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Comparison of the Forest Fire Danger Meter Mk.5 and the BEHAVE fire behavior prediction system in a dry eucalypt forest

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Comparison of the Forest Fire Danger Meter Mk.5

and the BEHAVE Fire Behaviour Prediction

System in a Dry Eucalypt Forest.

by

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Dedication:

To my Lord and Saviour, Jesus Christ, without whom none of this could have taken place.

and

To my delightful wife, Anne. Your love, devotion, support and warmth is more a part of this than the paper it is written on.

Peter Francis Moore

(Peter F. Moore)

Missoula, Montana, June 1986

On the runs to the west of the Dingo Scrubs there was
  drought, and ruin, and death,
And the sandstorm came from the dread north-east with the
  blast of a furnace-breath,
Till at last one day, at the fierce sunrise, a
  boundary-rider woke,
And saw, in place of the distant haze, a curtain of light
  blue smoke.

from "The Bushfire" by Henry Lawson

Table of Contents:

List of Tables:

List of Figures:

Chapter 1

1. Introduction:

1.1 Background:

Uncontrolled fire has long been a factor in the Australian landscape (Groves & Noble 1981). Since the settlement of the country by European man steps have been taken to protect property and reduce damage caused by wildfires, known locally as "Bushfires". The problems associated with fire control and the use of fire for management have been studied and researched with particular emphasis since the disastrous wildfires of Friday January, 13th, 1939 in Australia. In that period progress has been made in the field of fire danger prediction notably by A.G.McArthur (McArthur 1958) and the Western Australian Woods and Forests Department (Forests Department of W.A. 1976). The major emphasis of such studies has been empirically based. Development has been independent of other research in this field carried out overseas.

Fire is used extensively as a tool of management, predominantly in hazard reduction but also for regeneration and some wildlife applications. Eucalypt forests are regularly burnt by both planned and unplanned fire.

The history of Australia's settlement is liberally annotated with bad fire seasons and catastrophic fires (Cheney 1976).

Fuels management, fire behaviour prediction and fire danger rating in Australia have evolved in a different manner to those of North America. This is due in part to the fact that Australian fire behaviour prediction systems are based on an empirical approach as against the theoretically developed mathematical models of the United States. Historically there has been little effort placed in modelling fire behaviour mathematically in Australia. This trend may be changing, due to overseas influence and a new generation of research scientists with access to powerful and sophisticated computing facilities.

The mathematical models utilised by the U.S. Forest Service and the National Fire Danger Rating System of the United States (Rothermel 1983), may have potential to be used for fire behaviour prediction in Australia. The fuel-based models of North America have an obvious attraction to the fire-conscious forest manager in Australia. The explicit incorporation of fuel variables into the prediction of fire behaviour and fire danger is logical. A wide range of fuel conditions occur in any section of a forest during any day. There is a need for some account of fuels as a factor in fire behaviour.

Currently the McArthur Fire Danger Rating System (McArthur 1973) is used in New South Wales (N.S.W.) and much of Australia. It does not predict fire behaviour per se but rather derives it from a prediction of the fire danger rating for a given set of meteorological data.

1.2 Problem Statement:

Fire behaviour prediction of fire in wildlands is not available to forest managers in New South Wales (N.S.W.) in a direct form. A scientific basis for fire management is necessary, to meet legislative, ecological, fiscal and forest planning requirements, for all N.S.W. forest types. Dry eucalypt forests, due to increased flammability, rapid fuel build-up and higher potential for ignition, require immediate attention. Fine litter weight data from the Eden Region of south-eastern N.S.W. (Figure 1) will be used to build fuel models of a dry eucalypt forest for the BEHAVE computer system of fire behaviour prediction (Burgan & Rothermel 1984). Fuel models will be built utilising measurements of fuel parameters, for mature/overmature unlogged forest, logged forest and fire regenerated stands.

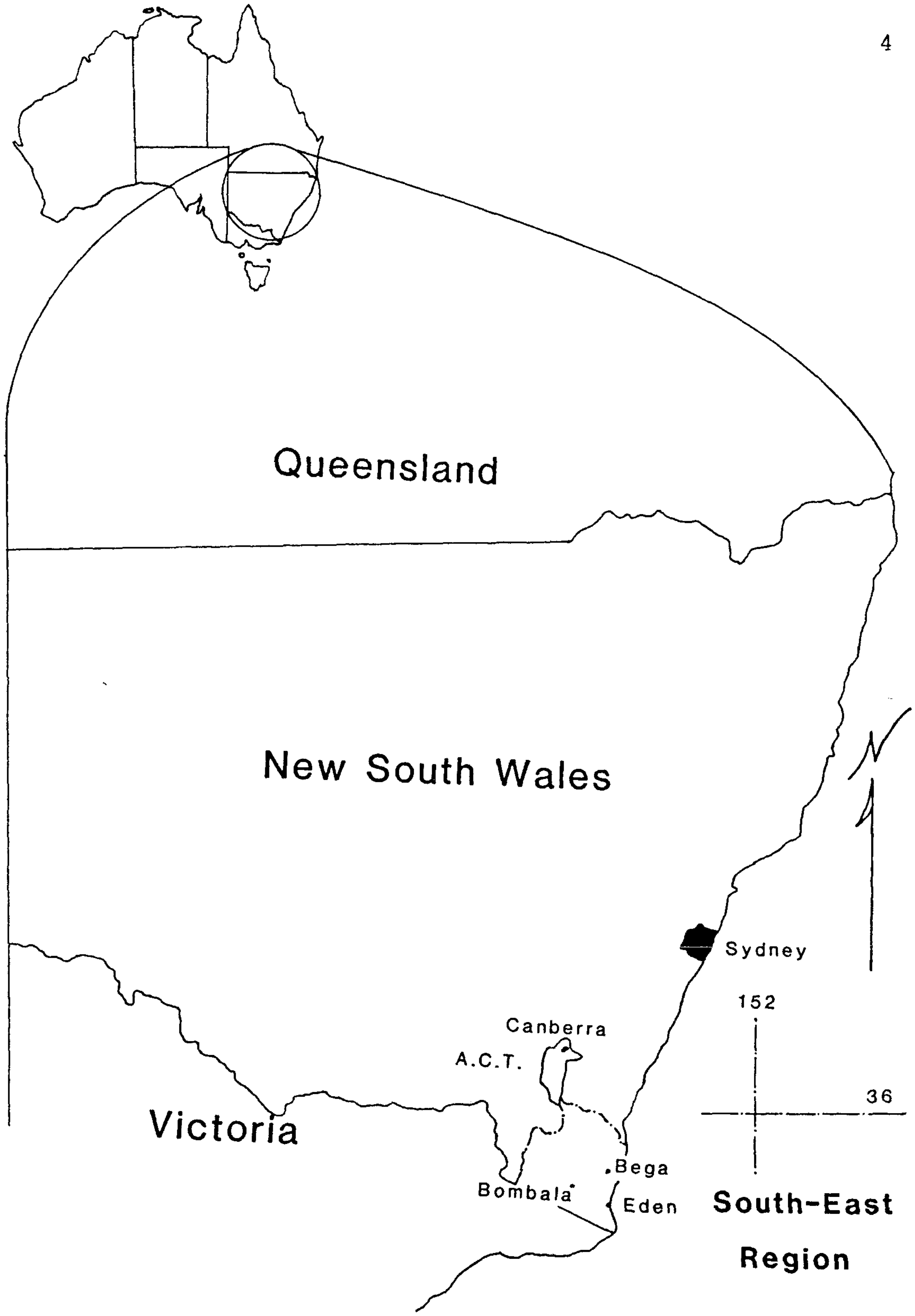


Figure 1: The Eden Region of N.S.W., Australia.

Fire tower weather records for a range of climatic conditions will provide a basis for calculation of fire behaviour prediction from both the Forest Fire Danger Meter Mk.5 (FFDM Mk.5) and the BEHAVE system.

1.3 Study Objectives:

This professional paper will use fuel data and meteorological data collected in the Eden Region of N.S.W.. The results of fire behaviour predictions will be compared between two of the systems for doing so. The Forest Fire Danger Meter Mk.5 (McArthur 1973), and the BEHAVE computerised system of the United States Department of Agriculture, Forest Service will be used. The paper will compare and contrast use of the two systems, their basis, their assumptions and their results in light of the professional development of the author.

Chapter 2

2. Literature Review:

2.1 Introduction:

The different approaches to modelling fire behaviour are discussed briefly in Chandler et al (1983). Empirical, statistical and theoretical methods of predicting fire spread are explained. McArthur's studies were empirical, including five-hundred prescribed fires and over five-thousand documented wildfires (McArthur & Luke 1963). Rothermel's theoretical mathematical model, used in the BEHAVE system (Rothermel 1972) is also discussed.

Cheney (1968) detailed methods of using the Forest Fire Danger Meter for site specific prediction of fire behaviour. He outlined the assumptions of the fire danger meter and the mechanism whereby variation from those assumptions could be taken into account.

Van Wilgen (1984) developed some fuel models for use in the BEHAVE fire behaviour prediction system. Working with vegetation types in South Africa he utilised fuel data specifically to predict fire behaviour in the fynbos.

Potential uses of fire behaviour predictions include the entire spectrum of fire related decision-making, such as planning prescribed fire, estimating fire effects and preparing wildfire suppression strategy.

Manual searches of available library resources and accession of the Commonwealth Agricultural Bureau Index by computer have not produced any other related studies. Relevant references to the FFDM Mk.5 have also proved scarce.

The mathematical model of fire behaviour developed by Rothermel (1972) has made it possible to account for the effects of weather and fuel moisture conditions on the burning potential of a given fuel (Sneeuwjagt 1974). The physical, chemical and moisture properties of fuels are combined in a fuel model (Burgan & Rothermel 1984). Site specific environmental factors of wind speed and slope, provide other inputs to the BEHAVE system which produces an estimate of the forward rate of spread, fireline intensity, flame length, heat per unit area and reaction intensity (Andrews 1986).

2.2 BEHAVE Fire Behaviour Prediction System:

2.2.1 System Structure:

BEHAVE is a group of computer programs designed to estimate certain fire behaviour characteristics. The computer programs are interactive and "user-friendly". Questions and prompting by the system guide the user.

Incorrect answers do not "abort" or "crash" the programs.

BEHAVE consists of two subsystems of two programs each (Figure 2), (Andrews 1986). The two subsystems are FUEL and BURN.

The FUEL subsystem provides the capability of building site-specific fuel models. NEWMDL (New Model) allows the values for a fuel model to be set. TSTMDL (Test Model) is used to assess fire behaviour predictions for the new fuel model and adjust values as required to "fine-tune" the model (Burgan & Rothermel 1984).

The BURN subsystem has two programs also, FIRE1 and FIRE2. Currently FIRE2 is not operational. It will consist of further modules expanding the options and capability of the system. There are six modules in the FIRE1 prediction program. SITE and DIRECT provide fire behaviour characteristics for fuel models under user-defined environmental conditions. Both estimate rate of forward spread, flame length, fireline intensity, heat per unit area, reaction intensity and effective windspeed. DIRECT requires all environmental and climatic values to be entered. SITE prompts the user and aids in estimation of fuel moisture content, windspeed and slope, if these have not been measured. Days since rain, the amount of precipitation, canopy cover and other specific information for the location is required.

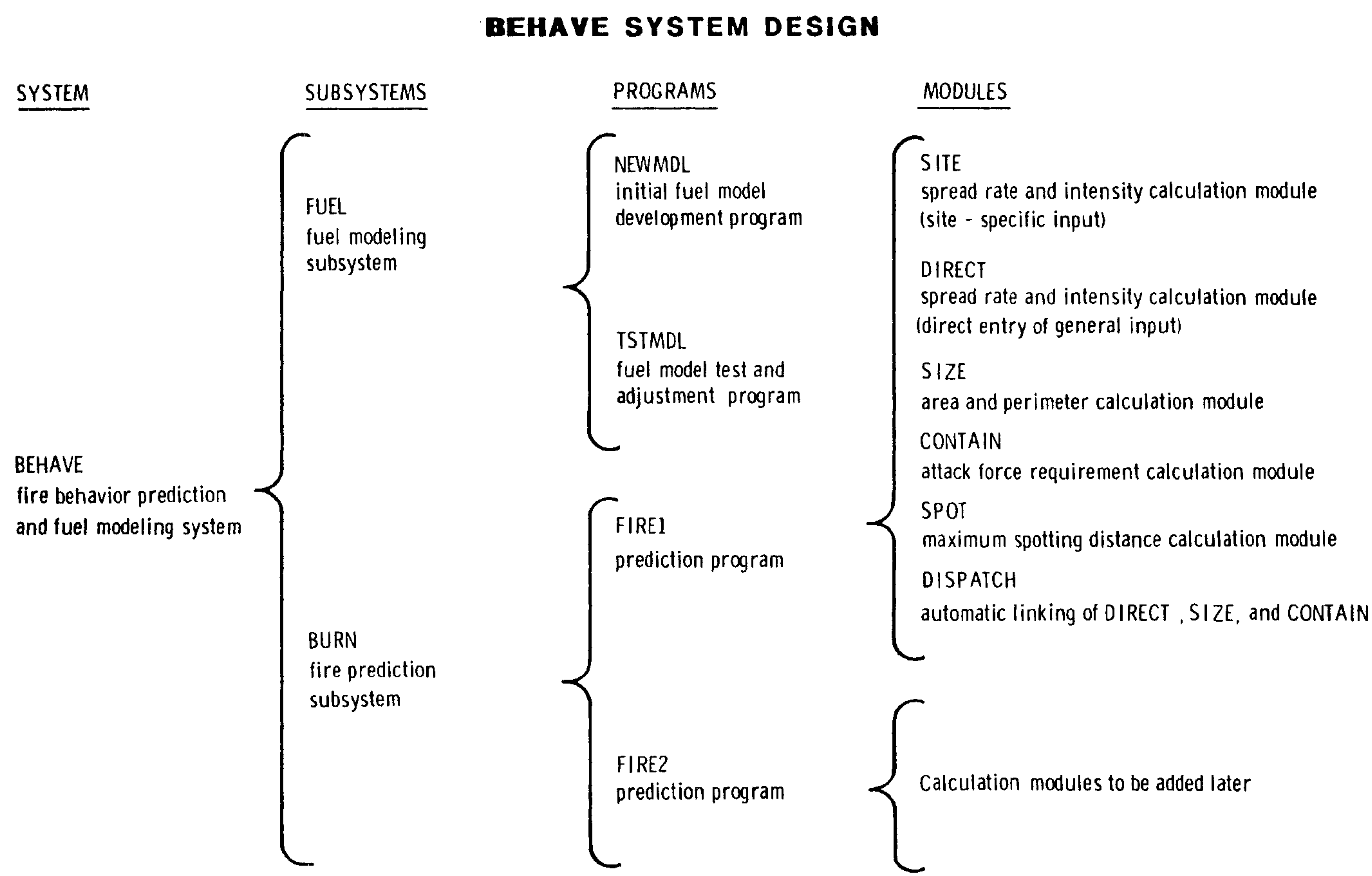


Figure 2: BEHAVE system design including subsystems, programs and modules (from Andrews 1986).

The SIZE module assumes a point-source fire and an elliptical shape to predict the fire area and perimeter.

Requirements for fire suppression, estimates of burned area and fireline construction rates for control given a defined fire size are calculated by the CONTAIN module.

SPOT is a module that estimates the maximum spotting distance from debris piles or from torching trees.

DISPATCH predicts fire behaviour from information that is typically available to a fire dispatcher in the United States.

The BEHAVE system is structured with a fuel model file as the link between the FUEL and BURN subsystems (Figure 3).

The minute-by-minute behaviour of a fire will probably never be predictable, certainly not from generalised models or weather predictions (Rothermel 1983a). In his manual, Rothermel (1983a) sets out in detail the systematic method of calculating fire behaviour that is encapsulated in the BEHAVE computer program. The mathematical basis for the equations used in BEHAVE is set out in an earlier publication (Rothermel 1972). BEHAVE is a "knowledge based expert system" (Andrews & Latham 1984). Consisting of four computer subroutines BEHAVE has a knowledge base that can be divided into three categories.

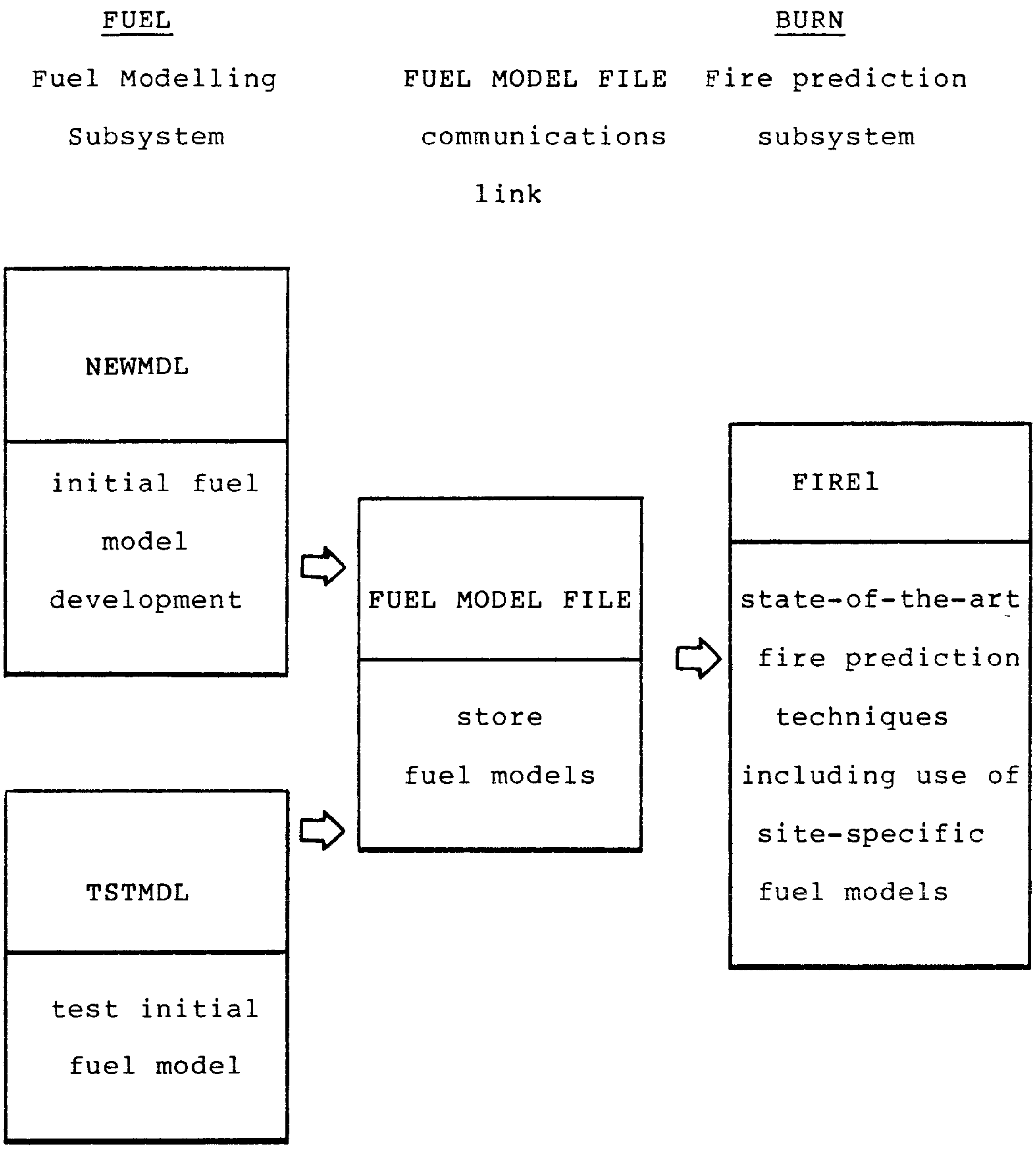


Figure 3: The structure of the BEHAVE system.

(from Burgan & Rothermel 1984)

They are:

1. Mathematical Prediction Models;
2. Fuel Models; and
3. Heuristics or Interpretive Predictions.

Each will be briefly discussed.

A full account of the mathematical models and system can be found in the original papers (Albini 1976, Andrews & Latham 1984, Rothermel 1983a, Rothermel 1972).

2.2.2 Mathematical Prediction Models:

Mathematical models of fire behaviour form the basis for the BEHAVE predictions (Andrews & Latham 1984). They were developed by Rothermel (1972) and represent the synthesis of a great deal of research in the area of fire behaviour. There are five equations utilised in the development of the fire behaviour model used by BEHAVE. They are as follows.

1. Heat Required for Ignition: is dependent on the ignition temperature, fuel moisture content, the amount of fuel and the type of fuel involved in the ignition process.

2. Propagating Flux: consists of two terms, the horizontal flux and the vertical flux. Vertical flux is more important during slope and wind-driven fires as flames tilt over the fuel.

3. Reaction Intensity: the heat release per unit area of the fire front per unit time.

4. Wind and Slope: alter the propogating flux by exposing the potential fuel to additional convective and radiant heat.

5. Approximate Rate of Spread Equation: developed by combining the relationships above into a single equation.

There are also mathematical prediction models for the estimation of flame length (Byram 1959), fire area and perimeter (Anderson, 1983), spotting distance (Albini 1983, 1981a, 1979), suppression force requirements (Albini & Chase 1980, Albini et al 1978), fine fuel moisture content (Rothermel et al in press), windspeed adjustment factor (Albini & Baughman 1979, Baughman & Albini 1980) and the curing of live fuel (Burgan 1979). The use of mathematical models is preferable in that quantitative determination of the factors of fire behaviour are repeatable. The experience of experts is thereby made available to less knowledgable or less confident fire managers.

2.2.3 Fuel Models:

The fuel model is a hypothetical fuel complex representing vegetation types that have fuel properties which affect fire behaviour in the same way.

Fuel parameters change continually in response to climate, decomposition and site manipulation. Dynamic models are possible in Rothermel's mathematical model of fire behaviour to account for this phenomenon.

Fuel models are not deterministic. They supply numerical inputs to the mathematical model used to predict rate of spread and fire intensity. In the BEHAVE system there are thirteen standard fuel models designed to apply generally to the United States. In addition to the standard models there is the capacity to tailor fuel models to particular sites. This ability to develop fuel models is part of the fuel subsystem of the BEHAVE program. Users of the system have NEWMDL and TSTMDL available to facilitate the creation and testing of site specific fuel models for fuel conditions not covered by the thirteen standard models (Burgan & Rothermel 1984). The fuel parameters will be dealt with in some depth since they form a major part of the study.

2.2.3.1 Fuel Properties:

There are two types of fuel properties; those attributed to the fuel particles and those of the fuel bed.

This has led to a variety of descriptors for fuel characteristics in the period since studies of fuels were instigated. Numerous researchers have studied the problem and each approach has been slightly different (Sneeuwjagt 1974). The fuel parameters used in the creation of fuel models will be defined individually.

The geometry of fuel particles has been found to influence fuel flammability and combustion (Fang & Steward 1969). Anderson (1969) found that a relationship exists between fuel particle diameter and the residence time of flame. Particle surface area to volume ratio is used in BEHAVE and incorporates fuel particle thickness or diameter. In the process of combustion the exchange of moisture and heat must take place across the fuel particle surface. The greater the surface area of a fuel particle the more easily these exchanges will occur. The fuel will therefore ignite and contribute to fire intensity in relation to its surface area. The higher the surface area to volume ratio the more likely a fuel will become part of the flame front, and in less time than a fuel particle with a lower ratio.

The potential energy of wildland fuels is known as the heat of combustion. It is an important variable affecting fire behaviour. The heat contents of many wildland fuels are similar on a mass basis (Davis 1959, Sneeuwjagt 1974).

The studies cited were in North American fuels. Van Wilgen (1984) determined heat content for fynbos fuels rather than accept the standard values utilised in BEHAVE. Eucalyptus grandis in California had a higher caloric content than any other fuel in the literature (Agee et al 1973). Fires in eucalyptus forest types are known to burn with very high intensity even with low flame lengths under mild conditions (Luke & McArthur 1978). The fuel energy content of the litter in a dry eucalypt forest probably exceeds the values used in BEHAVE.

There are two important groups of chemicals that affect fire behaviour. High energy ether extractives such as waxes, oils, terpenes and fats, can contribute to the heat content of the fuel and increase fire intensity. Total mineral content also affects combustion since the combustible organic portion of the fuel is reduced. This has been the subject of papers by Mutch (1970) and Gill (1981) in relation to adaptive traits in plant species. Both of these chemical groups are present in eucalyptus fuels.

One of the most important parameters of fuel particles is the moisture content. Fire behaviour is reduced as the moisture content of the fuel increases. Fuel moisture is usually considered as an environmental property rather than a fundamental fuel characteristic (Sneeuwjagt 1974).

The concept of extinction moisture content, the level of fuel moisture at which the fuel will not sustain combustion, is considered a fuel particle characteristic. Brown (1972) considered this property to be a function of particle size, loading and fuel arrangement. The value of the extinction moisture content appears to vary with fuel species (Blackmarr 1972).

The characterisitics of fuel particles are all affected by the size of the particle. Fuel models for the BEHAVE program are built up by separating the fuel according to the fuel moisture timelag concept (Byram 1963). A single timelag is the time taken for a fuel particle to lose two-thirds of its moisture content. The fuel is divided on this basis into four classes: 1-hour, 10-hour, 100-hour and 1000-hour timelag fuels. For dead fuel this is approximated to four fuel diameter classes: 0-6 mm, 7-25 mm, 26-75 mm and 75-200 mm.

2.2.3.2 Fuel Bed Properties:

Fuel loading, the weight of available fuel (tonnes/hectare) (Luke & McArthur 1978), is an important parameter that has a profound effect on fire behaviour. A fuel particle is considered available if it would be consumed by a fire in the fuel complex.

Fuel availability is influenced by the fuel particle size and fuel moisture content. McArthur (1962) found that there was a two-fold increase in the rate of spread for a ten tonne per hectare increase in the fuel load. In isolation from other factors fuel loading is not a complete descriptor of the fuel bed.

Rothermel (1972) has used the packing ratio, the fraction of the fuel bed volume occupied by fuel, to define the compactness of the fuel bed. This is an important characterisitic as it influences the availability of surface area for heating and exposure prior to ignition. The packing ratio is determined from the ratio of the fuel bed bulk density to the density of the fuel particle. The fuel bed bulk density is the ratio of the oven dry fuel loading over the fuel bed depth (Rothermel 1972). The density of a fuel particle is the weight per unit volume of the oven dry fuel.

The proportion of fuel particles in each size-class of the total fuel loading is a significant fire behaviour variable. The contribution of fine fuel to fuel loading is critical in providing the energy that propogates the spreading fire front (Brown 1972). The classification of fuels by size was reported earlier.

The presence of both dead and live fuels is important in characterising the fuel bed. Living fuels contain greater amounts of moisture. The amount of moisture varies with the growth phenology of the plant and the time of year. Live material does not usually burn well without a considerable dead fuel component being present and distributed throughout the fuel bed. The BEHAVE system can account for changing moisture content in live fuels by the use of dynamic fuel models (Burgan & Rothermel 1984).

2.2.4 Heuristics:

The use of hueristics in BEHAVE is primarily to allow the user to determine inputs and interpret fire behaviour predictions (Andrews & Latham 1984). Heuristics are those parts of the system that do not depend on mathematical relationships. There are in BEHAVE a number of interpretations that are based on fire experience or research in progress (Andrews & Latham 1984). In particular the determinations of control difficulty, the value for moisture content of extinction and final fire size are subjectively determined.

2.2.5 Parameters of the Fuel Models:

Fuel properties are characterised by eight variables or factors which serve as inputs to the behaviour prediction model. They are:

1. Fuel loading within moisture timelag classes (lbs/ft2);
2. Fuel bed depth (ft);
3. Fuel particle surface area to volume ratio within fuel moisture timelag classes (ft2/ft3);
4. Fuel particle density (lbs/ft3);
5. Fuel energy content (btu/lb);
6. Total mineral content (% oven dry weight);
7. Silica-free mineral content (% oven dry weight); and
8. Extinction moisture content (% oven dry weight)

Some of these are held constant in the BEHAVE program. The last five parameters display less natural variability than do the first three and are held standard. The NEWMDL subsystem of the BEHAVE system allows for alteration of the fuel energy content when building site-specific fuel models (Burgan & Rothermel 1984).

2.2.6 Environmental Parameters:

Environmental factors for BEHAVE are restricted to the fuel moisture content, live fuel moisture, the midflame wind speed and slope of the site in percent (Andrews 1986).

2.2.7 Mathematical Model Assumptions:

In creating the fire behaviour model some assumptions were made to simplify the process and ensure its feasibility. These assumptions are reasonable for most conditions. Since the natural conditions do not always conform to assumptions there can be differences between the predictions and observed fire behaviour (Burgan & Rothermel 1984).

2.2.7.1 Fuels:

The fire is assumed to be burning steadily in surface fuels. This requires that only surface fuel be considered in the development of fuel models. Also the model cannot be applied with accuracy to situations where the fire behaviour involves fuel in the canopy, aerial fuels or sub-surface fuels (Andrews 1986).

The model is intended to predict the fire behaviour in fine fuels at the fire front or "head" (Figure 4). Fine fuel is considered to be dead fuels less than one inch in diameter and live fuels less than one-quarter inch in diameter. Dead fuels from one to three inches in diameter are accounted for by a weighting process. Fuels that burn after the active fire front has passed are ignored (Andrews 1986).

Uniform continuous fuels are assumed to be present. The model calculates fire behaviour as though the fuel complex was mixed and uniformly distributed. Often in natural fuels this is not the case. Some variation can be accounted for in non-uniform fuels (Frandsen & Andrews 1979) or by use of the two-model concept (Rothermel 1978), where two fuel models are combined for prediction.

2.2.7.2 Fire Behaviour:

The flame front is assumed to be advancing in a "steady state" and no longer influenced by the source of ignition. This can limit the prediction of prescribed fire, particularly where the pattern of ignition is used to manipulate fire behaviour. A further consequence of this assumption is the system's unsuitability to smoldering combustion. This type of burning takes place in tightly compacted litter, duff or rotten wood.

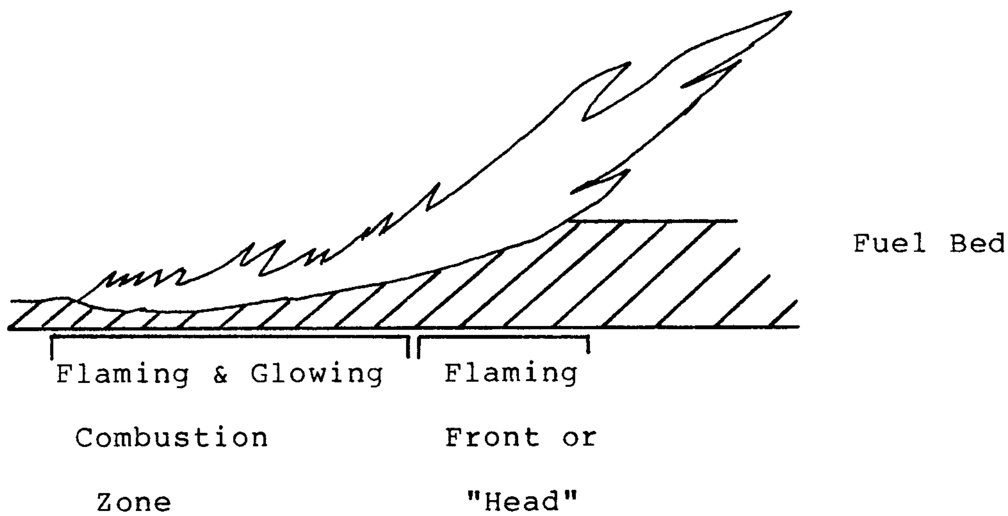


Figure 4: The flaming front or "head"

These situations are not as common in dry eucalypt forests as they are in North American conifer forests.

An assumption common to the BEHAVE system and the FFDM Mk.5 relates to severe fire behaviour. Crowning, long range spotting, firewhirls and other extreme fire activity is not accounted for in either system. The potential for such activity can be assessed from the predicted surface fire intensity (Rothermel 1983).

The short range spotting that can be associated with fire spread is not specifically dealt with by the BEHAVE system. Rothermel (1983) points out that to increase the rate of spread a firebrand must ignite fuels and create a spot-fire before the advancing flame front reaches it. This situation does not often occur. In reality short-range spotting can compensate for the discontinuous nature of the fuel which is assumed to be uniformly distributed.

2.2.7.3 Constant Conditions:

For the time period over which fire behaviour is to be predicted the conditions are assumed constant. The fuel, fuel moisture content, slope and windspeed are held constant in the BEHAVE system. Since fires do not burn under uniform conditions this assumption has to be carefully considered.

The period of time over which to predict the fire behaviour will be dependent upon how consistent the conditions are during that time (Andrews 1986).

2.3 Forest Fire Danger Meter Mk.5:

The use of the term "fire danger" is incorrect in relation to this meter. When properly used the term refers to all the constant factors and varying factors that contribute to the ignition, resistance to control and spread of fires in forest, shrublands or grasslands (Cheney 1968). The Forest Fire Danger Meter Mk.5 considers factors which have a direct effect on fuel flammability and rate of spread (Cheney 1968). It can more correctly be described as a " Burning Index ". A burning index has been defined as :

> "a relative number denoting the combined evaluation of the inflammability of forest fuels, rate of spread and behaviour of fire in such fuels, for specific combinations of fuel moisture content, herbaceous stage and wind velocity".

(Anon. 1953, quoted in Cheney 1968, McArthur 1958, Luke & McArthur 1978).

The term "fire danger" has become well known to the public and the forestry profession in Australia. For this reason, McArthur (1958), Cheney (1968), Luke and McArthur (1978) suggested its use should be continued.

The study of fire behaviour and its relationship to commonly measured meteorological factors was a "major project" of the Commonwealth Forestry and Timber Bureau in the 1950's (McArthur 1958). Originally presented as a series of tables, the meter was produced as a circular slide-rule in the early 1960's (Foster 1976). The current Mark 5 meter is an updated metric version published in 1973 (McArthur 1973). Mathematical equations that describe relationships of the McArthur Fire Danger Meter were inferred by Noble et al. (1980). These relationships are available on a pre-programmed calculator in Australia.

2.3.1 Development :

The McArthur Forest Fire Danger Meter was developed in the late 1950's by empirical fire behaviour measurement of test fires. Field experiments of fire behaviour were made in three fuel types : eucalypt litter , *Pinus radiata* litter and grassland. Only the data for fires in eucalypt fuels was used to develop the Forest Fire Danger Meter (McArthur 1958).

For each experimental burn measurement was made of :

rate of forward spread.

At the same time observations were taken of :

fire intensity;

flame height;

spotting potential;

fire instability;

suppression difficulty (line production figures);

fire damage (both to forest stand and soil).

All parameters were related to field measurements of:

air temperature;

fuel temperature;

relative humidity;

wind velocity (in the open and in the forest);

cloud cover;

rainfall; and

fuel moisture content.

In his paper to the Fire Weather Conference (1958) McArthur details the above measurements, observations and parameters. The methods of obtaining them are not described and no mention of such methods has been found in the literature. The initial study utilised eighty-nine experimental fires over a wide range of meteorological conditions. The system was continually monitored and updated for approximately fifteen years.

During this period additional data was collected. Chandler et al (1983) state that McArthur's data base

".... had to exceed 5000 wildfire documentaries and 500 intensively measured prescribed fires"

The primary factor studied was rate of forward spread (McArthur 1958). The forest type was:

"low to medium quality dry sclerophyll forest"

The stand was considered well stocked with trees to twenty metres high in drainage lines and midslope. Trees on ridge tops were up to thirteen metres in height. The sites carried a heavy, continuous layer of leaf litter with no undergrowth present. McArthur felt the data were typical of any low to medium quality eucalypt forest in the lower rainfall areas of Australia. The Eden Region and the forest types used in this study are typical of such forests. All test fires burnt with the wind, up slopes of between five and ten degrees.

The Forest Fire Danger Meter was developed in a series of stages:

1. Tables for rate of spread were developed in terms of midflame windspeed and fuel moisture content;

2. Tabulation of the fires based on suppression difficulty related to rate of forward spread and fuel moisture content;

3. Establishment of a relationship of fuel moisture to air temperature and relative humidity;

4. Establishment of a relationship between wind velocity in the forest and in the open; and

5. The final stage was the production of tables of rate of forward spread in terms of air temperature, relative humidity and open station wind velocity.

The original tables were given in air temperature interval classes of ten degrees Fahrenheit from fifty to one-hundred-and-ten degrees Fahrenheit. Tables of suppression difficulty were produced over the same temperature range.

The tables were combined into the current format as a Forest Fire Danger Meter in 1962. The meter has been updated and modified as information was added to the base data.

2.3.2 Fuel Properties:

The meter is based on the assumption of 12.5 tonnes/hectare of "fine" eucalypt litter. Understorey shrubs and grasses are assumed negligible. The litter is considered to be continuous (Luke & McArthur 1978). No definition of dimensions for "fine" fuels was given.

Fuels were sampled each hour of the days on which experimental burns were conducted. Samples were taken from the "top layer" of the litter only. Moisture content was determined on an oven dry basis. There was no definition of the depth or delineation of the "top layer" of litter. Presumably ovendrying of the fuels sampled was carried out in the laboratory, but this was not explicitly stated. Specific information on the method used is not available. The data were representative only of periods when no rain had fallen for at least two days (McArthur 1958).

In the FFDM Mk.5 the effects of short-term drying on fuel availability are determined by a relationship to the number of days since measurable rainfall. A drying trend typical of a temperature of twenty-eight degrees celsius and relative humidity of forty percent is assumed (Luke & McArthur 1978).

2.3.3 Environmental Parameters:

For the Mk.5 Forest Fire Danger Meter the requisite environmental inputs are:

Byram and Keetch drought index;

Rainfall to nine a.m.;

Number of days since rain;

Air temperature;

Relative Humidity; and

Windspeed.

The Byram and Keetch Drought Index (Keetch & Byram 1968) is used as an indication of seasonal severity and fuel availability. It is a cumulative measure of the moisture deficit of the soil. The index is calculated daily from rainfall and maximum temperature. Reference to a table provides a value for the daily reduction of the drought index. Rainfall in excess of five mm per day increases the BKDI. This parameter reflects the dryness or availability, of fuels larger than seventy-five mm.

Rainfall for use in the forest fire danger meter is measured, each day, at nine a.m. from a standard rain gauge set in the open away from canopy interception or artificial precipitation. If rain is recorded on successive days the nine a.m. totals are accumulated and treated as a single precipitation event.

The number of days since rainfall is cumulative and straightforward. It is part of the determination of short-term drying effects on fuels. This short term effect is based on the expected changes in surface litter less than six mm in diameter (Luke & McArthur 1978).

Air temperature is measured using a wet and dry bulb thermometer. Standard conditions of one-and-a-half metres above ground-level and the use of a screen to shield the instrument from direct sunlight, while allowing unrestricted air movement, are required (Schroeder & Buck 1970). Standard Tables and the difference in wet and dry bulb temperature permit calculation of relative humidity.

The average wind speed is estimated in an open area at ten metres above ground level using an anemometer. Observations are taken over an accumulative five minute period. The relationship of midflame windspeed to windspeed in the open is based on the dry eucalypt forest type (Luke & McArthur 1978).

2.3.4 Assumptions of the Meter:

As with any attempt to model biological systems assumptions were made to simplify the development of the Forest Fire Danger Meter. The meter is designed for general fire danger forecasting purposes. It is based on the expected behaviour of fires burning for an extended period in eucalypt forests.

2.3.4.1 Fuels:

Fuel weight is assumed to be 12.5 tonnes/hectare. The weight of fuel can vary widely in dry eucalypt forests. The data used in this study show a range of 4.40 to 21.85 tonnes/hectare (Newman 1983). Both heavier and fine fuels are specifically mentioned in the literature (McArthur 1958, Cheney 1968). It is not known if the breakdown of the assumed fuel weight has ever been defined. There is no indication if the figure is predominantly fine fuels or substantially composed of heavier fuels. The fuel complex is now defined by standardised diameter size classes and used around the world. The test fires commenced in the 1950's. In the absence of specific fuel parameters and in view of the pioneering nature of the work, assuming "fine" fuel particle sizes is not valid.

The fire danger meter can be adjusted if the actual fuel weight is known for a specific forest area (Cheney 1968). The actual fuel weight is divided by the fuel weight assumed in the development of the FFDM (12.5 tonnes/hectare). The product of this correction factor and the forest fire danger rating is the adjusted rating. The adjusted rating is then used for fire behaviour prediction.

The fuel bed is assumed to be continuous. Many species of eucalyptus shed bark in long strands. These strands tend to build up around the base of the tree creating "jackpots" of fuel. The fuel bed is rarely more than 50 mm in depth where such fuel concentrations are not present and does not develop a "duff" or organic layer as such (R.G.Bridges pers. comm.). Additionally little or no understory is considered in the FFDM Mk.5. For the dry eucalypt forests of the Eden Region this assumption is not grossly violated, there being little development of understorey shrubs and herbaceous plants.

2.3.4.2 Fire Behaviour:

The FFDM was developed using single fires burning underneath a forest canopy. A ground fire was assumed with no crowning. Since the measurements were empirical the presence of short-range spotting was accounted for by field measurements of experimental fires. If the fire is burning in a gum-barked (smooth-bark) forest type then short-range spotting may not be present. In such cases the FFDM can overpredict forward rate of spread (McArthur 1973).

The FFDM was not developed for prescribed burning applications. If used to determine "broad control burning conditions" then accurate prediction can not be expected (McArthur 1973).

The prediction of spotting distance assumes a high proportion of fibrous-barked eucalypts. This type has demonstrated an increased tendency for spotting activity.

2.3.4.3 Topography:

The fire for which predictions are being made is assumed to be burning over level to undulating topography. This condition can often be violated. Cheney (1968) sets out guidelines for adjusting predictions of fire behaviour by accounting for slope.

2.3.4.4 Atmospheric Conditions:

The need for fire danger rating and fire behaviour prediction was associated with the "worst" meteorological conditions. Unstable atmosphere is assumed and the FFDM makes predictions on this basis. If the fire is burning under stable atmospheric conditions the fire activity will be reduced (McArthur 1973).

2.3.4.5 Windspeed:

The windspeed used in the FFDM Mk.5 is taken in the open.

Within the FFDM Mk.5 this is converted to a midflame windspeed for use in fire behaviour predictions. The midflame windspeed used is typical of a "high forest" (greater than thirty metres) which is "well-stocked". In a lower quality forest, or logged areas midflame windspeed is higher. Consequently in such forest types the rate of forward spread will be underestimated by the meter.

2.3.4.6 Basis:

The FFDM was originally designed to allow estimation of the fire danger for forests given readily available meteorological information. It was seen as a regional rating system. Given these origins then it is not to be expected that the FFDM will be as definitive as the BEHAVE system, which was developed expressly for the purpose of fire behaviour prediction. Nonetheless it is the system currently in use.

Chapter 3

3. Methods:

3.1 Fine litter weight data:

In an internal paper for the Forestry Commission of N.S.W., Newman (1983) presented a summary of fine litter weight data. This was a compilation of many fine fuel studies carried out in the Eden Region between 1972 and 1979. Sixty-two study sites in four different forest categories were sampled in that period.

The area sampled extended south from Eden to the Victorian border and to the escarpment of the Great Dividing Range in the west and south-west (Figure 1). The forests are predominantly dry sclerophyll eucalyptus forest. Areas of higher quality wet sclerophyll eucalyptus forest occur along water courses and in areas of higher rainfall, increased elevation and better soils towards the escarpment (Newman 1983). The most common tree species is *Eucalyptus sieberi* (Silvertop Ash) which tends to form dense single species stands (Chippendale et al 1985).

Other species include _E.globoidea_, _E.agglomerata_, _E.muelleriana_ (Stringybarks), _E.consideniana_ (Yertchuk), _E.cypellocarpa_ (Monkey Gum), _E.obliqua_ (Messmate), _E.smithii_, _E.radiata_, _E.elata_ (Peppermints) and some _E.fastigata_ (Brown Barrel).

With the exception of three water catchments in 1977, the sampling has been random. The collection method is quoted from Newman (1983):

"Samples were of one square foot pre 1974. All organic matter both attached and deposited on the ground surface to a height of 0.9 m above ground was collected. A size limit of 1 inch (pre 1974) and 25 mm (after 1974) average diameter for twigs and bark was discarded. With removal of stone and soil samples were sorted into the categories of twigs up to 6mm diameter, twigs 6-12 mm, and 12-25 mm, bark, leaves, green vegetation and miscellaneous (and in pre 1974 into the same fractions in Imperial equivalent)."

The miscellaneous fraction contained eucalypt capsules charcoal and fragments too small to sort without a great expenditure of time. A forced draught cabinet was used to oven-dry the samples to constant weight at 105 degrees celsius. Mean fine litter weight in tonnes per hectare, and the percentage composition by components, were calculated.

This composition percentage enables the mean weight to be broken down into weights for each component. The four forest categories sampled were:

1. mature/overmature unlogged forest;
2. logged forest;
3. various forest types and conditions; and
4. fire regenerated forests.

Inadequate information was available for the third category and it was not utilised in this study.

The size limit on litter to be included in the sampling process has reduced the fuel loading. By excluding all material larger than 25 mm the study does not provide information on two fuel size-classes. Fire intensity and residence time may be influenced by the size of fuel present in the fuel complex (NWCG 1981). The 25-75 mm (100 hr timelag) fuels can contribute to fire intensity and residence time. Fuels less than 75 mm are considered in the flame front (Burgan & Rothermel 1984). The larger fuels, greater than 75 mm (1000 timelag fuels) can contribute to fire residence times but are not included in fuel models for fire behaviour prediction (Burgan & Rothermel 1984). The fuel models built from this information will describe a fuel complex without larger size fuels. The FFDM Mk.5 was developed using "fine" fuels (McArthur 1958).

The BEHAVE system uses a "weighting concept" to develop a single value for the characteristic surface-area-to-volume ratio of the fuel complex (Rothermel 1972). In both cases then the finer fuels 0-6 mm and 7-25 mm are given more consideration. As a result, although the fuel models may not be representative of the actual fuel complex, they will be viable for camparison.

3.2 Meteorological Data:

The meteorological data used in the study are from fire-tower records. The parameters measured are used to determine fire-danger rating using the Mk.5 Forest Fire Danger Meter. The weather record represents a range of Fire-Danger Ratings from 1-50, on a scale of 0-100. The readings were taken from the records of the fire seasons from 1982-1985. They were selected to fill all fire danger categories: Low, Moderate, High, Very High and Extreme (McArthur 1973). The latter occur infrequently. There are more observations in the categories of low to high fire danger.

The measurements are: dry and wet bulb temperatures, drought factor, days since rain, amount of precipitation and windspeed. The difference in the two temperatures is used in a two-way table giving relative humidity. Windspeed is measured with a hand-held wind gauge. The firetower is above tree canopy height so windspeed is assumed to be the wind velocity free of canopy interference, the open windspeed. Measurements were taken at the Bombala firetower.

Each of the days of recorded data was assessed for the "worst conditions". Observations were ranked from one to ninety-two, the lowest fire danger rating being one. The weather associated with these values was used in both the McArthur Forest Fire Danger Meter Mk.5 and the BEHAVE computer model to predict fire behaviour. The range of values for each of the meteorological variables is set out in Table 1.

3.3 Forest Fire Danger Meter Inputs:

The fire tower weather records were collected expressly to calculate the forest fire danger rating using the Mk.5 Forest Fire Danger Meter. The values of fire danger associated with each of the ninety-two records were used in this study.

Table 1: The range of meteorological variables used in the study.

Variable:	Range:	
Temperature	13 - 42	degrees celsius
Open Windspeed	0 - 90	kilometres/hour
Midflame Windspeed	0 - 41.4	kilometres/hour
Drought Factor	5 - 10	
Fuel Moisture Content		
1 hr (0-6 mm):	3 - 15	percent dry-weight
10 hr (6-25 mm):	4 - 16	percent dry-weight
Relative Humidity	20 - 81	percent saturated

By reference to the table on the back of the meter (Table 2) and with knowledge of the fuel quantity it is possible to determine predictions for the rate of forward spread (km/hr), flame height (m) and spotting distance (km). The first two factors were used to compare with the fire behaviour predictions of the BEHAVE system.

3.4 Fire Behaviour Prediction:

3.4.1 Spotting Distance:

The SPOT module of BEHAVE predicts on the basis of a single tree or pile of slash producing firebrands (Andrews 1986). The FFDM Mk.5 is empirically based on actual spotting of experimental fires and well-documented wildfires in eucalypt forest types (Luke & McArthur 1978). In many cases the wildfires were crown fires with considerable fire activity. These differences do not facilitate comparison of the two estimates.

3.4.2 Rate of Forward Spread :

The rate of forward spread is defined as the linear rate of advance of the head fire (Albini 1976).

Table 2: The fire behaviour prediction table from the FFDM Mk.5.

FUEL QUANTITY (t/ha)	FIRE BEHAVIOUR	FIRE DANGER INDEX												
		5	10	15	20	25	30	40	50	60	70	80	90	100
5	R (km/h)	0.03	0.06	0.09	0.12	0.14	0.17	0.23	0.28	0.34	0.39	0.45	0.50	0.56
	H (m)	0.3	0.6	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0
	S (km)	—	—	—	0.1	0.2	0.3	0.6	0.8	1.0	1.2	1.4	1.7	1.9
10	R (km/h)	0.06	0.12	0.18	0.23	0.29	0.34	0.45	0.56	0.67	0.78	0.89	1.00	1.11
	H (m)	1.0	2.0	3.0	4.0	5.0	5.5	7.0	8.5	10.0	11.0	12.0	13.0	14.0
	S (km)	-	—	0.2	0.4	0.6	0.8	1.2	1.7	2.1	2.5	3.0	3.4	3.8
15	R (km/h)	0.09	0.18	0.26	0.35	0.43	0.51	0.68	0.85	1.02	1.18	1.35	1.52	1.68
	H (m)	2.0	3.5	5.0	7.0	8.0	9.5	12.0	14.0	———	CROWN FIRE		———	
	S (km)	--	0.2	0.6	0.9	1.2	1.5	2.2	2.8	3.4	4.1	4.8	5.4	6.0
20	R (km/h)	0.12	0.24	0.36	0.48	0.60	0.72	0.96	1.20	1.44	1.68	1.82	2.16	2.39
	H (m)	2.5	5.0	7.0	9.0	11.0	13.0	———	CROWN FIRE		———			
	S (km)	0.1	0.5	0.9	1.3	1.7	2.2	3.0	3.8	4.7	5.6	6.4	7.2	8.1
25	R (km/h)	0.14	0.30	0.45	0.60	0.75	0.90	1.20	1.50	1.80	2.10	2.40	2.70	1.00
	H (m)	3.0	7.0	10.0	12.0	14.0	———	CROWN FIRE		———				
	S (km)	0.1	0.6	1.1	1.6	2.1	2.6	3.6	4.6	5.6	6.6	7.6	8.6	9.6

R = rate of forward spread in kilometres per hour H = flame height in metres. S = average spotting distance in kilometres Fuel Quantity is expressed in tonnes per hectare of combustible material less than 6 millimetres in diameter

The FFDM Mk.5 uses the same definition (McArthur 1958). The two predictions are directly comparable.

3.4.3 Flame Height:

The flame height can be converted to the flame length if the midflame windspeed and air density are known. With zero slope assumed the calculations are simplified. The tilt of the flame from vertical is a product of the force of the wind and of the energy of the fire. Rothermel and Anderson (1966) developed a relationship showing that the tangent of the flame tilt angle should be proportional to the energy rate per unit area of the airstream and the energy release rate of the flaming front.

The dynamic pressure (q) of the airstream is the product of air density and air velocity squared, divided by two times the acceleration due to gravity.

$$q = \frac{\rho U^2}{2g}$$

q = dynamic pressure (kg/m2)

ρ = air density (kg/m3)

U = air velocity (m/sec)

g = acceleration of gravity (m/sec2)

The dynamic pressure by the velocity of the airstream yields the energy rate per unit area of the airstream. The energy release rate of the flaming front is the reaction intensity by the mechanical equivalent of heat.

$$\text{energy ratio} = \frac{qU}{I_R J}$$

q = dynamic pressure of air (kg/m2)

U = air velocity (m/sec)

I_R = reaction intensity (kW/m2)

J = mechanical equivalent of heat

This is a dimensionless number used to determine the flame tilt from vertical:

$$\mathrm{Tan}\ \Phi = 6.9\left(\frac{qU}{I_R J}\right)^{0.18}$$

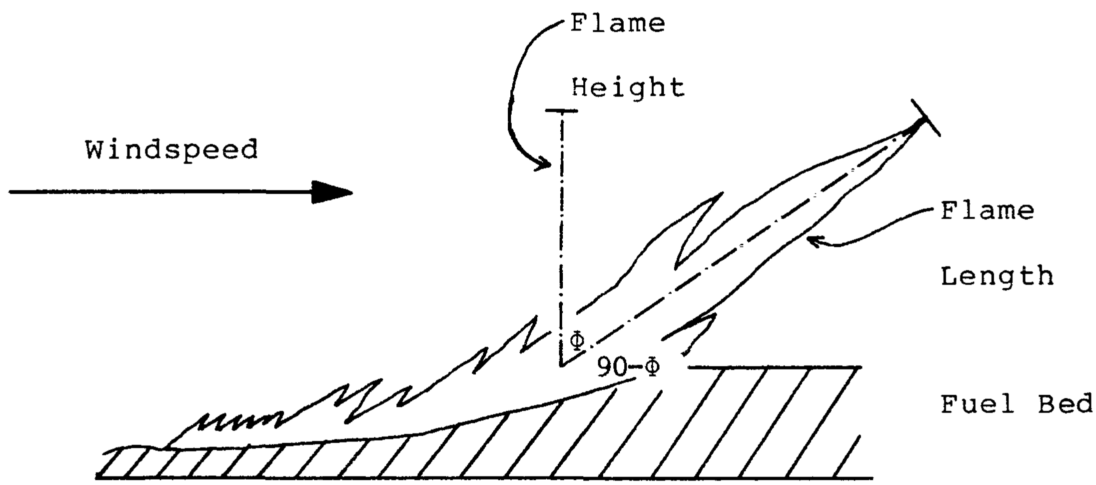
Φ = flame tilt angle from vertical

The flame height can then be converted to a flame length by application of basic trigonometry (Figure 5).

$$\mathrm{Sin}\ (90 - \Phi) = \frac{\text{flame height}}{\text{flame length}}$$

therefore

$$\text{flame length} = \frac{\text{flame height}}{\mathrm{Sin}\ (90 - \Phi)}$$



Φ = Flame Tilt from Vertical

90-Φ = Flame Angle

Figure 5: The trigonometry of the flame height to flame length conversion.

This process was utilised to convert the flame height predictions, generated by the FFDM Mk.5 to flame lengths for comparison with the BEHAVE system outputs.

Conversion factors for midflame windspeed from open windspeed were not available for Australian forest types or different forest conditions. Factors for conversion are set out in the Fire Behaviour Field Guide for the United States, developed by the National Wildfire Co-ordinating Group (1981). The basis for selecting a conversion factor is the exposure to the wind of the fuels and the thirteen fuel models developed by the Intermountian Fire Sciences Laboratory.

By use of a guide for selecting fuel models (Anderson 1982), and knowledge of the forest condition supplied by Newman (1983), the most suitable factors were selected.

The fuel bed in an unlogged forest could be considered a partially sheltered fuel. By comparison to the dense canopy of a conifer or American hardwood forest, the canopy of a dry eucalypt forest is more open and there are generally fewer trees per hectare. The slopes are not steep by comparison to those of the United States. The conversion factor is Ø.25. The forest is logged by clearcutting with seed and habitat trees retained. Fuels in this situation are fully exposed, and similiar to fuel model 13 Heavy Logging Slash, conversion factor Ø.46.

Fire regeneration in dry eucalypt forest is generally dense. Eucalypts are not shade tolerant as a rule. These two factors produce a conversion factor of Ø.12 from the field guide (NWCG 1981).

The product of the relevant conversion factor and the open windspeed is the midflame windspeed. This figure was used in the calculation of flame length from flame height as the air stream velocity.

The density of air for different temperatures is obtained by reference to standard tables (Weast et al. 1985).

The acceleration due to gravity is a constant (9.8 m/sec/sec), as is the mechanical equivalent of heat (116.7 kg/m/kW-1).

The reaction intensity is part of the BEHAVE prediction of fire behaviour. There are three independent factors for the conversion of midflame windspeed and three reaction intensity predictions for each of the ninety-two ranked weather observations, one for each fuel model developed. As a result of these different variables there are three predictions of flame length for each prediction of flame height.

3.4.4 Fireline Intensity:

This fire parameter has been defined as the product of the available heat of combustion and the rate of forward spread of the fire (Chandler et al 1983). The FFDM Mk.5 does not predict this variable directly. By use of Byram's equation for fireline intensity (Byram 1959) an estimate can be obtained from the predicted rate of forward spread. The equation is:

$$I = 0.007HWR$$

I = fireline intensity (kW/m)

H = heat yield of the fuel (cal/g)

W = fuel loading (tonnes/ha)

R = rate of forward spread (m/min)

3.4.5 Summary:

The use of ninety-two weather observations and three different forest conditions provided three estimates of flame length, one prediction of the rate of forward spread and one prediction of fireline intensity.

Due to a lack of information the use of some windspeed conversion factors derived for North America was necessary.

The relationship for flame tilt angle derived by Rothermel and Anderson (1966) has been supported by Albini (1981b), in laboratory studies but has not been applied to wildfire or wildland fuels in a natural setting.

3.5 Inputs to the BEHAVE system:

The BEHAVE system requires input to the BURN subsystem in order to arrive at predictions of fire behaviour (Andrews 1986). The information needed is a fuel model and the specification of fuel moisture content, windspeed and slope.

3.5.1 Fuel Model Building:

Three fuel models were developed from Newman's data (1983) according to the method and instructions set out in Burgan and Rothermel (1984). The information for Newman's category: "Various forest types and conditions" was insufficient to permit building a fuel model.

For the other three forest conditions mature/overmature unlogged, logged and fire regenerated forests, models were based on the breakdown of mean fine litter weight into size classes and types of fuel.

The fuel model data sheet from Burgan & Rothermel (1984) was used to record the weights of fuels by type and size class. Leaves and twigs were input as the "litter" fuel component and grass was input as the "grass" fuel component. The bark of eucalypts is dissimilar to the general forest litter of leaves and branch material. To account for this, bark was incorporated into all fuel models as a component of "slash". Separate entry allowed individual consideration of the surface area to volume ratio and heat content for this constituent of the fuel complex.

The "miscellaneous" category of fine litter contained capsules, charcoal and unidentified pieces of litter. This part of the fuel generally forms a soil-litter interface. Duff layers as such do not develop in dry eucalypt forests (R.G.Bridges pers. comm.). It is probable this part of the litter layer would not contribute to the flame front. Since only those fuels that do so contribute are considered in fuel models, this fraction was not included in the model building process.

When developing a fuel model the percentage of the fuel components for the fuel type being entered (litter, grass, shrubs or slash) must sum to one-hundred percent. The pecentage contribution of the components to the total weight was entered at this stage as a percentage.

The heat content of eucalyptus litter is widely recognised as being among the highest of all wildland fuels (Luke & McArthur 1978). The values quoted in the literature (Luke & McArthur 1978, Agee et al 1973, Chandler et al 1982) provided a figure of 20300 kJ/kg. This value was used for the heat of combustion of forest litter and for bark. Grasses were assumed to be 17400 kJ/kg the value for low volatile fuels of which dry grass is an example (Burgan & Rothermel 1984).

Surface area to volume ratios from the literature (Luke & McArthur 1978, Chandler et al 1982, Gill et al 1981) were averaged for relevant eucalyptus species present in the Eden Region. The value obtained of 104 cm2/cm3 was used for the surface area to volume ratio of bark and litter. Grass values from the literature (Luke & McArthur 1978) provided an average figure of 111 cm2/cm3 for their surface area to volume ratio.

The final form of the fuel models is set out in Table 3. The NEWMDL program calculates the fuel bed depth from the total fuel weight and the percentage of cover for each type of fuel component. The surface area to volume ratio and heat content are weighted averages based on fuel composition.

Table 3: Fuel model variables.

Fuel Weight (tonnes/ha) 1 hr	10 hr	Live Herb	Fuel Depth (cm)	Surface Area/Vol. (cm2/cm3)	Heat Content (kJ/kg)
Unlogged Forest:					
5.78	1.48	0.67	7.9	104	20061
Logged Forest:					
6.16	2.42	0.76	8.2	104	20042
Fire Regenerated Forest:					
5.51	2.33	0.90	10.7	104	19957

3.5.2 Remaining BEHAVE inputs:

The weather parameters, relative humidity and dry bulb temperature, were used in conjunction with the S-390 fire behaviour field guide (National Wildfire Co-ordinating Group 1981) to determine 1 hr fuel moisture content. An equator facing slope (increased insolation) was assumed, the actual time of day was utilised. The corresponding month of the season was used to adjust for the variation of seasons between northern and southern hemispheres. For example: the second month of summer in Australia, January, was equated with the second month of summer in the United States, July.

The 10 hr fuel moisture content was determined using an approximation. The value used was the 1 hr fuel moisture content plus one percent (Rothermel 1983).

The determination of mid-flame windspeed is inherent within the Forest Fire Danger Meter. Midflame windspeed was calculated from the open windspeed in the fire-tower weather records. There was no conversion for midflame windspeed from the open windspeed available that was specifically tailored to Australian vegetation types in various conditions. The guidelines established by the National Wildfire Co-ordinating Group (NWCG) in the United States were used [see discussion section 3.4.3].

For BEHAVE the open windspeed was converted by using the conversion factors for slope positions and overstorey types (NWCG 1981). The mature/overmature unlogged forest was considered a partially sheltered fuel (conversion factor 0.25). Logged forest is clearcut and therefore fully exposed (conversion factor 0.46). Fire regeneration is usually thick and the tree species are mostly shade intolerant (conversion factor 0.12). These factors were selected by reference to an aid for fuel model determination (Anderson H.E. 1982). The slope for all predictions was assumed zero to simplify calculation and comparison.

3.5.3 Fire behaviour predictions:

The parameters were entered into the DIRECT module of the BURN subsystem of BEHAVE. Predictions of fireline intensity, rate of forward spread, flame length, heat per unit area and reaction intensity were produced.

Reaction intensity was used as a factor in the conversion of flame height to flame length [section 3.4.3].

Fireline intensity, rate of forward spread and flame length were compared to the fire behaviour predictions of the FFDM Mk.5.

3.6 Units of measurement:

Scientific papers are usually presented in Systeme International units, the metric system. Australia converted to metric measurement in 1974 after a two year probation period. The FFDM Mk.5 is a metric version of the meter and all measurements of fine litter weight data (Newman 1983), and meteorological information were also metric.

The BEHAVE system yields its output in english units. It was necessary to convert between the two systems of measurement to carry out the study.

3.7 Analysis:

Due to natural variability of the meteorological data used in this study there are not predictions of fire behaviour for every combination of windspeed, temperature and humidity. Such a data set would be immense and very difficult to compile. Similarly there are not predictions of fire behaviour for the entire range of fire danger ratings present in the data. For the fire behaviour predictions that have been determined there are few replicates.

The most suitable statistical analysis for these data is the Kolmogorov-Smirnov two sample test. This test does not require specification of the underlying population distribution, it is non-parametric. The null hypothesis being examined is that the two populations are identical. Strictly, the populations should be continuous. If they are not the test can still be performed but will be conservative (Gibbons 1985). The Kolmogorov-Smirnov two sample test requires at least an ordinal scale of measurement. In this case kilowatts per metre (fireline intensity), metres per hour (rate of forward spread) and metres (flame length) are the interval scales used.

The sample size being tested, ninety-two cases, exceeds the range of tables for the Kolmogorov-Smirnov two sample statistic. The right tail points for the statistic "D" were calculated by use of the formula:

$$D = 1.63 \quad N/mn \qquad m = \text{size of sample one}$$

$$n = \text{size of sample two}$$

$$N = m + n$$

This calculated value was then compared with the statistic "D". The probability of occurrence for points from the above formula is 0.01 (Gibbons 1985).

The two sample test was first carried out on the three estimates of flame length obtained from the FFDM Mk.5.

The predictions of fire behaviour were then tested between the three different fuel models. Finally the fire behaviour predictions of the FFDM Mk.5 were compared to each of the fuel models, in turn.

Each of the fire behaviour predictions was plotted to aid in the presentation of results.

Chapter 4

4. Results:

There were no fire behaviour data available which can be related directly to the fuel characteristics of litter in a dry eucalypt forest. Neither the fuel models nor the FFDM Mk.5 were able to be verified by comparison to actual fire behaviour measurements. The results therefore consist of an assessment of the differences between the two methods of fire behaviour prediction.

4.1 Forest Fire Danger Meter Mk.5:

The first step was to compare the three predictions of flame length obtained frcm the FFDM Mk.5 (Table 4). In each case the probability of the Kolmogorov-Smirnov statistic is high under the null hypothesis the two samples come from populations with identical distributions. There is no reason to reject the null hypothesis.

It is concluded, that the flame heights for the three different conditions of forest are from the same population. This conclusion allows the average of the three flame height predictions to be used for the purpose of comparison between FFDM Mk.5 and the BEHAVE system.

Table 4: Results of Comparison between forest conditions within the FFDM Mk.5.

Comparison	K-S Statistic 'D'	Probability
Unlogged Forest with Logged Forest	0.04348	1.0000
Unlogged Forest with Fire Regenerated Forest	0.06522	0.990
Logged Forest with Fire Regenerated Forest	0.08696	0.878

The ranges of values for the four different predictions, FFDM Mk.5 and BEHAVE for unlogged, logged and fire regenerated forest are presented in table 5.

4.2 The BEHAVE system:

It was necessary to establish that the three fuel models provided significant differences in fire behaviour prediction. They were compared to each other under the null hypothesis that the populations from which the samples were drawn were identical. The probability values and the Kolmogorov-Smirnov statistic for these comparisons are set out in table 6.

The values of the Kolmogorov-Smirnov statistic in each case provide grounds to reject the null hypothesis. It is concluded that the three different forest conditions modelled produce significantly different predictions of fire behaviour and could not be from the same populations.

Table 5: The range of fire behaviour predictions:

	Rate of Forward Spread (m/hr)	Flame Length (m)	Fireline Intensity (kW/m)
FFDM Mk.5	12.0 - 560.0	0.2 - 10.8	66.9 - 3121.6
Unlogged Forest	20.1 - 2152.5	0.3 - 2.8	27.7 - 2402.7
Logged Forest	20.1 - 7161.6	0.3 - 4.9	27.7 - 8355.9
Fire Regenerated Forest	20.1 - 623.6	0.3 - 1.7	27.7 - 791.7

Table 6: Results of Comparison between fuel models for BEHAVE (all parameters).

Comparison	K-S statistic "D"	Probability
Rate of forward spread:		
Unlogged & logged forest	0.42931	< 0.01
Unlogged & fire regenerated forest	0.32609	< 0.01
Logged & fire regenerated forest	0.60870	< 0.01
Fireline intensity:		
Unlogged & logged forest	0.39130	< 0.01
Unlogged & fire regenerated forest	0.31522	< 0.01
Logged & fire regenerated forest	0.60870	< 0.01
Flame length:		
Unlogged & logged forest	0.35870	< 0.01
Unlogged & fire regenerated forest	0.28261	< 0.01
Logged & fire regenerated forest	0.57609	< 0.01

4.3 Statistical Comparison:

Having established differences between the fuel models for BEHAVE predictions of fire behaviour and a single set of predictions from the FFDM M.k5, the two systems could then be compared with each other. The results of the Kolmogorov-Smirnov two sample tests are shown in table 7.

In each comparison for every fire behaviour parameter the null hypothesis must be rejected. The set of predictions for any parameter from the FFDM Mk.5 could not have been from the identical population of the fuel model with which it was being compared. For lower ratings of fire danger the fire behaviour predicted for both systems show some agreement graphically.

Plots of the mean values were fitted to the data for graphical presentation. The differences highlighted by the Kolmogorov-Smirnov two sample test can be seen for rate of forward spread (Figure 6), fireline intensity (Figure 7) and flame length (Figure 8).

Table 7: Comparisons of the FFDM Mk.5 and BEHAVE (all fire behaviour predictions)

Comparison	K-S Statistic "D"	Probability
Rate of forward spread:		
FFDM Mk.5 & unlogged forest	0.27174	< 0.01
FFDM Mk.5 & logged forest	0.43478	< 0.01
FFDM Mk.5 & fire regenerated forest	0.57609	< 0.01
Fireline intensity:		
FFDM Mk.5 & unlogged forest	0.75000	< 0.01
FFDM Mk.5 & logged forest	0.43487	< 0.01
FFDM Mk.5 & fire regenerated forest	0.89130	< 0.01
Flame length:		
FFDM Mk.5 & unlogged forest	0.63043	< 0.01
FFDM Mk.5 & logged forest	0.44565	< 0.01
FFDM Mk.5 & fire regenerated forest	0.76087	< 0.01

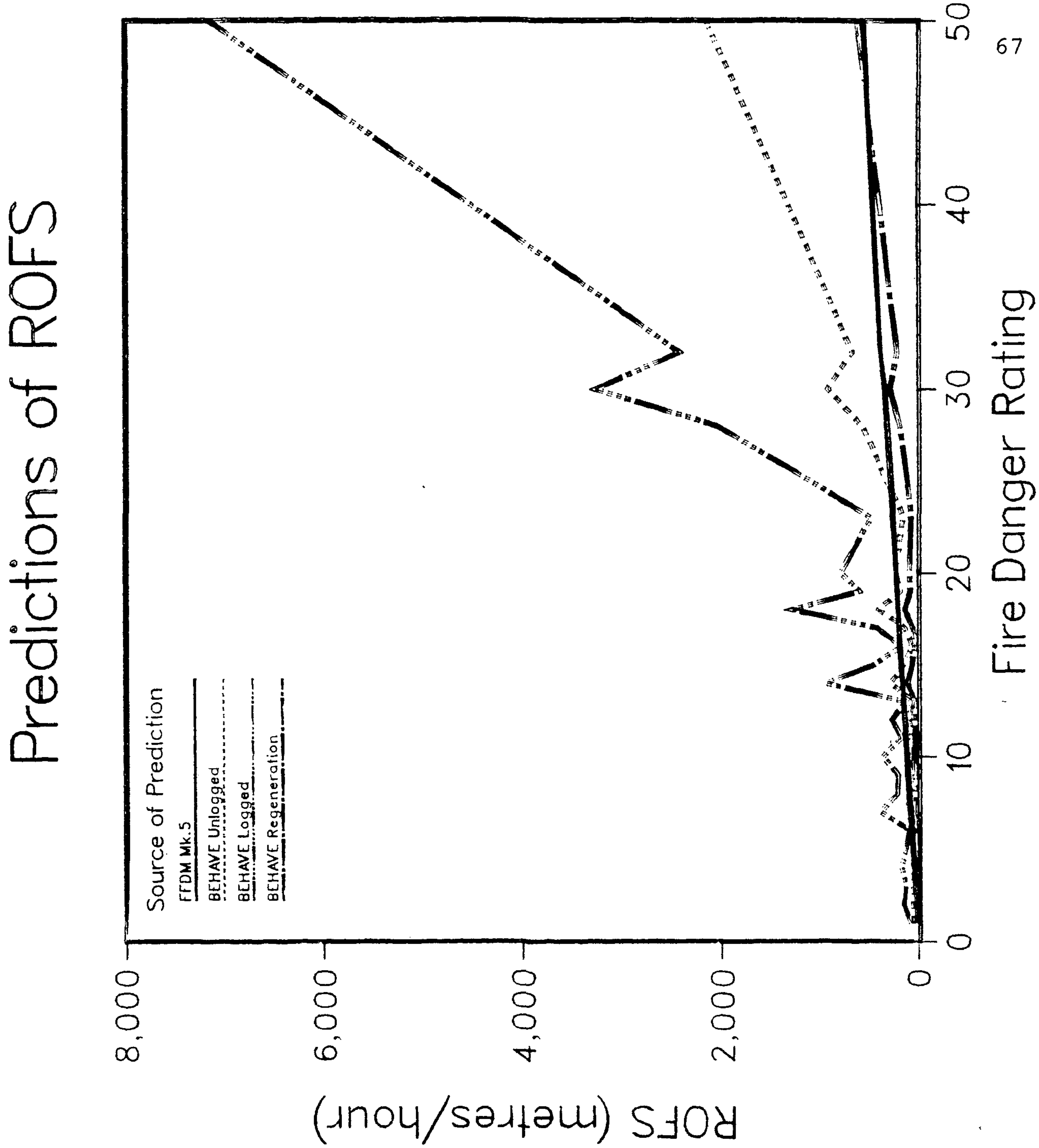


Figure 6: Plot of the rate of forward spread predicted by the FFDM Mk.5 and BEHAVE.

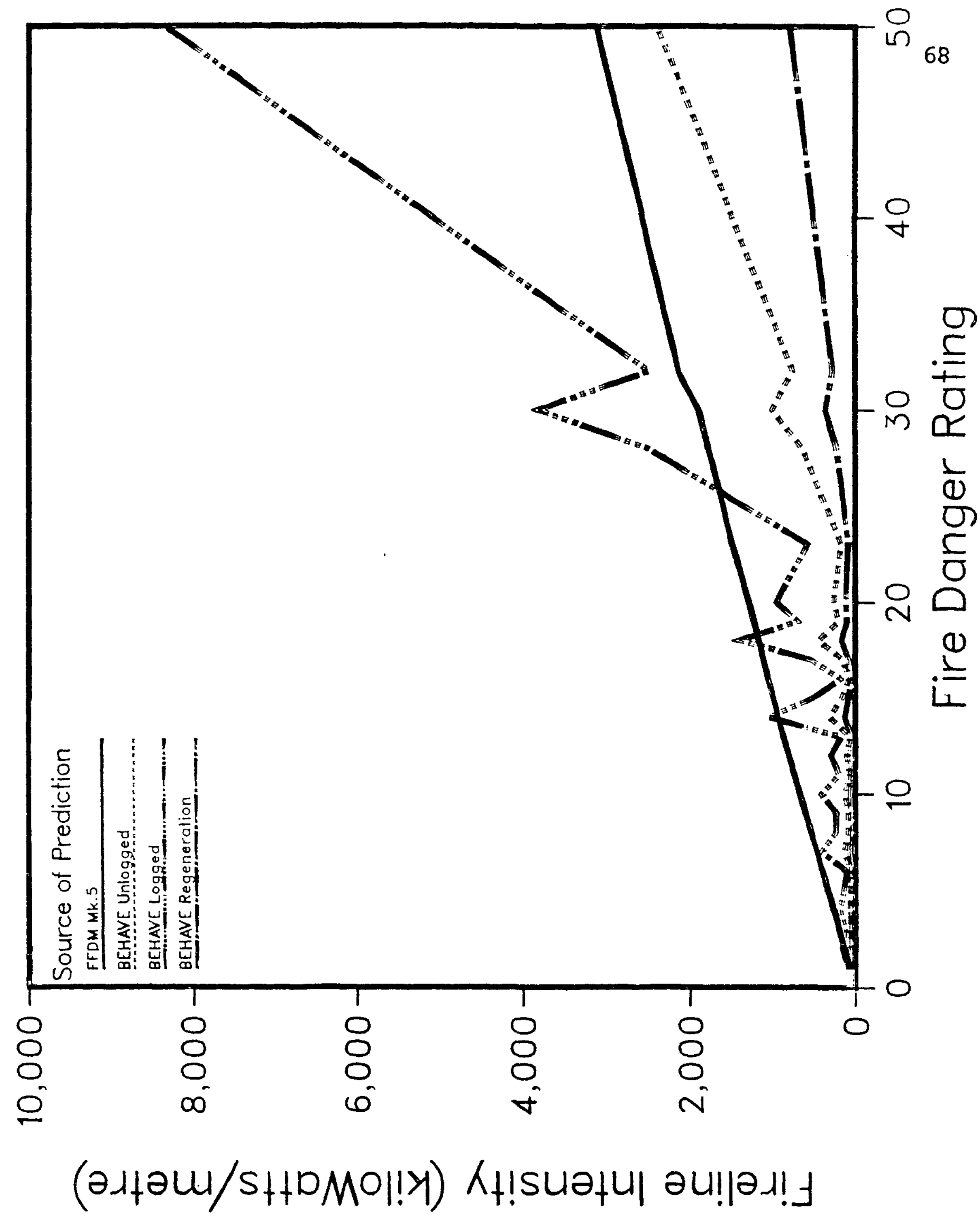


Figure 7: Plot of fireline intensity predicted by the FFDM Mk.5 and BEHAVE.

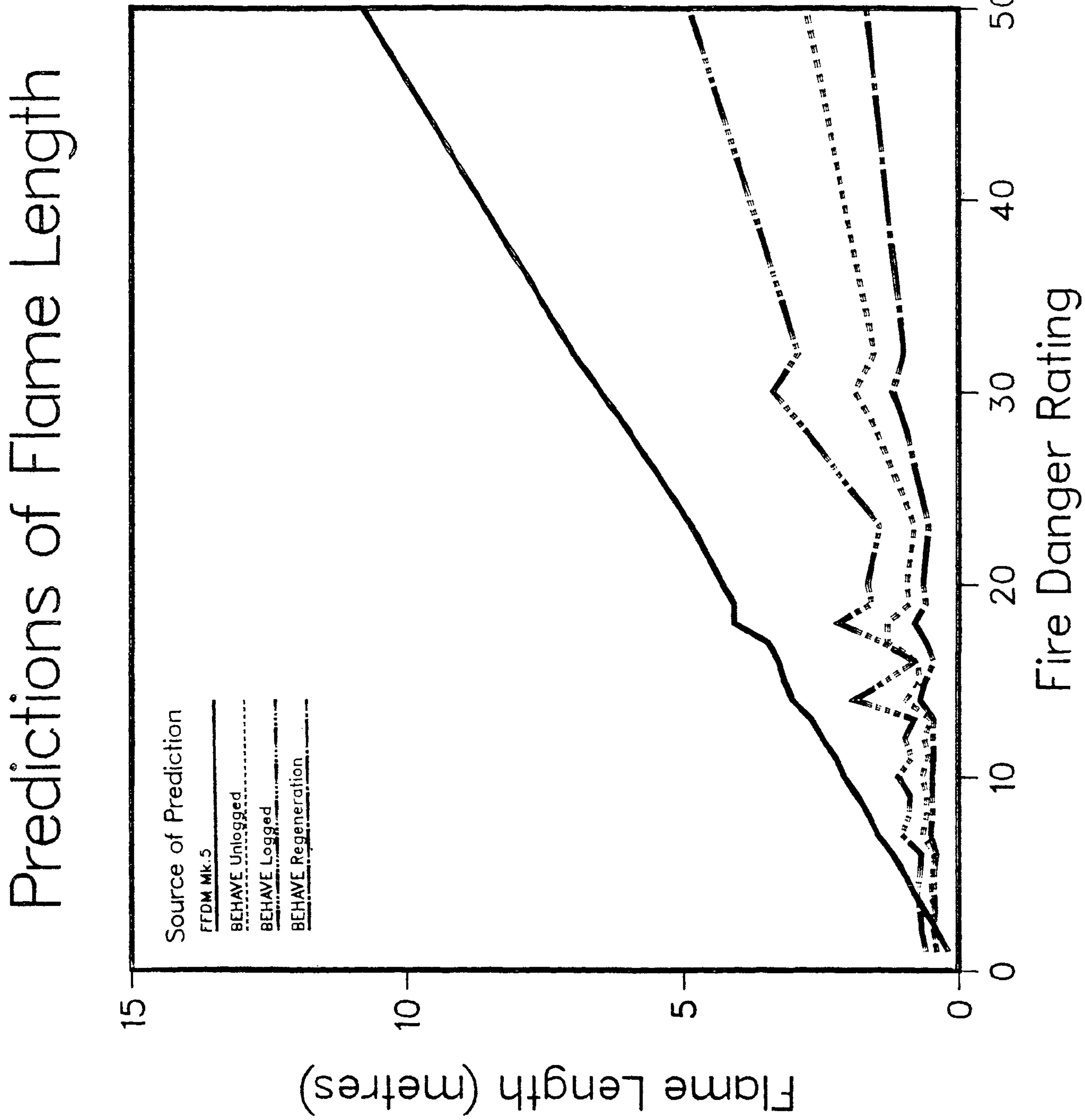


Figure 8: Plot of the flame length predicted by the FFDM Mk.5 and BEHAVE.

Chapter 5

5. Discussion:

Prior to any discussion of the results two parts of the method need to be noted. The midflame windspeeds used for the calculation of air velocity were developed from conversion factors determined for forest conditions in North America. Although the most accurate available they are being used out of context.

The reaction intensities used to calculate flame length from flame height, are from the BEHAVE system. The fireline intensities for all fuel models and the FFDM Mk.5 are significantly different. It seems likely the reaction intensity for the fire behaviour predicted by the FFDM Mk.5 would also differ from BEHAVE predictions.

Thus two of the values used to convert one of the FFDM Mk.5 outputs came from the fire behaviour prediction methods of the United States. Despite the possible influence this may have the analysis still appears valid since the levels of statistical significance were all less than 0.01 probability of occurrence.

5.1 Forest Fire Danger Meter Mk.5:

The initial result showed that flame heights for flame fronts burning in the three types of forest conditions, over a range of meteorological conditions, were not predicted to be significantly different by the FFDM Mk.5. This conclusion highlights one of the assumptions of the FFDM Mk.5 and one of its potential weaknesses.

The fire behaviour predicted by the FFDM Mk.5 assumes a ground fire under a commercial dry eucalypt forest. Due to this assumption the FFDM Mk.5 failed to separate three very different fuel arrangements. Unlogged Forest, logged forest and fire regenerated forest present three quite diverse stand conditions. All three types are significant in the Eden Region of N.S.W, yet the current method of fire behaviour prediction will not distinguish between them.

An experienced forest manager may be aware of the change in fire behaviour between fuel types. Even if full knowledge of the methods of site specific prediction using the FFDM Mk.5 (Cheney 1968) are known, there is no means of quantifying the variation between sites. A general assessment of "increased" or "reduced" rate of forward spread may be insufficient for planning or safety in wildfire situations or controlled ignition hazard reduction prescriptions.

5.2 The BEHAVE system:

The BEHAVE system distinguishes between fuel types. A major portion of its design was created explicitly to account for the range of wildland fuels across the United States. As a result it provides very different sets of fire behaviour parameters with variation in the fuels being consumed, as modelled for this study.

BEHAVE tended to underestimate flame length and fireline intensity compared to the FFDM Mk.5. The predicted forward rate of spread was less for fire regenerated forest, higher for unlogged and logged forest, compared to FFDM Mk.5 predictions.

The nature of eucalypt litter may account for part of this discrepancy. The major proportion of the litter is leaves (11.8-23.9%). As a fuel these are broad, falcate and hard, very different in shape and form to the leaves of North American hardwoods. The predominantly flat nature of the fuel may tend to increase the consumption of fuel in the active burning zone of the flame front. This would create longer flame lengths and higher intensity per unit length of the flame front.

The depth of litter in a dry eucalypt forest rarely exceeds five centimetres (R.G.Bridges pers. comm.). The fuel bed depths estimated by the NEWMDL module all exceeded this (Table 3).

The increase in fuel bed depth will provide fuel bed bulk density figures that are closer to optimal.

As a result the flame front, as modelled by BEHAVE, would progress through the fuel complex at a faster rate. A more rapid rate of spread will reduce the amount of available fuel consumed in the actively flaming zone and so reduce the flame length and the amount of energy released.

It is possible then that the variations observed between the two methods of fire behaviour prediction are due to a single factor, fuel bed depth, and its influence on the fuel bed bulk density. For this study the data were collected to a height of Ø.9 m above mineral soil (Newman 1983) and no litter depth data were available. Consequently the NEWMDL system was the determinant of fuel bed depth after the fuel loading was defined. With specific information about fuel bed depth it may be possible to progress part way to "fine-tuning" the fuel models and obtain better agreement with the FFDM Mk.5, or actual fire behaviour.

There are other factors of the fuel model development that can be manipulated to "fine tune" the fire behaviour prediction process. Sneeuwjagt (1974) used the moisture of extinction to adjust the predicted values of a grass fuel model for closer agreement with actual fire behaviour data collected on experimental fires.

The heat content of the fuel and the surface area to volume ratio of fuel particles can be altered to vary output. For this study both were higher than the standard values of BEHAVE (Burgan & Rothermel 1984). Further manipulation may permit more accurate prediction.

As discussed earlier (Section 3.4.3) the midflame windspeeds used for all models were derived using relationships developed in the United States. The use of a relationship between open windspeed and midflame windspeed derived for dry eucalypt forests may effect the predictions. This would be exaggerated if the relationship were dissimilar to those used in this study.

The fire behaviour data for fire regenerated forest show an interesting trend supported by Australian experience. The fuel sampling was all carried out in areas that had been burnt by wildfire in either 1952, 1964, or 1972. In most cases the areas sampled had also been hazard reduced within five years of sampling (Newman 1983). Cheney (1985) discussed a wildfire (the Timbillica Fire) that burnt through 45,000 Ha of the Eden Region on November 18th, 1980. Weather conditions were extreme. One part of the head-fire ran into an area that had been hazard reduced, similar to the fuel model developed for fire-regenerated forest. It was reported that:

> "in parts the fire self-extinguished during a period of low winds" (Cheney 1985).

The fire behaviour predictions from this fuel model agree with Cheney's description. All three fire behavior parameters are significantly less than those predicted by the FFDM Mk.5.

5.3 Comparison and Constrast:

In the process of obtaining fire behaviour predictions from these two methods they were compared and points of contrast noted. They are very different means of obtaining the desired outputs. Coming from separate continents they are also separated by the basis upon which their development rests.

The demand that created the FFDM Mk.5 called for a regional rating system of fire danger that would allow warnings to be issued, suitable preparations made and precautions taken. The FFDM Mk.5 satisfies these requirements. BEHAVE, as its name suggests, was specifically for the prediction of fire behaviour. Fuel type, arrangement and condition has been a consideration since the infancy of fire prevention and control in the United States (Brown & Davis 1973). Since this was the objective, development proceeded from a theoretical understanding of fire, flame front propagation and its interaction with the fuel bed.

This difference was accentuated, and intiated in part by the personnel carrying out the work. Those studying fire in Australia were foresters by training, with an interest in "bushfires". Conversely much of the fire research in the United States was carried out by people with some engineering background. Fire behaviour can be seen as a physics and fluid dynamics phenomena. This basic difference is the major cause of most other contrasting elements for the two methods of fire behaviour prediction.

The BEHAVE system directly accounts for wildland fuels and their variation in the factors by which they are measured. The moisture content of the fuel by size-classes is also required by BEHAVE (Burgan & Rothermel 1984).

The FFDM Mk.5 includes fuel by assuming forest type and condition, fuel loading at 12.5 tonnes/ha, and does not specify either size-class or moisture content for that fuel. It is possible to make adjustments by the ratio of known to assumed fuel loading (Cheney 1968).

The explicit incorporation of fuel variables provides BEHAVE with the ability to differentiate between the fire behaviour of changing fuel conditions. For site specific fire control and hazard reduction operations this is a considerable advantage over the FFDM Mk.5.

With the additional fiscal, environmental and operational pressure forest managers are being subjected to in N.S.W. a professional, quantifiable basis for decisions in relation to fire suppression and fuel management activities is necessary. The BEHAVE system of fire behaviour prediction should be carefully considered as a candidate to satisfy such needs.

On a practical level there are operational differences between the FFDM Mk.5 and BEHAVE. The meter has long been produced and used as a circular slide rule (figure 9). It requires only standard, readily obtained meteorological information for its operation. The BEHAVE system requires no knowledge of computer operations (Rothermel 1983b). It is designed for land managers familiar with fuels, weather, fire and the associated terminology. BEHAVE is available on a hand-held calculator, as micro-computer software (Cooney 1986) and as a mainframe computer system. The calculator has metric capability. A metric version of the software will soon be available.

The physical requirements of the two are distinctly separate. The N.S.W. Forestry Commission is currently in the process of equipping all regional offices and many district offices with microcomputers. The more difficult requirement would be updating the knowledge of fire behaviour, fuels and weather of personnel.

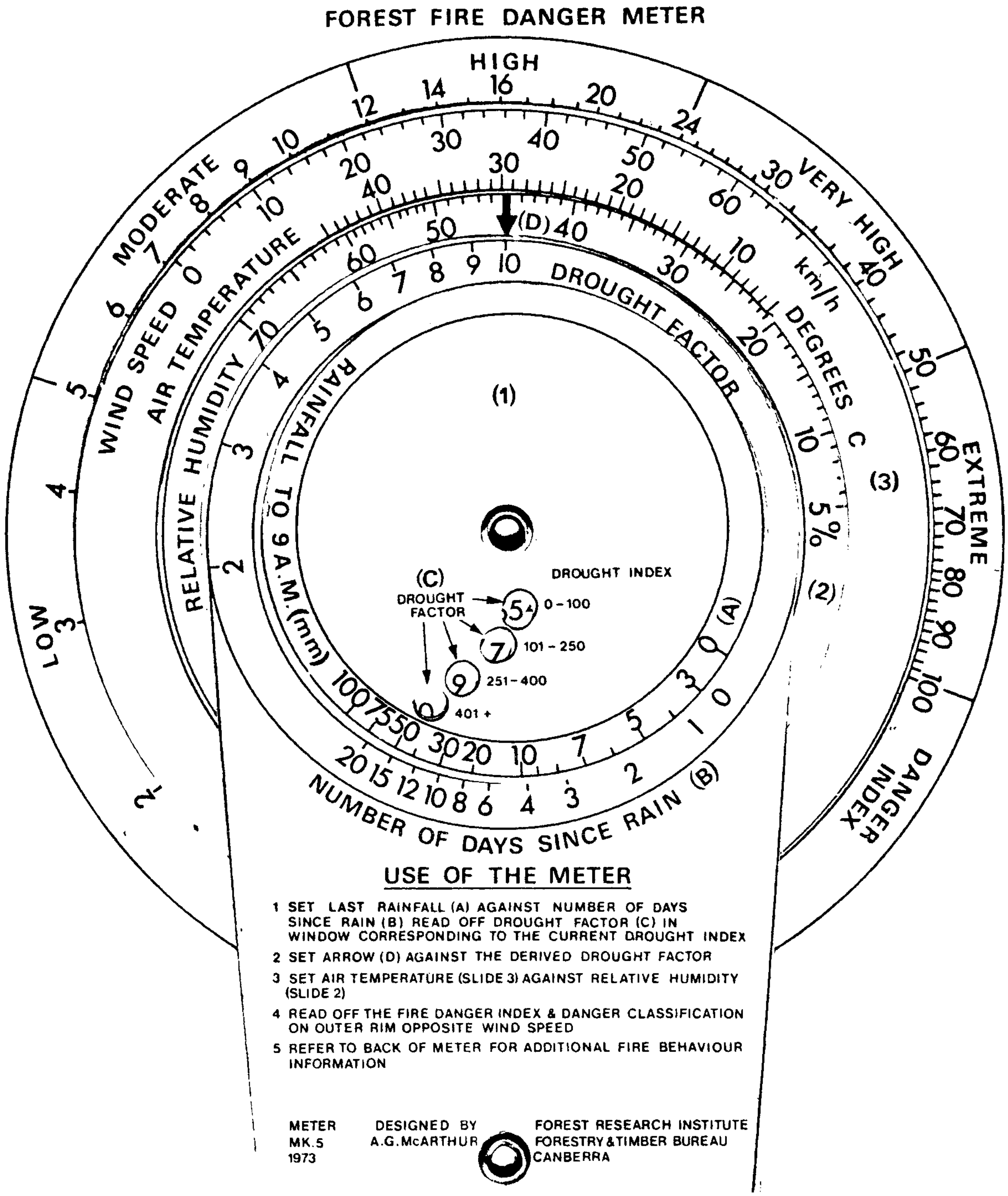


Figure 9: The Forest Fire Danger Meter Mk.5

Such training is not heavily emphasised in the undergraduate professional degree. Additionally many of those involved in fire suppression and control burning are volunteers. There is also the major task of developing and validating fuel models for the BEHAVE system. This study has shown this process should not prevent the use of BEHAVE.

Conversely the FFDM Mk.5 is familiar and well known. The adjustments for site specific fire behaviour are not. The meter is easy to use and easily taught to those not familiar with its operation. The meter is inexpensive and portable. It has also served in the past. The author is not aware of any use of the meter other than for the rating of fire danger.

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