD: Total dead-fuel loading.
WTOTL: Total live-fuel loading.
WWOOD: Specified woody shrub loading fuel model.
WWOODN: Net fuel loading of woody class.
X1000: Independent variable in herbaceous fuel moisture models.
YLOI: Previous day's LOI.
YM1000: MC1000 calculated previous day.
YMC10: Initial or current value of 10-hour timelag moisture content for calculating MC10P1.
YMC100: MC100 value calculated previous day.
YX1000: XI000 calculated previous day.
ZETA: No-wind propagating flux ratio in rate-of-spread (ROS) calculation.

The National Fire-Danger Rating System (NFDRS) provides indexes for measuring fire potential in wildlands. It is used by all Federal and many State natural resource management agencies. Data from fire-danger rating stations throughout the United States are processed through the interactive, time-share computer program AFFIRMS (Helfman and others 1980) or are computed manually each day. Fire weather stations record data on the 10-day fire weather record (NWS Form D-9b).

The concept of fire-danger rating and various methods of rating fire-danger have been around for decades. The analytical approach that is the basis for the current NFDRS began in 1968 with the establishment of a National Fire-Danger Rating research work unit. After 4 years of development and field trials, the 1972 NFDRS (Deeming and others 1972) became operational. A review and update was planned at that time.

In 1974, the Chief of the Forest Service, U.S. Department of Agriculture, chartered a technical committee to direct the updating of the NFDRS. A research work unit was chartered and actual work started in 1975. The update work was completed in November 1977, with implementation in May 1978. The results were reported in two publications: one describes the basic system and revisions (Deeming and others 1977); the other explains how to calculate manually fire-danger ratings using the NFDRS (Burgan and others 1977). A third publication summarizes the technical development of the NFDRS (Bradshaw and others 1983).

This report documents the mathematical equations required to calculate fire-danger indexes in the National Fire-Danger Rating System. The equations are in the coded format of FORTAN and BASIC computer languages. They are described in the order processed in the computer program AFFIRMS (Helfman and others 1980) and FIREFAMILY (Main and others 1982), except for equations used to calculate equilibrium moisture content.

CALCULATING MOISTURE CONTENT

The equilibrium moisture content (EMC) is fundamental to all fuel moisture computations in the NFDRS. The EMC, itself a computed value, represents a steady state moisture content of dead woody material. This steady state is achieved under constant conditions for a sufficiently long adjustment period. Steady-state conditions do not occur under normal circumstances and, therefore, do not represent the woody moisture contents. The EMC offers the basis for calculating the various moisture contents considered by the NFDRS.

Equilibrium Moisture Content

Equilibrium moisture contents can be derived from dry bulb temperature and relative humidity by calculating the equilibrium moisture content (EMC).

The following equations for EMC are the regression equations developed by Simard (1968) on the basis of tables in the *Wood Handbook* (U.S. Forest Products Laboratory 1955, revised 1974). Temperatures are expressed in degrees Fahrenheit, and the EMC is expressed as percent moisture content. All variables are explained in the glossary.

Relative Humidity Less Than 10 Percent:

EMC = 0.03229 + 0.281073
        * RH - 0.000578 * TEMP * RH   (1a)

in which
  RH is a relative humidity.
  TEMP is a dry bulb temperature.

Relative Humidity Equal to or Greater Than 10 Percent but Less Than 50 Percent:

EMC = 2.22749 + 0.160107
        * RH - 0.014784 * TEMP   (1b)

Relative Humidity Equal to or Greater Than 50 Percent:

EMC = 21.0606 + 0.005565 * RH ** 2
  - 0.00035 * RH * TEMP - 0.483199 * RH   (1c)

With these equations, the EMC's can be evaluated for (1) observation time, (2) the time of maximum temperature-minimum relative humidity, and (3) the time of minimum temperature-maximum relative humidity:

EMCOBS = f(TMPOBS, RHOBS)
EMCMIN = f(TMPMAX, RHMIN)
EMCMAX = f(TMPMIN, RHMAX)

in which

TMPOBS is the dry bulb temperature at the afternoon observation time.
TMPMIN is the 24-hour minimum dry bulb temperature.
TMPMAX is the 24-hour maximum dry bulb temperature.
RHOBS is the relative humidity at the afternoon observation time.
RHMIN is the 24-hour minimum relative humidity.
RHMAX is the 24-hour maximum relative humidity.

Environmental Parameters

Data Available

Calculating fuel moisture contents requires a set of environmental moisture and temperature variables that must be measured or derived. The variables are these:

- Dry bulb temperature and relative humidity at the afternoon observation time;
- Maximum and minimum dry bulb temperatures and relative humidities for the 24-hour period ending at the afternoon observation time; and
- Duration of precipitation during this same 24-hour period.

Operationally, the first and third items are required; measurements to obtain the second item are optional. Historical fire-weather records before 1972 typically do not include the second and third items, although they were often collected for 1972 or a later date. These parameters are calculated, derived, or assigned values.

The dry bulb temperature (TMPOBS) is observed directly and reported in degrees Fahrenheit or degrees Celsius. The relative humidity (RHOBS) may be reported directly, or derived from the dry and wet bulb temperature (TMPOBS and TMPWET) or from the dry bulb temperature and dewpoint (TMPOBS and DWPT). The psychometric equations used for these operations are from the Smithsonian Meteorological Tables (1949). For these calculations, the temperatures are converted to degrees Kelvin by these equations:

KELVIN = CELS + 273.16
KELVIN = (FAHR + 459.69) * 5/9

in which
KELVIN is the temperature in degrees Kelvin.
FAHR is the temperature in degrees Fahrenheit.
CELS is the temperature in degrees Celsius

The Moisture Variable Is Dewpoint Temperature:

RHOBS = 100.0
* EXP(-7482.6 / (DWPT + 398.36) + 15.674) /
EXP(-7482.6 / (TMPOBS + 398.36) + 15.674)

The Moisture Variable Is Wet Bulb Temperature: In this situation, the calculation is a bit more complicated. First, calculate the saturation vapor pressures for the wet and dry bulb temperatures (SATVPW and SATVPD).

(dry bulb) SATVPD = EXP(1.81 +
(TMPOBS * 17.27 - 4717.31) / (TMPOBS - 35.86))
(wet bulb) SATVPW = EXP(1.81 + (TMPWET
* 17.27 - 4717.31) / (TMPWET - 35.86))

Now calculate an intermediate variable (CORR) to correct for station elevation.

CORR = 6.6 * 10**-4.* (1.0 + (0.00115
* (TMPWET - 273.16)) * TMPOBS - TMPWET)
* (1013.09 / EXP(ELEV / 25,000.0))

in which ELEV is the elevation of the observing station in feet. For stations in Alaska, add 200 ft to the actual station elevation to adjust for generally lower surface atmospheric pressures.

Now, the ambient vapor pressure in millibars (AMBVP):

AMBVP = SATVPW – CORR

Relative humidity in percent:

RHOBS = 100.0 * (AMBVP / SATVPD) (2)

Data Unavailable

Relative Humidity—The most common situation observed is a report that includes TMPOBS, a humidity variable (DWPT, RHOBS or TMPWET), and maximum and minimum temperatures (TMPMAX and TMPMIN). Unfortunately, the 24-hour extreme relative humidity data were not collected and, therefore, are not available from pre-1972 reports, and are often not available from post-1972 reports.

When the 24-hour extreme temperatures are reported but the relative humidities are not, it is assumed that the specific humidity at observation time was conserved for the preceding 24-hour period.

Ambient Vapor Pressure:
Rearranging equation (2):

AMBVP = (RHOBS * SATVPD) / 100.0 (3)

Saturation Vapor Pressure for the 24-Hour Maximum and Minimum Temperatures:

(max temp) SATVPX = EXP(1.81 + (TMPMAX
* 17.27-4717.31)
/ (TMPMAX - 35.86))

(min temp) SATVPN = EXP(1.81 + (TMPMIN
* 17.27 - 4717.31)
/ (TMPMIN - 35.86))

24-Hour Maximum and Minimum Relative Humidities:

RHMAX = 100.0 * (AMBVP / SATVPN)
RHMIN = 100.0 * (AMBVP / SATVPX)

Relative Humidity and Temperature--When neither temperature nor relative humidity 24-hour extremes are reported, we estimate EMCMAX and EMCMIN directly. (These data are needed only to obtain values of EMCMAX and EMCMIN, the 24-hour extremes of EMC.) First, we assume that:

EMCMIN = EMCOBS

EMCMAX is assigned a value according to the following scheme:

NFDRS climate class:	Defaulted EMCMAX
1or 2	15 percent
3 or 4	23 percent

These values were judged to be typical of nighttime recovery values for moderately severe fire-danger situations.

Precipitation--In pre-1972 fire-weather reports, precipitation duration (PPTDUR) was not reported, but precipitation amount (PPTAMT) was. So by assuming a rainfall rate (WETRAT), a pseudo-duration can be calculated as follows:

PPTDUR = IRND((PPTAMT / WETRAT) + 0.49)

in which
IRND indicates that the quantity in parentheses is a rounded integer.
PPTDUR cannot be greater than 8 hours.
WETRAT is a function of climate class as follows:

NFDRS climate class:	WETRAT *Inches/hour*
1 or 2	0.25
3 or 4	0.05

One-quarter inch per hour was judged typical of dry areas (NFDRS climate classes 1 and 2) where the precipitation during the fire season comes usually in the form of moderately intense rain showers. In wetter areas, climate classes 3 and 4, the precipitation is typically much lighter and more or less continuous. PPTDUR, if estimated by this method, is not allowed to exceed 8 hours.

Models of Dead-Fuel Moisture

Fire-danger rating considers two major groups of fuels; live and dead. The live fuels are further classified into annual herbaceous, perennial herbaceous, and lesser woody plants (shrubs and young trees). The 1-, 10-, 100-, and 1000-hour timelag classes represent the dead fuels.

The movement of water vapor between dead-fuel elements and the atmosphere is controlled by the vapor pressure gradient that exists between the two mediums. This gradient is proportional to the difference between the moisture content of the fuel element and the EMC corresponding to the temperature and relative humidity of the air in immediate contact with the fuel element. The dead-fuel moisture calculations are those developed and documented in Fosberg and Deeming (1971); Fosberg (1971); and Fosberg and others (1981).

Fuels: 1-Hour Timelag

The response of 1-hour timelag fuels to changes in the environmental conditions is so rapid that only the potential moisture content, which is equivalent to the EMC at the fuel-atmosphere interface, is required. The first task is to estimate the relative humidity and dry bulb temperature of the air in immediate contact with the fuel elements (TMPPRM and RHPRM). The approach, based on work by Byram and Jemison (1943), consists of correcting the dry bulb temperature and relative humidity values existing at instrument height (4.5 ft) according to the intensity of the insolation (amount of sunshine). Time of year or variables affecting insolation other than cloudiness are not considered. The amount of cloudiness is indicated by the state-of-weather code. The temperature correction is *added* (° F); the relative humidity correction is a *multiplier*.

State-of-weather code:	Corrections: Temperature *° F*	Relative humidity
0	+ 25	* 0.75
1	+ 19	* 0.83
2	+ 12	* 0.92
3	+ 5	* 1.00

Boundary Layer EMC:
From equations (1a), (1b), or (1c)

EMCPRM = f(TMPPRM, RHPRM)

When Fuel Moisture Sticks Are Not Used:

MC1 = 1.03 * EMCPRM

When Fuel Moisture Sticks Are Used:

MC1 = (4.0 * EMCPRM + MC10) / 5.0

in which MC10 is the 10-hour timelag fuel moisture.

This method was developed for the California wildland fire-danger rating system (U.S. Dep. Agric., Forest Serv. 1958, revised 1968).

If It Is Raining at the Afternoon Observation Time:

MC1 = 35.0

Fuels: 10-Hour Timelag

If an Observation Is Being Processed and Fuel Sticks Are Being Used:

MC10 = Fuel Stick Moisture Content (age corrected)

Because fuel sticks lose weight as they weather, a correction to the measured, apparent moisture content is required. The correction for weathering used in the NFDRS is based on work done by Haines and Frost (1978) as modified by Deeming. A linear model that uses the number of days the sticks have been exposed to the elements and the climate class of the station where the sticks are located are the independent variables.

MC10=AA*CC+BB*CC* (WT - 100.0)

in which

WT is the weight of the fuel sticks in grams.
AA = 0.5 * AGE / 30.0
BB = 1.0 + (0.02 * AGE / 30.0)
CC = CLIMAT / 4.0
AGE is the number of days since the sticks were set out.
CLIMAT is the NFDRS climate class.

If an Observation Is Being Processed and Fuel Sticks Are Not Being Used:

MC10 = 1.28 * EMCPRM

in which EMCPRM is the same value used in the calculation of MC 1.

If a Forecast Is Being Processed and Stick Moisture Content Is Predicted Directly: AFFIRMS allows the fire-weather forecaster to predict stick moisture content directly. A method of making such a prediction was not developed as an integral part of the NFDRS. If this practice is to be used, existing methods such as that by Cramer (1961) are suggested.

If a Forecast Is Being Processed and MC10 Is To Be Calculated: In this situation the model is considerably more complex requiring two computational steps on the basis of work by Fosberg (1977). A fire-weather forecast includes predictions of the minimum temperature and maximum relative humidity for the next 24 hours, the state of weather, temperature, and relative humidity at observation time the next day, and precipitation durations for (a) the first 16 hours of the 24-hour period, and (b) the last 8 hours of the 24-hour period.

The model first predicts the MC10 as of 0600 the next morning (MC10P1), with the current day's MC10 as the initial value (YMC 10). With MC l OP I as the initial value, it predicts the potential MC10 at observation time the next afternoon (MC10P2).

Average Boundary Values for Periods 1 and 2 are these:

BNDRY1 = ((16.0 - PDURI) * EMCBR1
+ (2.7 * PDUR1 + 76.0) * PDUR1) / 16.0
BNDRY2 = ((8.0 - PDUR2) * EMCBR2
+ (2.7 * PDUR2 + 76.0) * PDUR2) / 8.0

in which

PDUR1 and PDUR2 are the predicted durations of precipitation, in hours, for periods 1 and 2.
EMCBR1 and EMCBR2 are the EMC values calculated with the average temperatures and average relative humidities predicted for periods 1 and 2. (The temperatures and relative humidities at observation time the current day and predicted for observation time the next day are corrected for insolation before being averaged with the predicted maximum relative humidity and minimum temperature.)

Moisture Content of the 10-Hour Fuels as of the End of Period 1:

MC10P1 = YMC10 - (BNDRY1 - YMC10)
* (1.0 - 1.1 * EXP(-1.6))

in which YMC10 is the initial value of the 10-hour fuel moisture as of observation time.

Moisture Content of the 10-Hour Fuels as of the End of Period 2:

MC10P2 = MC10P1 - (BNDRY2 - MC10P1)
* (1.0 - 0.87 * EXP(-0.8))
MC10 = MC10P2

Fuels: 100-Hour Timelag

Because of the slow response of the 100-hour and the 1000-hour classes of fuels to changes in environmental conditions, we use an EMC that represents the average drying-wetting potential of the atmosphere for the preceding 24-hour period. The 24-hour average EMC is denoted as EMCBAR, a weighted average of EMCMAX and EMCMIN. Weighting is done on the basis of hours of daylight and hours of darkness that are functions of latitude and date.

Duration of Daylight:

PHI = LAT * 0.01745

in which

LAT is the station latitude in degrees.
DECL = 0.41008 * SIN((JDATE-82) * 0.01745)

in which

JDATE is the Julian date.

DECL is the solar declination in radians.

$$DAYLIT = 24 * (1. - ACOS(TAN(PHI) * TAN(DECL))/3.1416)$$

in which DAYLIT is the number of hours between sunrise and sunset.

Weighted 24-Hour Average EMC:

$$EMCBAR = (DAYLIT * EMCMIN + (24.0 - DAYLIT) * EMCMAX) / 24.0$$

Weighted 24-Hour Average Boundary Condition:

$$BNDRYH = ((24.0 - PPTDUR) * EMCBAR + PPTDUR * (0.5 * PPTDUR + 41.0)) / 24.0$$

in which PPTDUR is the hours of precipitation reported (predicted) for the 24-hours.

100-Hour Timelag Fuel Moisture: The model used in the manual version of the 1978 NFDRS to calculate the 100-hour timelag fuel moisture differs from this model in two ways: (1) daylength is not considered, and (2) the 24-hour average EMC is a function of the simple averages of the 24-hour temperature and relative humidity extremes.

$$MC100 = YMC100 + (BNDRYH - YMC100) * (1.0 - 0.87 * EXP(-0.24))$$

in which YMC100 is the MC100 value calculated the previous day.

Initializing YMC100 at the Beginning of a Computational Period:

$$YMC100 = 5.0 + (5.0 * CLIMAT)$$

Fuels: 1000-Hour Timelag

Weighted 24 Hour Average Boundary Condition:

$$BNDRYT = ((24.0 - PPTDUR) * EMCBAR + PPTDUR * (2.7 * PPTDUR + 76.0)) / 24.0$$

Seven Day Running Average Boundary Condition:

$$BDYBAR = (BNDRYT(1) + \ldots\ldots\ldots\ldots + BNDRYT(7)) / 7.0$$

in which ( ) denotes a day in the 7-day series. It is necessary, therefore, to maintain a 1 x 7 array of BNDRYT values.

1000-Hour Timelag Fuel Moisture: The model used in the manual version of the 1978 NFDRS to calculate the 1000-hour timelag fuel moisture differs from this model in the following ways: (1) daylength is not considered, (2) the 24-hour average EMC is a function of the simple averages of the 24-hour temperature and relative humidity extremes, and (3) BNDRYT is calculated daily, but BDYBAR and MC1000 are calculated only every seventh day.

$$MC1000 = PM1000 + (BDYBAR - PM1000) * (1.00 - 0.82 * EXP(-0.168))$$

in which PM 1000 is the MC 1000 calculated for the seventh previous day.

It is necessary, therefore, to maintain a 1 x 7 listing of MC1000 values:

BNDRYT and MC1000 array

	1		2		3		4		5		6		7	
X_a		X_b		X_c		X_d		X_e		X_f		X_g		X_h
(next day)														
X_b		X_c		X_d		X_e		X_f		X_g		X_h		X_i

When a new value is added to the BNDRYT or MC 1000 (X_h) arrays, the existing values are moved one position down the array. The value for the oldest day of the 7-day series (X_a) is replaced by the value for the next most recent day (X_b) and so on through the entire array. The latest BNDRYT and MC1000 values (X_i) are placed in the seventh position of the arrays.

Initializing the MC1000 and BNDRYT Arrays at the Beginning of a Computational Period:

$$MC1000\ (n) = 10.0 + (5.0 * CLIMAT)$$
$$BNDRYT\ (n) = 10.0 + (5.0 * CLIMAT)$$

in which (n) denotes cells 1 through 7 in the two arrays.

Fuels: Wet or Ice-Covered

Rather than complicate the component models of the NFDRS with intricate logic, these conditions were judged better dealt with by rules. The wildfire potential is zero when the ground fuels are wet or covered with ice or snow. The expected data must be provided to the computer (AFFIRMS), however, and the 100- and 1000-hour fuel moisture calculations must continue without interruption.

The logic of the rules is not difficult to accept:

- No wildfire potential exists when ice, snow, or both are present.
- Free water affects fuels in essentially the same way, whether it comes in the various forms of precipitation or from the thawing of ice or snow.
- When precipitation is frozen or fuels are covered with ice, snow, or both, and there is no thaw, fuel moistures respond as if the relative humidity were 100 percent (McCammon 1974).

Raining, Snowing, and Thawing, or Fuels Wet (Observation and Forecast):

1. Set SC, ERC, BI, IC, MCOI, LOI, and FLI to Zero (0).
2. Record MC1 as 35 percent.
3. Record MC10 as 35 percent for the predicted value and for the observed value if sticks are not used: if sticks are

used, shake off the water and weigh as usual for the observed value.

4. Calculate the 100- and 1000-hour fuel moistures as usual.

Snowing or Fuels Covered by Ice, Snow, or Both, No Thaw (Observation and Forecast):

1. Set SC, ERC, BI, IC, MCOI, LOI, and FLI to zero (0).
2. Record MC1 as 35 percent.
3. Record MC10 as 35 percent for the predicted value and for the observed value if sticks are not used; if sticks are used, shake off the snow and weigh as usual for the observed value.
4. Calculate the 100- and 1000-hour fuel moistures as usual except use zero (0) for PPTDUR and 100 percent for both RHMAX and RHMIN.

Fuels Covered by Ice, Snow, and Thawing:

1. Set SC, ERC, BI, IC, MCOI, LOI, and FLI to zero (0).
2. Record MC1 as 35 percent.
3. Record MC10 as 35 percent for the predicted value and for the observed value if sticks are not used: if sticks are used, shake off the snow and weigh as usual for the observed value.
4. Calculate the 100- and 1000-hour fuel moistures as usual except use the duration of the thaw during that 24-hour period for PPTDUR and 100 percent for both RHMAX and RHMIN.

Models of Live-Fuel Moisture

For a more complete description of the live-fuel moisture models, refer to the publication by Burgan (1979).

Essentially, two live-fuel moisture models are contained in the NFDRS:

1. Herbaceous fuel moisture model with variations for annual and perennial types;
2. Woody shrub fuel moisture model.

Herbaceous Fuels

The loading of the herbaceous fuels is a fuel model parameter just as the 1-hour timelag fuel loading is a fuel model parameter. The user specifies the herbaceous type as annual or perennial and the NFDRS climate class of the observation site. Those parameters control the rate at which the model passes through these five stages:

1. pregreen (MCHERB 30 percent or less)
2. greenup
3. green (MCHERB greater than 120 percent)
4. transition (MCHERB 30 to 120 percent)
5. cured or frozen (MCHERB 30 percent or less)

in which MCHERB is the moisture content of the herbaceous plants.

In late summer or fall herbaceous plants die or are killed back by frost. They remain, in either state, waiting for the warmth and moisture of spring before starting another growth cycle. When the herbaceous plants are in the *pregreen* stage, the model assumes their moisture content responds to the environment the same as the moisture content of the 1-hour fuels. The model accounts for this by transferring the entire loading of herbaceous plants to the 1-hour fuel class.

When greenup is declared by the user in spring, the herbaceous moisture content is initially at 30 percent. The loading of the herbaceous fuel is then reclaimed from the 1-hour dead-fuel class as the herbaceous moisture content increases to 120 percent. The length of the greenup period depends on the NFDRS climate class of the observation site being 1 week for class 1, 2 weeks for class 2, 3 weeks for class 3, and 4 weeks for class 4.

If greenup is complete, the MCHERB is 120 percent, the model has reached the *green* stage. The moisture content of perennials is allowed to increase or decrease as the available moisture increases or decreases. The moisture content of annuals can only remain the same or decrease once the greenup process is complete. The maximum value of MCHERB is 250 percent.

When MCHERB falls below 120 percent, the herbaceous vegetation enters *transition;* that is, the curing process begins. As MCHERB decreases below 120 percent, the herbaceous loading is transferred to the 1-hour fuel class--the reverse of what occurred during greenup. When MCHERB falls to 30 percent, the loading of herbaceous fuel is zero. During transition, perennial plants are allowed to pick up moisture, but annual plants are not.

If MCHERB decreases to 30 percent, the plants are considered *cured.* Perennial plants are allowed to recover and "re-green" on their own if moisture conditions improve. Once cured, however, annuals stay cured until the user declares "GREEN."

The user can force the model to cure the herbaceous plants by specifying either "CURED" or "FROZEN." The herbaceous moisture prediction model responds identically to these two declarations. ("FROZEN" forces shrubs into dormancy, however). In this situation, both annuals and perennials remain cured until the next greenup is declared.

Equations for the model through the pregreen, greenup, green, transition, and cured-frozen stages are these:

Pregreen Stage--This stage is best described as that existing in late winter before new growth appears. The herbaceous plants are "straw-brown," having been killed by low moisture or freezing temperatures the previous year. The pregreen stage is set up in AFFIRMS only if a "FROZEN" command has been entered or if there has been a break in the data of at least 60 days. In milder climates, such as the Southeast, Gulf Coast, or Southwest, a killing freeze may not occur. So in those areas, if AFFIRMS is run year-long, the pregreen state should be forced during the winter with a "FROZEN" command.

The following model settings are made for the pregreen stage:

MCHERB = MC1
W1P = W1 + WHERB

in which
W1 is the fuel model 1-hour fuel loading.
WHERB is the fuel model herbaceous fuel loading.
W1P is the pregreen 1-hour fuel loading.

Greenup Stage--When the greenup process is begun the model settings are these:

MCHERB = MCHRBI
W1P=W1+ WHERB
X1000=MC1000
GRNDAY = 0

in which
MCHRBI is the maximum of 30 percent or MCHERB calculated the day before to the greenup.
W1P is the pregreen 1-hour fuel loading.
X1000 is the independent variable in the herbaceous fuel moisture models
GRNDAY is the number of days elapsed since greenup started.

MCHERB is a function of X1000, the herbaceous plant type, and the NFDRS climate class. With the start of greenup, X1000 is set equal to MC1000. From that point on, the X1000 is calculated as follows:

DIFF = MC1000 - YM1000
X1000 = YX1000 + (DIFF * KWET * KTMP)

in which
YM1000 is the MC1000 calculated the previous day.
YX1000 is the X1000 calculated the previous day.
DIFF is the 24-hour change in MC1000.
KWET is the wetting factor.
KTMP is the temperature factor.

in which
If MC1000 is greater than 25 percent, KWET = 1.0.
If MC1000 is less than 26 percent and greater than 9 percent, KWET = (0.0333 * MC1000 + 0.1675).
If MC1000 is less than 10 percent, KWET = 0.5.
If DIFF is less than or equal to 0.0, KWET = 1.0.
If (TMPMAX + TMPMIN) / 2.0 is less than or equal to 50°F, KTMP = 0.6; otherwise, a value of 1.0 is used.

Next needed is the moisture content that herbaceous fuels would have *if the greenup period were over;* this we call MCHRBP (P for Potential). MCHRBP is linearly related to X 1000, but the constants of the relationship are functions of the NFDRS climate class.

MCHRBP = HERBGA + HERBGB * X1000

in which the constant and coefficient are determined by the NFDRS climate class.

NFDRS Climate class:	HERBGA	HERBGB
1	- 70.0	12.8
2	-100.0	14.0
3	-137.5	15.5
4	-185.0	17.4

The length of the greenup period, in days, is seven times the NFDRS climate class. The fraction of greenup period that has elapsed must be calculated so that the loading of the herbaceous fuel can be calculated.

GREN = GRNDAY / (7.0 * CLIMAT) (4)

in which GRNDAY is the number of days since the greenup sequence was started.

During greenup, MCHERB is phased up.

MCHERB = MCHRBI
+ (MCHRBP - MCHRBI) * GREN

The fraction of the fuel model herbaceous fuel loading transferred to the 1-hour class is FCTCUR.

FCTCUR = 1.33 - 0.0111 * MCHERB (5)

in which FCTCUR cannot be less than 0.0 nor more than 1.0.

The actual amount of fuel transferred can now be calculated.

WHERBC = FCTCUR * WHERB (6)

The I-hour and herbaceous fuel loadings, W1P and WHERBP, therefore, become:

W1P = W1 +WHERBC (7)

WHERBP = WHERB - WHERBC (8)

Green Stage--At the end of the greenup period GREN = 1.0; therefore, MCHERB = MCHRBP. If it has been exceptionally dry during the greenup period, X1000 will be low, and MCHRBP may not reach 120 percent. When this situation occurs, the green stage is bypassed and the model goes directly into transition. As long as MCHRBC is greater than 120 percent, however, MCHERB (for both perennials and annuals) is calculated by the linear equation and constants determined by the climate class (see tabulation of HERBGA AND HERBGB above).

MCHERB = HERBGA + HERBGB * X1000

in which MCHERB is not allowed to exceed 250 percent.

Transition Stage--When MCHERB drops below 120 percent, these transition equations are used:

For annuals:

MCHERB = ANNTA + ANNTB * X1000

For perennials:

MCHERB = PERTA + PERTB * X1000

in which

MCHERB cannot exceed 150 or be less than 30 percent if plants are perennials.

MCHERB cannot be higher than MCHERB calculated the previous day if plants are annuals.

The constant and coefficient for the equations are determined by the NFDRS climate class as follows:

NFDRS	Annuals		Perennials	
climate class:	ANNTA	ANNTB	PERTA	PERTB
1	-150.5	18.4	11.2	7.4
2	-187.7	19.6	-10.3	8.3
3	-245.2	22.0	-42.7	9.8
4	-305.2	24.3	-93.5	12.2

For both herbaceous types, the model causes fuel to be transferred back and forth between the herbaceous and 1-hour classes as MCHERB fluctuates between 30 and 120 percent. Equations 5, 6, 7, and 8 are used to calculate the amount of fuel moving back and forth between classes.

Cured or Frozen Stage--If curing occurs by way of normal, seasonal drying (MCHERB drops to 30 percent without intervention by the user), these equations are used:

For annuals:

MCHERB = MC1

For perennials:

MCHERB = PERTA + PERTB * X1000

in which MCHERB cannot be less than 30 percent nor more than 150 percent if the plants are perennials.

Perennials are treated no differently than they are in the transition stage unless the user forces curing with a FROZEN or CURED command. If that is the situation, the equation for MCHERB for perennials becomes:

MCHERB = MC1

In automated systems such as AFFIRMS and FIREFAMILY, once curing has taken place, the herbaceous moisture content of annual plants is displayed with the same value as the moisture content of the I-hour fuels. If the perennial designation has been used, the herbaceous moisture content will remain at 30 percent until moisture conditions improve or FROZEN or CURED has been declared. Operationally, a killing freeze is declared by the user. With historical fire-weather data, FIREFAMILY handles freezing as follows: the user designates on a lead card the earliest date that a killing frost is plausible. FIREFAMILY, for observations after that date, will then set the FROZEN flag:

1. The first time a minimum temperature (TMPMIN) 25° F or less occurs; or
2. The fifth day that a minimum temperature falls in the range 26° to 32° F.

Shrub Fuels

The prediction model for woody fuel moisture is much simpler than that for herbaceous fuel moisture. Only four stages in the annual growth cycle are recognized, and loadings between fuel classes are not transferred. The four stages of the model are:

1. pregreen (MCWOOD = PREGRN)
2. greenup
3. green (MCWOOD greater than PREGRN)
4. frozen (MCWOOD = PREGRN)

in which

MCWOOD is the predicted moisture content of the twigs and foilage [sic] of the shrubs.

PREGRN is the moisture content of shrubs when dormant.

Pregreen Stage--This stage is analagous to the pregreen stage of the herbaceous fuel moisture model.

MCWOOD = PREGRN

in which PREGRN is 50 for NFDRS climate class 1, 60 for class 2, 70 for class 3, or 80 percent for class 4.

Greenup Stage--MCWOOD is a function of MC1000 and the NFDRS climate class. During greenup, as in the herbaceous fuel moisture model, MCWOOD increases to its potential value over a period equal to seven times the climate class of the observation site.

The first step is the calculation of the potential woody fuel moisture

MCWODP = WOODGA + WOODGB * MC1000

in which the constant and coefficient are determined by the NFDRS climate class.

NFDRS climate class:	WOODGA	WOODGB
1	12.5	7.5
2	-5.0	8.2
3	-22.5	8.9
4	-45.0	9.8

The fraction of the greenup period that has elapsed, GREN, is calculated by equation 4. The woody fuel moisture during greenup is then calculated by this equation:

MCWOOD = MCWODI
+ (MCWODP - MCWODI) * GREN

n which MCWODI is the greater of PREGRN or the MCWOOD calculated the day previous to greenup.

Green Stage--After greenup, GREN = 1.0 and MCWOOD = MCWODP, and, therefore, MCWOOD can be calculated by the linear equation and constants from the preceding table.

MCWOOD = WOODGA + WOODGB * MC1000

in which MCWOOD cannot be less than the appropriate PREGRN value or greater than 200 percent.

Frozen Stage--This is the same as the pregreen stage, but is included to provide consistency between the discussions of the herbaceous and woody moisture models.

The model for woody fuel moisture does not respond to CURED if and when it is declared by the user. The types of shrubs considered here are not deciduous, therefore, no condition analogous to herbaceous cured exists. Shrubs will go into dormancy if the weather is cold enough, however, so the model for woody fuel moisture responds to FROZEN by setting MCWOOD to the appropriate PREGRN value. MCWOOD will not change until the next greenup.

SYSTEM COMPONENTS AND INDEXES

The NFDRS spread and energy release components (SC and ERC) are taken from Rothermel (1972) as modified by Albini (1976). The burning index (BI) is based on Byram's flame-length model (Byram 1959). The ignition and the two occurrence models were developed for the NFDRS, as was the fire load index (FLI). The SC, ERC, and BI relate to the characteristics of fire. These models will be dealt with first.

Models of Fire Characteristics

Preliminary Calculations

All fuel loadings are converted to pounds per square foot by multiplying the tons per acre value by 0.0459137 (lb-acre)/(ton-ft^2). Fuel model characteristics are listed in the *appendix.*

Total Dead and Live-Fuel Loadings:

(dead) WTOTD = W1P + W 10 + W100 + W1000
(live) WTOTL = WHERBP + WWOOD

in which
W1P is the 1-hour timelag fuel loading in addition to the portion of the live herbaceous loading that has cured. W 10, W100, and W1000 are the loadings of the 10-, 100-, and 1000-hour timelag fuels specified in the fuel model.
WHERBP is the herbaceous fuel loading remaining.
WWOOD is the loading of the woody shrub plants specified in the fuel model.

Total Fuel Loading:

WTOT = WTOTD + WTOTL

Net Fuel Loading of Each Fuel Class:

(1-hour) W1N = W1P * (1.0 - STD)
(10-hour) W10N = W10 * (1.0 - STD)
(100-hour) W100N = W100 * (1.0 - STD)
(herbaceous) WHERBN = WHERBP * (1.0 - STL)
(woody) WWOODN = WWOOD * (1.0 - STL)

in which STD and STL are the fractions of the dead and live fuels made up of inert, noncombustible minerals. A value of 0.0555 is used for both.

Bulk Density of the Fuel Bed:

RHOBED = (WTOT - W1000) / DEPTH

in which DEPTH is the effective fuel bed depth measured in feet.

Weighted Fuel Density:

RHOBAR = ((WTOTL * RHOL)
+ (WTOTD * RHOD)) / WTOT

in which
RHOL and RHOD are the live and dead-fuel particle densities.
A constant value of 32 lb/ft^3 is used.
Packing Ratio:

BETBAR = RHOBED/ RHOBAR

Mineral Damping Coefficient of Live and Dead Fuels:

(dead) ETASD = 0.174 * SD**(-0.19)
(live) ETASL = 0.174 * SL**(-0.19)

in which SD and SL are the fractions of the dead and live fuels made up of silica-free, noncombustible minerals. A constant value of 0.01 is assumed for both SD and SL.

Heating Numbers of Each Fuel Class:

(1-hour) HN1 = W1N * EXP(-138.0 / SG1)
(10-hour) HN10 = W10N * EXP(-138.0 / SG10)
(100-hour) HN 100 = W100N
* EXP(-138.0 / SG100)
(herbaceous) HNHERB = WHERBN
* EXP(-500.0 / SGHERB)
(woody) HNWOOD = WWOODN
* EXP(-500.0 / SGWOOD)

in which SG1, SG10, SG100, SGHERB, and SGWOOD are the surface-area-to-volume ratios of the 1-, 10-, 100-hour herbaceous and woody fuels specified in the fuel model.

Because the surface-area-to-volume ratio of the 1000-hour fuel class is so low (8.0 ft^{-1}), its influence is minimal and is omitted to simplify the computation. No net 1000-hour fuel loading is computed for the same reason.

Ratio of Dead-to-Live Fuel Heating Numbers:

WRAT = (HN1 + HN10 + HN100)
/ (HNHERB + HNWOOD)

Spread Component

In this model, the influence each fuel class has on the result is determined by the fraction of the total *surface area* of the fuel complex contributed by that fuel class.

Surface Area of Each Fuel Class:

(1-hour) SA1 = (W1P/RHOD) * SG1
(10-hour) SA10 = (W10/RHOD) * SG10
(100-hour) SA100 = (W100/RHOD) * SG100
(herbaceous) SAHERB = (WHERB/ RHOL)
* SGHERB
(woody) SAWOOD = (WWOOD/RHOL)
* SGWOOD

Total Surface Area of Dead and Live Fuels:

(dead) SADEAD = SA1 + SA10 + SA100
(live) SALIVE = SAHERB
+ SAWOOD

Weighting Factors of Each Fuel Class:

(1-hour) F1 = SA1/SADEAD
(10-hour) F10 = SA10/SADEAD
(100-hour) F100 = SA100/SADEAD
(herbaceous) FHERB = SAHERB/SALIVE
(woody) FWOOD = SAWOOD/SALIVE

Weighting Factors of Dead and Live Fuels:

(dead) FDEAD = SADEAD/(SADEAD + SALIVE)
(live) FLIVE = SALIVE/(SADEAD + SALIVE)

Weighted Net Loadings of Dead and Live Fuels:

(dead) WDEADN = (Fl * WIN) + (F10 * W10N)
+ (F100 * W100N)
(live) WLIVEN = (FWOOD * WWOODN)
+ (FHERB * WHERBN)

Dead and Live Fuel Characteristic Surface-Area-to-Volume Ratios:

(dead) SGBRD = (Fl * SG1) + (F10 * SG10)
+ (F100 * SG100)
(live) SGBRL = (FHERB * SGHERB)
+ (FWOOD * SGWOOD)

Characteristic Surface-Area-to-Volume Ratio:

SGBRT = (FDEAD * SGBRD) + (FLIVE * SGBRL)

Optimum Packing Ratio:

BETOP = 3.348 * SGBRT**(-0.8189)

Maximum Reaction Velocity:

GMAMX = (SGBRT** 1.5) / (495.0
+ 0.0594 * SGBRT**1.5)

Optimum Reaction Velocity:

GMAOP = GMAMX*(BETBAR/BETOP)**AD
* EXP(AD * (1.0 - BETBAR / BETOP))

in which AD = 133.0 * SGBRT**(-0.7913)

No Wind Propagating Flux Ratio:

ZETA = EXP((0.792 + 0.681 * SGBRT**0.5)
* (BETBAR + 0.1)) / (192.0 + 0.2595 * SGBRT)

Weighted Dead-Fuel Moisture Content for Live-Fuel Extinction Moisture:

MCLFE = ((MC1 * HN1) + (MC10 * HN10)
+ (MC100 * HN100)) / (HN1 + HN10 + HN100)

Moisture of Extinction of Live Fuels:

MXL = (2.9 * WRAT * (1.0 - MCLFE/MXD)
- 0.226) * 100.0

in which

MXD is the moisture of extinction of the dead fuels from the fuel model.
MXL cannot be less than MXD.

Weighted Moisture Content of Dead and Live Fuels:

(dead) WTMCD = (F1 * MC1) + (F10 * MC10) + (F100 * MC100)
(live) WTMCL = (FHERB * MCHERB) + (FWOOD * MCWOOD)

Moisture Damping Coefficients of Dead and Live Fuels:

(dead) ETAMD = 1.0 - 2.59 * DEDRT + 5.11 * DEDRT**2.0 - 3.52 * DEDRT**3.0
(live) ETAML = 1.0 - 2.59 * LIVRT + 5.11 * LIVRT**2.0 - 3.52 * LIVRT**3.0

in which

DEDRT = (WTMCD / MXD)
LIVRT = (WTMCL/MXL)
ETAMD and ETAML cannot be less than zero or greater than 1.0.
Wind Effect Multiplier Coefficients and Exponents:

B = 0.02526 * SGBRT**0.54
C = 7.47 * EXP(-0.133 * SGBRT**0.55)
E = 0.715 * EXP(-3.59 * 10.0**(-4.0) * SGBRT)
UFACT = C * (BETBAR/BETOP)**(-E)

Wind Effect Multiplier:

PHIWND = UFACT * (WS * 88.0 * WNDFC)**B

in which
WS is the 10-minute average 20-ft windspeed in mph.
WNDFC is the fuel model wind reduction factor.
The effect of high winds is limited:
If (WS * 88.0 * WNDFC) is greater than (0.9 * IR), then (0.9 * IR) replaces (WS * 88.0 * WNDFC). Then the equation becomes

PHIWND = UFACT * (0.9 * IR)**B

Slope Effect Multiplier Coefficient:

SLPFCT = 5.275 * (TAN(slope angle))**2.0

in which

NFDRS slope class:	Slope angle	SLPFCT
1	12.67°	0.267
2	17.63°	0.533
3	24.23°	1.068
4	32.46°	2.134
5	41.99°	4.273

Slope Effect Multiplier:

PHISLP = SLPFCT * BETBAR**(-0.3)

Reaction Intensity:

IR = GMAOP * ((WDEADN * HD * ETASD * ETAMD) + (WLIVEN * HL * ETASL * ETAML))

in which HD and HL are the heat values for dead and live fuels specified in the fuel model, Btu/lb.

Heat Sink:

HTSINK = RHOBED * (FDEAD
* (F1 * EXP(-138.0/SG1) * (250.0 + 11.16 * MC1)
+ Fl0 * EXP(-138.0/SG10) * (250.0 + 11.16 * MC10)
+ F100 * EXP(-138.0/SG100) * (250.0 + 11.16 * MC100)))
+ (FLIVE * (FHERB * EXP(-138.0/SGHERB)
* (250.0 + 11.16 * MCHERB) + FWOOD
* EXP(-138.0/SGWOOD)
* (250.0 + 11.16 * MCWOOD)))

Rate of Spread:

ROS = IR * ZETA * (1.0 + PHISLP + PHIWND)/HTSINK (ft/ min)

Spread Component:

SC = IRND(ROS)

Energy Release Component

In this model the influence of each fuel class is deter-ined by the fraction of the total fuel loading contributed by that class. As a result, the conditions of the larger fuels have more influence on the fire-danger.

Weighting Factors of Each Fuel Class:

(1-hour) F1E= WIP/WTOTD
(10-hour) F10 = 10/WTOTD
(100-hour) F100E = W100/WTOTD
(1000-hour) FI000E = W1000/WTOTD
(herbaceous) FHERBE = WHERBP/ WTOTL
(woody) FWOODE = WWOOD/WTOTL

Weighting Factors of Dead and Live Fuels:

(dead) FDEADE = WTOTD/ WTOT
(live) FLIVEE = WTOTL/ WTOT

Net Loadings of Dead and Live Fuels:

(dead) WDEDNE = WTOTD * (1.0-STD)
(live) WLIVNE = WTOTL * (1.0-STL)

Dead and Live Fuel Characteristic Surface-Area-to-Volume Ratios:

(dead) SGBRDE = (FIE * SG1) + (FLOE * SG10)
+ (FC100E * SG100)
+ (FI000E * SG1000)
(live) SGBRLE = (FWOODE * SGWOOD)
+ (FHERBE * SGHERB)

Characteristic Surface-Area-to-Volume Ratio:

SGBRTE = (FDEADE * SGBRDE)
+ (FLIVEE * SGBRLE)

Optimum Packing Ratio:

BETOPE = 3.348 * SGBRTE**(-0.8189)

Maximum Reaction Velocity:

GMAMXE = SGBRTE**1.5/(495.0
+ 0.0594 * SGBRTE**1.5)

Optimum Reaction Velocity:

GMAOPE = GMAMXE
* (BETBAR/BETOPE)**ADE*EXP(ADE
* (1.0 - BETBAR/BETOPE))
in which ADE = 133.0 * SGBRTE**(-0.7913)

Weighted Moisture Contents of Dead and Live Fuels:

(dead) WTMCDE = (F1E * MC1) + (F10E * MC10)
+ (F100E * MC100)
+ (F1000E * MC1000)
(live) WTMCLE = (FWOODE * MCWOOD)
+ (FHERBE * MCHERB)

Moisture Damping Coefficients of Dead and Live Fuels:

(dead) ETAMDE = 1.0 - 2.0 * DEDRTE
+ 1.5 * DEDRTE**2.0
- 0.5 * DEDRTE**3.0
(live) ETAMLE = 1.0 - 2.0 * LIVRTE
+ 1.5 * LIVRTE**2.0
- 0.5 * LIVRTE**3.0

in which
DEDRTE = (WTMCDE/MXD)
LIVRTE = (WTMCLE/ MXL)
ETAMDE and ETAMLE cannot be less than zero or greater than 1.0

Reaction Intensity:

IRE = GMAOPE * ((FDEADE * WDEDNE * HD
* ETASD * ETAMDE) + (FLIVEE * WLIVNE
* HL * ETASL * ETAMLE))

Residence time of the Flaming Front:

TAU = 384.0/ SGBRT

The surface area weighted surface area-to-volume ratio, SGBRT, is used rather than the mass weighted form (SGBRTE). The mass weighted residence time produced unrealistic results.

Energy Release Component:

ERC = IRND(0.04 * IRE * TAU)

The 0.04 scaling factor has the units ft^2/ Btu. As such, a unit value of ERC is equivalent to 25 Btu of available energy per square foot.

Burning Index

The BI is numerically equivalent to 10 times the predicted flame length, in feet. The equation developed by Byram (1959) is used with some liberties, enabling us to use parameters that are outputs from Rothermel's fire spread model.

Byram's equation:

FL = 0.45 * I**0.46 (ft.)

in which I is the fireline intensity, Btu/ft-sec
but I = IRE * D/60.0, Btu/ft-sec
in which D = ROS * TAU, ft
so I = (ROS/60.0) * IRE * TAU, Btu/ft-sec
but ROS = SC and IRE * TAU = 25.0 * ERC
therefore FL = 0.45 * ((SC/60.0) * (25.0 * ERC))**0.46
and FL = 0.301 * (SC * ERC)**0.46

Burning Index:

BI = IRND(3.01 * (SC * ERC)**0.46)

If the fuels are wet or covered by snow or ice at observation time, the BI is set to zero.

Models of Fire Occurrence

Ignition Component

The IC consists of two parts: (1) the probability that a firebrand will produce a successful fire start in dead, fine fuels, P(I); and (2) the probability that a reportable fire will occur, given an ignition P(F/ I).

P(I) is a function of the amount of heat required to produce an ignition (QIGN) which, in turn, is a function of the 1-hour fuel moisture, MC1. P(I) is scaled such that it is 100 when MC1 = 1.5 percent and zero when MC1 = 25.0 percent. Three scaling factors are used for this purpose:

PNORM1 = 0.00232
PNORM2 = 0.99767
PNORM3 = 0.0000185

Heat of Ignition:

QIGN = 144.5 - (0.266 * TMPPRM) - (0.00058 * TMPPRM**2.0) - (0.01 * TMPPRM * MC1) + (18.54 * (1.0 - EXP(-0.151 * MC1))) + 6.4 * MC1)

in which TMPPRM is the estimated observation time dry bulb temperature of the air in immediate fuel contact, in degrees Celsius.

Intermediate Calculations:

CHI = (344.0 - QIGN) / 10.0

in which, if (CHI**3.6 * PNORM3) is equal to or less than PNORMI, then P(I) and the IC are set to zero.

Probability of Ignition:

P(I) = (CHI**3.6 * PNORM3 - PNORMI) * 100.0/PNORM2

in which P(I) is limited to the range of values from 0 to 100.

P(F/ I) is a function of the spread component for that fuel model normalized to the value the spread component would have under a specific set of severe burning conditions (slope class 1; 20-ft wind 20 mph; herbaceous vegetation cured; woody vegetation moisture content at the pregreen level; and the 1-, 10-, and 100-hour fuel moistures 3.0 percent.) This function was derived empirically by Main and others (1982).

Normalized Rate of Spread:

SCN = 100.0 * SC/SCM

in which SCM is, in the developers' best judgment, the SC for which all ignitions become reportable fires. An SCM was calculated for each fuel model and is included as a fuel model parameter.

Probability of a Reportable Fire:

P(F/I) = SCN**0.5

Ignition Probability:

IC = IRND(0.10 * P(I) * P(F/I))

in which the factor 0.10 is required to limit the range of IC to 0 to 100.

Human-Caused Fire Occurrence Index

MCOI = IRND(0.01 * MRISK * IC)

in which MRISK is the human-caused risk. See Deeming and others (1977) for details about its evaluation.

Lightning-Caused Fire Occurrence Index

For information about this model, see the publications by Fuquay and others (1979) and Fuquay (1980). The model assumes that a thunderstorm traversing an area forms a corridor aligned with the storm's track that receives both rain and lightning. Flanking the rain-lightning corridor on both sides are areas subjected to lightning only.

The width of the rain-lightning corridor affected (STMDIA), the total width of the lightning-only and lightning-rain corridors (TOTWID), and the discharge rate (CGRATE) for cloud-to-ground lightning are functions of the NFDRS lightning activity level (LAL):

NFDRS LAL	CGRATE *strikes/min*	STMDIA *miles*	TOTWID *miles*
1	0.0	0.0	0.0
2	12.5	3.0	7.0
3	25.0	4.0	8.0
4	50.0	5.0	9.0
5	100.0	7.0	11.0
6	(LRISK = 100, LOI = 100)		

Duration of Lightning at a Point Within the Affected Area:

LGTDUR = -86.83 + 153.41 * CGRATE**0.1437.

Fractions of the Area Occupied by the Lightning-Rain and Lightning-Only Corridors:

(Lightning-rain) FINSID = ((STMDIA * STMSPD *LGTDUR) + (0.7854 *STMDIA**2.0)) /((STMDIA * STMSPD *TOTWID) + (0.7854 *TOTWID**2.0))

(Lightning-only) FOTSID = (1.0 - FINSID)

Rain Duration at a Point Within the Lightning-Rain Corridor:

RAIDUR = STMDIA/STMSPD

in which STMSPD is the translational speed of the storm in miles per hour. For the NFDRS, a constant speed of 30 mph is used.

Moisture Content of the 1-Hour Fuels Within the Rain Area:

FMF = MC1 + ((76.0 + 2.7 * RAIDUR) - MC1) * (1.0 - EXP(-RAIDUR))

The ignition component within the area affected by rain is calculated exactly as the IC except that FMF is used instead of MC1. The IC for the rain-affected corridor is denoted as ICR and is a significant deviation from the Fuquay model. As a simplification, it was decided to use the NFDRS IC function rather than the ignition probability function developed for the model. The difference was judged to be minor. Also, the LRSF was introduced to account for area-specific fuel conditions that affect the fire-starting efficiency of the lightning (Bradshaw and others 1983).

Area Weighted Ignition Component:

ICBAR = ((FINSID * ICR) + (FOTSID * IC))/ 100.0

Lightning-Risk:

LRISK = CGRATE * LRSF

in which

LRSF is the lightning risk scaling factor. See Deeming and others (1977) for a complete description.

LRISK is limited to a numerical range of 0-100.

Lightning-Caused Fire Occurrence Index Computation:

If it is not lightning, or if it is raining at the time of the afternoon weather observation at the fire-weather station, 25 percent of the previous day's LOI is used to account for carry-over fires.

LOI = IRND(0.25 * YLOI)

in which YLOI is the previous day's LOI; otherwise

LOI = IRND(10.0 * (LRISK * ICBAR) + 0.25 * YLOI)

in which the multiplier 10.0 scales the LOI such that the expected number of lightning fires per million acres increases by 1.0 for every 10 points of LOI. The LOI is limited to a value range of 0 to 100.

If LAL 6 is observed or predicted, the lightning risk (LRISK) and lightning-caused fire occurrence index (LOI) are set to 100.

Fire Load Index

FLI = 0.71 * SQRT(BI**2.0 + (LOI + MCOI)**2.0)

in which the BI is limited to 100 as is the sum of LOI and MCOI.

APPENDIX--Parameters for fuel models

Fuel model	Ratios and Fuel loadings[1]						Depth (ft)[8]	MXD (pct)[9]	HD&HL (Btu/lb)[10]	SCM[11]	WNDFC[12]
	1-h[2]	10-h[3]	100-h[4]	1000-h[5]	Wood[6]	Herb[7]					
A Western grasses	3000	----	----	----	----	3000	0.80	15	8000	300	0.6
(annual)	0.20	----	----	----	----	0.30					
B California	700	109	30	----	1250	----	4.50	15	9500	58	0.5
chaparral	3.50	4.00	0.50	----	11.50	----					
C Pine-grass	2000	109	----	----	1500	2500	0.75	20	8000	32	0.4
savanna	0.40	1.00	----	----	0.50	0.80					
D Southern rough	1250	109	----	----	1500	1500	2.00	30	9000	25	0.4
	2.00	1.00	----	----	3.00	0.75					
E Hardwood litter	2000	109	30	----	1500	2000	0.40	25	8000	25	0.4
(winter)	1.50	0.50	0.25	----	0.50	0.50					
F Intermediate	700	109	30	----	1250	----	4.50	15	9500	24	0.5
brush	2.50	2.00	1.50	----	9.00	----					
G Short needle	2000	109	30	8	1500	2000	1.00	25	8000	30	0.4
(heavy dead)	2.50	2.00	5.00	12.0	0.50	0.50					
H Short needle	2000	109	30	8	1500	2000	0.30	20	8000	8	0.4
(normal dead)	1.50	1.00	2.00	2.00	0.50	0.50					
I Heavy slash	1500	109	30	8	----	----	2.00	25	8000	65	0.5
	12.00	12.00	10.00	12.00	----	----					
J Intermediate	1500	109	30	8	----	----	1.30	25	8000	44	0.5
slash	7.00	7.00	6.00	5.50	----	----					
K Light slash	1500	109	30	8	----	----	0.60	25	8000	23	0.5
	2.50	2.50	2.00	2.50	----	----					
L Western grasses	2000	109	----	----	----	2000	1.00	15	8000	178	0.6
(perennial)	0.25	1.50	----	----	----	0.50					
N Sawgrass	1600	109	----	----	1500	2000	3.00	25	8700	167	0.6
	1.50	3.00	----	----	2.00	0.50					
O High pocosin	1500	109	30	8	1500	----	4.00	30	9000	99	0.5
	2.00	1.00	3.00	2.00	7.00	----					
P Southern pine	1750	109	30	----	1500	----	0.40	30	8000	14	0.4
plantation	1.00	2.50	0.50	----	0.50	----					
Q Alaskan black	1500	109	30	8	1200	1500	3.00	25	8000	59	0.4
spruce	2.00	0.50	2.00	1.00	4.00	0.50					
R Hardwood litter	1500	109	30	----	1500	2000	0.25	25	8000	6	0.4
(summer)	0.50	0.50	0.50	----	0.50	0.50					
S Tundra	1500	109	30	8	1200	1500	0.40	25	8000	17	0.6
	0.50	0.50	0.50	0.50	0.50	0.50					
T Sagebrush-grass	2500	109	----	----	1500	2000	1.25	15	8000	73	0.6
	1.00	1.50	----	----	2.50	0.50					
U Western pines	1750		30	----	1500	2000	0.50	20	8000	16	0.4
	1.50		1.00	----	0.50	0.50					

[1]For each fuel model, the top value is surface-area-to-volume ratio (ft^{-1}), and the bottom value is fuel loading (tons/acre).
[2]1-hour timelag dead fuel moisture class.
[3]10-hour timelag dead fuel moisture class.
[4]100-hour timelag dead fuel moisture class.
[5]1000-hour timelag dead fuel moisture class.
[6]Live fine woody fuel class.
[7]Live fine herbaceous fuel class.
[8]Effective fuel bed depth.
[9]Assigned dead fuel moisture of extinction.
[10]Dead and live fuel heat of combustion.
[11]Assigned spread component value when all ignitions become reportable fires.
[12]Wind reduction factor from 20-foot standard height to the midflame height.

REFERENCES

Albini, Frank A. **Estimating wildfire behavior and effects.** Gen. Tech. Rep. INT-30. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1976. 92 p.

Bradshaw, Larry; Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. **1978 National Fire-Danger Rating System--technical documentation.** Gen. Tech. Rep. INT 169. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1983. 44 p.

Burgan, Robert E. **Estimating live-fuel moisture for the 1978 National Fire-Danger Rating System.** Res. Pap. INT 226. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 17 p.

Burgan, Robert E.; Cohen, Jack D.; Deeming, John E. **Manually calculating fire-danger rating-- 1978 National Fire Danger Rating System.** Gen. Tech. Rep. INT-40. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 51 p.

Byram, George M. **Combustion of forest fuels.** In: Forest fire control and use. New York, NY: McGraw Hill Book Company; 1959: Chapter 3, p. 61.

Byram, George M.; Jemison, George M. **Solar radiation and forest fuel moisture.** J. Agric. Res. 67(4):149-176; 1943 August.

Cramer, Owen P. **Predicting moisture contents of fuel moisture indicator sticks.** Res. Pap. PNW-41. Portland, OR: Pacific Northwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1961. 17 p.

Deeming, John E.; Burgan, Robert E.; Cohen, Jack D. **The National Fire-Danger Rating System--1978.** Gen. Tech. Rep. INT-39. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 63 p.

Deeming, John E.; Lancaster, J. W.; Fosberg, Michael A.; Furman, William R.; Schroeder, Mark J. **The National Fire-Danger Rating System.** Res. Pap. RM-84. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972, revised 1974. 165 p.

Fosberg, Michael A. **Moisture content calculations for the 100-hour timelag fuel in fire-danger rating.** Res. Note RM-199. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1971. 7 p.

Fosberg, Michael A. **Forecasting the 10-hour timelag fuel moisture.** Res. Pap. RM-187. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1977. 10 p.

Fosberg, Michael A.; Deeming, John E. **Derivation of the 1- and 10-hour timelag fuel moisture calculations for fire-danger rating.** Res. Note RM-207. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, 1971. 8 p.

Fosberg, Michael A.; Rothermel, Richard C.; Andrews, Patricia L. **Moisture content calculations for the 1000-hour timelag fuels**. Forest Sci. 27(l):19-26; 1981.

Fuquay, Donald M. **Forecasting lightning activity level and associated weather.** Res. Pap. INT-244. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 30 p.

Fuquay, D. M.; Baughman, R. G.; Latham, D. J. **A model for predicting lightning-fire ignition in wildlands fuels.** Res. Pap. INT-217. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1979. 22 p.

Haines, Donald A.; Frost, John S. **Weathering effects on fuel moisture sticks: corrections and recommendations.** Res. Pap. NC-154. St. Paul, MN: North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1978. 7 p.

Helfman, Robert S.; Straub, Robert J.; Deeming, John E. **User's guide to AFFIRMS: time-share computerized processing of fire-danger rating.** Gen. Tech. Rep. INT-82. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1980. 159 p.

Main, William A.; Straub, Robert J.; Paananen, Donna M. **FIREFAMILY: fire planning with historic weather data.** Gen. Tech. Rep. NC-73. St. Paul, MN: North Central Forest Experiment Station, Forest Service, U.S. Department of Agriculture; 1982. 31 p.

McCammon, Bruce P. **Snowpack influences on dead-fuel moisture.** Fort Collins, CO: Colorado State University; 1974. Dissertation.

Rothermel, Richard C**. A mathematical model for fire spread predictions in wildland fuels.** Res. Pap. INT-1 15. Ogden, UT: Intermountain Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1972. 40 p.

Simard, Albert J**. The moisture content of forest fuels I. A review of basic concepts.** Ottawa, ONT: Forest Fire Research Institute; 1968. Rep. FF-X-14. 47 p.

Smithsonian Institution. **Smithsonian meteorological tables.** Smithsonian Miscellaneous Collection 114(6):527, Washington DC: Smithsonian Institution Press; 1949. 526 p.

U.S. Department of Agriculture, Forest Service. **The wildland fire-danger rating system.** Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1958, revised 1968. 108 p.

U.S. Forest Products Laboratory. **Wood handbook: Wood as an engineering material.** Agric. Handb. 72. Washington, DC: U.S. Department of Agriculture; 1955, revised 1974. Paged by chapter.

Cohen, Jack D.; Deeming, John E. **The National Fire-Danger Rating System: basic equations.** Gen. Tech. Rep. PSW-82. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 1985. 16 p.

Updating the National Fire-Danger Rating System (NFDRS) was completed in 1977, and operational use of it was begun the next year. The System provides a guide to wildfire control and suppression by its indexes that measure the relative potential of initiating fires. Such fires do not behave erratically-- they spread without spotting through continuous ground fuels. Estimates of fire potential have a basis in the mathematical models used for fire behavior. The fire manager must select the fuel model that best represents the fuels in the protection area. Among the 20 fuel models available, not more than two or three are appropriate for any one area. This documentation of the 20 fuel models and their equations supplements previous reports on the System. The equations are presented in the coded format of FORTRAN and BASIC computer languages.

Retrieval Terms: fire modeling, fire occurrence, fire-danger indexes, forest-fire behavior, forest-fire risk, fuel moisture, fuel models.