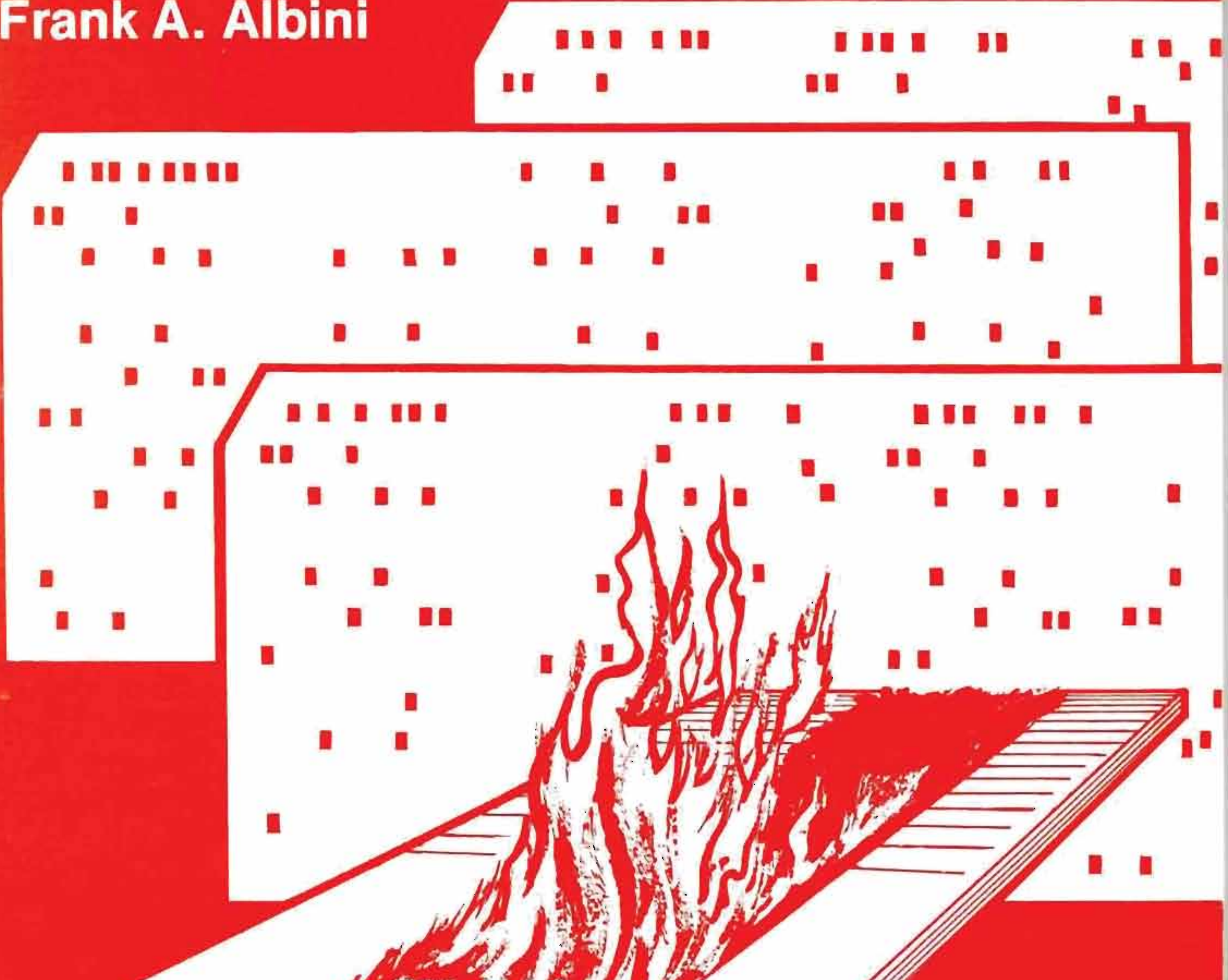
COMPUTER-BASED MODELS OF WILDLAND FIRE BEHAVIOR: A USERS' MANUAL

Frank A. Albini



USDA Forest Service
Intermountain Forest and Range
Experiment Station

1976

COMPUTER-BASED MODELS OF WILDLAND FIRE BEHAVIOR: A USERS' MANUAL

Frank A. Albini

INTERMOUNTAIN FOREST AND RANGE EXPERIMENT STATION
Forest Service
U.S. Department of Agriculture
Ogden, Utah 84401

THE AUTHOR

DR. FRANK A. ALBINI is a Research Mechanical Engineer in the Fire Fundamentals research work unit at the Northern Forest Fire Laboratory in Missoula, Montana. He received a B.S. in 1958, an M.S. in 1959, and a Ph. D in 1962 in Aeronautical and Mechanical Engineering, with a Philosophy minor, from the California Institute of Technology. From 1960 to 1963 he worked at Hughes Aircraft Company as a member of a small research staff in the Engineering Laboratories of the Space Systems Division. From 1963 to 1966, and again from 1971 to 1973, he worked as a member of the research staff at the non-profit Institute for Defense Analyses, performing engineering evaluations and systems analyses for the Department of Defense. From 1966 to 1971 he was with the General Research Corporation in Santa Barbara, as a member of the technical staff and as Director of the Defensive Systems Department. In 1973 he joined the staff at the Northern Forest Fire Laboratory to devote full time to what had been a continuing avocation--research on free-burning fire.

CONTENTS

ABSTRACT

This document comprises a reference manual for computer programs (FIREMODS) pertaining to wildfire behavior and its effects, maintained by the Fire Fundamental research work unit, Northern Forest Fire Laboratory, Missoula, Montana. The subroutines embody mathematical models that permit the prediction of the linear rate of advance of a fire, perimeter and area growth rate, intensity, flame length, area fire intensity, fuel consumption, and duff burnout, under specifiable conditions of wind, slope, and fuel moisture. The routines are written in FORTRAN IV, extended, and stored in UPDATE (a CDC file-maintenance utility program) format.

The algorithms are described in terms of input, output, organization, and the purpose and precision of calculations. Where the theory is not documented elsewhere, considerable detail is given on the mathematical bases for the calculations performed. Examples of input and output are included.

Periodic revisions of and additions to this manual are anticipated.

INTRODUCTION

This document is a manual for users of the FIREMØDS library of computer subroutines maintained by the Northern Forest Fire Laboratory. The subroutines are stored in semi-permanent condition, on magnetic tape and data cell, at the Lawrence Berkeley Laboratory computer center (BKY) on the University of California campus at Berkeley.

All users are encouraged to communicate any difficulties or suggestions to the author:

F. A. Albini
Northern Forest Fire Laboratory
Drawer G
Missoula, Montana 59801

Telephone
FTS (406)585-3485
Commercial (406)329-3485

The subroutines represent research models that are offered for general use to the research community without any official sanction or status. Users are urged to check the internal consistency and accuracy of the models for their own purposes. Each routine is subject to periodic revision to expand capabilities. Addenda to this manual will be issued as required.

UNLABELED COMMON VARIABLES

Each major subroutine stored on the permanent file space has a large unlabeled common block through which are passed the fuel array and site-description variables, and some fire-behavior data. The contents of this common block are described below. The common block is:

```
 CØMMØN ND,NL,BETA1,SIGMA,GAMMA,XIR,RHØBQIG,PHIS,WINDX,PHIWX,RATEX,
1BYRAMX,IR(2),MEXT(2),DEPTH,TTHETA,MØIS(2,100),MPS(2,100),MWG(2,100
2),LHV(2,100),RHØP(2,100),ST(2,100),SE(2,100),RUN,WINDI,WINDF,DELW,
3HEADING(10),NAMES(2,100),IFINES(2),ØPT,BYRAM(100),RATE(100),NN,XIØ
4,WINDS(100),ISIZE(2,100),LARGE1,LARGE2
```

DESCRIPTION OF VARIABLES

Name	Type	Value from	Description
ND	INTEGER	SETUP	Number of dead fuel size classes present in the fuel list (0 ≤ ND ≤ 100). The fuel elements are ordered on size (see ISIZE), by FIREMØD, so ND is the ordinal number of the largest dead fuel size class in the list. See LARGE1.
NL	INTEGER	SETUP	Number of live fuel size classes present. See ND. See LARGE2.
BETA1	REAL	FIREMØD	Packing ratio of fuel complex (fraction of fuel array volume filled by "homogenized" fuel).
SIGMA	REAL	FIREMØD	Surface/volume ratio (ft^{-1}) of "homogenized" fuel particles.
GAMMA	REAL	FIREMØD	Reaction velocity (min^{-1}) established by SIGMA and BETA1 (see eq. 67, Rothermel 1972).
XIR	REAL	FIREMØD	Reaction intensity ($Btu/min/ft^2$).
RHØBQIG	REAL	FIREMØD	Heat of ignition per unit volume (Btu/ft^3) (see eq. 77, Rothermel 1972).
PHIS	REAL	FIREMØD	Slope factor for rate-of-spread (see eq. 80, Rothermel 1972).
WINDX	REAL	FIREMØD	Windspeed (mi/h) at which maximum value of wind factor for rate-of-spread achieved (see eq. 86, Rothermel 1972).
PHIWX	REAL	FIREMØD	Maximum wind factor for rate-of-spread.
RATEX	REAL	FIREMØD	Maximum rate-of-spread (ft/min) for upslope wind of WINDX (mi/h).
BYRAMX	REAL	FIREMØD	Byram's fireline intensity (Btu/min/ft) for maximum rate-of-spread.
IR(I)	REAL	FIREMØD	Reaction intensity ($Btu/min/ft^2$) for dead (I=1) and live (I=2) fuel category. XIR=IR(1)+IR(2).

Name	Type	Value from	Description
MEXT(1)	REAL	SETUP	Moisture of extinction of dead fuel (fraction dry weight).
MEXT(2)	REAL	FIREMØD	Computed moisture of extinction of live fuel (fraction dry weight).
DEPTH	REAL	SETUP	Depth of fuel array (ft) normal to slope.
TTHETA	REAL	SETUP	Slope tangent of fire site.
MØIS(I,J)	REAL	SETUP	Fuel moisture (fraction dry weight) for J^{th} size class of category I. Value of J established by order of input list, not size class. See ISIZE.
MPS(I,J)	REAL	SETUP	Surface/volume ratio (ft^{-1} for fuel particles of size class J, category I. See ISIZE.
MWG(I,J)	REAL	SETUP	Dry weight loading (lb/ft^2) of size class J, category I. See ISIZE.
LHV(I,J)	REAL	FUELS	Heat of combustion (Btu/lb) of size class J, category I. See ISIZE.
RHØP(I,J)	REAL	FUELS	Dry density (lb/ft^3) of size class J, category I. See ISIZE.
ST(I,J)	REAL	FUELS	Total mineral content (fraction dry weight) of size class J, category I. See ISIZE.
SE(I,J)	REAL	FUELS	Silica-free mineral content (fraction dry weight) of size class J, category I. See ISIZE.
RUN	INTEGER	FIREMØD	Count of number of times FIREMØD has been called. Also used as initializing switch in other subroutines.
WINDI	REAL	SETUP	Initial (or only) windspeed at midflame height (mi/h).
WINDF	REAL	SETUP	Final windspeed at midflame height (mi/h).
DELW	REAL	SETUP	Increment of windspeed (mi/h) to be used in filling out table of spread rate-versus-windspeed by FIREMØD, etc., between WINDI and WINDF.
HEADING	INTEGER	SETUP	Free-field alphanumeric description of run, printed as identifier by various subroutines (maximum-10A8 words).

Name	Type	Value from	Description
NAMES(I,J)	INTEGER	SETUP	Eight-character alphanumeric name of fuel in size class J, category I. See ISIZE.
IFINES(I)	INTEGER	SETUP	Ordinal number of finest size class fuel of category I used in describing fuel array. See ISIZE.
ØPT	INTEGER	SETUP	Flag quantity controlling quantity of output printed by FIREMØD and other subroutines.
BYRAM(K)	REAL	FIREMØD	Byram's intensity (Btu/min/ft) for windspeed of index K. See NN.
RATE(K)	REAL	FIREMØD	Rate-of-spread (ft/min) for windspeed of index K. See NN.
NN	INTEGER	FIREMØD	Number of entries in the list of windspeeds and spread rates generated by FIREMØD, as determined by the parameters WINDI, WINDF, and DELW.
XIØ	REAL	FIREMØD	Propagating intensity (Btu/min/ft^2), as determined by XIR and factor ξ (see eq. 76, Rothermel 1972).
WINDS(K)	REAL	FIREMØD	Windspeed (mi/h) number K. $1 \leq K \leq NN$.
ISIZE(I,N)	INTEGER	FIREMØD	Second subscript value (size class subscript J) of the Nth--finest fuel category I. That is, if J=ISIZE(1,1), then NAMES(1,J) identifies the finest dead fuel in the array and MWG(1,J) is the dry loading of that fuel type. The fuel array descriptors are input in arbitrary order, and ISIZE is the array that orders this list on a size basis (in order of descending MPS).
LARGE1	INTEGER	SETUP	Ordinal number of the largest size class *dead* fuel component to be included in fuel array description processed. Although there are ND dead fuel size classes described, only those between IFINES(1) and LARGE1 are included in the fuel array description being calculated.
LARGE2	INTEGER	SETUP	Ordinal number of the largest size class *live* fuel component to be included in fuel array description processed. Although there are NL live fuel size classes described, only those between IFINES(2) and LARGE2 are included in the fuel array description being calculated.

SUBROUTINE SETUP

Subroutine SETUP is an input-processing service module that facilitates use of FIREMØD and other subroutines employing the variables described in the UNLABELED CØMMØN section. Use of this subroutine to process input data gives the user considerable freedom in specifying run conditions for repetitive exercises of the subroutines in the FIREMØDS library.

Subroutine SETUP has the capability to facilitate the generation of fuel array descriptions which are "standard fuel models," eliminating the necessity of describing the fuel elements in terms of loading by size class or fuel particle properties. This has been accomplished through the use of subroutine STDFUEL, which is called by SETUP when the appropriate input card is encountered.

CØMMØN DATA: UNLABELED CØMMØN

CALLING SEQUENCE: CALL SETUP

PRECONDITIONS

The integer variable RUN in UNLABELED CØMMØN serves as a signal parameter for subroutine SETUP. When RUN=0, all input variables are initialized to zero by SETUP before any input data are accepted. When RUN≠0, the current values of all input variables are maintained and new data are read immediately. If repetitive runs are desired, with data modifications specified by input through SETUP, care should be taken that RUN is not reset to zero, to prevent data destruction through reinitializing by SETUP. Note: FIREMØD uses RUN to count calls to itself, and other routines make use of this indicator.

Be sure that subroutines FUELS and STDFUEL are compiled (or FUELS is compiled and a dummy routine with the STDFUEL name is included), or the loader will abort the job on unsatisfied external references.

INPUT DATA ORGANIZATION

Subroutine SETUP allows a nearly random organization of input data by using a "package and label" technique. In this scheme, a "package" of input data is preceded by an identifying "label." SETUP reads in a single "label" card, which identifies the type and quantity of data that are to follow, and so branches to the appropriate set of read statements to read in the "package" of data.

The "label" cards are all read in with the same format (A8, I3). The eight-character alphanumeric word is the identifying label and the following integer is (where appropriate) the number of cards in the "package" of data following the label. SETUP recognizes the following labels (all are left-justified).

LABEL NAMES:

SUPPRESS	SITEDATA
SHØWDATA	SIZELIMS
HEADING	STDFUELS
NEW FUEL	ØPTIØN
FUELTYPE	STØP

If the label is not one of the above, the job is aborted by SETUP.

The following restrictions apply to the organization of the input data:

1. STØP should be the last card in the data deck because it signals the program to end by way of a normal CALL EXIT statement.

2. ØPTIØN should be the last card in a sequence that specifies a particular run because it signals subroutine SETUP that the input cycle is complete. SETUP then transfers control back to the calling program.

3. The FUELTYPE package specifies which fuels are present, by *name*, size class, loading, and moisture content. The other parameters that describe any particular fuel type (density, heat of combustion, mineral content, silica-free ash content) are stored in a "dictionary" maintained by subroutine FUELS, under the appropriate name. Thus, if a specific fuel type is to be used, this name must be in the dictionary when it is consulted. Therefore, if specific fuel descriptions are to be used by *name*, and if these *names* are not already in the dictionary, they must be inserted in the dictionary by use of a NEW FUEL package before specifying the fuel array by means of the FUELTYPE package. Once the fuel description is listed in the dictionary, it will remain there for the rest of the run, so it can be called out in subsequent FUELTYPE specifications without reentering it in the dictionary. The fuel properties listed under any *name* can be revised in the dictionary if desired, and it is not necessary that the fuel types being used be in the dictionary at all, if rough estimates of the dictionary-maintained fuel properties are adequate (more on these options below).

4. A job setup may include any number of NEW FUEL packages because the fuels will be added into the dictionary according to instructions implicit in the card data. In other words, the NEW FUEL package can be broken into any number of smaller packages, even in the same run. But the FUELTYPE package must be a single unit for any given run. The last encountered FUELTYPE package will be the fuel bed specification until another FUELTYPE package is encountered.

5. When using the STDFUELS package, a conflict can arise because the SITEDATA package card specifies the moisture of extinction of the dead fuel category. This parameter can also be specified on the STDFUELS package card, and the last value input will be used. When the STDFUELS package card is used to specify it, the moisture of extinction of the dead fuel can be left blank or set to zero, and subroutine STDFUEL will supply a value.

6. When using the STDFUELS package, a HEADING package input is automatically produced. It can be overridden by inserting a HEADING package later in the data sequence.

7. It is not necessary to use either NEW FUEL or FUELTYPE packages when using a STDFUELS package, nor is it necessary to use a SIZELIMS package because the STDFUELS package generates a complete description of the fuel array. A SIZELIMS package, following the STDFUELS package in the input sequence, overrides the "NØNE" entry automatically supplied by the STDFUELS option.

PRINTED OUTPUT AND ERROR TERMINATIONS

The "label" names SUPPRESS and SHØWDATA are used to control the printed output from subroutine SETUP. Whenever a label card is encountered with SUPPRESS as the label name, thereafter SETUP will produce no printed output save for a diagnostic phrase in the event of error termination. When a SHØWDATA label name is encountered, the effect of the SUPPRESS card is canceled. Neither card is ever required, and until a SUPPRESS card is encountered, a SHØWDATA instruction is assumed to be in effect. Whenever the "SHØWDATA" condition is in effect, the printed output is as follows:

SETUP skips a page and heads it with a phrase "INPUT DATA IMAGE, SUBRØUTINE SETUP..RUN NØ. N" before producing a near-verbatim replication of the input cards. As subroutine SETUP reads in each card, it prints the data out; if the data are incomplete or inconsistent, SETUP will terminate the job with an error message. Because each card is printed out as it is read, it is usually easy to spot an offending card and the error in it.

The "SUPPRESS" option is intended to reduce printed output when a great amount of data are to be entered through subroutine SETUP, when the user is confident that there are no unprocessable cards in the data stack. Note that if the first card in the data stack is a "SUPPRESS" label card, SETUP will produce no output except diagnostic messages on error termination.

CARD FORMATS AND CONTENTS

A label card is of the form (TYPE,NUMBER) where NUMBER=number of package cards to follow.

The format for the label cards is A8,I3. In the case of NEW FUEL and FUELTYPE labels, the number of cards in the package following must be specified in the integer field. For all other labels, the number of cards in the package is assumed to be 1. The formats of the cards in each package are given below:

HEADING package card.

FORMAT (10A8).

This is a free-field card which is often reproduced en toto as a job description heading when FIREMØD and other routines are called.

NEW FUEL package cards.

FORMAT (A8,2X,A4,2X,4(5X,F6.1),2(2X,A8))

VARIABLES: NAME,LIFE,HEAT,DENS,TMIN,EMIN,WØRD,RUFF

DEFINITIONS OF VARIABLES

NAME=8-character alphanumeric identifier of fuel type, such as S NEEDLE (spruce needle) or DF TWIGS (Douglas-fir twigs).

LIFE=4-character word identifying fuel as live (LIFE=LIVE) or dead (LIFE=DEAD) category. Default aborts input.

HEAT=low heat of combustion in Btu/lb

DENS=dry density of fuel in lb/ft^3

TMIN=total mineral content, fraction of dry weight

EMIN=silica-free mineral content, fraction of dry weight

WØRD=8-character alphanumeric, signaling whether this fuel-identifying card represents a revision of properties of a fuel type already in the dictionary (WØRD=REVISIØN) or a new fuel type to be added to the dictionary (WØRD=NEW FUEL). On default (i.e., WØRD=anything other than these two) the input cycle may be aborted when the dictionary-keeping subroutine FUELS is called, because an internally maintained flag quantity will have a value specified by the last call to FUELS. If this NEW FUEL package represents the first time the dictionary is consulted, the default value of WØRD will be considered to be the same as the last-recognized value.

RUFF=8-character alphanumeric that has only one significant value (RUFF=ESTIMATE). If RUFF≠ESTIMATE, the input values of HEAT,DENS,TMIN, and EMIN are to be inserted in the dictionary as properties of the fuel type (NAME,LIFE). If RUFF=ESTIMATE, the input values are ignored and default values are used instead. These values are:

HEAT = 8,000 Btu/lb

DENS = 32 lb/ft^3

TMIN = 0.0555

EMIN = 0.0100

FUELTYPE package cards.

The label card is of the form (LABEL,NUMBER), where NUMBER=number of FUELTYPE cards to follow:

FORMAT (A8,2X,A4,1X,3(9X,F6.1),12X,A8)

VARIABLES: NAM,LIFE,SIG,XLØAD,XMST,RUFF

DEFINITIONS OF VARIABLES

NAM=8-character alphanumeric name, to be found in the dictionary of fuel characteristics (e.g., corresponds to NAME on NEW FUEL package card).

LIFE=4-character word identifying fuel as live (LIFE=LIVE) or dead (LIFE=DEAD) category. (If neither, run will be terminated.)

SIG=surface/volume ratio of fuel particles of this type, ft^{-1}

XLØAD=dry weight loading of fuel of this type, lb/ft^2

XMST=moisture content of this fuel type, fraction of dry weight

RUFF=8-character alphanumeric that has only one significant value (RUFF=ESTIMATE). This flag quantity is consulted if the fuel type (NAM,LIFE) is *not* in the dictionary, and the default value of HEAT,DENS,TMIN, and EMIN will be returned only if RUFF=ESTIMATE. Otherwise, the input cycle is aborted with an error message. The default value of RUFF≠ESTIMATE.

SITEDATA package card.

FORMAT (6(8X,F5.2))

VARIABLES: WINDI,WINDF,DELW,SLØPE,DEPTH,MEXT(1)

DEFINITIONS OF VARIABLES

WINDI=minimum upslope windspeed, in mi/h, at midflame height.

WINDF=maximum upslope windspeed, in mi/h, at midflame height.

DELW=windspeed increment to be used in filling spread rate values (and Byram's intensity values) between WINDI and WINDF, in mi/h, at midflame height.

SLØPE=angle of slope, in degrees.

DEPTH=mean depth of fuel bed in direction normal to slope, ft.

MEXT(1)=moisture of extinction of dead fuel, fraction of dry weight.

The usage of degrees to describe slope is contrary to the common forestry practice of specifying slope by the value of the tangent of this angle, expressed usually as "percent" rather than a fraction. The correspondence between these specifications is as follows:

Percent slope :	10	20	30	40	50	60	70	80	90	100
Angle, degrees:	5.71	11.31	16.70	21.80	26.57	30.96	34.99	38.66	41.99	45.00

SIZELIMS package card.

FORMAT (2(A4,15X,I3,10X,I3,5X))

VARIABLES: NW1,IA,IB,NW2,IC,ID

DEFINITIONS OF VARIABLES

NW1=4-character alphanumeric that *must* have one of the following values: NØNE,LIVE, or DEAD.

Use of the option NW1=NØNE causes SETUP to ignore the other variables on the card, and to use all the fuel elements in the list as an array description.

If NW1=LIVE, then IA and IB are taken to be, respectively, the smallest and largest size classes of the LIVE fuel category that are present in the fuel complex specified by the FUELTYPE package. Furthermore, NW2 now *must* be DEAD to prevent an abort.

Similarly, if NW1=DEAD, then IA and IB are taken to be, respectively, the smallest and largest size classes in the DEAD fuel category that are to be included. Furthermore, NW2 now *must* be LIVE or the program run will be aborted.

IC and ID are taken to be, respectively, the smallest and largest size classes in the NW2 category.

NOTE: IA and IC, or both, can be zero or blank or negative and the smallest size class will be set to 1. Likewise, IB and/or ID can exceed the number of fuel types in the category, and the largest size class will be set to the number of size classes in the appropriate category. That is, IA,IB and IC, ID are taken to be "not to exceed" bounds, and do not have to be precisely specified if the bounds are fixed by the length of the list determined by the FUELTYPE package. For instance, if there are 23 dead and 17 live size classes specified in the FUELTYPE package, and the investigator wishes to include in a particular fuel complex all dead fuels *except* the three smallest and the two largest, but wants to include all the live fuels, the SIZELIMS card could be constructed in any of the following equivalent ways:

A) NW1=DEAD,IA=4,IB=21,NW2=LIVE,IC=1,ID=17

B) NW1=DEAD,IA=4,IB=21,NW2=LIVE,IC=BLANK,ID=100

C) NW1=LIVE,IA=0,IB=50,NW2=DEAD,IC=4,ID=21

D) NW1=LIVE,IA=1,IB=60,NW2=DEAD,IC=4,ID=21

Etc.

STDFUELS package card.

FORMAT (A4,1X,A1,4X,5(10X,F4.2))

VARIABLES: NSØURCE,MØDEL,XMD,CM1,CM2,CM3,CM4

DEFINITIONS OF VARIABLES

NSØURCE=4-character alphanumeric name, identifying the source entity of the fuel model. Currently only two source names are recognized: NSØURCE= NFDR or NFFL. The NFDR source produces the standard fuel models of the National Fire-Danger Rating System (Deeming and others 1972). The NFFL source produces a set of typical wildland fuel models that are very similar to those of the NFDR and virtually identical to those described by Rothermel (1972).

MØDEL=1-character alphanumeric (letter designator of fuel model). The set of fuel models that are available are listed for the two sources in the writeup of subroutine STDFUEL.

XMD=moisture of extinction of the dead fuel category. If this entry is blank or zero, subroutine STDFUEL provides a value.

CM1=moisture content of finest dead fuel size class.

CM2=moisture content of medium-sized dead fuel class.

CM3=moisture content of largest dead fuel size class.

CM4=moisture content of live fuel (only one size class exists for live fuel).

ØPTIØN card.

There is no package for this card. The label card is of the form (TYPE,NUMBER). When TYPE=ØPTIØNbb, (b=blank), the integer NUMBER value specifies the output option and control is immediately transferred from SETUP to the calling program. The quantity of printed output from the FIREMØD (and other) subroutines is controlled by the value of NUMBER, which is set equal to the blank common variable ØPT.

STØP card.

If a "label" card with STØP in the first four columns is encountered, SETUP immediately terminates the job.

GENERAL NOTE

Note that all the "package" cards have blank spaces interleaved between the numerical fields. This was done intentionally so that data cards could be punched with identifying phrases preceding each of the numerical entries. The "label" cards have a 69-character free field on the right-hand side so the "packages" can be labeled with identifying remarks. A typical data deck setup is shown below, illustrating the use of mnemonic identifiers of data fields and remarks on label cards.

SAMPLE DATA DECK FOR SETUP

A sample data deck suitable for use with subroutine SETUP is shown below. The output produced by this sample data is given in the writeup of PRØGRAM SAMPLE.

```
         11111111112222222222333333333344444444445555555555666666666677777777778
12345678901234567890123456789012345678901234567890123456789012345678901234567890

HEADING             SAMPLE-OUTPUT GENERATING DATA SET
 HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT
SITEDATA
MIN WIND 0.0 MAX WIND 6.0 STEPSIZE 1.0 SLOPE = 30.96 DEPTH = 2.8 DEADMEXT .25
NEW FUEL   3      LIVE FUEL COMPONENTS
GRASSES    LIVE   HEAT=8100. DENS= 29.0 MINL=.0700 EMIN=.0015   NEW FUEL  MEASURED
BUSHLEAF   LIVE   HEAT=9300. DENS= 26.0 MINL=.0650 EMIN=.0052   NEW FUEL  MEASURED
BUSHTWIG   LIVE                                                 NEW FUEL  ESTIMATE
NEW FUEL   6           DEAD FUEL COMPONENTS (SLASH)
NEEDLES    DEAD   HEAT=8300. DENS= 34.5 MINL=.0500 EMIN=.0200   NEW FUEL  OLD DATA
SM TWIGS   DEAD   HEAT=7800. DENS= 36.2 MINL=.0300 EMIN=.0220   NEW FUEL  OLD DATA
SM LIMBS   DEAD   HEAT=7900. DENS= 31.0 MINL=.0400 EMIN=.0190   NEW FUEL  NEW DATA
LG LIMBS   DEAD   HEAT=7900. DENS= 31.0 MINL=.0400 EMIN=.0190   NEW FUEL  NEW DATA
TREE TOP   DEAD                                                 NEW FUEL  ESTIMATE
PUNKYLOG   DEAD   HEAT=7000. DENS= 14.0 MINL=.0600 EMIN=.0140   NEW FUEL  CULL LOG
FUELTYPE   9      LOADINGS, SURFACE/VOLUME RATIOS, MOISTURE CONTENTS
NEEDLES    DEAD   SURF/VOL 1750. DRY LOAD .630   MOISTURE 0.07
SM TWIGS   DEAD   SURF/VOL  343. DRY LOAD .280   MOISTURE 0.09
SM LIMBS   DEAD   SURF/VOL   91. DRY LOAD .470   MOISTURE 0.10
LG LIMBS   DEAD   SURF/VOL   27. DRY LOAD .530   MOISTURE 0.12
TREE TOP   DEAD   SURF/VOL   11. DRY LOAD 1.45   MOISTURE 0.15
PUNKYLOG   DEAD   SURF/VOL   4.5 DRY LOAD 1.60   MOISTURE 0.30
GRASSES    LIVE   SURF/VOL 2800. DRY LOAD .091   MOISTURE 0.90
BUSHLEAF   LIVE   SURF/VOL 1250. DRY LOAD .007   MOISTURE 1.10
BUSHTWIG   LIVE   SURF/VOL  295. DRY LOAD .024   MOISTURE 0.70
SIZFLIMS
NONE
OPTION     1
OPTION     3        RERUN JUST TO SHOW OPTIONS INFLUENCE
STDFUELS        RERUN HEAVY SLASH MODEL FOR COMPARISON
NFFL J STD MOIS EXT.      FINE MOIS 0.07 MED MOIS 0.10 LGE MOIS 0.15 ALL DEAD
OPTION     1
STOP
```

SUBROUTINE FUELS

Subroutine FUELS stores a "dictionary" of fuel properties that are constants, not environmentally influenced variables. Specifically, the dictionary is a randomly organized list of fuel type names, and associated with each name is a set of four parameters: dry density, heat of combustion, total mineral content, and silica-free mineral content. FUELS also provides for temporary additions to and revisions of the contents of the dictionary. Adding, revising, and extracting of data using subroutine FUELS are accomplished by setting flag parameter INØUT in the calling argument.

CØMMØN DATA: None

CALLING SEQUENCE: CALL FUELS(NAME,LIFE,INØUT,HEAT,DENS,TMIN,EMIN,RØUGH,FLAG)

PRECONDITIONS

1. To extract data from file maintained by FUELS, INØUT=(Negative integer).
2. To add data to file maintained by FUELS, INØUT=0.
3. To revise data in file maintained by FUELS, INØUT=(Positive integer).

NOTE-The role of flag parameter, RØUGH, is controlled by INØUT.

VARIABLES IN CALLING SEQUENCE

NAME=8-character alphanumeric name of fuel type.

LIFE=*must* be either 4HLIVE or 4HDEAD, specifying the category of the fuel type as LIVE or DEAD.

INØUT=integer. See PRECØNDITIØNS.

HEAT=heat of combustion of fuel type (Btu/lb).[1]

DENS=dry density of fuel type (lb/ft^3).[1]

TMIN=total mineral content of fuel type (fraction dry weight).[1]

EMIN=Silica-free mineral content of fuel type (fraction dry weight).[1]

RØUGH=floating point flag quantity (1.0 is only meaningful value).

FLAG=output floating point flag quantity (0. or 1. is output).

VARIABLE RØUGH

When inserting (adding or revising) data, if RØUGH=1.0, the values of HEAT,DENS, TMIN, and EMIN are ignored, and prestored rough estimate values are used.

[1]These can be either input or output, depending upon INØUT input value.

When extracting data, if RØUGH=1.0, then if *NAME,LIFE* do not correspond to an entry in the dictionary, the rough estimate values of HEAT,DENS,TMIN, and EMIN are returned. In this case FLAG is set to 1.0.

The rough estimate values are:

HEAT = 8,000 Btu/lb

DENS = 32 lb/ft^3

TMIN = 0.0555

EMIN = 0.010

VARIABLE FLAG

Plays no role when data are inserted.

Is set to zero when data are extracted by matching *NAME* and *LIFE* to entries in the dictionary. Is set to 1.0 when extracting data and *NAME,LIFE* do not match entries in the dictionary *and* RØUGH=1.0, so estimates are returned.

PRINTED OUTPUT AND PROGRAM TERMINATION CONDITIONS

Printed output occurs whenever conflicting requirements are placed on the subroutine. A diagnostic message, along with an image of the calling sequence variables, is output and the run is terminated.

Conditions for termination are:

1. Trying to extract data and *NAME,LIFE* entry not in dictionary and RØUGH≠1.

2. Trying to revise data and *NAME,LIFE* entry not in dictionary.

3. Trying to add data and exceeded storage bounds.

4. Trying to add data and *NAME,LIFE* already in dictionary.

5. Category *LIFE* is neither *LIVE* nor *DEAD*.

SUBROUTINE FIREMØD

Subroutine FIREMØD is a FØRTRAN IV embodiment (with some variations) of the equations for predicting rate of fire spread in wildland fuels (Rothermel 1972). The permanently stored version of this subroutine contains about 190 lines of statements that define the input, output, and internal variables, and give reference to the appropriate equations in the cited monograph. Internal variables are not described here. Input and output are passed through UNLABELED CØMMØN, so the reader is referred to that discussion in this manual. Those parameters that are listed under "FIREMØD" in the column labeled "VALUE FROM" are output from FIREMØD; the other variables are input to FIREMØD.

ϹØMMØN DATA: UNLABELED CØMMØN
CALLING SEQUENCE: CALL FIREMØD(Y)

The output variable, Y, is a flag quantity that will have the value 0. or 1. If the fuel complex analyzed has a characteristic surface area/volume per particle of 175 ft^{-1} or less, and a wind is present, the flag parameter Y is set to 1., indicating that the reliable range of correlation of spread rate-vs-windspeed has been violated, and all wind-driven spread rate output may be suspect.

PRECONDITIONS

The input variables must be defined before FIREMØD is called, or execution errors are likely to result. To establish the values of input variables that describe the site, environment, and fuel array, the input-processing subroutine SETUP can be used. Otherwise, these variables must be read in or computed. (Refer to SETUP description for a thorough discussion of these variables.)

FIREMØD tests to be certain that dead fuels are included in the fuel array, and that the dead fuel array has an average moisture content (based on weighting by fuel particle surface area) less than the moisture of extinction specified, before proceeding with calculations. If these conditions are not met, an advisory message is printed out, and control is transferred to the calling program. This avoids the problem of error termination during computations on a fuel array that would not support fire spread anyway. This check is made *after* fuel size list ordering and after the fuel list has been printed out.

DEVIATIONS FROM ROTHERMEL'S EQUATIONS

Several changes in the model as published by Rothermel (1972) have been incorporated in this version of subroutine FIREMØD. The changes, and a brief discussion of the rationale for them, are listed below:

1. *Correction for mineral content*--The dry weight loading of any particular fuel element, w_o, includes the noncombustible mineral fraction, S_T. The loading of combustible dry fuel is:

$$w_o(1-S_T), \text{ not } w_o/(1+S_T)$$

as in Rothermel (1972).

2. *Mineral damping coefficient*.--The expression for the mineral damping coefficient, which modifies the reaction intensity, is:

$$\eta_s = 0.174(S_e)^{-0.19}$$

where S_e is the silica-free ash content of the fuel. When S_e is less than $\tilde{}1.5\times10^{-4}$, this equation produces η_s >1.0. To preclude this possibility, the value of η_s is "clamped" in the subroutine so that it never exceeds unity.

3. *Reaction velocity correlation*.--The equation for the reaction velocity, Γ', includes an exponent, A, which is calculated from Rothermel's equation 39 (1972).

$$A = (4.77\ \sigma^{0.1} - 7.27)^{-1}$$

This equation is singular for $\sigma \approx 67.63$, and A is negative for values of σ less than this. Negative values of A give values of Γ' greater than Γ'_{MAX}, and frequently very much greater.

To prevent this anomaly, a new equation for A has been programed into the spread model:

$$A = 133\sigma^{-0.7913}$$

This equation fits the data as well as the one it replaces over the range of σ for which experimental data exist, but some change in spread rate between the two methods can be anticipated, particularly at high packing ratios and values of σ around 1,000 ft^{-1}.

4. *Weighting factors for fuel loading*.--The net loading of the live and dead fuel categories is calculated by summing the loading of each size class in the category, with a weighting factor based on the fraction of that category's fuel surface area contributed by that size class:

$$w_{net,i} = \sum_{\substack{\text{size} \\ \text{class } j}} f_{ij} w_{n,ij}$$

In Rothermel's version (1972) of the model, the f_{ij} were calculated simply from

$$f_{ij} = (\sigma_{ij} w_{oij}/\rho_{ij}) / \sum_j (\sigma_{ij} w_{oij}/\rho_{ij})$$

where $\sigma_{ij} w_{oij}/\rho_{ij}$ is the surface area of the fuel component i,j per unit area of the ground. This method suffers from the logical flaw that the net loading is sensitive to the partitioning of the fuel loading amongst nearly equal size classes. (For example, if half of w_{oij} is placed in the size class i,j', and the other half in i,j'', the *net* loading contribution of w_{oij} is reduced to half its former value, even if $\sigma_{ij}' = \sigma_{ij}''$.)

To alleviate this difficulty, subroutine FIREMØD partitions the fuels, by size, into six subclasses, and gives all the members of each subclass the same weighting factor. The weighting factor for a subclass is the fraction of the total fuel surface area contributed by that subclass:

$$w_{net,i} = \sum_j g_{ij} w_{n,ij}$$

$$g_{ij} = \sum_{\substack{\text{subclass} \\ \text{to which} \\ j \text{ belongs}}} f_{ij}$$

The subclasses are defined in terms of the surface/volume ratio, σ, of the fuel elements shown below. These definitions are largely arbitrary, and do not represent any recommendations as to how fuel element size classes should be specified for sampling purposes.

Size (σ), ft^{-1}	*Equivalent diameter, D, inches*	*Subclass*
$\sigma \geq 1{,}200$	$0.04 \geq D$	1
$1{,}200 > \sigma \geq 192$	$0.25 \geq D > 0.04$	2
$192 > \sigma \geq 96$	$0.5 \geq D > 0.25$	3
$96 > \sigma \geq 48$	$1 \geq D > 0.5$	4
$48 > \sigma \geq 16$	$3.0 \geq D > 1$	5
$16 > \sigma$	$D > 3.0$	6

NOTE: Subclass 6 is ignored in the calculations (the weighting factor is set to zero), since fuels of >3-inch diameter do not contribute to the spread process.

5. *Moisture of extinction of live fuels.*--The moisture of extinction of the live fuel category is calculated from the ratio of the loadings of dead and live "fine" fuels and the moisture content of "fine" dead fuel. In order to reduce the sensitivity of the model output to arbitrary definitions of "fine," a method of calculating the relevant loading ratio and the "fine" dead fuel moisture content using *all* size classes was generated. Because the Chamise "dynamic fuel model" (Rothermel and Philpot 1973) is being used in southern California and represents a most important application of the model with mixed live and dead fuels, this model was used as a benchmark in order to derive an explicit definition of "fine fuels" for general use. William H. Frandsen, of the Northern Forest Fire Laboratory, discovered in 1973 that by using a weighting factor of the form $\exp(-K_i/\bar{\sigma}_{ij})$ for the loading in each category, the results of the computation would be the same (using all size classes) as when using the "Chamise model" arbitrary definition of "fine" for chaparral-type fuels.

Using the values of K = 138 for dead fuel and 500 for live fuel, the "Chamise model" output is almost exactly reproduced. The current model uses the following equations to calculate the dead/live loading ratio and "fine" dead fuel moisture.

$$\text{Dead/Live Loading Ratio} = W = \frac{\sum_{j=1}^{n_1} \bar{w}_{o1j} \exp(-138/\bar{\sigma}_{1j})}{\sum_{j=1}^{n_2} \bar{w}_{o2j} \exp(-500/\bar{\sigma}_{2j})}$$

$$\text{"Fine" Dead Fuel Moisture} = M_{f,Dead} = \frac{\sum_{j=1}^{n_1} \bar{M}_{f1j} \bar{w}_{o1j} \exp(-138/\bar{\sigma}_{1j})}{\sum_{j=1}^{n_1} \bar{w}_{o1j} \exp(-138/\bar{\sigma}_{1j})}$$

where n_1 and n_2 are, respectively, the number of dead and live fuel size classes, $(\bar{w}_o)_{ij}$ is the ovendry loading, and $\bar{\sigma}_{ij}$ is the surface/volume ratio of category i (i=1, dead; i=2, live) and size class j, $(\bar{M}_f)_{1j}$ is the moisture content of the dead fuel of size class j.

The live fuel moisture of extinction, $(M_x)_{Live}$, employed in Rothermel (1972) is given by his equation 88:

$$(M_x)_{Live} = 2.9W(1-M_{f,Dead}/0.3) - 0.226 \qquad \text{(min value 0.3)}$$

Implicit in this formula is the assumption that the dead fuel moisture of extinction is equal to 0.3.

Because many fuel models employ other moistures of extinction than 0.3, this equation is not always consistent with the fuel model being exercised. In some cases it is possible to have the live fuel burning while the dead fuel will not burn, using this formula. To correct this inconsistency, this equation was replaced by:

$$(M_x)_{Live} = 2.9W(1-M_{f,Dead}/(M_x)_{Dead}) - 0.226, \quad \text{(min value } (M_x)_{Dead})$$

The effect of this change on the performance of the four Northern Forest Fire Laboratory Standard Fuel Models with live components (Models B,C,F, and G) is shown in the four accompanying figures (fig. 1 through 4) as the ratios of spread rates and/or intensities computed by the two methods. In general, the new method produces slower-spreading, less-intense fires when $(M_x)_{Dead} < 0.3$.

6. *Weighting factor on intensity by category.*--Frandsen (1973) pointed out the possible difficulty in using the category weighting factor, f_i, originally used by Rothermel's (1972) equation 57, to calculate the total reaction intensity. He proposed to substitute the "effective heating number" $\varepsilon_i = \exp(-138/\sigma_i)$ for the factor f_i.

After reviewing the rationale behind the use of a category weighting factor on intensity, and noting that in virtually all wildland fuel complexes $\tilde{\sigma} \geq 500$, a concensus was reached that there was no necessity for having any weighting factor on reaction intensity by category. This becomes more apparent if one considers the limiting case of a laboratory fuel bed of one category of constant size class: Using the effective heating number as a weighting factor would cancel this term from the denominator, where its presence is required.

The current model uses no category weighting factor on intensity. Rothermel's (1972) equation (58) for computing reaction intensity becomes:

$$I_R = \Gamma' \sum_{i=1}^{i=m} (\tilde{w}_n)_i \tilde{h}_i (\tilde{\eta}_s)_i (\tilde{\eta}_m)_i$$

SEQUENCE OF COMPUTATIONS BY FIREMØD

The sequence of the major computations performed by FIREMØD is listed below:

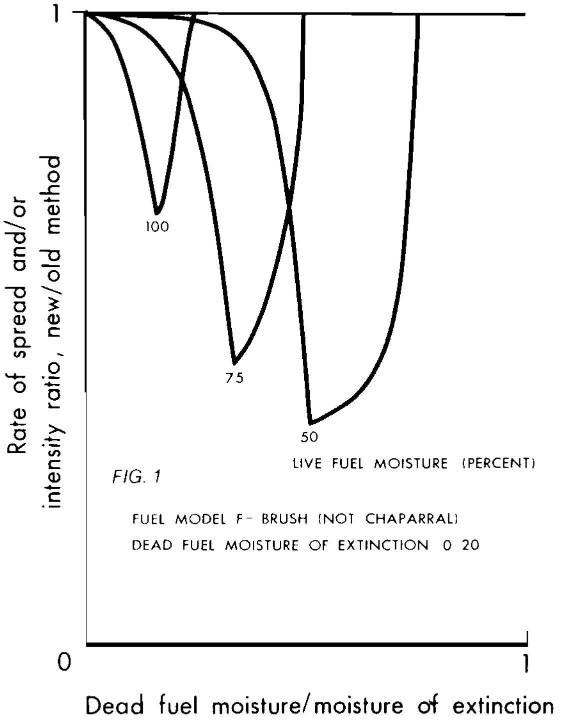
1. Zero working arrays and initialize output variables to zero.
2. Sort fuel components by size (see ISIZE array under UNLABELED CØMMØN).
3. Delete large size fuel elements (>3-inch diameter) from consideration.
4. Calculate size class weighting factors.
5. Check to be certain that at least dead fuel category moisture content does not exceed moisture of extinction.
6. Calculate moisture of extinction of live fuels.
7. Calculate reaction intensity of live and dead categories.
8. (Optional) output fuel descriptors, site descriptors, and run heading.
9. (Optional) output results of live and dead category array calculations.
10. Calculate intensity and spread rate versus wind for fuel array as a whole.
11. (Optional) output gross parameters--"homogenized" fuel descriptors.
12. Calculate array of spread rates versus windspeeds.
13. (Optional) output windspeed, spread rate, Byram's intensity arrays.

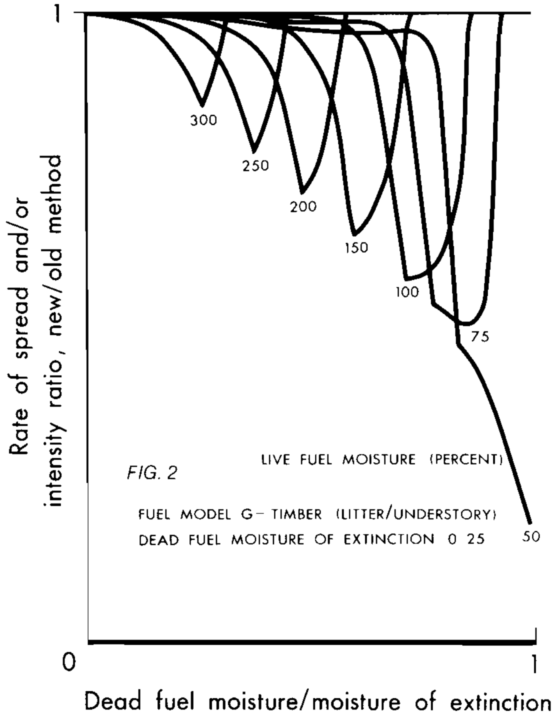
PRINTED OUTPUT

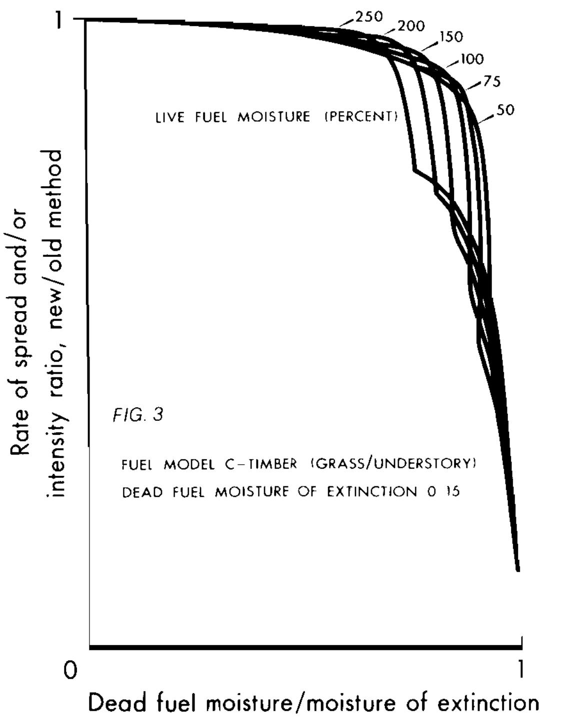
All printed output from subroutine FIREMØD is controlled by the input parameter ØPT, an integer. (See the ØPTIØN package writeup under subroutine SETUP.) If ØPT=1, all output prerogatives are exercised. If ØPT <1 or ØPT >3, no printed output is generated by FIREMØD. ØPT=2 produces intermediate and final output, but no fuel description, while ØPT=3 produces spread rate versus windspeed table only.

ØPT >3 suppresses all printed output from FIREMØD and some other routines.

ØPT=3 causes FIREMØD to print requested range of windspeeds (as specified by the SITEDATA package card) along with associated spread rate wind factors, spread rates, and Byram's fireline intensity.







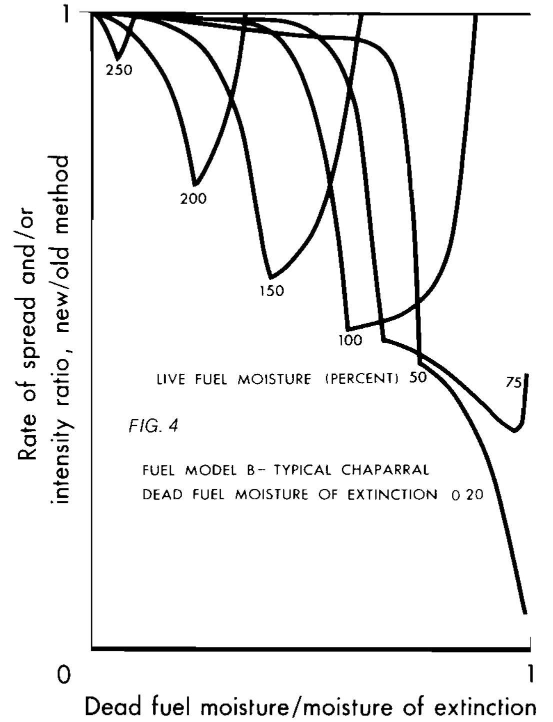


Figure 1.--Variation of reaction intensity and spread rate with dead fuel moisture--comparison of current and previous-method results, for standard fuel model NFFL-F.

Figure 2.--Variation of reaction intensity and spread rate with dead fuel moisture--comparison of current- and previous-method results, for standard fuel model NFFL-G.

Figure 3.--Variation of reaction intensity and spread rate with dead fuel moisture--comparison of current- and previous-method results, for standard fuel model NFFL-C.

Figure 4.--Variation of reaction intensity and spread rate with dead fuel moisture--comparison of current- and previous-method results, for standard fuel model NFFL-B.

ØPT=2 causes FIREMØD to print all of the above, plus gross fire spread parameters (packing ratio, optimum packing ratio, slope factor, characteristic surface/volume ratio, reaction velocity, reaction intensity, and heat sink).

ØPT=1 causes FIREMØD to print all of the above, plus page heading, including date and run number, fuel depth, and slope tangent.

A list of all the fuel types used (along with all fuel properties, including moisture of extinction), ordered in terms of increasing particle size.

Category descriptors, including percentage contribution to reaction intensity, characteristic surface/volume ratio, mineral damping coefficient, moisture damping coefficient, and effective loading.

ØPT <1 suppresses all printed output from FIREMØD.

SUBROUTINE STDFUEL

Subroutine STDFUEL is a utility subroutine intended to facilitate the specification of fuel arrays that are "standard models." Two sets of standard models are available: Those used in the National Fire-Danger Rating System (Deeming and others 1972) and a similar set of typical wildland fuel models used internally at the Northern Forest Fire Laboratory (Rothermel 1972). A complete description of the fuel array is generated by a single call to STDFUEL, which establishes the data in unlabeled common data suitable for use by FIREMØD and other subroutines in the library package. Environmental variables (wind and slope) must be supplied externally. Data for subroutine STDFUEL can be supplied by using subroutine SETUP, but it is not necessary to do so.

CØMMØN DATA: UNLABELED CØMMØN

CALLING SEQUENCE: CALL STDFUEL (ISØURCE,IWHICH,MSTURE,XMD,CM1,CM2,CM3,CM4)

PRECONDITIONS

1. STDFUEL uses subroutine FUELS, so FUELS must also be compiled.

2. STDFUEL generates a dead-fuel moisture of extinction, a heading array, and size limits specification, so the order of data input through subroutine SETUP is important. See writeup of subroutine SETUP.

3. If flag quantity MSTURE=0, dead fuel moisture of extinction is set to input variables XMD. If MSTURE $\neq$ 0, a standard value (dependent upon fuel model selected) is supplied by STDFUEL.

VARIABLES IN CALLING SEQUENCE

All variables are input quantities.

ISØURCE = 4-character alphanumeric variable specifying the source entity for the fuel model selected. ISØURCE *must* be either 4HNFDR (to select National Fire-Danger Rating System fuel models) or 4HNFFL (to select Northern Forest Fire Laboratory fuel models). Program will be terminated if ISØURCE is not recognized as one of these names.

IWHICH = 1-character alphanumeric designator of fuel model. (See table of model types below.)

MSTURE = Integer flag quantity, specifying source of the value of dead fuel moisture of extinction (see PRECONDITIONS above).

XMD = Dead fuel moisture of extinction (specified by input value only if MSTURE=0).

CM1 = Moisture content of the finest size class of dead fuel.

CM2 = Moisture content of the intermediate size class of dead fuel.

CM3 = Moisture content of the largest size class of dead fuel.

CM4 = Moisture content of (only size class of) live fuel.

PRINTED OUTPUT

Printed output occurs only when incompatible specifications are supplied to STDFUEL, such as ISØURCE not recognized or IWHICH specifies a model which does not exist for given ISØURCE. The output message images the input variables.

PROGRAM TERMINATION CONDITIONS

1. ISØURCE *is not* either NFDR or NFFL.
2. When ISØURCE=NFDR, and IWHICH *is not* a letter between A and I.
3. When ISØURCE=NFFL, and IWHICH *is* the letter D or *is not* a letter between A and L.

FUEL MODELS AVAILABLE

Table 1 describes the fuel models available through STDFUEL.

Table 1.--*Standard fuel models available through subroutine STDFUEL*

Model	Name	Surface/volume (ft^{-1}) and Loading (lb/ft^2) Dead	Live	Depth (ft)	Moisture of extinction, dead fuel
NFDR FUEL MODELS					
A	Short grass	3000/.0574	--	0.75	0.25
B	Chaparral	2000/.23,109/.184,30/.0918	1500/.0918	6.00	.25
C	Timber (grass & understory)	2700/.0689,109/.0459	--	1.00	.25
D	Sage & low pocosins	1750/.0689,109/.115,30/.0918	--	2.50	.25
E	Hardwood litter	2500/.0689,109/.0459	--	.30	.25
F	Brush (not chaparral)	1500/.0459,109/.023	1500/.0918	2.00	.25
G	Timber (litter & understory	1500/.138,109/.0918,30/.23	--	1.25	.25
H	Closed timber litter	2000/.0459,109/.0459,30/.0459	--	.40	.25
I	Medium logging slash	1500/.184,109/.23,30/.459	--	3.50	.25
NFFL FUEL MODELS					
A	Short grass	3500/.034	--	1.0	.12
B	Chaparral	2000/.23,109/.184,30/.092	1500/.23	6.0	.20
C	Timber (grass & understory)	3000/.092,109/.046,30/.023	1500/.023	1.0	.15
D	None				
E	Hardwood litter	2500/.134,109/.019,30/.007	--	.2	.25
F	Brush (not chaparral)	2000/.046,109/.023	1500/.092	2.0	.20
G	Timber (litter & understory)	2000/.138,109/.092,30/.23	1500/.092	1.0	.25
H	Closed timber litter	2000/.069,109/.046,30/.115	--	.2	.30
I	Medium logging slash	1500/.184,109/.644,30/.759	--	2.3	.20
J	Heavy logging slash	1500/.322,109/1.058,30/1.288	--	3.0	.25
K	Light logging slash	1500/.069,109/.207,30/.253	--	1.0	.15
L	Tall grass	1500/.138	--	2.5	.25

For all fuel particles, the following properties are used: Ovendry density 32 lb/ft^3, heat of combustion 8,000 Btu/lb, total mineral content 0.0555, silica-free mineral content 0.0100.

SUBROUTINE FLAME

Subroutine FLAME uses the output of subroutine FIREMØD to estimate characteristics of the flame produced by the reaction zone of a spreading fire. The bases for these calculations are published research papers that include experimental verifications of the correlation equations over at least part of the range over which the parameters can be expected to vary in wildland fire situations. Nevertheless, the accuracy of the predictions of subroutine FLAME over the entire range possible is not known. The subroutine is made available for information and for research purposes; the user is cautioned that the Northern Forest Fire Laboratory has not verified the accuracy of each output from the models.

CØMMØN DATA: UNLABELED CØMMØN

CALLING SEQUENCE: CALL FLAME

PRECONDITIONS

1. Output from FIREMØD is anticipated by subroutine FLAME, so if the variable RUN is zero when FLAME is called, then FLAME will call FIREMØD. So if the data are supplied by some other source than FIREMØD, the programer should be certain to set the value of the variable RUN to something other than zero before a call to FLAME.

2. If FIREMØD is not to be used with this subroutine, the programer should include a dummy subroutine with the name FIREMØD to avoid having the loader abort the job for want of an external routine by that name.

PRINTED OUTPUT

Subroutine FLAME produces a pageskip, reproduces the HEADING message, and titles the page, along with a message that the wind is upslope, with the slope tangent given. Then eight column headings are printed, and as many rows of data are printed as there are entries in the list of spread rates-vs-windspeed as output from FIREMØD. The output data are, in order:

1. Windspeed at midflame height, mi/h
2. Byram's intensity, Btu/min/ft
3. Flame length, ft, from Byram's formula (see below)
4. Crown scorch height, ft, from Van Wagner's formula (see below)

5.-8. Flame length, height, horizontal reach (ft), and tilt angle from vertical, from Thomas' formulas (see below).

A cautionary message is output as a footnote to the table when windspeeds exceed the value for which spread rate increases. Following this warning, the maximum "reliable" values for the entries in the first four columns are printed.

When the slope exceeds 50 percent, a cautionary message is output, warning the user that the crown scorch height can be badly underestimated due to a change in the pattern of flow of the hot, buoyant column of air from the fire front. The equation used to estimate the maximum height of lethal crown scorch is based on level-ground experimental data, and evidence exists that it may fail dramatically in high-slope terrain.

PROGRAM TERMINATION CONDITIONS

No provisions are made for normal program termination by subroutine FLAME. Error termination can occur if the input variables are not specified fully.

CALCULATIONS PERFORMED

The windspeed, rate of spread, reaction intensity, and Byram's intensity are input to the subroutine. Byram's equation for flame length (Brown and Davis 1973)

$$\ell = 0.45\ I^{0.46}$$

(ℓ in ft, I in Btu/s/ft) is used to calculate the flame length printed in the third column.

The lethal scorch height for coniferous crowns is calculated from Van Wagner's equation (Van Wagner 1973):

$$h_s = 3.94\ I^{7/6}/((0.107I + U^3)^{1/2}(60-T))$$

(h_s in m, I in kcal/m/s, U is windspeed in m/s, T is ambient temperature, C). This equation uses Byram's intensity, I, and is based on scorch temperature of 60° C (140° F). The ambient temperature, T, is assumed to be 77° F for the calculation in subroutine FLAME, but the scorch height for any other ambient temperature can quickly be established from the scaling relationship:

$$h_s(T) = (63/(140-T))h_s(77^oF).$$

The correlation equations developed by P. H. Thomas (1962, 1967) are used to generate the last four columns of output. His equations contain the parameters D (depth of flaming zone) and m_f'' (the rate of mass production per unit area of ground surface) and predict flame length and flame height. (Thomas also developed equations in which he used the symbol D as a characteristic dimension of a nonspreading fire. We use this formulation in order to be able to predict flame height and horizontal reach. Thomas also derived a line-fire equation much like Byram's with $\ell = 0.20I^{2/3}$. It doesn't seem to work as well over the wide range as does Byram's correlation, and is not used here.) The depth, D, is calculated from the rate of spread, R, and the characteristic-particle surface/volume ratio, $\tilde{\sigma}$, as (Anderson 1969):

$$D = 384\ R/\tilde{\sigma}.$$

The mass production rate per unit area, m_f'', is estimated from the reaction intensity, I_R, and a rough estimate of the heat of combustion of 8,000 Btu/lb:

$$m_f'' \doteq I_R/8{,}000 \qquad (\text{lb/ft}^2/\text{min})$$

Thomas' relationships are:

$$\ell = \text{flame length} = \begin{cases} 42D(m_f''/\rho(gD)^{1/2})^{0.61}, & \text{no wind} \\ 70D((m_f'')^2/\rho^2 gD)^{0.43}(gD/U^2)^{0.11}, & \text{windspeed} = U \end{cases}$$

$$h = \text{flame height} = \begin{cases} \ell, & \text{no wind} \\ 56D\ (m_f''/\rho U)(U^2/gD)^{0.13}, & \text{windspeed} = U \end{cases}$$

where ρ is the density of ambient air, g is the acceleration of gravity, and the units are any consistent set so that the expressions in parentheses are dimensionless.

Note that these equations are singular for extremely low wind velocities, but the no-wind values are given. Subroutine FLAME restricts the low windspeed value of the flame length to the no-wind value, and constrains the height not to exeed the length. The low windspeed condition exists when the wind coefficient that changes spread rate falls below a minimum value. The wind coefficient for spread rate, ϕ_w, is of the form (Rothermel 1972):

$$\phi_w = AU^B.$$

Because spread rate determines D, and spread rate is related to wind and slope through coefficients ϕ_w and ϕ_s,

$$R = (1 + \phi_s + \phi_w)R_o.$$

The dependence of flame length on windspeed can be written as

$$\ell = K(1 + \phi_s + AU^B)^{0.68}U^{-0.22}.$$

Taking the logarithmic derivative of this expression gives the critical value for the wind coefficient

$$(\phi_w)_{critical} = \frac{1 + \phi_s}{34B/11 - 1}.$$

When ϕ_w falls below the value, flame length increases with decreasing windspeed. So when this condition prevails, the flame length from Thomas' formula is restricted not to exceed the no-wind value.

SUBROUTINE CØNTAIN

Subroutine CØNTAIN provides two methods whereby the rates of area and perimeter growth can be calculated for a fire on a uniform site, under the influence of both wind and slope. Under the assumptions implicit in the formulations used, the fire is initially extremely small (mathematically, a point) and grows in time with a constant rate of increase of linear dimensions, maintaining its shape as dictated by the slope, windspeed, and (in one model) wind direction. The accuracy of the predictions of the models used in this subroutine is unknown, but the values computed should be considered only to be rough estimates, useful for comparative evaluations and order-of-magnitude determination, but not for detailed planning or data analysis.

CØMMØN DATA:

1. UNLABELED CØMMØN

2. CØMMØN/WIND/WINDMAX,B,U,UC,W

3. CØMMØN/SLØPE/SLØPEMX,CØSPHI2,HAFPI

CALLING SEQUENCE: CALL CØNTAIN (METHØD)

PRECONDITIONS

1. Subroutine CØNTAIN employs the output from subroutine FIREMØD, so these values in unlabeled CØMMØN must be established before calling CØNTAIN. The value of the variable RUN is checked when CØNTAIN is called, and if RUN=0, CØNTAIN calls FIREMØD. If FIREMØD is not used to generate the values needed by CØNTAIN, set the value of RUN to something other than 0 before calling CØNTAIN.

2. If FIREMØD is not compiled along with CØNTAIN, the programer should include a dummy subroutine named FIREMØD in the deck containing the driver program to avoid an abort by the loader for want of an external routine by that name.

VARIABLES IN CALLING SEQUENCE

METHØD=Integer quantity determining the method(s) by which the calculations are to be performed. If METHØD=1, only the first method (described below) will be used. If METHØD=2, only the second method (described below) will be used. If METHØD=ANY VALUE BUT 1 OR 2, both methods will be used.

PRINTED OUTPUT

Method 1--produces a pageskip, reproduces the HEADING message including run number, prints the slope tangent, and titles the page. Then seven tables are printed out, each appropriately identified, with the rows in each table each corresponding to a value of windspeed as specified in the unlabeled common data. The columns of each table are, from left to right, for wind directions of 0, 45, 90, 135, and 180 degrees from upslope. The table entries are, respectively:

Table No.	*Meaning of entries*
1.	Fire area in square feet ÷ (burning time in minutes)^2
2.	Fire perimeter in feet ÷ (burning time in minutes)
3.	Maximum rate of fire spread, ft/min
4.	Direction (degrees from upslope) in which spread rate is maximum
5.	Fire area in acres ÷ (burning time in hours)^2
6.	Fire perimeter in chains ÷ (burning time in hours)
7.	Maximum rate of fire spread, chains/h

A footnote explains the conversion of tables 1, 2, 5, and 6 to units of area or length.

Method 2--produces a pageskip, reproduces the HEADING message including run number, prints the slope tangent, and titles the page. Then a seven-column table is printed, with each row corresponding to a windspeed. The windspeeds are those represented in the unlabeled CØMMØN variables. The entries in the columns, from left to right, are:

Column No.	*Meaning of entries*
1.	Windspeed at midflame height (uphill) in mi/h
2.	Fire perimeter in feet ÷ (burning time in minutes)
3.	Fire perimeter in chains ÷ (burning time in hours)
4.	Fire area in ft^2 ÷ (burning time in hours)^2
5.	Fire area in acres ÷ (burning time in hours)^2
6.	Maximum rate of spread in ft/min
7.	Maximum rate of spread in chains/h

A footnote explains the conversion of the area and perimeter outputs to area and lineal units.

In both cases, a cautionary message is printed whenever the rate-of-spread value is limited to the maximum value reliably predicted by the wind-coefficient correlation parameter reported by Rothermel (1972).

PROGRAM TERMINATION CONDITIONS

No provisions are made in subroutine CØNTAIN for normal program termination. Error termination can be produced if input variables are not defined in the expected manner.

CALCULATIONS PERFORMED

Method 1--calculates area and perimeter growth rates based on the assumptions that:

1. The rate of spread in any particular direction is determined by the slope tangent *in that direction*, with the rate-of-spread coefficients calculated according to the formulas given by Rothermel (1972) using the "component" values of slope tangent and windspeed indicated.

2. Negative slope or backing wind do not influence spread rate, i.e., the downhill and/or against-the-wind spread rate is the same as the no-slope and/or no-wind value.

Method 2--calculates area and perimeter growth rates based on the assumptions that:

1. The wind is blowing uphill.

2. The fire perimeter is described by two semiellipses with a common minor axis. The values of the major axes of the ellipses, relative to the common minor axis, are computed using a formula based on data by Fons[2] for wind-driven fire shapes. The formulas were developed by Hal Anderson[3] and use maximum rate-of-spread and windspeed as independent variables.

[2] Fons, Wallace L. 1940. Unpublished data on file at the Northern Forest Fire Laboratory, Missoula, Montana 59801.

[3] Anderson, Hal E. Memorandum (Fire Shape and Size) to R. C. Rothermel and W. C. Fischer, Northern Forest Fire Laboratory, Missoula, Montana 59801, August 10, 1973.

Method 1 equations.--The rate of spread in the direction Θ (an angle measured from uphill) is calculated from the equation

$$R(\Theta) = (1 + \phi_s(\Theta) + \phi_w(\Theta,w))R_o$$

where

$\phi_s(\Theta)$ = slope coefficient based on the slope sensed in the direction Θ from uphill,

$= \phi_s(\Theta=0)/(1+\tan^2\Theta/\cos^2\Theta_s)$,

where Θ_s is the slope angle.

For $|\Theta| > \pi/2$, $\phi_s = 0$.

$\phi_w(\Theta,w)$ = wind coefficient, based on the wind component in the direction, Θ, when the wind is blowing in the direction w from uphill.

$= \phi_w{*}\cos^B(w-\Theta)$, where $\phi_w{*}$ is the wind coefficient when the spread rate is in the direction of the wind, and the parameter B is that given by Rothermel (1972) in the equation relating windspeed, U, to wind coefficient:

$$\phi_w{*} = CU^B$$

When the spread direction is at a right angle (or greater), the wind direction, $\phi_w = 0$.

The equations for perimeter and area growth rate are:

$$\text{Perimeter : time} = \int_0^{2\pi} (R^2 + \left(\frac{dR}{d\theta}\right)^2)^{\frac{1}{2}} d\Theta$$

$$\text{Area : time}^2 = \int_0^{2\pi} \tfrac{1}{2} R^2 d\Theta$$

The integrals are evaluated numerically, using the Romberg quadrature procedure, to an accuracy of about 0.1 percent. The functions necessary to evaluate the numerical integrals are included as function subroutines in the same package with CØNTAIN in the subroutine library.

Method 2 equations.--The area and perimeter growth equations based on the two-ellipse model use only two parameters. These are the maximum rate of spread, R (assuming the wind is blowing uphill) and the windspeed, U. The semiminor axis (common to both halves of the perimeter shape function) is b, where

$$b = (a_1 p)^{\frac{1}{2}}$$

$$a_1 = (1 + 0.46 \exp(-0.00199U))/(1 + 1.16 \exp(-0.000983U))$$

$$p = 0.56 \exp(-0.00164U)$$

and U is in ft/min.

The long semimajor axis in the direction of the wind is a_2, where

$$a_2 = a_1 \exp(0.000983U)$$

and the semimajor axis in the direction against the wind is a_1.

All these parameters are proportional to the maximum rate-of-spread, R, which is used to scale these shape parameters with time. The spread rates are input values to subroutine CØNTAIN. The area-vs-time, normalized by the square of the maximum spread rate, is given by

$$\text{area} \div (\text{maximum spread rate})^2 = (\pi/2)(a_1 + a_2)b$$

implemented as a function subroutine included in the CØNTAIN entry in the library.

The perimeter of an elliptical contour is, of course, given by an elliptic integral. The approximate formula used in this implementation is

$$\text{perimeter} \div (\text{maximum rate of spread}) \doteq (\pi/2)((2(a_1{}^2 + b^2))^{\frac{1}{2}} + (2(a_2{}^2 + b^2))^{\frac{1}{2}})$$

Both the area and perimeter calculations are embodied in function subroutines included in the CØNTAIN entry in the library. These functions are written to use U in ft/min, and are independent of the maximum rate of spread, (R).

OTHER ROUTINES STORED WITH SUBROUTINE CØNTAIN

As mentioned above, several auxiliary calculations used by subroutine CØNTAIN are implemented as functions or subroutines, and are stored under the same name. For completeness, these additional routines are listed below.

FUNCTIØN AREL(U)

is the fire area ÷ (maximum rate of spread)^2 as a function of windspeed (U), in ft/min, by method 2 outlined above.

FUNCTIØN PEREL(U)

is the fire perimeter ÷ (maximum rate-of-spread) as a function of windspeed (U), in ft/min, by method 2 outlined above.

FUNCTIØN WIND(X)
CØMMØN/WIND/WINDMAX,B,U,UC,W

is the wind coefficient for fire spread rate in direction X, in radians, with respect to uphill, according to the formulation of method 1 outlined above. WINDMAX is the maximum value of the wind coefficient, B the exponent on windspeed used in computing the wind coefficient, U the windspeed in ft/min, UC the value of windspeed (in ft/min) at which the wind coefficient achieves its maximum value, and W is the wind direction, measured from uphill, in radians.

FUNCTIØN SLØPE(X)
COMMØN/SLØPE/SLØPEMX,CØSPHI2,HAFPI

is the slope coefficient for fire spread rate in direction X, radians with respect to uphill, according to the formulation of method 1 outlined above. SLØPEMX is the slope coefficient for spread uphill, CØSPHI2 is the square of the cosine of the slope angle, and HAFPI is $\pi/2$.

FUNCTIØN DWIND(X)
CØMMØN/WIND/WINDMAX,B,U,UC,W

is the derivative of function WIND(X) with respect to X.

FUNCTION DSLØPE(X)
CØMMØN/SLØPE/SLØPEMX,CØSPHI2,HAFPI

is the derivative of function SLØPE(X) with respect to X.

FUNCTION DSDX(X)
CØMMØN/SLØPE/SLØPEMX,CØSPHI2,HAFPI
CØMMØN/WIND/WINDMAX,B,U,UC,W

is the derivative of perimeter length with respect to polar angle X, formed by combining the wind and slope coefficients and their derivatives. Implicit in the calculations is normalization of the perimeter length by the no-wind, no-slope rate of spread.

ENTRY DADX(X)

is the derivative of fire area with respect to polar angle X, formed by combining the wind and slope coefficients for direction X. Implicit in the formulation is normalization of the area by the square of the no-wind, no-slope rate of spread.

SUBROUTINE RØMBERG

CØMMØN DATA: NONE

CALLING SEQUENCE: CALL RØMBERG(F,A,B,ACC,QUAD,FLAG)

This subroutine is a purely mathematical service routine, which computes the integral of function F from A to B by Romberg's quadrature procedure. ACC is input as the desired absolute accuracy, QUAD is the desired integral, and FLAG is an output quantity equal to 0, if the accuracy (convergence) specification has been achieved. If the accuracy specification has not been met, FLAG=1., and ACC is returned as an estimate of the accuracy achieved (Ralston and Wilf 1967).

SUBROUTINE BURNØUT

Subroutine BURNØUT estimates fire behavior in dead fuels after the passage of an igniting flame front. The output of subroutine FIREMØD is used by BURNØUT. This computation aims to predict the degree of fuel consumption and the time history of the intensity of fire in heavy fuel arrays such as logging slash, windthrown timber, piled fuels, etc. The theory behind the model is still largely untested, and users are cautioned to view output as tentative estimates.

CØMMØN DATA: UNLABELED CØMMØN

CALLING SEQUENCE: CALL BURNØUT(NPØINS, TPRINS,WDUFF,DMØIS,FLAG,TBØW,THEAT,RI,S)

DESCRIPTION OF VARIABLES

Variable	Mode	Range	Description
NPØINS	INTEGER	1-100	Input which defines how many time snapshots of the burnout process are to be generated. Internally limited to the inclusive range 1 to 100.
TPRINS	FLØATING	$\geq$ 0.1	Input which is the time, in minutes, between successive time snapshots of burnout process generated by the subroutine. Internally limited to equal or exceed 0.1 min.
WDUFF	FLØATING	NO LIM	Input total litter/duff loading on site, lb/ft^2, normally. If user wishes to input amount of litter/duff burned out on site, it is input as WDUFF, lb/ft^2, with a signal to the subroutine that this is the case, by setting DMØIS $\leq$ 0.
DMØIS	FLØATING	NO LIM	Input mass-average value of litter/duff moisture content, as fraction of dry weight, ordinarily. When DMØIS $\leq$ 0, then WDUFF is interpreted as being actual amount of litter/duff consumed, lb/ft^2
FLAG	FLØATING	0. to 1. or -1.	Output variable is ordinarily the fraction of the total loading--excluding litter/duff--on the site (dry weight) which is consumed by fire. If there are no dead fuels present, or if there are more than 100 size classes of dead fuel, so the estimate cannot be made, then FLAG=-1. is returned and BURNØUT prints a diagnostic message.

Variable	Mode	Range	Description
TBØW	FLØATING	NO LIM	Output variable is the dry weight loading--excluding litter/duff--consumed by fire, lb/ft^2.
THEAT	FLØATING	NO LIM	Output variable is the total heat loading generated by the burning of fuels--excluding litter/duff--on the site, Btu/ft^2.
RI	FLØATING	NO LIM	Output variable is the peak reaction intensity found amongst the NPOINS time snapshots generated, in Btu/ft^2-min.
S	FLØATING	0. to NPØINS* TPRINS	Output variable is the time, in minutes, from arrival of igniting flame front to the time of maximum intensity (RI) discovered amongst the NPOINS time snapshots generated.

PRECONDITIONS

1. Output from FIREMØD is assumed to be in unlabeled common, so a call to FIREMØD should be made prior to calling BURNØUT.

2. Printed output from BURNØUT is controlled by the common variable ØPT, just as it controls output from FIREMØD. So the variable ØPT should be set to the desired value before a call to BURNØUT.

PRINTED OUTPUT

Quantity of printed output is controlled by the integer variable ØPT in unlabeled common. For *ØPT = 1*, everything listed below is printed:

Pageskip, run number (integer variable RUN in unlabeled common), heading (alphanumeric word string HEADING(1-10) in unlabeled common), and a table of 10 variables versus time. The table entries, by column, are:

Column No.	*Meaning of entries*
1.	Time since arrival of igniting flame front, minutes. Values include zero and the characteristic particle residence time, $384/\tilde{\sigma}$ (see writeup of subroutine FIREMØD). The variables listed below are output for these first two time entries, but are not generated by the algorithm outlined below, and are listed for reference only. A statement to this effect is printed across the page, where the third row entries would be. After that advisory message there are up to 100 more rows. These rows include the time since arrival of igniting flame front, minutes. Values are in steps of (input variable) TPRINS, and there are (input variable) NPØINS of them.

2.	Gross (wet weight) loading remaining, as a fraction of the initial gross loading.
3.	Dry loading remaining, as a fraction of the initial dry loading.
4.	Gross (wet weight) loading remaining, lb/ft^2.
5.	Dry loading remaining, lb/ft^2.
6.	Gross loading-loss rate as a fraction of initial gross loading, min^{-1}.
7.	Dry loading-loss rate as a fraction of initial dry loading, min^{-1}.
8.	Gross loading-loss rate, lb/min/ft^2.
9.	Dry loading-loss rate, lb/min/ft^2.
10.	Fire intensity, as sensible heat release per unit area per unit time, Btu/min/ft^2.
11.	Cumulative sensible heat released per unit area, Btu/ft^2.

For *ØPT=2*, the above outputs are omitted, but everything below is printed:

Pageskip, run number (integer variable RUN in unlabeled common), heading (alphanumeric word string HEADING(1-10) in unlabeled common), and a list of five variables. The first row is again an output not generated by the algorithm outlined below, but is a restatement of FIREMØD outputs for reference only.

If a litter/duff loading is specified, and some (or all) of it is burned, then a second row of variables is printed which must be interpreted slightly differently. A verbal message to that effect is printed across the list just below the first one or two rows.

The rows are listed in order of increasing size (see variable ISIZE in FIREMØD writeup) and columns are from left to right:

Column No.	*Meaning of entries*
1.	Name of fuel element (NAMES(1,J) in unlabeled common). Each dead fuel element with ordinal size ranking equal to or larger than IFINES(1) and equal to or smaller than LARGE1 (see UNLABELED CØMMØN writeup) is included in the fuel description and is listed here. The first row is named "IGNITION" and the numerical variables in the first row are derived from FIREMØD output. If the litter/duff output row is present, it is named "LIT/DUFF".

2. Burnout time of the fuel element named, minutes. For the first row, this time is 384/$\tilde{\sigma}$ the "characteristic particle" flame residence time (see FIREMØD writeup and Anderson 1969). If an entry for litter/duff is made, this time is indeterminate, and "I" is printed.

3. Fraction of the intial dry loading of the named element consumed. For fuel elements completely consumed, this quantity is $(1 - S_T)$, where S_T is the total mineral content of the named fuel element. For the first row entry, this quantity is the product of the reaction intensity (XIR) and the characteristic particle residence time (384/$\tilde{\sigma}$) divided by the product of the total inital (dry) fuel loading and 8,000. The latter number is a rough estimate of the heat of combustion (Btu/lb dry weight) of the fuels. For the second row entry, the litter/duff load consumed, as a fraction of the total load, is output. If the option of specifying the amount of litter/duff burned out is exercised, this quantity will be unity.

4. Dry loading of the named element which is consumed, lb/ft^2. For the first row entry this variable is calculated as the product of the reaction intensity (XIR) and the characteristic particle residence time (384/$\tilde{\sigma}$) divided by 8,000 (Btu/lb dry weight), the approximate heat of combustion value.[4] If there is an entry for the litter/duff load burned, the value will be printed out here for the dry weight loading burned out. This may be either an estimate using Van Wagner's formula (see below) or the value of WDUFF input to the subroutine.

5. Cumulative sensible heat released by the burning of all elements listed so far, Btu/ft^2. For the "IGNITIØN" element, this entry is simply the product of the reaction intensity (XIR) and the characteristic particle residence time (384/$\tilde{\sigma}$). For the "LIT/DUFF" element it is the product of the dry loading consumed (see the previous item) and 8,000. These two contributions are not included in the cumulative values printed below the advisory message.

[4] See FIREMØD writeup for more discussion of these variables.

For *ØPT=3* only the following single line is printed, after a lineskip:

A final entry in the above-described table is named "TØTAL", and the four variables printed are:

1. The longest element burnout time, min.

2. The fraction of the total loading in dry weight lb/ft^2 which is burned, not including any litter/duff contribution or the "IGNITIØN" entry described above.

3. The total dry loading, lb/ft^2, which is burned, not including any litter/duff contribution or the "IGNITIØN" entry described above.

4. The cumulative sensible heat release, Btu/ft^2, due to burning of all the listed elements (except the "LIT/DUFF" and "IGNITIØN" entries).

For ØPT<1 and ØPT>3, all printed output from BURNØUT is suppressed.

Diagnostic error messages are output when the subroutine is unable to generate output for one of three catastrophic reasons:

1. There is no dead fuel specified in the inputs, or

2. There are more than 100 dead fuel elements specified. In either of these two cases, a one-line output is generated, the flag parameter FLAG is set to -1., and control is returned to the calling program.

3. There is no fuel element with moisture content below its maximum burning moisture calculated for that element size (see below). In this case, a one-line output is generated, the flag parameter FLAG is set to 0., and control is returned to the calling program.

PROGRAM TERMINATION CONDITIONS

No provisions are made in subroutine BURNØUT for normal program termination. As presently configured, if the basic data will run through FIREMØD successfully, then there should not be cause for execution faults in subroutine BURNØUT.

ALGORITHM STRUCTURE

The subroutine proceeds linearly through the sequence of computations outlined below. Only one major branch in the chain of computations is indicated. Most of the branch points in the coding deal with limiting values of computations, checks to see if results are computable, and output option exercises. The sequence of operations is as follows:

1. Establish basic constants, initialize output variables to zero, and check input variable ranges.

2. Assign each fuel element size class to appropriate subcategory and calculate amount of overlap of each size class by members of the same subcategory to which it belongs.

3. Determine amount of overlap by all size classes, of all others (as fractional planform area).

4. Determine amount, if any, of litter/duff burned out.

BRANCH: If no litter/duff burnout is indicated, jump ahead to step 7.

5. Calculate fraction of dry load of each size class that is burned out through interaction with others of equal or smaller size.

6. Recalculate fraction of dry load of each size class that is burned out through interaction with others of its own subcategory size group, adding in the contribution to its burnout through the burning of the litter/duff layer.

7. Calculate fraction of dry load of each size class that is burned out through interaction with all other size classes. (This is a "bootstrap" recalculation for cases with litter/duff burnout.) As each size class is examined, in order of increasing size, the density of the fuel particles is tested to determine if the fuel should be considered rotten. If rotten, and if its moisture content is below the critical value for its size, the fraction burned out is set to unity.

8. Initialize output variables to zero and calculate time-snapshot times.

9. In one pass, calculate the time of burnout of each size class while accumulating total dry weight and gross weight loadings. While examining some particular size class, determine what amount of its total burnout is to be attributed to each other size class, burnout time appropriate for that pairing, the dry weight loading loss of the size class considered to be attributed to the other size classes, and the ratio of this loss to the burnout time for that pair. Finally, determine the total dry weight loading loss of each size class as it is considered.

10. Proceed to generate output required to calculate the amount of load loss and the load-loss rate due to interaction of any two size classes; use is made of a universal "burnout function" FBT(X), and its first derivative, DFBT(X) (fig. 5). This function is discussed in the appendix. Suffice it to say here that this function was chosen arbitrarily, because it appears to have the proper shape with time. The theory behind the calculations, model calibration exercises, and supporting analytical details are found in appendix I.

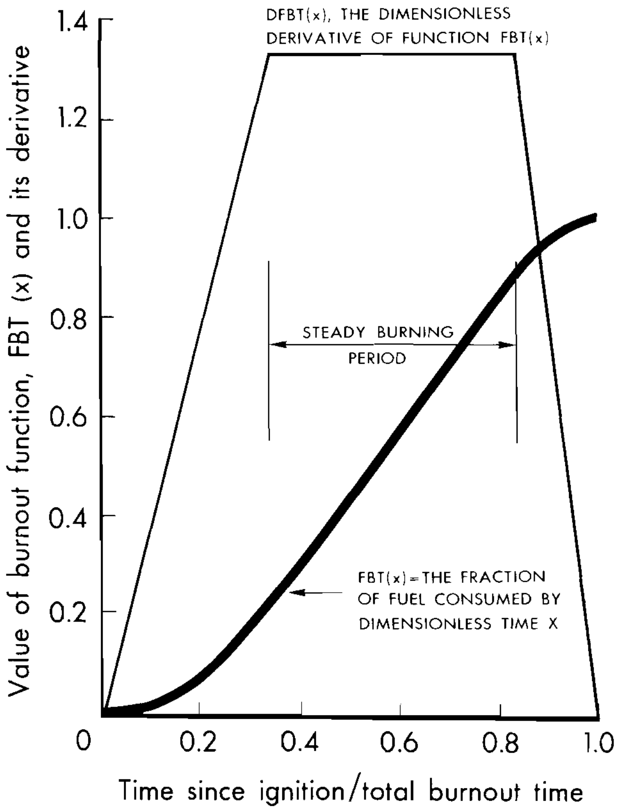


Figure 5.--The burnout function and its first derivative.

PROGRAM SAMPLE (WITH EXAMPLE OUTPUT)

The library of subroutines includes a short "driver" program that can be used to sample output from each subroutine. It also can be used to build special-purpose programs, by adding and deleting lines with the file-manipulation program (UPDATE) available at BKY and other CDC installations. The program, named SAMPLE, merely calls, in turn, subroutines SETUP, FIREMØD, FLAME, CØNTAIN, and BURNØUT. A copy of the program is reproduced below, illustrating how one can assemble the various subroutines into a program.

CØMMØN DATA: UNLABELED CØMMØN.

INPUT PROCEDURE: See Subroutine SETUP.

PROGRAM TERMINATION CONDITIONS: Via Subroutine SETUP.

PROGRAM OUTPUT: Sample produces no output of its own. The individual subroutines produce all the output.

EXAMPLE EXERCISE:

The sample input data presented at the end of the description of subroutine SETUP were used to generate example output for each of the subroutines. An image of the actual output is presented in the following pages, for reference.

```
      PROGRAM SAMPLE(INPUT,OUTPUT)                                      SAMPLE.2
      COMMON ND,NL,BETA1,SIGMA,GAMMA,XIR,RHOBQIG,PHIS,WINDX,PHIWX,RATEX,SAMPLE.3
     1BYRAMX,IR(2),MEXT(2),DEPTH,TTHETA,MOIS(2,100),MPS(2,100),MWG(2,100SAMPLE.4
     2),LHV(2,100),RHOP(2,100),ST(2,100),SE(2,100),RUN,WINDI,WINDF,DELW,SAMPLE.5
     3HEADING(10),NAMES(2,100),IFINES(2),OPT,BYRAM(100),RATE(100),NN,XIOSAMPLE.6
     4,WINDS(100),ISIZE(2,100),LARGE1,LARGE2                            SAMPLE.7
      INTEGER HEADING,RUN,OPT                                           SAMPLE.8
      REAL MPS,MWG,LHV,MOIS,MEXT,IR                                     SAMPLE.9
      RUN=0                                                             SAMPLE.10
   10 CALL SETUP                                                        SAMPLE.11
      CALL FIREMOD(X)                                                   SAMPLE.12
      CALL FLAME                                                        SAMPLE.13
      CALL CONTAIN(3)                                                   SAMPLE.14
      CALL BURNOUT(30,.4,.8,.4,FG,TB,TH,RI,SS)                          SAMPLE.15
      GO TO 10                                                          SAMPLE.16
      END                                                               SAMPLE.17
```

```
             INPUT DATA IMAGE, SUBROUTINE SETUP..RUN NO.    1

   HEADING  -0
    HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT
   SITEDATA -0
LEAST WIND     0, MOST WIND  6.0, INCREMENT  1.00, SLOPE (DEG) 31.0, DEPTH 2.80, MOIST. EXT.  .2500
   NEW FUEL  3
     3 NEW FUEL DESCRIPTIONS (HEATVAL, DENSITY, MINERAL CONTENT, EFFECTIVE MINERAL CONTENT)
   GRASSES   LIVE        8100.0        29.0        .0700       .0015            NEW FUEL  MEASURED
   BUSHLEAF  LIVE        9300.0        26.0        .0650       .0052            NEW FUEL  MEASURED
   BUSHTWIG  LIVE            -0          -0          -0          -0             NEW FUEL  ESTIMATE
   NEW FUEL  6
     6 NEW FUEL DESCRIPTIONS (HEATVAL, DENSITY, MINERAL CONTENT, EFFECTIVE MINERAL CONTENT)
   NEEDLES   DEAD        8300.0        34.5        .0500       .0200            NEW FUEL  OLD DATA
   SM TWIGS  DEAD        7800.0        36.2        .0300       .0220            NEW FUEL  OLD DATA
   SM LIMBS  DEAD        7900.0        31.0        .0400       .0190            NEW FUEL  NEW DATA
   LG LIMBS  DEAD        7900.0        31.0        .0400       .0190            NEW FUEL  NEW DATA
   TREE TOP  DEAD            -0          -0          -0          -0             NEW FUEL  ESTIMATE
   PUNKYLOG  DEAD        7000.0        14.0        .0600       .0140            NEW FUEL  CULL LOG
   FUELTYPE  9
     9 FUEL CATEGORIES TO BE USED
   SURF/VOL, LOADING, MOISTURE CONTENT
   NEEDLES   DEAD      1750.00000         .63000        .07000
   SM TWIGS  DEAD       343.00000         .28000        .09000
   SM LIMBS  DEAD        91.00000         .47000        .10000
   LG LIMBS  DEAD        27.00000         .53000        .12000
   TREE TOP  DEAD        11.00000        1.45000        .15000
   PUNKYLOG  DEAD         4.50000        1.60000        .30000
   GRASSES   LIVE      2800.00000         .09100        .90000
   BUSHLEAF  LIVE      1250.00000         .00700       1.10000
   BUSHTWIG  LIVE       295.00000         .02400        .70000
   SIZELIMS -0
   NONE                -0          -0                           -0          -0
   OPTION    1
```

DATE 14 MAR 75 RUN NO. 1

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT

FUEL DEPTH, FT = 2.80 SLOPE TANGENT = .600

FUEL	DESCRIPTION	I	J	SURF/VOL RATIO (1/FT)	DRY LOADING (LB/SQFT)	LOW HEAT VALUE (BTU/LB)	MOISTURE CONTENT (FRAC DRY)	PARTICLE DENSITY (LB/CUFT)	TOTAL MINERAL (FRAC DRY)	EFFECTIVE MINERAL (FRAC DRY)	MOISTURE EXTINCTION (FRAC DRY)
DEAD	NEEDLES	1	1	1750.0	.6300	8300.0	.0700	34.50	.0500	.0200	.2500
DEAD	SM TWIGS	1	2	343.0	.2800	7800.0	.0900	36.20	.0300	.0220	.2500
DEAD	SM LIMBS	1	3	91.0	.4700	7900.0	.1000	31.00	.0400	.0190	.2500
DEAD	LG LIMBS	1	4	27.0	.5300	7900.0	.1200	31.00	.0400	.0190	.2500
..THE FOLLOWING FUELS ARE EXCLUDED AS TOO LARGE TO CONTRIBUTE TO FIRE SPREAD..											
DEAD	TREE TOP	1	5	11.0	1.4500	8000.0	.1500	32.00	.0555	.0100	.2500
DEAD	PUNKYLOG	1	6	4.5	1.6000	7000.0	.3000	14.00	.0600	.0140	.2500
LIVE	GRASSES	2	1	2300.0	.0910	8100.0	.9000	29.00	.0700	.0015	20.2809
LIVE	BUSHLEAF	2	2	1250.0	.0070	9300.0	1.1000	26.00	.0650	.0052	20.2809
LIVE	BUSHTWIG	2	3	295.0	.0240	8000.0	.7000	32.00	.0555	.0100	20.2809

INTERMEDIATE CALCULATIONS...

FUEL TYPE	REACTION CONTRIBUTION PERCENTAGE	WTD. AVG SURF/VOL 1/FT	MINL. DAMPING COEFFICIENT	MOIS. DAMPING COEFFICIENT	WTD. AVG. LOADING LB/SQFT
DEAD	72.93	1563.0	.3656	.5913	.5680
LIVE	27.07	2684.9	.5761	.8946	.0896

GROSS FIRESPREAD PARAMETERS, NO WIND CONDITION

PACKING RATIO	OPTIMUM PCKG. RATIO	SLOPE FACTOR	SURF/VOL (1/FT)	REACT. VEL. (1/MIN)	REACT. INTENSITY (BTU/MIN/SQFT)	HEAT SINK (BTU/CUFT)	PROPAGATING FLUX (BTU/MIN/SQFT)
.02229	.00726	5.942	1791.9	10.833	15034.5	340.75	856.2

WIND AT MIDFLAME HEIGHT (MPH)	WIND AT MIDFLAME HEIGHT (FT/MIN)	WIND FACTOR -HEADING-	RATE OF SPREAD (FT/MIN)	BYRAMS INTENSITY (BTU/MIN/FIRELINE FT)
0	0	0	17.44	56205.5
1.0	88.00	.8705	19.63	63253.2
2.0	176.00	2.3666	23.39	75365.3
3.0	264.00	4.2481	28.12	90598.0
4.0	352.00	6.4338	33.61	108292.8
5.0	440.00	8.8775	39.75	128077.3
6.0	528.00	11.5489	46.46	149704.2

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN 1

CHARACTERISTICS OF FLAME FROM SPREADING COMBUSTION REGION

WIND IS UP SLOPE OF .600 TANGENT (GRADE)

WIND SPEED (MPH) AT MIDFLAME HEIGHT	BYRAMS INTENSITY BTU/MIN/FT	BYRAMS FLAME LENGTH (FEET)	VAN WAGNERS CROWN SCORCH HEIGHT (FEET) ON 77 F DAY	P. THOMAS EQUATIONS FOR FLAME			
				LENGTH (FEET)	HEIGHT (FEET)	HORIZ. REACH (FEET)	TILT ANGLE FROM VERTICAL (DEGREES)
0	.562E+05	10.5	95.3	21.4	21.4	0	0
1.0	.633E+05	11.1	103.0	21.4	21.4	0	0
2.0	.754E+05	12.0	115.5	25.7	25.7	0	0
3.0	.906E+05	13.0	129.8	26.6	23.7	12.1	27.0
4.0	.108E+06	14.2	144.9	28.2	22.4	17.2	37.4
5.0	.128E+06	15.3	160.3	30.1	22.0	20.6	43.1
6.0	.150E+06	16.4	175.5	32.2	22.0	23.5	46.9

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN NO. 1
SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATE

RATE OF SPREAD IN ANY DIRECTION BASED ON SLOPE AND WIND COEFFICIENTS USING SLOPE SENSED AND WIND COMPONENT IN THAT DIRECTION

WIND SPEED MPH AT MIDFLAME	WIND VECTOR FROM UPSLOPE, DEGREES 00	45	90	135	180
	AREA IN SQFT/(MIN SQUARED)				
0	.192E+03	.192E+03	.192E+03	.192E+03	.192E+03
1.00	.244E+03	.232E+03	.213E+03	.206E+03	.205E+03
2.00	.348E+03	.315E+03	.263E+03	.244E+03	.243E+03
3.00	.506E+03	.446E+03	.353E+03	.319E+03	.317E+03
4.00	.727E+03	.637E+03	.495E+03	.445E+03	.442E+03
5.00	.102E+04	.898E+03	.703E+03	.633E+03	.629E+03
6.00	.141E+04	.124E+04	.989E+03	.898E+03	.892E+03
	PERIMETER IN FT/MIN				
0	.520E+02	.520E+02	.520E+02	.520E+02	.520E+02
1.00	.582E+02	.562E+02	.542E+02	.555E+02	.568E+02
2.00	.691E+02	.648E+02	.599E+02	.633E+02	.669E+02
3.00	.828E+02	.766E+02	.690E+02	.747E+02	.804E+02
4.00	.988E+02	.911E+02	.813E+02	.890E+02	.963E+02
5.00	.117E+03	.108E+03	.966E+02	.106E+03	.114E+03
6.00	.136E+03	.127E+03	.114E+03	.125E+03	.134E+03
	MAXIMUM RATE OF SPREAD, FT/MIN				
0	.174E+02	.174E+02	.174E+02	.174E+02	.174E+02
1.00	.196E+02	.188E+02	.174E+02	.174E+02	.174E+02
2.00	.234E+02	.214E+02	.175E+02	.174E+02	.174E+02
3.00	.281E+02	.249E+02	.177E+02	.174E+02	.174E+02
4.00	.336E+02	.293E+02	.187E+02	.187E+02	.187E+02
5.00	.398E+02	.345E+02	.248E+02	.248E+02	.248E+02
6.00	.465E+02	.406E+02	.315E+02	.315E+02	.315E+02
	DIRECTION OF MAXIMUM SPREAD RATE, DEGREES FROM UPSLOPE				
0	0	0	0	0	0
1.00	0	3.0	0	0	0
2.00	0	6.0	3.0	0	0
3.00	0	12.0	12.0	0	0
4.00	0	18.0	30.0	135.0	180.0
5.00	0	21.0	90.0	135.0	180.0
6.00	0	24.0	90.0	135.0	180.0

AREA IN ACRES/(HOUR SQUARED)

0	.159E+02	.159E+02	.159E+02	.159E+02	.159E+02
1.00	.202E+02	.192E+02	.176E+02	.170E+02	.170E+02
2.00	.288E+02	.260E+02	.217E+02	.202E+02	.201E+02
3.00	.418E+02	.369E+02	.292E+02	.264E+02	.262E+02
4.00	.601E+02	.526E+02	.409E+02	.367E+02	.365E+02
5.00	.846E+02	.742E+02	.581E+02	.523E+02	.520E+02
6.00	.116E+03	.103E+03	.817E+02	.742E+02	.737E+02

PERIMETER IN CHAINS/HOUR

0	.473E+02	.473E+02	.473E+02	.473E+02	.473E+02
1.00	.529E+02	.511E+02	.493E+02	.504E+02	.517E+02
2.00	.628E+02	.589E+02	.545E+02	.576E+02	.609E+02
3.00	.752E+02	.696E+02	.627E+02	.679E+02	.731E+02
4.00	.898E+02	.828E+02	.739E+02	.809E+02	.875E+02
5.00	.106E+03	.980E+02	.878E+02	.961E+02	.104E+03
6.00	.124E+03	.115E+03	.104E+03	.113E+03	.122E+03

MAXIMUM RATE OF SPREAD, CHAINS/HOUR

0	.159E+02	.159E+02	.159E+02	.159E+02	.159E+02
1.00	.178E+02	.171E+02	.159E+02	.159E+02	.159E+02
2.00	.213E+02	.194E+02	.159E+02	.159E+02	.159E+02
3.00	.256E+02	.226E+02	.161E+02	.159E+02	.159E+02
4.00	.306E+02	.266E+02	.170E+02	.170E+02	.170E+02
5.00	.361E+02	.314E+02	.226E+02	.226E+02	.226E+02
6.00	.422E+02	.369E+02	.287E+02	.287E+02	.287E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN 1
SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATES BASED ON HAL E ANDERSON DOUBLE-ELLIPSE SHAPE USING FONS WIND/SHAPE DATA

WIND SPEED (MPH) AT MIDFLAME (UPHILL)	PERIMETER GROWTH FEET/MIN	PERIMETER GROWTH CHAINS/HOUR	AREA GROWTH SQFT PER SQ MIN	AREA GROWTH ACRES PER SQ HOUR	MAXIMUM SPREAD RATE FEET PER MINUTE	MAXIMUM SPREAD RATE CHAINS PER HOUR
0	.740E+02	.673E+02	.429E+03	.355E+02	.174E+02	.159E+02
1.0	.770E+02	.700E+02	.457E+03	.378E+02	.196E+02	.178E+02
2.0	.854E+02	.776E+02	.550E+03	.454E+02	.234E+02	.213E+02
3.0	.963E+02	.875E+02	.678E+03	.560E+02	.281E+02	.256E+02
4.0	.109E+03	.988E+02	.833E+03	.688E+02	.336E+02	.306E+02
5.0	.122E+03	.111E+03	.101E+04	.833E+02	.398E+02	.361E+02
6.0	.136E+03	.124E+03	.120E+04	.990E+02	.465E+02	.422E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

RUN NO. 1

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT

INTENSITY AND FUEL LOADING -VS- TIME AFTER ARRIVAL OF FLAME FRONT

TIME (MIN.)	TOTAL FUEL LOAD NOT YET BURNED OUT (FRACTION) GROSS	(FRACTION) DRY WT	(LB/SQFT) GROSS	(LB/SQFT) DRY WT	INSTANTANEOUS FUEL LOAD LOSS RATE (FRACTION/MIN) GROSS	(FRACTION/MIN) DRY WT	(LB/MIN/SQFT) GROSS	(LB/MIN/SQFT) DRY WT	FIRE INTENSITY (BTU/MIN/SQFT)	TOTAL HEAT RELEASED (BTU/SQFT)
0	1.0000	1.0000	5.8374	4.9600	0	0	0	0	0	0
.2	.9188	.9188	5.3634	4.5573	.3789	.3789	2.212	1.879	.150E+05	.322E+04
CONDITIONS ABOVE OBTAIN AS SPREADING FRONT HAS PASSED...TIME ORIGIN IS ARRIVAL TIME OF IGNITING FLAME FRONT										
.4	.9348	.9305	5.4569	4.6155	.3051	.3251	1.781	1.612	.128E+05	.272E+04
.8	.8100	.7976	4.7283	3.9562	.3189	.3395	1.861	1.684	.133E+05	.793E+04
1.2	.7323	.7151	4.2748	3.5468	.0352	.0367	.205	.182	.140E+04	.112E+05
1.6	.7180	.7001	4.1913	3.4727	.0364	.0380	.212	.188	.144E+04	.117E+05
2.0	.7032	.6847	4.1049	3.3961	.0376	.0392	.220	.195	.149E+04	.123E+05
2.4	.6879	.6688	4.0156	3.3170	.0388	.0405	.227	.201	.154E+04	.129E+05
2.8	.6747	.6550	3.9383	3.2486	.0223	.0231	.130	.115	.877E+03	.134E+05
3.2	.6695	.6496	3.9081	3.2222	.0097	.0100	.057	.049	.377E+03	.136E+05
3.6	.6654	.6454	3.8840	3.2012	.0109	.0111	.064	.055	.421E+03	.138E+05
4.0	.6610	.6409	3.8584	3.1790	.0110	.0112	.064	.056	.425E+03	.140E+05
4.4	.6566	.6364	3.8326	3.1566	.0111	.0113	.065	.056	.429E+03	.141E+05
4.8	.6521	.6319	3.8066	3.1340	.0112	.0114	.065	.057	.433E+03	.143E+05
5.2	.6476	.6273	3.7803	3.1112	.0113	.0116	.066	.057	.437E+03	.145E+05
5.6	.6431	.6226	3.7538	3.0882	.0114	.0117	.067	.058	.441E+03	.147E+05
6.0	.6385	.6179	3.7270	3.0649	.0115	.0118	.067	.058	.445E+03	.148E+05
6.4	.6338	.6132	3.7000	3.0415	.0116	.0119	.068	.059	.449E+03	.150E+05
6.8	.6292	.6084	3.6727	3.0178	.0117	.0120	.068	.059	.453E+03	.152E+05
7.2	.6245	.6036	3.6452	2.9940	.0118	.0121	.069	.060	.456E+03	.154E+05
7.6	.6197	.5988	3.6175	2.9699	.0119	.0122	.070	.060	.460E+03	.156E+05
8.0	.6149	.5939	3.5895	2.9457	.0120	.0123	.070	.061	.464E+03	.158E+05
8.4	.6101	.5889	3.5613	2.9212	.0121	.0124	.071	.061	.468E+03	.159E+05
8.8	.6052	.5840	3.5328	2.8965	.0122	.0125	.071	.062	.472E+03	.161E+05
9.2	.6005	.5792	3.5053	2.8726	.0109	.0111	.063	.055	.419E+03	.163E+05
9.6	.5966	.5752	3.4824	2.8528	.0087	.0089	.051	.044	.336E+03	.165E+05
10.0	.5935	.5720	3.4644	2.8373	.0066	.0067	.039	.033	.254E+03	.166E+05
10.4	.5913	.5698	3.4514	2.8261	.0045	.0045	.026	.023	.172E+03	.167E+05
10.8	.5899	.5684	3.4433	2.8191	.0028	.0028	.016	.014	.106E+03	.167E+05
11.2	.5887	.5672	3.4367	2.8135	.0029	.0029	.017	.014	.110E+03	.168E+05
11.6	.5875	.5660	3.4297	2.8076	.0030	.0030	.018	.015	.114E+03	.168E+05
12.0	.5863	.5648	3.4226	2.8015	.0031	.0031	.018	.016	.118E+03	.169E+05

RUN NO. 1

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT

SUMMARY OF LOAD LOSS BY FUEL ELEMENT, WITH ELEMENT BURNOUT TIME

FUEL TYPE	BURNOUT TIME	DRY LOAD FRACTION	BURNED OUT LB/SQFT	HEAT RELEASED BTU/SQFT
IGNITION	.21	.0812	.4027	.322E+04
LIT/DUFF	T	.4245	.3396	.257E+04

ABOVE FOR REFERENCE ONLY -- NOT INCLUDED IN TOTAL

NEEDLES	1.11	1.0000	.5985	.492E+04
SM TWIGS	3.02	1.0000	.2716	.701E+04
SM LIMBS	10.72	1.0000	.4512	.105E+05
LG LIMBS	36.34	.7356	.3743	.134E+05
TREE TOP	81.66	.7003	.9591	.210E+05
PUNKYLOG	239.00	.6045	.9092	.270E+05
TOTAL	239.00	.7185	3.5639	.270E+05

INPUT DATA IMAGE, SUBROUTINE SETUP..RUN NO. 2

OPTION 3

WIND AT MIDFLAME HEIGHT (MPH)	(FT/MIN)	WIND FACTOR -HEADING-	RATE OF SPREAD (FT/MIN)	BYRAMS INTENSITY (BTU/MIN/FIRELINE FT)
0	0	0	17.44	56205.5
1.0	88.00	.8705	19.63	63253.2
2.0	176.00	2.3666	23.39	75365.3
3.0	264.00	4.2481	28.12	90598.0
4.0	352.00	6.4338	33.61	108292.8
5.0	440.00	8.8775	39.75	128077.3
6.0	528.00	11.5489	46.46	149704.2

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN 2

CHARACTERISTICS OF FLAME FROM SPREADING COMBUSTION REGION

WIND IS UP SLOPE OF .600 TANGENT (GRADE)

WIND SPEED (MPH) AT MIDFLAME HEIGHT	BYRAMS INTENSITY BTU/MIN/FT	BYRAMS FLAME LENGTH (FEET)	VAN WAGNERS CROWN SCORCH HEIGHT (FEET) ON 77 F DAY	P. THOMAS EQUATIONS FOR FLAME: LENGTH (FEET)	HEIGHT (FEET)	HORIZ. REACH (FEET)	TILT ANGLE FROM VERTICAL (DEGREES)
0	.562E+05	10.5	95.3	21.4	21.4	0	0
1.0	.633E+05	11.1	103.0	21.4	21.4	0	0
2.0	.754E+05	12.0	115.5	25.7	25.7	0	0
3.0	.906E+05	13.0	129.8	26.6	23.7	12.1	27.0
4.0	.108E+06	14.2	144.9	28.2	22.4	17.2	37.4
5.0	.128E+06	15.3	160.3	30.1	22.0	20.6	43.1
6.0	.150E+06	16.4	175.5	32.2	22.0	23.5	46.9

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN NO. 2
SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATE

RATE OF SPREAD IN ANY DIRECTION BASED ON SLOPE AND WIND COEFFICIENTS USING SLOPE SENSED AND WIND COMPONENT IN THAT DIRECTION

WIND SPEED MPH AT MIDFLAME	WIND VECTOR FROM UPSLOPE, DEGREES 00	45	90	135	180
	AREA IN SQFT/(MIN SQUARED)				
0	.192E+03	.192E+03	.192E+03	.192E+03	.192E+03
1.00	.244E+03	.232E+03	.213E+03	.206E+03	.205E+03
2.00	.348E+03	.315E+03	.263E+03	.244E+03	.243E+03
3.00	.506E+03	.446E+03	.353E+03	.319E+03	.317E+03
4.00	.727E+03	.637E+03	.495E+03	.445E+03	.442E+03
5.00	.102E+04	.898E+03	.703E+03	.633E+03	.629E+03
6.00	.141E+04	.124E+04	.989E+03	.898E+03	.892E+03
	PERIMETER IN FT/MIN				
0	.520E+02	.520E+02	.520E+02	.520E+02	.520E+02
1.00	.582E+02	.562E+02	.542E+02	.555E+02	.568E+02
2.00	.691E+02	.648E+02	.599E+02	.633E+02	.669E+02
3.00	.828E+02	.766E+02	.690E+02	.747E+02	.804E+02
4.00	.988E+02	.911E+02	.813E+02	.890E+02	.963E+02
5.00	.117E+03	.108E+03	.966E+02	.106E+03	.114E+03
6.00	.136E+03	.127E+03	.114E+03	.125E+03	.134E+03
	MAXIMUM RATE OF SPREAD, FT/MIN				
0	.174E+02	.174E+02	.174E+02	.174E+02	.174E+02
1.00	.196E+02	.188E+02	.174E+02	.174E+02	.174E+02
2.00	.234E+02	.214E+02	.175E+02	.174E+02	.174E+02
3.00	.281E+02	.249E+02	.177E+02	.174E+02	.174E+02
4.00	.336E+02	.293E+02	.187E+02	.187E+02	.187E+02
5.00	.398E+02	.345E+02	.248E+02	.248E+02	.248E+02
6.00	.465E+02	.406E+02	.315E+02	.315E+02	.315E+02
	DIRECTION OF MAXIMUM SPREAD RATE, DEGREES FROM UPSLOPE				
0	0	0	0	0	0
1.00	0	3.0	0	0	0
2.00	0	6.0	3.0	0	0
3.00	0	12.0	12.0	0	0
4.00	0	18.0	30.0	135.0	180.0
5.00	0	21.0	90.0	135.0	180.0
6.00	0	24.0	90.0	135.0	180.0

AREA IN ACRES/(HOUR SQUARED)

0	.159E+02	.159E+02	.159E+02	.159E+02	.159E+02
1.00	.202E+02	.192E+02	.176E+02	.170E+02	.170E+02
2.00	.288E+02	.260E+02	.217E+02	.202E+02	.201E+02
3.00	.418E+02	.369E+02	.292E+02	.264E+02	.262E+02
4.00	.601E+02	.526E+02	.409E+02	.367E+02	.365E+02
5.00	.846E+02	.742E+02	.581E+02	.523E+02	.520E+02
6.00	.116E+03	.103E+03	.817E+02	.742E+02	.737E+02

PERIMETER IN CHAINS/HOUR

0	.473E+02	.473E+02	.473E+02	.473E+02	.473E+02
1.00	.529E+02	.511E+02	.493E+02	.504E+02	.517E+02
2.00	.628E+02	.589E+02	.545E+02	.576E+02	.609E+02
3.00	.752E+02	.696E+02	.627E+02	.679E+02	.731E+02
4.00	.898E+02	.828E+02	.739E+02	.809E+02	.875E+02
5.00	.106E+03	.980E+02	.878E+02	.961E+02	.104E+03
6.00	.124E+03	.115E+03	.104E+03	.113E+03	.122E+03

MAXIMUM RATE OF SPREAD, CHAINS/HOUR

0	.159E+02	.159E+02	.159E+02	.159E+02	.159E+02
1.00	.178E+02	.171E+02	.159E+02	.159E+02	.159E+02
2.00	.213E+02	.194E+02	.159E+02	.159E+02	.159E+02
3.00	.256E+02	.226E+02	.161E+02	.159E+02	.159E+02
4.00	.306E+02	.266E+02	.170E+02	.170E+02	.170E+02
5.00	.361E+02	.314E+02	.226E+02	.226E+02	.226E+02
6.00	.422E+02	.369E+02	.287E+02	.287E+02	.287E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

HYPOTHETICAL LOGGING SLASH OVERGROWN WITH GRASS AND BRUSH - FOR EXAMPLE OUTPUT RUN 2
SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATES BASED ON HAL E ANDERSON DOUBLE-ELLIPSE SHAPE USING FONS WIND/SHAPE DATA

WIND SPEED (MPH) AT MIDFLAME (UPHILL)	PERIMETER GROWTH FEET/MIN	PERIMETER GROWTH CHAINS/HOUR	AREA GROWTH SQFT PER SQ MIN	AREA GROWTH ACRES PER SQ HOUR	MAXIMUM SPREAD RATE FEET PER MINUTE	MAXIMUM SPREAD RATE CHAINS PER HOUR
0	.740E+02	.673E+02	.429E+03	.355E+02	.174E+02	.159E+02
1.0	.770E+02	.700E+02	.457E+03	.378E+02	.196E+02	.178E+02
2.0	.854E+02	.776E+02	.550E+03	.454E+02	.234E+02	.213E+02
3.0	.963E+02	.875E+02	.678E+03	.560E+02	.281E+02	.256E+02
4.0	.109E+03	.988E+02	.833E+03	.688E+02	.336E+02	.306E+02
5.0	.122E+03	.111E+03	.101E+04	.833E+02	.398E+02	.361E+02
6.0	.136E+03	.124E+03	.120E+04	.990E+02	.465E+02	.422E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

	BURNOUT TIME	DRY LOAD BURNED OUT FRACTION	DRY LOAD BURNED OUT LB/SQFT	HEAT RELEASED BTU/SQFT
TOTAL	239.00	.7185	3.5639	.270E+05

INPUT DATA IMAGE, SUBROUTINE SETUP..RUN NO. 3

STDFUELS -0
STANDARD FUEL MODEL NFFL J WITH DEAD FUEL MOISTURE OF EXTINCTION -0
MOISTURE CONTENT OF FUEL COMPONENTS = .070 .100 .150 -0
OPTION 1

DATE 14 MAR 75 RUN NO. 3

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL ....J.. HEAVY LOGGING SLASH

FUEL DEPTH, FT = 3.00 SLOPE TANGENT = .600

FUEL	DESCRIPTION	I	J	SURF/VOL RATIO (1/FT)	DRY LOADING (LB/SQFT)	LOW HEAT VALUE (BTU/LB)	MOISTURE CONTENT (FRAC DRY)	PARTICLE DENSITY (LB/CUFT)	TOTAL MINERAL (FRAC DRY)	EFFECTIVE MINERAL (FRAC DRY)	MOISTURE EXTINCTION (FRAC DRY)
DEAD	FINES	1	1	1500.0	.3220	8000.0	.0700	32.00	.0555	.0100	.2500
DEAD	HALFINCH	1	2	109.0	1.0580	8000.0	.1000	32.00	.0555	.0100	.2500
DEAD	1-3 INCH	1	3	30.0	1.2880	8000.0	.1500	32.00	.0555	.0100	.2500

INTERMEDIATE CALCULATIONS...

FUEL TYPE	REACTION CONTRIBUTION PERCENTAGE	WTD. AVG SURF/VOL 1/FT	MINL. DAMPING COEFFICIENT	MOIS. DAMPING COEFFICIENT	WTD. AVG. LOADING LB/SQFT
DEAD	100.00	1159.0	.4174	.5787	.4853
LIVE	0	0	0	.8946	0

GROSS FIRESPREAD PARAMETERS, NO WIND CONDITION

PACKING RATIO	OPTIMUM PCKG. RATIO	SLOPE FACTOR	SURF/VOL (1/FT)	REACT. VEL. (1/MIN)	REACT. INTENSITY (BTU/MIN/SQFT)	HEAT SINK (BTU/CUFT)	PROPAGATING FLUX (BTU/MIN/SQFT)
.02779	.01037	5.562	1159.0	9.818	9207.2	218.47	400.1

WIND AT MIDFLAME HEIGHT (MPH)	(FT/MIN)	WIND FACTOR -HEADING-	RATE OF SPREAD (FT/MIN)	BYRAMS INTENSITY (BTU/MIN/FIRELINE FT)
0	0	0	12.02	36657.4
1.0	88.00	1.2317	14.27	43538.0
2.0	176.00	2.7150	16.99	51824.5
3.0	264.00	4.3110	19.91	60740.3
4.0	352.00	5.9848	22.98	70090.9
5.0	440.00	7.7190	26.15	79778.7
6.0	528.00	9.5028	29.42	89744.1

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL ....J.. HEAVY LOGGING SLASH RUN 3

CHARACTERISTICS OF FLAME FROM SPREADING COMBUSTION REGION

WIND IS UP SLOPE OF .600 TANGENT (GRADE)

WIND SPEED (MPH) AT MIDFLAME HEIGHT	BYRAMS INTENSITY BTU/MIN/FT	BYRAMS FLAME LENGTH (FEET)	VAN WAGNERS CROWN SCORCH HEIGHT (FEET) ON 77 F DAY	P. THOMAS EQUATIONS FOR FLAME LENGTH (FEET)	HEIGHT (FEET)	HORIZ. REACH (FEET)	TILT ANGLE FROM VERTICAL (DEGREES)
0	.367E+05	8.6	71.6	16.6	16.6	0	0
1.0	.435E+05	9.3	80.3	16.6	16.6	0	0
2.0	.518E+05	10.1	89.8	18.2	18.2	0	0
3.0	.607E+05	10.9	99.0	18.6	15.7	9.9	32.1
4.0	.701E+05	11.6	107.4	19.2	14.4	12.7	41.5
5.0	.798E+05	12.3	115.0	20.0	13.7	14.6	46.9
6.0	.897E+05	13.0	121.6	20.8	13.2	16.0	50.5

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL ....J.. HEAVY LOGGING SLASH   RUN NO. 3
SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATE

RATE OF SPREAD IN ANY DIRECTION BASED ON SLOPE AND WIND COEFFICIENTS USING SLOPE SENSED AND WIND COMPONENT IN THAT DIRECTION

AREA IN SQFT/(MIN SQUARED)

WIND SPEED MPH AT MIDFLAME	WIND VECTOR FROM UPSLOPE, DEGREES 00	45	90	135	180
0	.926E+02	.926E+02	.926E+02	.926E+02	.926E+02
1.00	.132E+03	.124E+03	.110E+03	.105E+03	.104E+03
2.00	.191E+03	.173E+03	.142E+03	.129E+03	.128E+03
3.00	.266E+03	.237E+03	.188E+03	.168E+03	.167E+03
4.00	.358E+03	.318E+03	.251E+03	.223E+03	.221E+03
5.00	.468E+03	.417E+03	.330E+03	.294E+03	.291E+03
6.00	.597E+03	.534E+03	.427E+03	.383E+03	.380E+03

PERIMETER IN FT/MIN

WIND SPEED	00	45	90	135	180
0	.361E+02	.361E+02	.361E+02	.361E+02	.361E+02
1.00	.427E+02	.410E+02	.390E+02	.400E+02	.417E+02
2.00	.509E+02	.480E+02	.440E+02	.461E+02	.496E+02
3.00	.597E+02	.559E+02	.504E+02	.535E+02	.583E+02
4.00	.691E+02	.645E+02	.579E+02	.619E+02	.676E+02
5.00	.787E+02	.737E+02	.662E+02	.710E+02	.773E+02
6.00	.887E+02	.832E+02	.751E+02	.806E+02	.873E+02

MAXIMUM RATE OF SPREAD, FT/MIN

WIND SPEED	00	45	90	135	180
0	.120E+02	.120E+02	.120E+02	.120E+02	.120E+02
1.00	.143E+02	.136E+02	.121E+02	.120E+02	.120E+02
2.00	.170E+02	.156E+02	.123E+02	.120E+02	.120E+02
3.00	.199E+02	.179E+02	.128E+02	.120E+02	.120E+02
4.00	.230E+02	.204E+02	.138E+02	.128E+02	.128E+02
5.00	.262E+02	.231E+02	.160E+02	.160E+02	.160E+02
6.00	.294E+02	.260E+02	.192E+02	.192E+02	.192E+02

DIRECTION OF MAXIMUM SPREAD RATE, DEGREES FROM UPSLOPE

WIND SPEED	00	45	90	135	180
0	0	0	0	0	0
1.00	0	3.0	3.0	0	0
2.00	0	6.0	9.0	0	0
3.00	0	12.0	18.0	0	0
4.00	0	15.0	27.0	135.0	180.0
5.00	0	18.0	90.0	135.0	180.0
6.00	0	21.0	90.0	135.0	180.0

AREA IN ACRES/(HOUR SQUARED)

0	.765E+01	.765E+01	.765E+01	.765E+01	.765E+01
1.00	.109E+02	.103E+02	.913E+01	.865E+01	.862E+01
2.00	.158E+02	.143E+02	.117E+02	.107E+02	.106E+02
3.00	.219E+02	.196E+02	.156E+02	.139E+02	.138E+02
4.00	.296E+02	.263E+02	.207E+02	.184E+02	.182E+02
5.00	.387E+02	.344E+02	.273E+02	.243E+02	.241E+02
6.00	.494E+02	.441E+02	.353E+02	.316E+02	.314E+02

PERIMETER IN CHAINS/HOUR

0	.328E+02	.328E+02	.328E+02	.328E+02	.328E+02
1.00	.388E+02	.373E+02	.355E+02	.364E+02	.379E+02
2.00	.463E+02	.436E+02	.400E+02	.419E+02	.451E+02
3.00	.543E+02	.508E+02	.458E+02	.487E+02	.530E+02
4.00	.628E+02	.587E+02	.526E+02	.563E+02	.615E+02
5.00	.716E+02	.670E+02	.601E+02	.645E+02	.703E+02
6.00	.806E+02	.756E+02	.683E+02	.733E+02	.793E+02

MAXIMUM RATE OF SPREAD, CHAINS/HOUR

0	.109E+02	.109E+02	.109E+02	.109E+02	.109E+02
1.00	.130E+02	.124E+02	.110E+02	.109E+02	.109E+02
2.00	.154E+02	.142E+02	.112E+02	.109E+02	.109E+02
3.00	.181E+02	.163E+02	.116E+02	.109E+02	.109E+02
4.00	.209E+02	.186E+02	.126E+02	.116E+02	.116E+02
5.00	.238E+02	.210E+02	.145E+02	.145E+02	.145E+02
6.00	.267E+02	.236E+02	.175E+02	.175E+02	.175E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL ....J.. HEAVY LOGGING SLASH RUN 3

SLOPE TANGENT (GRADE) .600

AREA AND PERIMETER GROWTH RATES BASED ON HAL E ANDERSON DOUBLE-ELLIPSE SHAPE USING FONS WIND/SHAPE DATA

WIND SPEED (MPH) AT MIDFLAME (UPHILL)	PERIMETER GROWTH		AREA GROWTH		MAXIMUM SPREAD RATE	
	FEET/MIN	CHAINS/HOUR	SQFT PER SQ MIN	ACRES PER SQ HOUR	FEET PER MINUTE	CHAINS PER HOUR
0	.510E+02	.464E+02	.204E+03	.168E+02	.120E+02	.109E+02
1.0	.560E+02	.509E+02	.241E+03	.200E+02	.143E+02	.130E+02
2.0	.620E+02	.564E+02	.290E+03	.240E+02	.170E+02	.154E+02
3.0	.682E+02	.620E+02	.340E+03	.281E+02	.199E+02	.181E+02
4.0	.743E+02	.675E+02	.389E+03	.322E+02	.230E+02	.209E+02
5.0	.803E+02	.730E+02	.436E+03	.360E+02	.262E+02	.238E+02
6.0	.864E+02	.786E+02	.480E+03	.397E+02	.294E+02	.267E+02

TO OBTAIN FIRE AREA AT TIME T AFTER START, MULTIPLY AREA ENTRIES BY (T SQUARED)
TO OBTAIN FIRE PERIMETER AT TIME T AFTER START, MULTIPLY PERIMETER ENTRIES BY (T)

RUN NO. 3

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL .....I.. HEAVY LOGGING SLASH

INTENSITY AND FUEL LOADING -VS- TIME AFTER ARRIVAL OF FLAME FRONT

TIME (MIN.)	TOTAL FUEL LOAD NOT YET BURNED OUT (FRACTION)		(LB/SQFT)		INSTANTANEOUS FUEL LOAD LOSS RATE (FRACTION/MIN)		(LB/MIN/SQFT)		FIRE INTENSITY (BTU/MIN/SQFT)	TOTAL HEAT RELEASED (BTU/SQFT)
	GROSS	DRY WT	GROSS	DRY WT	GROSS	DRY WT	GROSS	DRY WT		
0	1.0000	1.0000	2.9895	2.6680	0	0	0	0	0	0
.3	.8571	.8571	2.5623	2.2867	.4314	.4314	1.290	1.151	.921E+04	.305E+04
CONDITIONS ABOVE OBTAIN AS SPREADING FRONT HAS PASSED...TIME ORIGIN IS ARRIVAL TIME OF IGNITING FLAME FRONT										
.4	.9582	.9574	2.8646	2.5544	.2089	.2129	.625	.568	.448E+04	.896E+03
.8	.8489	.8460	2.5377	2.2572	.2917	.2970	.872	.793	.625E+04	.324E+04
1.2	.7302	.7252	2.1823	1.9348	.3019	.3072	.902	.820	.647E+04	.578E+04
1.6	.6348	.6283	1.8977	1.6762	.0787	.0792	.235	.211	.167E+04	.782E+04
2.0	.6158	.6093	1.8408	1.6256	.0508	.0506	.152	.135	.106E+04	.822E+04
2.4	.5934	.5870	1.7739	1.5661	.0610	.0608	.182	.162	.127E+04	.869E+04
2.8	.5672	.5609	1.6956	1.4965	.0678	.0675	.203	.180	.142E+04	.924E+04
3.2	.5400	.5338	1.6144	1.4243	.0681	.0679	.203	.181	.142E+04	.980E+04
3.6	.5127	.5067	1.5328	1.3518	.0683	.0680	.204	.182	.143E+04	.104E+05
4.0	.4853	.4794	1.4510	1.2791	.0686	.0683	.205	.182	.143E+04	.109E+05
4.4	.4578	.4520	1.3688	1.2060	.0689	.0686	.206	.183	.144E+04	.115E+05
4.8	.4302	.4246	1.2862	1.1327	.0692	.0689	.207	.184	.144E+04	.121E+05
5.2	.4025	.3970	1.2034	1.0591	.0694	.0691	.208	.184	.145E+04	.127E+05
5.6	.3747	.3693	1.1202	.9852	.0697	.0694	.208	.185	.146E+04	.133E+05
6.0	.3467	.3414	1.0366	.9110	.0700	.0697	.209	.186	.146E+04	.138E+05
6.4	.3187	.3135	.9528	.8365	.0703	.0699	.210	.187	.147E+04	.144E+05
6.8	.2911	.2860	.8701	.7631	.0634	.0630	.189	.168	.132E+04	.150E+05
7.2	.2696	.2647	.8060	.7062	.0439	.0436	.131	.116	.914E+03	.155E+05
7.6	.2560	.2511	.7652	.6701	.0244	.0242	.073	.064	.506E+03	.157E+05
8.0	.2501	.2454	.7478	.6546	.0055	.0054	.017	.014	.113E+03	.159E+05
8.4	.2478	.2432	.7410	.6487	.0058	.0057	.017	.015	.119E+03	.159E+05
8.8	.2455	.2408	.7338	.6425	.0061	.0059	.018	.016	.124E+03	.160E+05
9.2	.2430	.2384	.7264	.6360	.0064	.0062	.019	.017	.130E+03	.160E+05
9.6	.2404	.2359	.7186	.6293	.0067	.0065	.020	.017	.136E+03	.161E+05
10.0	.2376	.2332	.7104	.6222	.0069	.0068	.021	.018	.141E+03	.161E+05
10.4	.2348	.2305	.7020	.6149	.0071	.0070	.021	.019	.146E+03	.162E+05
10.8	.2320	.2277	.6935	.6074	.0071	.0070	.021	.019	.146E+03	.162E+05
11.2	.2291	.2249	.6849	.6000	.0071	.0070	.021	.019	.146E+03	.163E+05
11.6	.2262	.2221	.6764	.5926	.0071	.0070	.021	.019	.146E+03	.163E+05
12.0	.2234	.2193	.6678	.5851	.0071	.0070	.021	.019	.146E+03	.164E+05

RUN NO. 3

NORTHERN FOREST FIRE LABORATORY STANDARD FUEL MODEL ....J.. HEAVY LOGGING SLASH

SUMMARY OF LOAD LOSS BY FUEL ELEMENT, WITH ELEMENT BURNOUT TIME

FUEL TYPE	BURNOUT TIME	DRY LOAD BURNED OUT FRACTION	DRY LOAD BURNED OUT LB/SQFT	HEAT RELEASED BTU/SQFT
IGNITION	.33	.1429	.3813	.305E+04
LIT/DUFF	I	.4245	.3396	.257E+04

ABOVE FOR REFERENCE ONLY -- NOT INCLUDED IN TOTAL

FUEL TYPE	BURNOUT TIME	DRY LOAD BURNED OUT FRACTION	DRY LOAD BURNED OUT LB/SQFT	HEAT RELEASED BTU/SQFT
FINES	1.64	1.0000	.3041	.241E+04
HALFINCH	7.99	.9854	.9847	.102E+05
1-3 INCH	30.91	.9021	1.0974	.188E+05
TOTAL	30.91	.8944	2.3863	.188E+05

SUMMARY OF STORAGE REQUIREMENTS

The listing below allocates core storage for items stored in the FIREMØDS library. Although listed separately, the unlabeled CØMMØN package is part of almost every routine. Quantities are subject to change as subroutines are revised.

	Storage Requirement	
Library Entry	*Octal*	*Decimal*
Unlabeled CØMMØN	4133	2139
Subroutine SETUP	1140	608
Subroutine FUELS	2524	1364
Subroutine FIREMØD	5473	2875
Subroutine STDFUEL	1337	735
Subroutine FLAME	540	352
Subroutine CØNTAIN (group)	14226	6294
(CØNTAIN ONLY)	(6431)	(3353)
(RØMBERG ONLY)	(5072)	(2618)
(Others in group)	(503)	(323)
Subroutine BURNØUT	66421	27921
Program SAMPLE	50	40
Complete package	122530	42328

PUBLICATIONS CITED

Anderson, Hal E.
1969. Heat transfer and fire spread. USDA For. Serv. Res. Pap. INT-69, 20 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Brown, Arthur A., and Kenneth P. Davis.
1973. Forest fire control and use. 2nd ed. 163 p. McGraw-Hill Book Co., New York.

Byram, G. M., H. B. Clements, M. E. Bishop, and R. M. Nelson, Jr.
1966. An experimental study of model fires. Southeast. For. Exp. Stn. final rep., Project Fire Model OCD-PS-65-40, 51 p., Asheville, N.C.

Countryman, Clive M.
1969. Project FLAMBEAU...an investigation of mass fire (1964-1967). Final Report--vol. I, 68 p. USDA For. Serv. Pac. Southwest For.and Range Exp.Stn., Berkeley,Calif.

Deeming, J. E., J. W. Lancaster, M. A. Fosberg, R. W. Furman, and M. J. Schroeder.
1972. National fire-danger rating system. USDA For. Serv. Res. Pap. RM-84, 165 p. Rocky Mt. For. and Range Exp. Stn., Ft. Collins, Colo.

Frandsen, William H.
1973. Using effective heating number as a weighting factor in Rothermel's fire spread model. USDA For. Serv. Gen. Tech. Rep. INT-10, 7 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Norum, Rodney A.
1975. Characteristics and effects of understory fires in western larch/Douglas-fir stands. Ph.D. Thesis. Univ. Mont., Missoula. 157 p.

Philpot, Charles W.
1965. Temperature in a large natural fuel fire. USDA For. Serv. Res. Note PSW-90. 14 p. Pac. Southwest For. and Range Exp. Stn., Berkeley, Calif.

Philpot, Charles W.
1968. Mineral content and pyrolysis of selected plant materials. USDA For. Serv. Res. Note INT-84, 4 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Ralston, Anthony, and H. S. Wilf.
1967. Mathematical methods for digital computers. Vol. II. John Wiley and Sons, N.Y.

Rothermel, Richard C.
1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Pap. INT-115, 40 p. Intermt. For. and Range Exp. Stn., Ogden, Utah.

Rothermel, Richard C., and Charles W. Philpot.
1973. Predicting changes in chaparral flammability. J. For. 71(10):640-643.

Stocks, Brian J., and John D. Walker.
1972. Fire behavior and fuel consumption in jack pine slash Ontario. Can. For. Serv. Inform. Rep. 0-X-169, 19 p.

Thomas, P. H.
1962. The size of flames from natural fires. Ninth Int. Symp. Combust. Proc.:844-859. Acad. Press, Inc., New York.

Thomas, P. H.
1967. Some aspects of the growth and spread of fire in the open. Forestry 40(2): 139-164.

Van Wagner, Charles E.
1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. 2:34-39.

Van Wagner, Charles E.
1973. Height of crown scorch in forest fires. Can. J. For. Res. 3:373-378.

APPENDIX I

Basis for Subroutine BURNØUT

The algorithm, viewed as a whole, is lengthy and somewhat unclear as to structure or intent. When it is understood that much of the first 50 percent of the coding is "bookkeeping" and most of the last 50 percent is intended to establish "the degree of planform overlap of size class i by size class j," it becomes much clearer. For that reason, only the rough theoretical outline of the computations is given here. The theory behind the algorithm and model calibration and also the probability expressions underlying the theory are discussed in this appendix.

Theory Behind Calculations

The basic tenets of the theory underlying the computations can be stated in straightforward terms. Keeping in mind that this theory attempts to predict the burning out of fuels *after* the arrival of the igniting flame front helps in understanding the rationale for these tenets:

1. In order to burn at all, a fuel piece must be overlapped in planform projection by at least one other piece of equal size (diameter) or smaller, which itself can burn. If the piece is rotten (i.e., has a density of 15 lb/ft^3 or less), it is assumed to burn completely without the necessity of interaction with another piece, unless its moisture content is too high.

2. A piece that has a moisture content greater than a maximum burning moisture calculated for its size will not cause pieces of its own size or larger to burn, but may be consumed by the burning of overlapping smaller sized pieces.

3. For the purpose of determining the degree of planform-view overlap amongst fuel pieces of "the same" general size, fuel elements are classified into subcategories, depending on surface/volume ratio. The surface/volume ratios that mark the divisions between categories are 500, 200, 100, 50, 25, and 12 ft^{-1}. That is, all fuel elements with surface/volume ratio equal to or greater than 500 are considered to be in the same subcategory, as are all with surface/volume ratio less than 12, etc. "Being in the same subcategory" is of significance to the computation of the amount of fuel of each size class that is consumed (see below).

4. The maximum burning moisture of a fuel element with surface/volume ratio σ (ft^{-1}) is given by

$$M_x = 0.75 - 0.066 \ln(\sigma).$$

This wholly arbitrary function was chosen because it is simple, slowly varying (with σ) and meets the following two general observations:

a. Pine needle beds, $\sigma \approx 2{,}000$, generally will not spread fires with fuel moisture above about 25 percent (Anderson 1969).

b. "Most fuels"--here taken to be logs with $\sigma \approx 10$--will not burn in small fires with moisture contents above about 60 percent (Brown and Davis 1973).

Note that 1/2-inch sticks ($\sigma \approx 100$) would have a maximum burning moisture of about 45 percent, so most of the fuel elements of concern in this theory will have maximum burning moistures in the range of 45 to 65 percent. Laboratory wood cribs of 0.44-in-square sticks have been burned at moistures greater than 45 percent, with very high packing ratios (Byram and others 1966), indicating that this parameter should probably be included in the formula as well.

5. If there is an underlying litter/duff layer that would burn by itself, consuming a loading of W_D lb/ft^2 of the L and F layers, then fuel pieces in contact (planform area with an unoccluded projection onto the litter/duff layer) with this layer will be consumed to the extent of

$$W_D(1 - M/0.60),\ \text{lb/ft}^2$$

where M is the fuel piece moisture content. This is an arbitrary equation also, and is only heuristically justified.

6. The burning time, T, of a fuel element is calculated from the following formula:

$$T = (384/\sigma\ \eta_M \eta_S) K_T,\ \text{minutes}$$

where

σ = surface/volume ratio, ft^{-1}

η_M = a moisture-damping coefficient, calculated from the ratio M/M_x, where M_x is the maximum burning moisture mentioned above, and

η_S = a mineral-damping coefficient, a function of the silica-free ash content, S:

= $0.174\ S^{-0.19}$, (Philpot 1968)

K_T = an empirically determined fudge factor of 0.60, chosen to best fit some large crib experimental data (see calibration, below).

If only the single size class, σ, were present, the particles would burn out in the time T after ignition. However,

7. No size class is allowed to have a burning time less than the value T_{ig}, which is an estimate of the time it takes the igniting flame front to propagate vertically downward through the fuel array.

$$T_{ig} = D\ Q_{ig}/I_p$$

where

D = depth of the fuel bed, ft

Q_{ig} = bulk heat of preignition of the fuel bed (the parameter RHØBQIG output from FIREMØD), Btu/ft^3

I_p = the propagating flux from the fire, without the influence of wind or slope (the parameter XIØ output from FIREMØD), Btu/ft^2/min.

8. When two fuel elements overlap, each will lose a calculable amount of mass through interaction. The losses will occur in the shorter of the two burning times. Only such "binary" interactions are considered in this theory.

9. The fuel elements are strewn at random over the area of concern. For a sufficiently large sample area, the number of elements per unit area of any particular size class is constant. Fuel elements of each diameter (size class) are of uniform length.

10. Fuel elements do not have to overlap physically in planform projection to interact and cause mutual burning. They may be only near each other and still interact. To account for this effect, the planform area of each piece being considered is increased by a factor (K_A) of 2.23. A similar factor (K_D = 2.23) also applies to the area of influence of a burning litter/duff layer under an exposed fuel piece. These empirical constants were determined from calibration trials against logging slash data.

Calibration of Model

Several arbitrary factors and functional forms are imbedded in this algorithm. With so many degrees of freedom it should not be difficult to experiment with coefficients and factors until the output of the model fits reasonably well whatever data are at hand to match. To recapitulate, these are the arbitrary or adjustable features of the model:

1. The maximum burning moisture equation

$$M_x = 0.75 - 0.066 \ln(\sigma)$$

2. The moisture correction term on the litter/duff-induced burnout of exposed planform

$$W_D(1 - M/0.60)$$

3. The burnout time correction factor

$$K_T = 0.60$$

4. The planform area influence factor for the burning of one fuel element by interaction with another

$$K_A = 2.23$$

5. The planform area influence factor for the burning of a fuel element by interaction with burning litter/duff

$$K_D = 2.23$$

6. The functional form of the burnout function

$$FBT(X=t/T) = \begin{cases} 2\,X^2 & X \leq 1/3 \\ (2/3)(2X - 1/3) & 1/3 < X < 5/6 \\ 1 - 4(1 - X)^2 & X \geq 5/6 \end{cases}$$

where FBT is the fraction of the fuel to be consumed that is actually consumed by time t, if all is to be consumed by time T.

The variable features of the model influence different aspects of the performance of the model. The two things this model attempts to predict are:

a. How much fuel is consumed,

b. The time history of the intensity.

The influence of the variable features listed above on these two factors is:

VARIABLE FEATURE	1	2	3	4	5	6
AFFECTS FACTOR a	YES	YES	NO	YES	YES	NO
AFFECTS FACTOR b	YES	NO	YES	YES	YES	YES

Because of all these interdependences, calibration of the model may not yield unique results. The process followed was:

1. Freezing features 1 and 2 arbitrarily as presented, factors K_A and K_D were varied independently over a wide range of values, to obtain (statistically) the best fit to the results of some carefully measured light logging slash experimental burns.

2. Keeping everything else fixed, factor K_T and function FBT were varied independently to obtain good reproduction of the fractional gross weight loading time histories of three large-scale heavy crib burns.

The data for step 1 were taken from Stocks and Walker's experimental fires in light jack pine logging slash (Stocks and Walker 1972).[5] To establish the best values for K_A and K_D, the measured values of the litter/duff burnout were used, rather than calculated values based on duff moisture content (Van Wagner 1972). The results of the comparison between measured and calculated slash load consumption, using the measured litter/duff burnout as input, are shown in figures 6 and 7. Figure 6 shows the comparison on a fractional load basis; figure 7 in terms of actual load loss in tons/acre. When the litter/duff burnout is calculated from upper duff moisture (the only values available), the comparisons are as shown in figures 8 and 9.

Data taken from a series of burns in litter and deadfall under mature stands of Douglas-fir/western larch (Norum 1975) were tested against the model after the previous calibration trials. In these burns, significant quantities of rotten wood were present, and most often were completely consumed in the fires. Trials were made in which the rotten wood was treated as though it were sound but of a different density. The results were wholly unsatisfactory, indicating the need for the special treatment of rotten wood. Figures 10 and 11 show the comparisons between predicted and observed values of load loss, including both the jack pine slash data shown in the previous figures and Norum's data. The possibility exists of a bias in the predictions towards underestimation of load loss at high values of load loss (fig. 10 and 11), but the available data are insufficient to establish its existence.

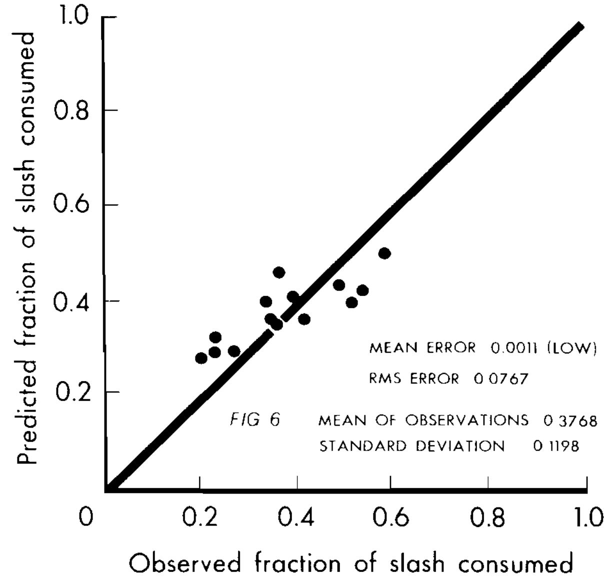
The selection of the functional form of FBT(X) was not extensively investigated. The form chosen seems to fit the large crib data reasonably well, so it was frozen fairly early in the pursuit of the final form of the model. Then the value of K_T was varied systematically over a rather wide range, with the final selection based on a judgment of the goodness of fit of experimental data to the theory's predictions.

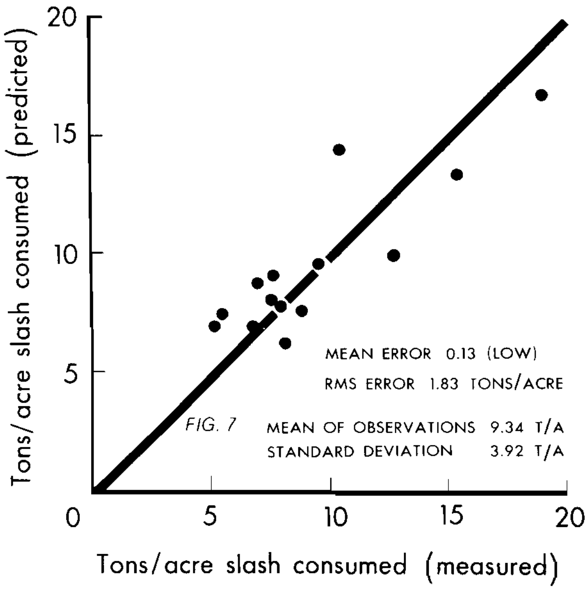
The results of such comparisons are shown in figures 12 through 14. The fires shown there were large-scale crib fires (Countryman 1969) with a mix of fuels from excelsior to 4- by 4-in milled lumber, stacked to over 5 ft high, with a dry weight loading of about 17 lb/ft^2 (370 tons/acre). The fires were of different total size. SR-4 and SR-5 were about 1.5 tons total fuel, and 12A-2 was 17.5 tons. Fuel moistures and ambient winds were the only other variables that differed (Countryman)[6] and these differences were not great.

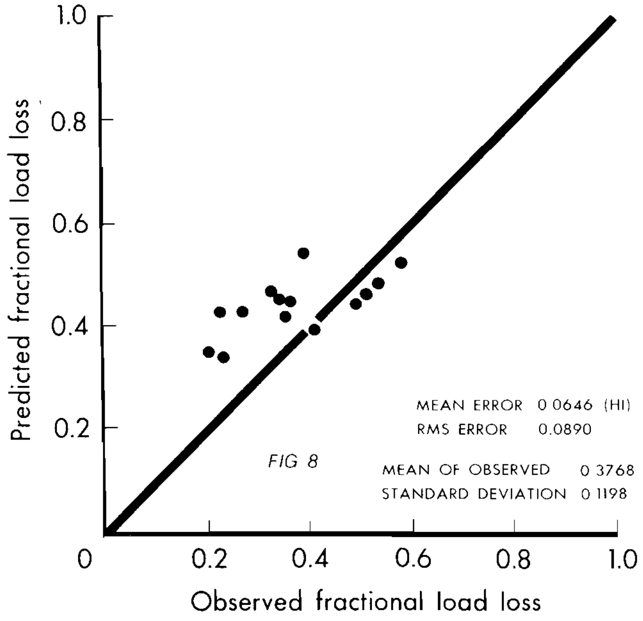
---

[5] Stocks, Brian J. 1973. Private communication to W. H. Frandsen, on file at the Northern Forest Fire Laboratory, Missoula, Montana 59801.

[6] Countryman, Clive M. 1974. Correspondence on file at Northern Forest Fire Laboratory, Missoula, Montana 59801.







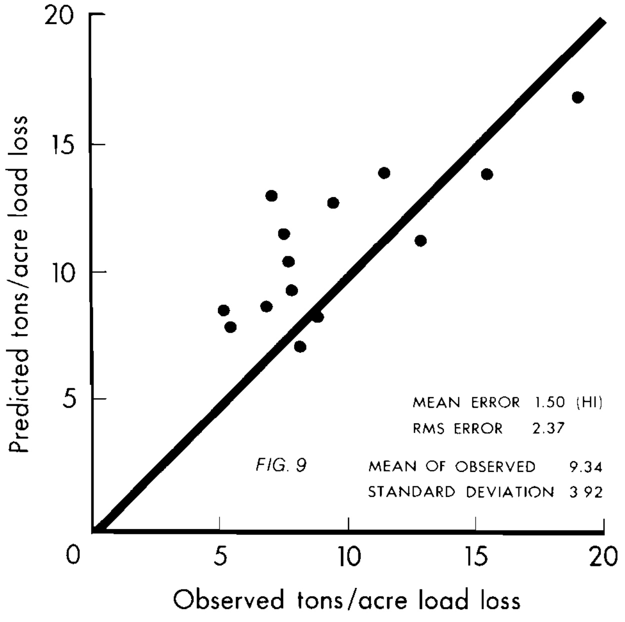


Figure 6.--Comparison of predicted and observed fractions of slash loads consumed in light jack pine slash, using observed duff burnout as input variable.
Figure 7.--Comparison of predicted and observed slash consumption in light jack pine clearcut burns, using observed duff burnout as input variable.
Figure 8.--Comparison of predicted and observed fractional load losses for light jack pine clearcut slash, using duff moisture to predict amount of duff burned out.
Figure 9.--Comparison of predicted and observed tons/acre load losses for light jack pine logging slash, using duff moisture to predict amount of duff burned out.

Figure 10.--Comparison of predicted and observed values of load loss (fuel consumed) by fires in fresh jack pine slash and in deadfall under mature Douglas-fir/western larch stands. The contribution of burning of litter and duff was estimated using Van Wagner's model to calculate duff consumption. Litter/duff not included in load loss calculations or observations.

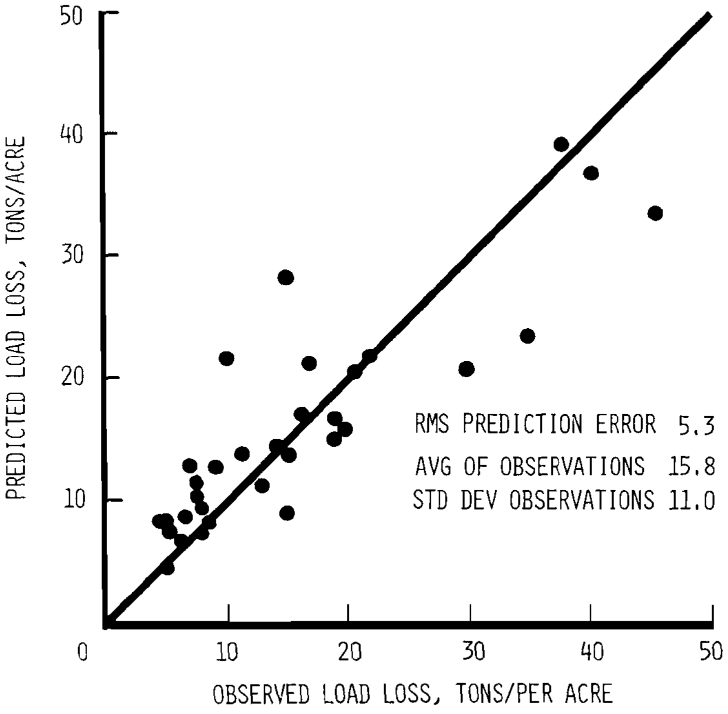
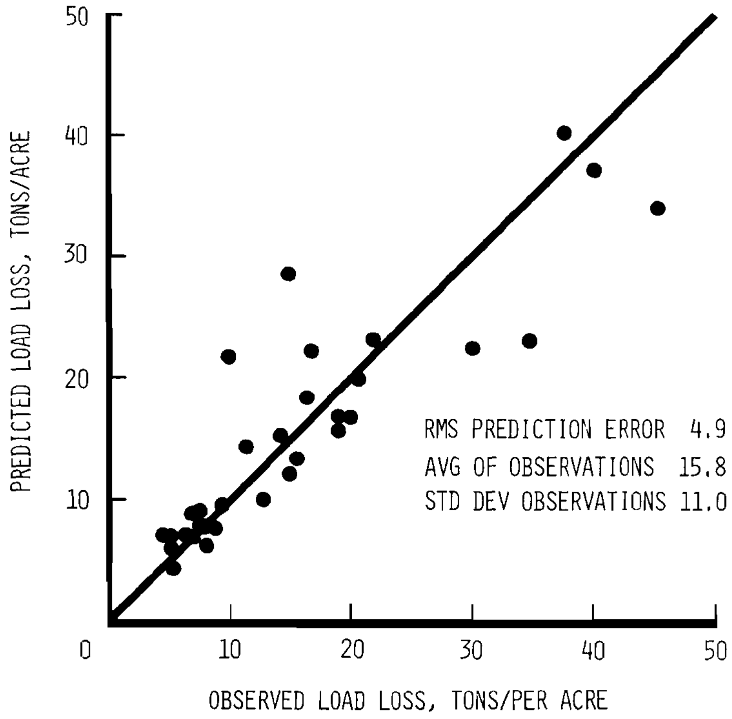
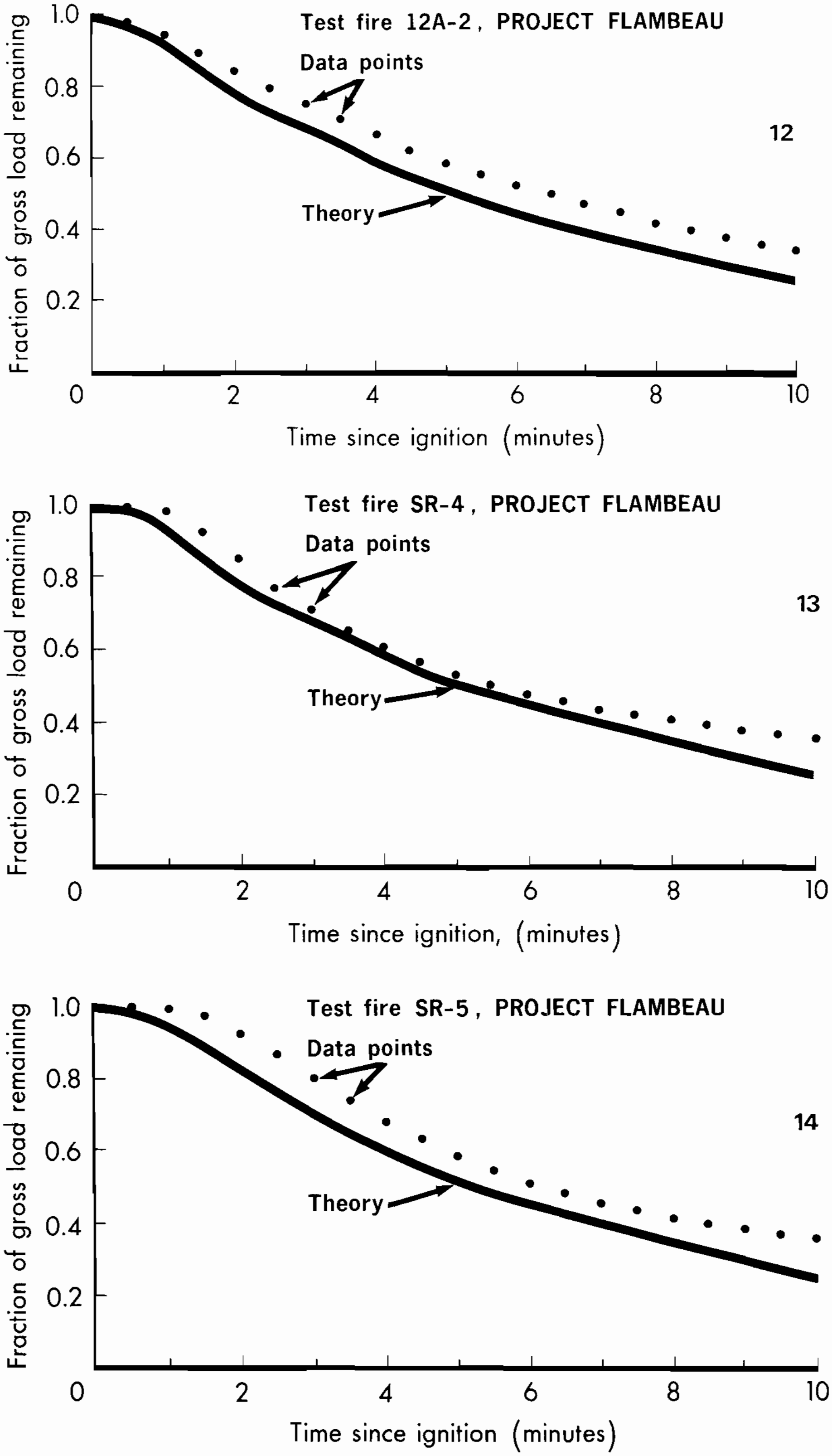


Figure 11.--Comparison of predicted and observed values of load loss (fuel consumption) by fires in fresh jack pine slash and in deadfall under mature Douglas-fir/western larch stands. The contribution of burning of litter and duff was accounted for by using measured values of duff consumption on each plot burned. Litter/duff not included in load loss calculations or observations.





Figures 12, 13, 14.--Comparisons of predicted and observed gross weights for a large crib fire.

One reason for the shift in the data points to the right of the theoretical curves is due to the choice of $K_T = 0.60$, which was chosen to match the slope of the curves rather than the curves themselves. This was done because of the uncertainty in the ignition delay for the three test fires. The experimental fires were ignited by firing electrical squibs in bags of jellied gasoline. SR-4 had one igniter, SR-5 had four, and 12A-2 had 49. Thus, the ignitions were nearly but not completely uniform and instantaneous over the whole crib. The theory deals with a differential area of ground beneath a free-spreading fire, so replication of the theoretical conditions is not possible with finite scale instrumentation.

The inflection points in the curves of figures 9 through 11 are more pronounced when the intensity-vs-time plots are shown. In general, they roughly correspond to the patterns of some temperature-history data taken on the large-scale, piled natural fuel burns of Project FLAMBEAU (Philpot 1965), but the comparison can be of no more than anecdotal support to the theory. More emphasis was given test fires SR-4 and SR-5 than 12A-2 because some "scale effect" was felt to be apparent in the data for the last (and by far the largest) burn.

Mathematical Relationships

This section presents the derivation of various expected-value expressions dealing with the overlap in planform projection of randomly strewn fuel pieces. The expressions underlie the logic behind various equations in the burnout algorithm. First, expressions are generated that appear to have no connection to the problem at hand; the need for these terms becomes apparent later. We deal here with the planform projection of cylindrical fuel elements and consider them to be rectangles.

1. If J rectangles are randomly strewn in a fixed planar area, and each occludes a fraction α of the area, let $F_N(J;\alpha)$ be the expected fraction of the total area which is overlapped exactly N times. The evolution of $F_N(J;\alpha)$ with increasing J can be written as

$$F_N(J+1;\alpha) = \alpha F_{N-1}(J;\alpha) + (1-\alpha)F_N(J;\alpha) \tag{1}$$

Equation (1) is clearly not exact, but in the author's experience is a good approximation if α is small. This equation can be summed in closed form. Suppressing the explicit use of α as a parameter of $F_N(J)$, the result can be written as:

$$F_N(J) = \binom{J}{N} \alpha^N (1-\alpha)^{J-N} \tag{2}$$

which might almost be written immediately if the problem is viewed as a Bernoulli Trials process.

2. Of the total planform area represented by the J randomly strewn elements, some fraction $\psi_N(J;\alpha)$ is itself covered over by others N times. Note that this area, as a fraction of the planar area in which the pieces are strewn, can be written as $(J\alpha)\psi_N(J;\alpha)$. But this area is also derivable from the expression $(N+1)F_{N+1}(J)$, which states that, for every unit of plot area covered N+1 times, there are N+1 units of fuel element planform area covered N times, so

$$\psi_N(J;\alpha) = \frac{N+1}{J\alpha} F_{N+1}(J). \tag{3}$$

3. Equation (3) can be used directly to calculate the fraction of the planform area of the fuel elements not covered at all by others. The reasoning is the same:

$$\psi_o(J;\alpha) \cdot (J \times \text{planform area of one fuel element}) =$$

$$F_1(J) \cdot (\text{Planar area in which fuel elements strewn})$$

Or, in terms of the parameter α,

$$\psi_o(J;\alpha) = F_1(J)/\alpha J \qquad (4)$$

4. If the same area (plot area) is strewn with K fuel elements, each of which covers α_k of the plot, and also with L fuel elements, each of which covers α_ℓ of the plot, let $\phi_N(K,L)$ represent the fraction of the fuel element planform area of size class k elements which is covered N times by pieces of size class ℓ.

The total planform area of size k fuel elements covered N times by size ℓ planforms can be written as $(K\alpha_k)$(Plot area)$(\phi_N(K,L))$. But this area can be written also as (Plot area)$(F_N(L;\alpha_\ell))$(M) where M is the expected number of size k fuel element planform area overlaps to be found at any point in the plot, or

$$M = \sum_{j=1}^{K} jF_j(K;\alpha_k) = K\alpha_k \qquad (5)$$

From these two expressions we obtain the unsurprising result:

$$\phi_N(K,L) = F_N(L;\alpha_\ell) \qquad (6)$$

5. It is assumed that the amount of weight loss of a larger piece of fuel, due to burning in interaction with a smaller piece of fuel, is proportional to the ratio of diameters of the two interacting pieces. This postulation allows the simple expression of the fraction of the loading of size class k fuels which would be burned out due to the burning of size class ℓ fuels (ℓ smaller than k), if all the ℓ-size fuel burned and there were no other size classes present except k and ℓ. Let this fraction be represented by $\beta_o(k,\ell)$. Again, there are K pieces of size α_k and L pieces of size α_ℓ. Let their respective surface/volume ratios be σ_k and σ_ℓ (where $\sigma_k < \sigma_\ell$).

Then,

$$\begin{aligned}\beta_o(k,\ell) &= (K_A\sigma_k/\sigma_\ell)\sum_{n=1}^{L} n\phi_n(K,L) \\ &= (K_A\sigma_k/\sigma_\ell)(L\alpha_\ell)\end{aligned} \qquad (7)$$

where K_A is the area-factor determined by the calibration trials.

6. Since the fraction of the size-k total planform area which would be overlapped at least once by its own size class is $(1-\psi_o(K;\alpha_k))$, it follows that the fraction of the size-k loading which would be burned out by interaction with its own size class, were there no other size classes present, would be $\beta_o(k,k)$, where

$$\beta_o(k,k) = 1 - \psi_o(K;K_A\alpha_k) = 1 - (1-K_A\alpha_k)^{K-1} \qquad (8)$$

7. Of that portion of size class k which is actually burned out, some fraction is due to interaction with size class ℓ. If the fraction of the size k loading which burns out is B_k, and the fraction of the size k loading which burns out due to interaction with size ℓ is $\lambda_{k\ell}$, then

$$\lambda_{k\ell} = B_k \cdot (\beta_o(k,\ell)/\sum_{j=1}^{k} \beta_o(k,j)) \tag{9}$$

where the sizes are arranged in ascending order, so that $\sigma_1 > \sigma_2 > \sigma_3$, etc.

8. Assuming that the fractional loading burned of any size class can be calculated as though there were no larger size classes (purely for computational convenience at this point--the effect of this assumption is largely balanced out in the selection of the empirical constant K_A), an algorithm can be specified for the computation of B_k, the fractional loading of size class k which is burned.

By ordering the size classes so k=1 is the finest (largest value of σ), k=2 the next finest, etc., the algorithm can be written concisely as:

$$B_1 = \beta_o(1,1) \tag{10}$$

$$B_N = 1 - (1-\beta_o(N,N))\prod_{j=1}^{N-1} (1-B_j\beta_o(N,j)) \tag{11}$$

9. The parameter α_k, which appears in so many equations above, always occurs multiplied by K, or in an expression in which a good approximation can be made in that form. Since $\alpha_k \lll 1$, and $K \gg 1$,

$$(1-\alpha_k)^K \doteq \exp(-\alpha_k K) \tag{12}$$

so the equation for $\beta_o(i,j)$ can be written as:

$$\beta_o(i,j) = \begin{cases} \min(1,K_A(\sigma_i/\sigma_j)(J\alpha_j)) & j<i \\ 1 - \exp(-K_A J\alpha_j) & j=i \\ 0 & j>i \end{cases} \tag{13}$$

Now the product $(J\alpha_j)$ can be readily calculated. It is the ratio of the total fuel planform area of size j to the area of the plot in which the fuel is strewn. Or, it is the product of the average number of size j fuel elements per unit area of plot and the planform area of an individual piece. If the elements are circular cylinders, the planform area of a fuel element can be approximated as the surface area divided by π. But the surface area can be written as the surface/volume ratio, σ_j multiplied by the volume. The volume, in turn, is the weight of an element divided by its density. And the weight of an element, multiplied by the mean number of elements per unit plot area, is simply the loading of that size class. Thus we have:

$$J\alpha_j \equiv w_j\sigma_j/\rho_j\pi \tag{14}$$

where

w_j = dry weight loading of size class j, lb/ft^2

σ_j = surface/volume ratio of size class j, lb/ft

ρ_j = ovendry density of fuel element of size class j, lb/ft^3

Burning Litter/Duff Layer Contribution

If a combustible mat underlies the fuel array, of which W_D lb/ft^2 will be consumed by burning, on the average, then it should cause some additional burnout of the larger fuel pieces. For the purpose of completing this algorithm without additional research, the assumption is made that *for every unit of fuel element planform area which would not be burned out by other fuel elements anyway,* a local loading reduction of $\eta'_M K_D W_D$ would occur where η'_M is a fuel element moisture-dependent factor (1-M/0.6) described in the text. Because the local value of the loading by a fuel element of size class j is the weight of the fuel element divided by its planform projection area, or approximately $\pi\rho_j/\sigma_j$, and because the fraction of the size j fuel that would be burned out by fuel element interactions is B_j, we can calculate an updated value of the self-interaction fractional load reduction $\beta^*_o(j,j)$, from the formula:

$$\beta^*_o(j,j) = \beta_o(j,j) + (1-B_j)f_j \tag{15}$$

where

f_j = local fractional load reduction due to litter/duff burnout

$$f_j = \min(1,\eta'_M K_D W_D/(\pi\rho_j/\sigma_j)) \tag{16}$$

When the quantity of litter/duff burnout is known, or parameter-variation studies are intended, W_D can be input to the algorithm directly. If a prediction of W_D is desired, the appropriate formula should be for burnout of the litter/duff mat uninfluenced by the overburden fuels. Additional burnout due to interaction with the overburden fuels would be a fine-scale correction not warranted by the precision of the rest of the model.

Fortunately, Van Wagner (1972) has published just such a predictive equation for L and F layer burnout under standing timber (Eastern Canadian Pine). Van Wagner's equation employs the fractional moisture content (average) of the L and F layers combined, to predict the weight loading loss by burning. Recast in British units for consistency, his equation can be written as

$$W_D = \min(W^*_D, 0.1926(1.418-M_D)/(0.1774+M_D)) \tag{17}$$

where

W^*_D = total litter/duff loading, lb/ft^2

M_D = average fractional moisture content of the L and F layers combined.

☆U.S. GOVERNMENT PRINTING OFFICE. 1975 — 677-328 / 37 REGION NO.8

Headquarters for the Intermountain Forest and Range Experiment Station are in Ogden, Utah. Field programs and research work units are maintained in:

- Billings, Montana
- Boise, Idaho
- Bozeman, Montana (in cooperation with Montana State University)
- Logan, Utah (in cooperation with Utah State University)
- Missoula, Montana (in cooperation with University of Montana)
- Moscow, Idaho (in cooperation with the University of Idaho)
- Provo, Utah (in cooperation with Brigham Young University)
- Reno, Nevada (in cooperation with the University of Nevada)