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Concepts and Interpreted Examples In Advanced Fuel Modeling

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RESEARCH SUMMARY

The basic concepts of fuel modeling were presented in the fuel subsystem of BEHAVE. This report expands on these concepts in an attempt to provide a better understanding of the technical details of constructing site-specific fire behavior fuel models.

The discussion is mathematical. It is aimed at fire managers who are familiar with the fire model and who may be dealing with difficult fuels situations.

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ERRATA—General Technical Report INT-238, Concepts and Interpreted Examples in Advanced Fuel Modeling, by Robert E. Burgan (November 1987).

Curve lines were misplaced in figures 1 and 2 in this publication. Correct figures follow.

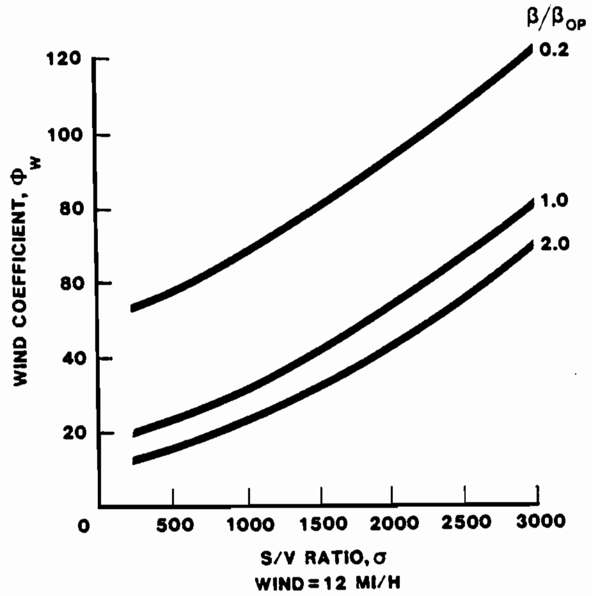

Figure 1—The wind coefficient increases as the surface-area-to-volume ratio of the fuels increases, and the effect becomes greater as the fuel bed density decreases.

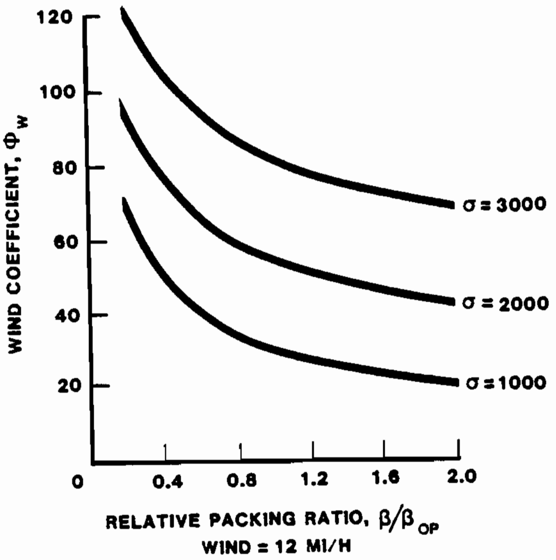

Figure 2—The wind coefficient decreases rapidly as the fuel bed density increases.

Concepts and Interpreted Examples In Advanced Fuel Modeling

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INTRODUCTION

The basic concepts of fuel modeling were presented in the manual for the fuel subsystem of BEHAVE (Burgan and Rothermel 1984). This paper expands on these concepts in an attempt to provide a better understanding of technical details of fuel modeling. The reader should be familiar with the basic concepts before studying the more detailed discussion presented here.

This discussion is necessarily mathematical. It is aimed at fire managers who wish to become more proficient in fuel modeling and who may be dealing with difficult fuels situations. Basic concepts will be reviewed to provide a foundation for discussing examples of fuel models. These examples will be used to illustrate how changes in various fuel model parameters affect predicted fire behavior and to provide insight into the technical details of fuel modeling.

The equation developed to calculate the rate of spread in wildland vegetation (Rothermel 1972) is:

$$R = \frac{I_R \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}}$$

where:

R = rate of spread, ft/min

I_R = reaction intensity, Btu/ft^2/min

ξ = propagating flux ratio, dimensionless

ϕ_w = wind coefficient, dimensionless

ϕ_s = slope coefficient, dimensionless

ρ_b = ovendry bulk density, lb/ft^3

ε = effective heating number, dimensionless

Q_{ig} = heat of preignition, Btu/lb.

We will rely primarily on ϕ_w, ξ, I_R, and a fourth term, Γ', in this discussion because the size of individual particles (σ) and density of the fuel bed (ρ_b) exercise their strongest effect through these parameters. Briefly, Γ' is defined as the optimum reaction velocity and is used in calculating I_R. Each of these four terms will be further defined, its equation presented, and its characteristics discussed.

WIND COEFFICIENT (ϕ_w)

The wind coefficient is a dimensionless multiplier that accounts for the increased spread rate resulting from improved radiant and convective heat transfer and oxygen flow in wind-driven fires.

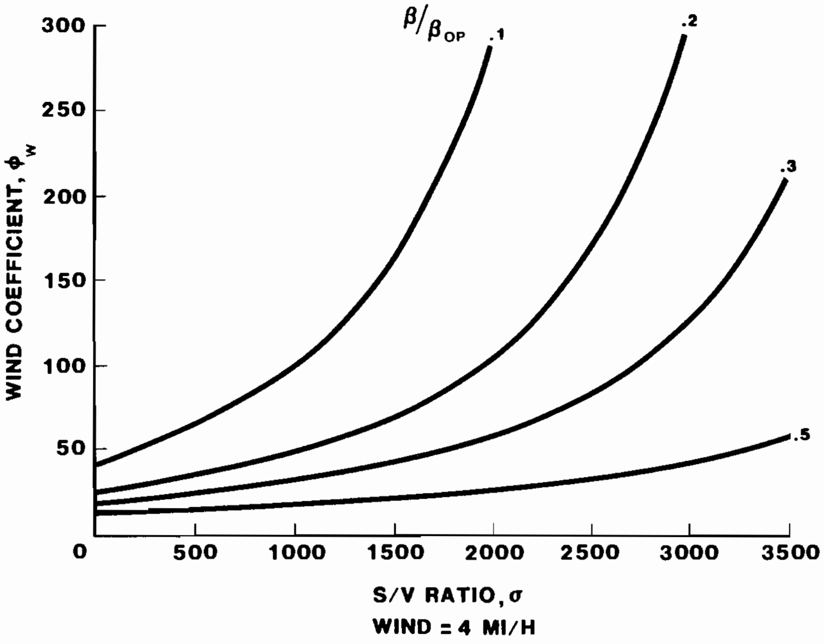

Figure 1—The wind coefficient increases as the surface-area-to-volume ratio of the fuels increases, and the effect becomes greater as the fuel bed density decreases.

The equation for ϕ_w is:

$$\phi_w = CU^B (\beta/\beta_{op})^{-E}$$

where:

C, B and E are functions of fuel particle size only and thus are constant for any given "characteristic" surface-area-to-volume ratio (σ). Unless otherwise noted, σ will mean the "characteristic" or weighted average surface-area-to-volume ratio that represents all the fuels in the fuel model.

U is the windspeed in feet per minute (mi/h * 88).

β/β_{op} is the ratio of the actual packing ratio (β) to the optimum packing ratio (β_{op}). β_{op} is constant for any given σ.

Thus ϕ_w is a function of the characteristic σ, the packing ratio (β), and the windspeed (U). C, B and E are σ-dependent correlation parameters used to fit the equation to the original data. The upward slope of ϕ_w (fig. 1) is produced by the fact that windspeed (U) is raised to an increasingly larger power (B) as σ increases. C decreases as σ increases, but not enough to counteract the effect of U^B. Figure 1 also shows the wind coefficient increases faster for lightly loaded fuel beds; that is, those whose β/β_{op} ratio is low.

Figure 2 shows that ϕ_w decreases rapidly as β/β_{op} increases, but as fuel beds become more and more tightly packed, the rate of decrease in ϕ_w slows.

In summary, remember that for a given windspeed:

1. ϕ_w increases as the windspeed increases.
2. ϕ_w increases as σ increases. (The effects of wind are more pronounced in fine fuels.)
3. ϕ_w increases as β/β_{op} decreases; that is, as the fuel bed becomes more airy or fluffy.
4. The slope coefficient (ϕ_s) (which will not be discussed in detail), also decreases as the packing ratio increases, but the effect of slope is much less than the effect of wind.

In general, a fuel model can be made more sensitive to wind by increasing σ, by increasing fuel bed depth, or by decreasing fuel load.

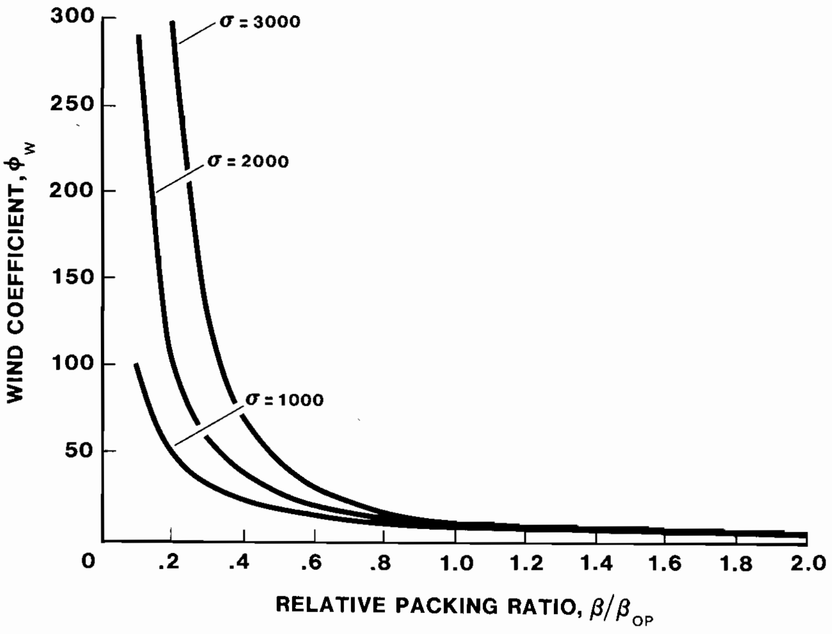

Figure 2—The wind coefficient decreases rapidly as the fuel bed density increases.

REACTION VELOCITY (Γ)

Reaction velocity is defined as the ratio of the efficiency of the fire to the reaction time. It is a measure of the actual rate of fuel consumption; that is, a measure of the speed of the combustion reaction. The units are per minute.

Discounting the effects of moisture and minerals upon burning rate, the potential reaction velocity, Γ' is given by:

$$\Gamma' = \Gamma'_{\max} (\beta/\beta_{op})^A \exp [A (1-\beta/\beta_{op})]$$

where:

$\Gamma'_{\max}$ is the rate of fuel consumption when the fuel bed packing ratio is optimum ($\beta = \beta_{op}$), dimensionless.

β/β_{op} is the ratio of actual to optimum packing, dimensionless.

A is an arbitrary variable dependent on σ.

Throughout the discussion, the potential reaction velocity will be referred to as the reaction velocity and be represented by the symbol Γ'.

Figure 3 shows that Γ' increases as β/β_{op} increases from 0 to 1, at which point Γ' is at a maximum, and then decreases again as the fuel bed is more tightly packed. At optimum packing, $\Gamma' = \Gamma'_{\max}$ by definition. The influence of σ on the exponent, A, produces a family of reaction velocity curves for various σ's, with the interpretation being that fires burn faster in finer fuels.

In summary, remember that:

1. Γ' increases rapidly to a maximum value at β_{op}, then tapers off as the packing ratio increases.
2. Γ' peaks at higher values as σ increases.

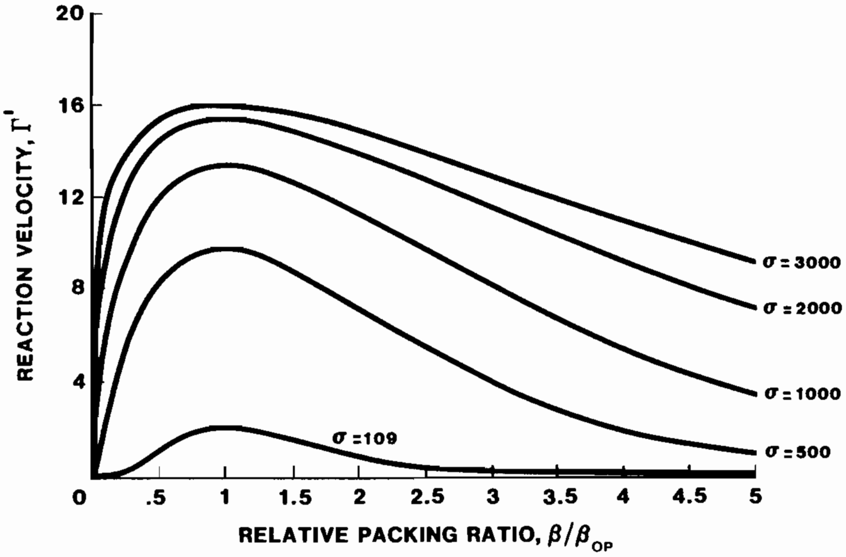

Figure 3—The reaction velocity is at a maximum when the fuel bed density is optimized to provide the best fuel/air ratio. This occurs when the relative packing ratio is 1.

PROPAGATING FLUX RATIO (ξ)

The propagating flux ratio is a dimensionless number indicating the proportion of the total heat produced in the combustion zone that actually preheats adjacent fuel particles to ignition.

The equation for ξ is:

$$\xi = (192 + 0.2595\sigma)^{-1} \exp [(0.792 + 0.681\sigma^{0.5})(\beta + 0.1)]$$

where:

σ is the surface area to volume ratio, ft^2/ft^3

β is the packing ratio, dimensionless.

ξ can theoretically vary from nearly 0 to 1 (fig. 4). It tends toward 0 as either β or σ decreases; that is, as the fuel bed gets more fluffy or the fuel particle size increases.

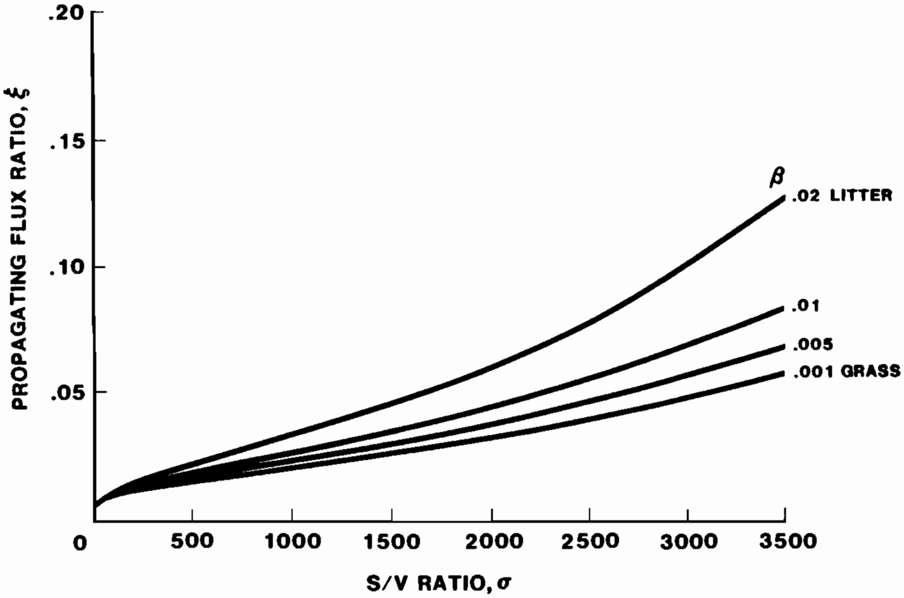

Figure 4—The proportion of heat produced in the combustion zone that actually contributes to fire propagation ranges from 0 to 20 percent, depending on fuel particle size and fuel bed compactness.

Figure 4 shows how ξ increases as σ increases for various packing ratios. Notice that ξ increases more rapidly as σ increases in tightly packed fuel beds such as litter than in loose fuel beds such as grass. Figure 5 illustrates that, as β increases, ξ increases exponentially to a theoretical maximum value of 1. In reality, values above about 0.2 are not likely in surface fires.

In summary, remember that ξ increases when **either** β or σ increases.

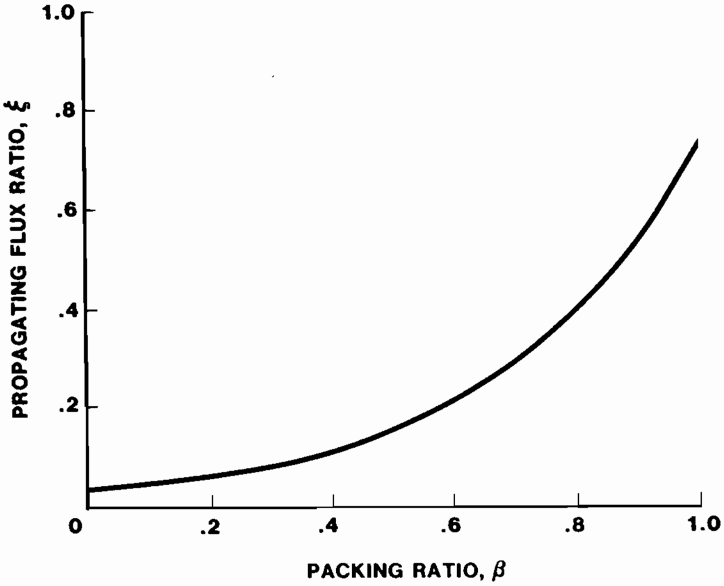

Figure 5—The proportion of heat that contributes to fire propagation increases as the fuel bed becomes more tightly packed. Values above 20 percent are not likely in surface fires.

REACTION INTENSITY (I_r)

Reaction intensity is a measure of the energy release rate per unit area of combustion zone. The units are Btu/ft²/min. There is no implication of where this energy is going; it is just a **total** energy production rate per unit area in the flaming zone.

The equation for I_r is:

$$I_r = \Gamma' w_n h \eta_m \eta_s$$

where

$$w_n = w_o (1 - S_t)$$

and

S_t = mineral content fraction of total fuel load (0.0555), a value determined by analysis to be common for many wildland fuels and assumed constant in this paper

but

$$w_o = \rho_b \delta$$

so

$$w_n = \rho_b \delta (1 - S_t)$$

but since $(1 - S_t) = 0.9445$ it can be approximated to 1 to simplify this discussion.

Then

$$w_n \cong \rho_b \delta$$

and

$$I_r \cong \Gamma' \rho_b \delta h \eta_m \eta_s$$

where:

Γ' = reaction velocity (1/min)
ρ_b = the ovendry bulk density (lb/ft^2)
δ = fuel bed depth (ft)
h = heat content (Btu/lb)
η_m = moisture damping coefficient, dimensionless
η_s = mineral damping coefficient, dimensionless.

The heat content, h, is very straightforward in its effects on fire behavior—fire potential increases as heat content increases and vice versa. That is, fire behavior outputs respond directly and linearly with changes in heat content. For forest fuels, a common heat content is 8,000 Btu/lb.

For the moment, consider the moisture and mineral damping coefficients to be constant. Thus, if h, η_m, and η_s can be ignored momentarily, we need concern ourselves with only three parameters in the reaction intensity equation: Γ', ρ_b, and δ. Remember Γ' is a function of the relative packing ratio (β/β_{op}) and σ, while ρ_b is a function of load and depth. Γ' will always peak when the packing ratio is optimum, but I_r may peak at a higher than optimum packing ratio. This occurs because the addition of more fuel per unit volume (ρ_b and β increasing) will continue, for a while, to increase the total energy release rate even though the combustion rate for individual fuel particles is slowing, because there are simply more fuel particles burning. Eventually, however, the fuel bed becomes so compact and the reaction velocity (Γ') is slowed sufficiently so that the total rate of heat output, I_r, begins to decrease.

In summary, remember that I_r:

1. Is a function of reaction velocity (Γ'), which depends on packing ratio (β) and fuel particle size (σ).
2. Will eventually decrease with increased packing ratio due to the drop in reaction velocity (Γ').
3. Does not necessarily peak at the optimum packing ratio as does Γ'.
4. Is affected by the heat content.
5. Is affected by fuel moisture.

INTERPRETING FUEL MODEL EFFECTS ON STANDARD FIRE BEHAVIOR OUTPUTS

We now apply the above concepts to ascertain how changes in fuel model parameters might affect:

1. Rate of spread.
2. Byram's fireline intensity.
3. Flame length.

Rate of Spread

Remember the rate of spread equation is:

$$R = \frac{I_r \, \xi \, (1 + \phi_w + \phi_s)}{\rho_b \, \varepsilon \, Q_{ig}}$$

But in the reaction intensity discussion we left

$$I_r \cong \Gamma' \rho_b \, \delta h \, \eta_m \, \eta_s$$

so

$$R \cong \frac{\Gamma' \rho_b \, \delta \xi h \, \eta_m \, \eta_s \, (1 + \phi_w + \phi_s)}{\rho_b \varepsilon \, Q_{ig}}$$

Knowing that heat content (h), moisture damping (η_m), and mineral damping (η_s) are important, we will recognize their presence by assigning the product of these three parameters a constant value V for this discussion. That is, $V = h \, \eta_m \eta_s$ and cancelling ρ_b.

$$R \cong \frac{\Gamma' \, \delta \xi V (1 + \phi_w + \phi_s)}{\varepsilon \, Q_{ig}} \qquad \text{(Eq. X)}$$

where the two unfamiliar parameters are:

ε = an effective heating number
Q_{ig} = the heat of preignition.

Unless fuel moistures are changed, Q_{ig} is constant, so we may disregard it for the moment. ε is an estimator of the proportion of a fuel particle that must be heated to ignition in the flaming front. It increases as σ increases, that is, a larger fraction of finer fuels must be heated.

To see how the rate of spread in equation X is going to be affected by changes in a fuel model parameter, we only need to evaluate how that change will affect the size of the numerator with respect to the size of the denominator. Let us look at how our three most important fuel model parameters—load, S/V ratio, and depth—affect the numerator and denominator of the above-simplified rate of spread equation.

Load—Increasing load (holding depth constant) increases the packing ratio. This will:

1. Increase the reaction velocity (Γ') until the packing ratio is optimum, then as load is increased further, Γ' will begin to decrease (fig. 3). Thus, increasing load can either increase or decrease the numerator.
2. Increase the propagating flux ratio (ξ) (fig. 4), and therefore increase the numerator of the spread equation.
3. Decrease the wind coefficient ϕ_w very rapidly at first, then more slowly as the fuel bed becomes more tightly packed (fig. 2), and therefore decrease the numerator.
4. Decrease the slope coefficient in a manner similar to the wind coefficient. Compared to the effect of wind, the effect of slope is small and therefore it is not discussed in detail.

S/V Ratio—Increasing the S/V ratio, σ, will:

1. Increase the reaction velocity, and thus the numerator in loosely packed fuels. The point of maximum reaction velocity will be shifted to lower packing ratios (fig. 3). Remember that fine fuels burn best when loosely packed, while coarse fuels burn best when packed more tightly.
2. Increase the propagating flux ratio (fig. 4) and thus the numerator.
3. Increase the wind coefficient considerably for fuel beds with a low packing ratio, but not much for tightly packed fuel beds (fig. 1). The numerator would increase.
4. Increase the effective heating number, which would increase the denominator, thus producing an opposing effect to the first three. This will be minor, however, and the general trend is that for increasing σ, spread rate will increase in loosely packed fuel and decrease in tightly packed fuel.

Depth—Increasing depth (holding load constant) decreases the packing ratio. This will:

1. Increase the reaction velocity when the packing ratio is greater than optimum, decrease it when reaction velocity is less than optimum (fig. 3). Thus a change in depth may either increase or decrease this term of the numerator.
2. Decrease the propagating flux ratio (fig. 4), and the numerator.
3. Increase the wind coefficient (fig. 2) and thus the numerator.

A good rule of thumb is that increasing depth usually increases rate of spread due to the more porous fuel bed.

Byram's Fireline Intensity

Byram's fireline intensity is a measure of the rate of heat production per lineal foot of flaming front per second (Btu/ft·s).

The equation for fireline intensity (I_B) is:

$$I_B = 384\ I_r\ R/(60 * \sigma)$$

Thus, all the previously discussed interactions that affect reaction intensity (I_r) and rate of spread (R) also affect the fireline intensity.

Flame Length

Flame length is purely a function of Byram's fireline intensity:

$$FL = 0.45\ I_B^{0.46}$$

Flame length is responsive to changes in the fuel model parameters in approximate proportion to the square root of Byram's fireline intensity.

EXTINCTION MOISTURE

Extinction moisture is a fuel model parameter that can have a moderate to a strong influence on predicted fire behavior, depending on a number of factors. Basically, it is defined as the dead fuel moisture content at which a fire will no longer spread with a uniform flame front and the model predicts zero spread rate. Predicted fire intensity and spread rate will increase when the difference between the actual fuel moisture and the dead fuel extinction moisture increases. This occurs as dead fuels become drier. Increasing

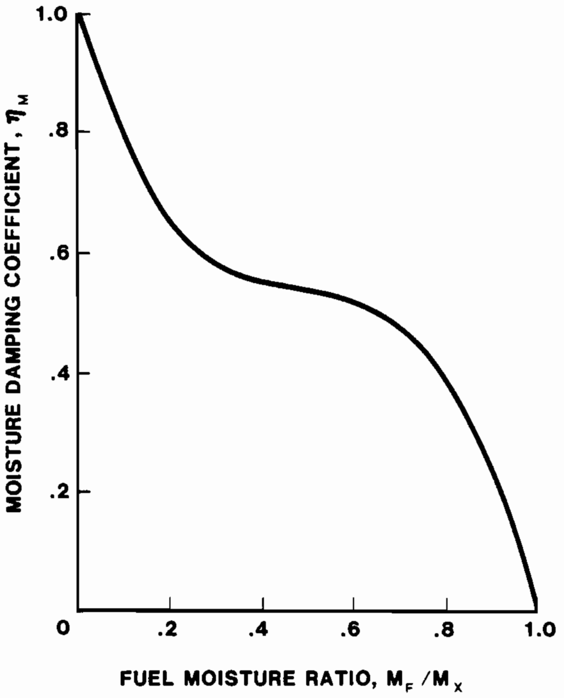

Figure 6—Fire behavior is most responsive to changes in dead fuel moisture when the fuels are either relatively dry or relatively wet.

the dead fuel moisture will have an opposite effect. Fire behavior predictions are much more responsive to changes in the difference between actual and extinction moistures when the actual moisture is close to the extinction moisture. That is, the response of a fuel model to changes in moisture is not linear (fig. 6).

INTERPRETATION OF EXAMPLE FUEL MODELS

With the above guides, we will interpret some graphs produced by the technical version of TSTMDL. The first model will have 1 ton/acre of fuel in the 1-h class and no load in any other class. Subsequent examples will be generated by adding 1 ton/acre in each of the remaining classes. There are a total of six examples as summarized in the following tabulation:

Example	Load (tons/acre)					Model type	
No.	1-h	10-h	100-h	Herb	Woody	Static	Dynamic
1	1					x	
2	1	1				x	
3	1	1	1			x	
4	1	1	1	1		x	
5	1			1		x	
6	1			1			x

In all cases, the 1-h S/V ratio will be 2,000 ft^2/ft^3; when applicable, the herb and woody S/V ratio will also be 2,000, the depth will be 0.5 ft, and the heat content will be 8,000 Btu/lb.

We will also use standard environmental data, either low or high moisture as tabulated below.

	Environmental conditions	
	Low moisture	High moisture
	Percent	
1-h	3	12
10-h	4	13
100-h	5	14
Live herb	70	170
Live woody	70	170
Windspeed, mi/h	4	4
Slope, percent	30	30

Example 1

Data for the first example are shown in the following tabulation:

Fuel Model Test Run—User-Defined Environmental Inputs

Static 14. Load 1 By: Burgan

Load (T/AC)		S/V Ratios		Other	
1 HR	1.00	1 HR	2000.	Depth (feet)	0.50
10 HR	0.00	Live herb	0.	Heat content (Btu/lb)	8000.
100 HR	0.00	Live woody	0.	Ext moisture (%)	25.
Live herb	0.00	Sigma	2000.	Packing ratio	0.00287
Live woody	0.00	S/V = (sqft/cuft)		PR/OPR	0.43

Environmental Data		Fire Behavior Results			
		Fire Variable	Midflame Wind		
			0.	4.	8.
1 HR FM	3.				
10 HR FM	4.				
100 HR FM	5.	ROS (ft/m)	8.	38.	93.
Live herb FM	70.	FL (ft)	2.	5.	8.
Live woody FM	70.	IR (Btu/sq ft/m)	1546.	1546.	1546.
		H/A (Btu/sq ft)	297.	297.	297.
Slope (%)	30.	FLI (Btu/ft/sec)	41.	187.	462.

The optimum packing ratio for this model is 0.00667 and the optimum loading is 2.32 tons/acre.

Load Effects—The spread rate peaks at about 0.75 ton/acre, the flame length at about 7 tons/acre, and the reaction intensity at about 10 tons/acre (fig. 7). Why does each of these fire behavior outputs peak at a different load?

First consider what is happening to the reaction intensity (fig. 7). Remember that I_r is a product of reaction velocity and fuel load, assuming heat content, and moisture and mineral damping coefficient are constant. The reaction velocity **always** peaks at the optimum packing ratio, which occurs at a load of 2.32 tons/acre in this case. So, because the reaction velocity is decreasing at loadings greater than 2.32 tons/acre, the reaction intensity can continue to increase beyond that point only because the reaction velocity is being multiplied by an increasing load. Finally, however, beyond about 10 tons/acre, the reaction velocity is decreasing so much that it begins to dominate, so the reaction intensity begins to decrease as the fuel load increases beyond 10 tons/acre.

Spread rate (fig. 7) increases to a maximum at about 0.75 ton/acre, then slowly tapers off. The abrupt end to the rapid increase in spread rate is particularly interesting. At 0.75 ton/acre the reaction velocity and reaction intensity are still increasing because the optimum packing ratio, which occurs at 2.32 tons/acre, has not yet been reached. The propagating flux ratio always increases as load increases, so none of these can account for the cap on spread rate. But the windspeed is 4 mi/h, and the wind coefficient is decreasing rapidly as the packing ratio increases (fig. 2). The slope coefficient is acting similarly. Lightly loaded models like this one are very sensitive to the ϕ_w and ϕ_s multipliers; thus, they exert a strong influence on the spread rate numerator, which represents a heat source. In addition, the heat sink, represented by the denominator, is increasing because of the addition of more fuel. At 0.75 ton/acre these effects in the numerator and denominator suddenly stop the increase in spread rate. The long, gradual decrease in spread rate results from decreasing reaction velocity, wind, and slope coefficients, and an increasing heat sink. These combined effects just barely offset the increase in reaction intensity up to about a 10 tons/acre load. Beyond that, even the reaction intensity decreases.

Flame length (fig. 7) is a function of both spread rate and reaction intensity, and so peaks when the product of the decreasing spread rate and the increasing reaction intensity is a maximum.

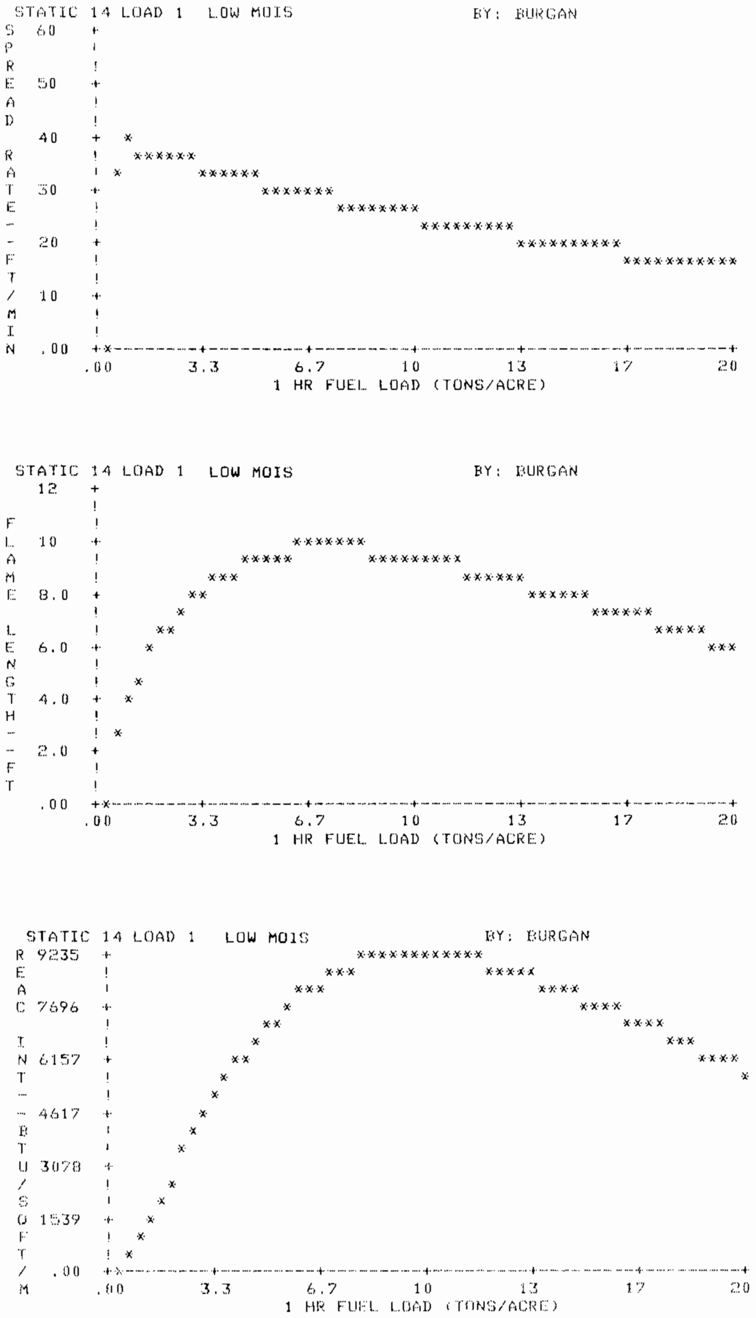

Figure 7—One-hour fuel load, example 1.

S/V Effects—Spread rate increases when the S/V ratio increases (fig. 8) because Γ', ϕ_w, and ϕ_s and ξ all increase with increasing S/V ratios. Refer to figure 3 to note the effect on Γ', figure 1 to see the effect on ϕ_w, and figure 4 to see the effect on the propagating flux ratio. Thus, every parameter in the numerator of the previously defined approximation of the rate of spread equation:

$$R \cong \frac{\Gamma' \delta \xi V(1 + \phi_w + \phi_s)}{\varepsilon Q_{ig}}$$

is increasing. The denominator is also increasing because a larger proportion of the fuel particles are heated to ignition temperature as the fuel particle size decreases and the ef-

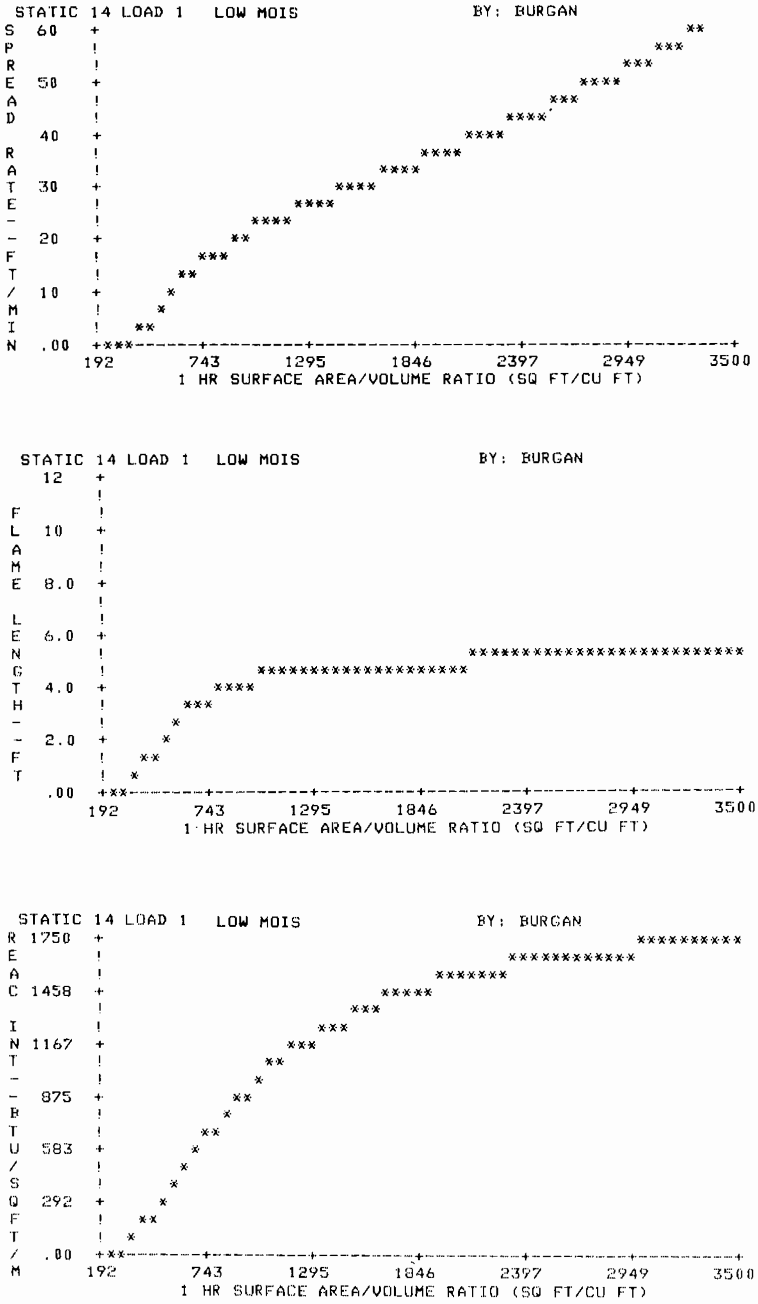

Figure 8—One-hour surface area/volume ratio, example 1.

fective heating number, ε, increases. Thus, the heat sink is becoming larger. But the numerator of the spread rate equation dominates in this case, so the spread rate increases.

Flame length increases (fig. 8) for a while and then flattens out because σ is in both the numerator and denominator of Byram's fireline intensity equation. Thus, even though spread rate is increasing, flame length increases as long as I_r increases rapidly, but stops increasing when I_r begins to flatten out.

Reaction intensity (fig. 8) is linearly related to reaction velocity, and, because in this case the packing ratio is less than optimum, the reaction velocity increases as the S/V ratio increases. So reaction intensity must also increase.

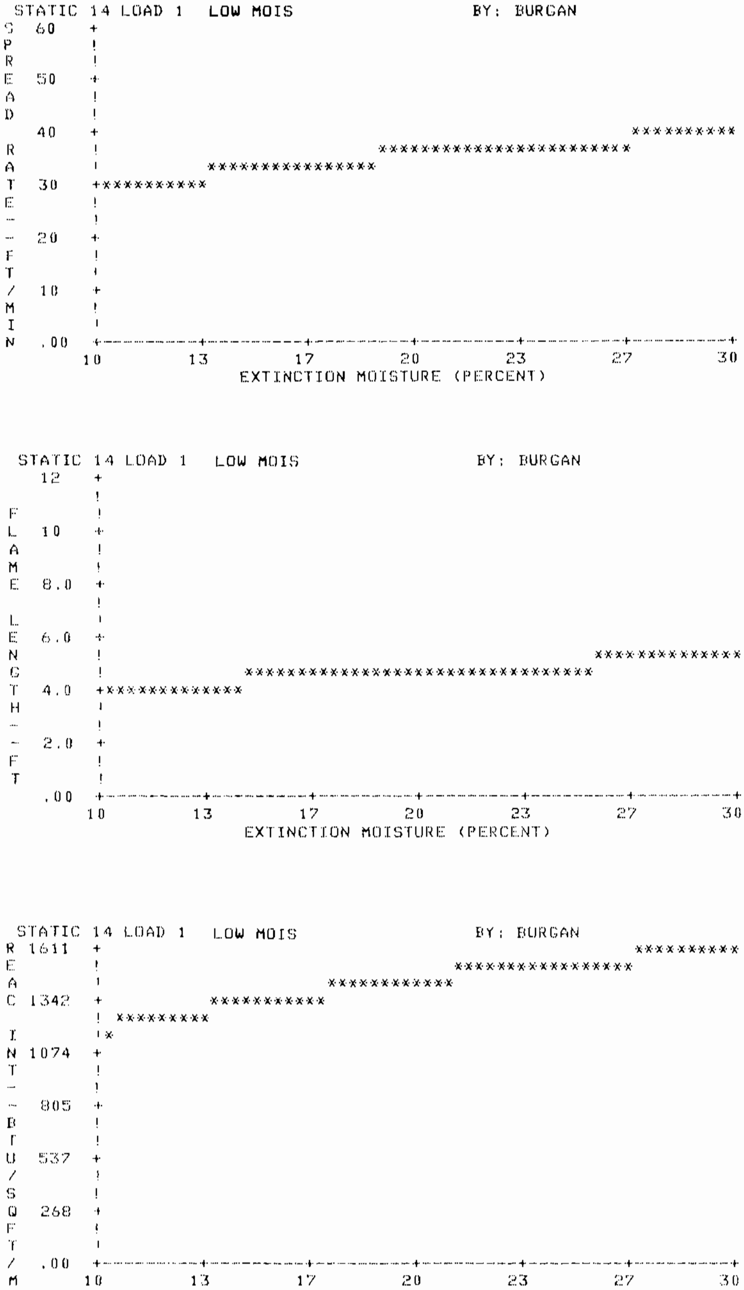

Figure 9—Extinction moisture, example 1, low fuel moisture.

Extinction Moisture Effects—Spread rate, flame length, and reaction intensity all increase as the extinction moisture increases, but notice that the effect is less pronounced at low fuel moisture (fig. 9) than at high fuel moisture (fig. 10).

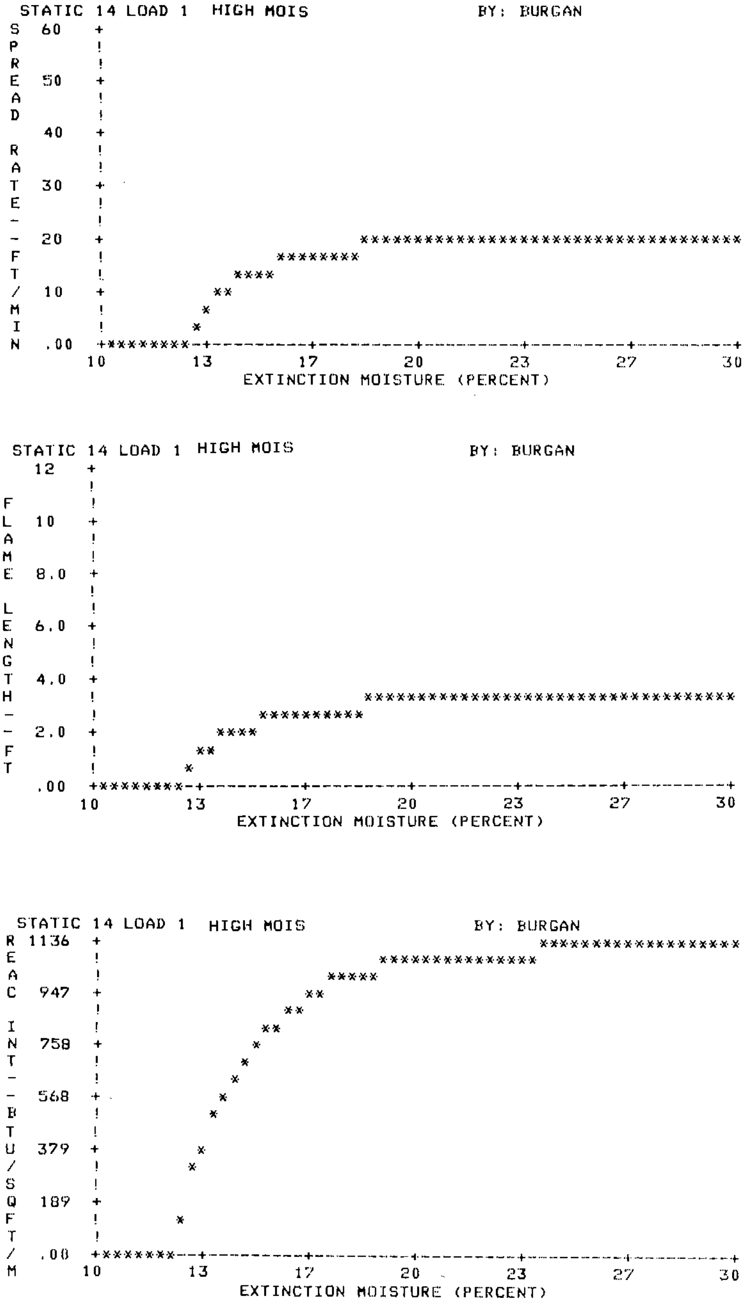

Figure 10—Extinction moisture, example 1, high fuel moisture.

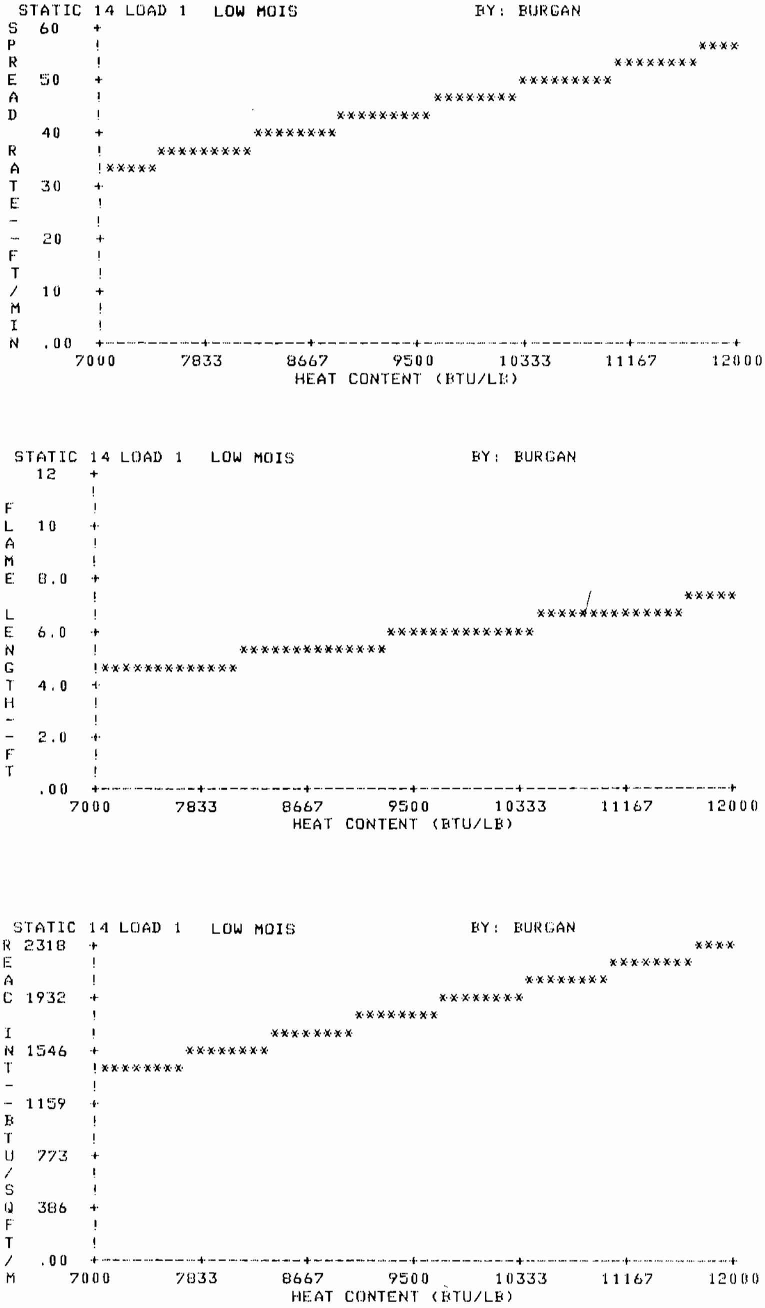

Figure 11—Heat content, example 1.

Heat Content Effects—Because heat content is a mulitiplier in the numerator of the spread equation, predicted fire behavior always increases when the heat content is increased (fig. 11).

Example 2

For the second example, 1 ton of fuel will be added to the 10-hour load.

```
Fuel Model Test Run—User-Defined Environmental Inputs
Static 15. Load 1,10                                          By: Burgan
   Load (T/AC)              S/V Ratios                 Other
1 HR           1.00     1 HR        2000.   Depth (feet)              0.50
10 HR          1.00     Live herb      0.   Heat content (Btu/lb)    8000.
100 HR         0.00     Live woody     0.   Ext moisture (%)           25.
Live herb      0.00     Sigma       1902.   Packing ratio          0.00574
Live woody     0.00     S/V = (sqft/cuft)   PR/OPR                    0.83
                                      Fire Behavior Results
   Enfironmental
       Data                  Fire                  Midflame Wind
                             Variable          0.        4.        8.
1 HR FM           3.
10 HR FM          4.
100 HR FM         5.    ROS (ft/m)             4.       18.       43.
Live herb FM     70.    FL (ft)                2.        4.        6.
Live woody FM    70.    IR (Btu/sq ft/m)    1660.     1660.     1660.
                        H/A (Btu/sq ft)      335.      335.      335.
Slope (%)        30.    FLI (Btu/ft/sec)      23.      100.      238.
```

In this case, the optimum packing ratio is 0.00691 and the optimum loading is 2.41 tons/acre.

Load Effects (1-h Varies)—When 1-h fuel load is varied in this model, a comparison of figure 12 with figure 7 shows the additional 10-h fuel slows the spread rate, as compared with example 1 because:

1. The characteristic S/V ratio (σ) is smaller (1,902 vs. 2,000), thus reducing the reaction velocity (fig. 3) and consequently the reaction intensity.
2. ϕ_w (and ϕ_s) are also reduced because σ is smaller (fig. 1).
3. The heat sink is increased because of the larger fuel load.

Notice also that the spread rate peaks at a much higher loading in example 2 (about 6 tons/acre) than in example 1 (about 1 ton/acre). The key to this change is that we are now mixing two fuel sizes (1-h and 10-h) **and** that the 1-h load is increasing from 0 to 20 tons/acre as the 10-h load remains constant.

Example 1 shows what happens when the fuel model is pure 1-h load; let us see what happens when the fuel model is pure 10-h load (fig. 13). Now the spread rate peaks at about 25 tons/acre. This is the situation in example 2 when the 1-h load is zero. Then, as 1-h load is added, the peak in figure 13 would shift to the left until the peak spread rate is produced at about 6 tons/acre for the combined 1-h and 10-h loads (fig. 12). Both packing ratio and the characteristic S/V ratio increase as the 1-h load is increased.

Flame length is lower in example 2 than example 1 because the reaction intensity and spread rate are both lower in example 2. The flame length peak shifts to the right (heavier loadings) because the spread rate, which is used to calculate flame length, peaks at a high load. The flame length peak is more rounded because the spread rate peak flattens.

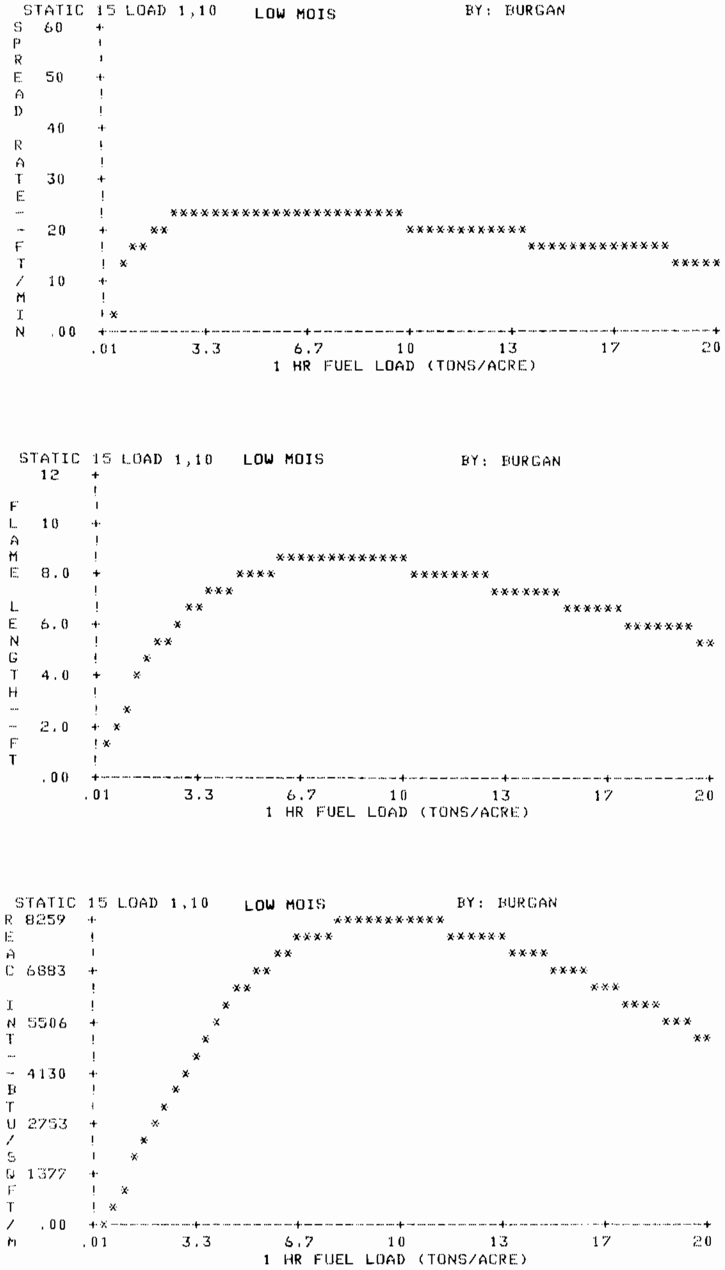

Figure 12—One-hour load, example 2.

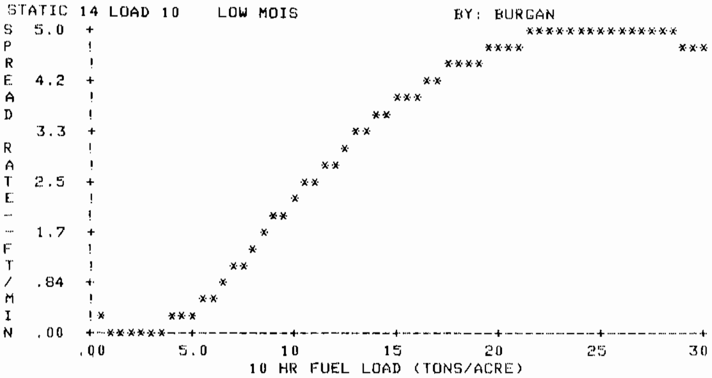

Figure 13—Ten-hour load only, example 2.

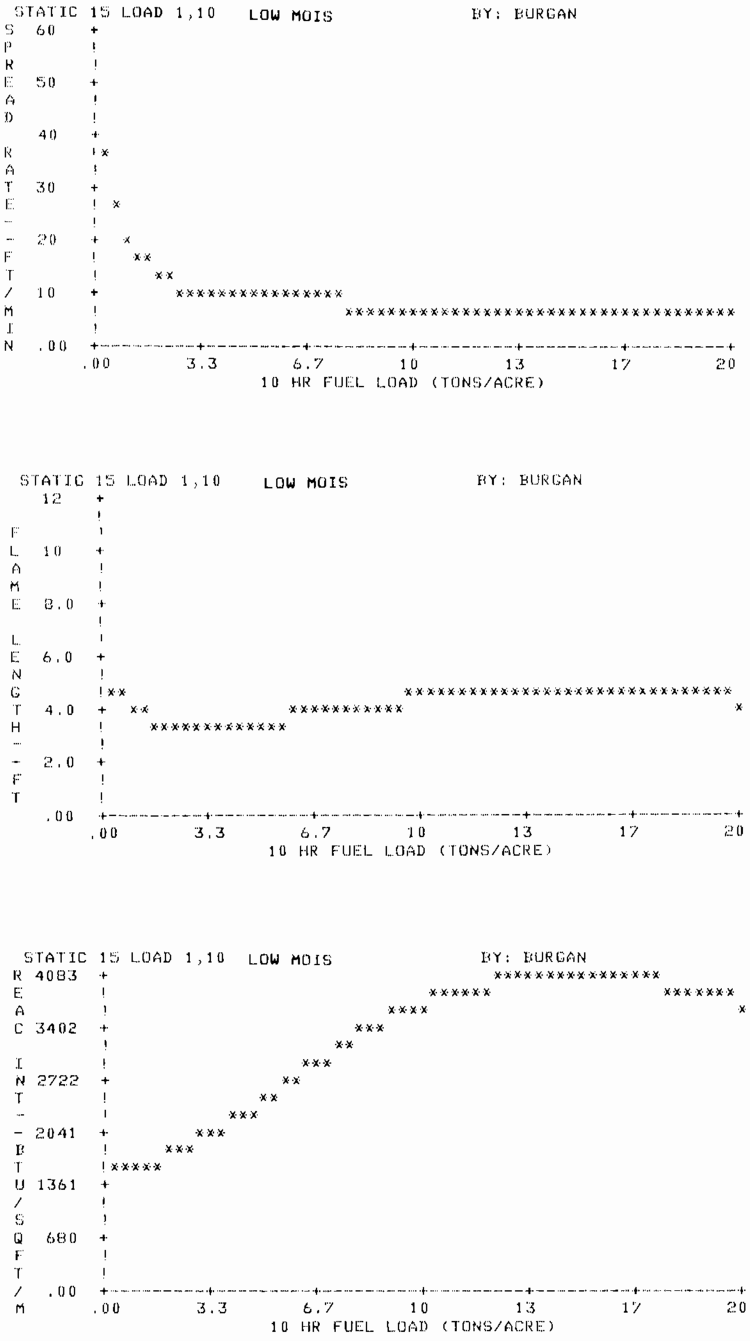

Figure 14—Ten-hour load with 1-hour load, example 2.

Load Effects (10-h Varies)—The addition of 10-h load decreases the characteristic S/V ratio, thereby reducing the wind coefficient (fig. 1). The heat sink (denominator of the spread equation) increases as 10-h fuel is added. Although the reaction intensity increases as 10-h fuel is added, it increases too slowly at first to offset the above effects so the spread rate drops rapidly at first, then more slowly as the reaction intensity begins to increase faster (fig. 14).

Flame length is a function of both spread rate and reaction intensity so it decreases while the rapidly decreasing spread rate dominates, then increases again as the reaction intensity begins to dominate (fig. 14).

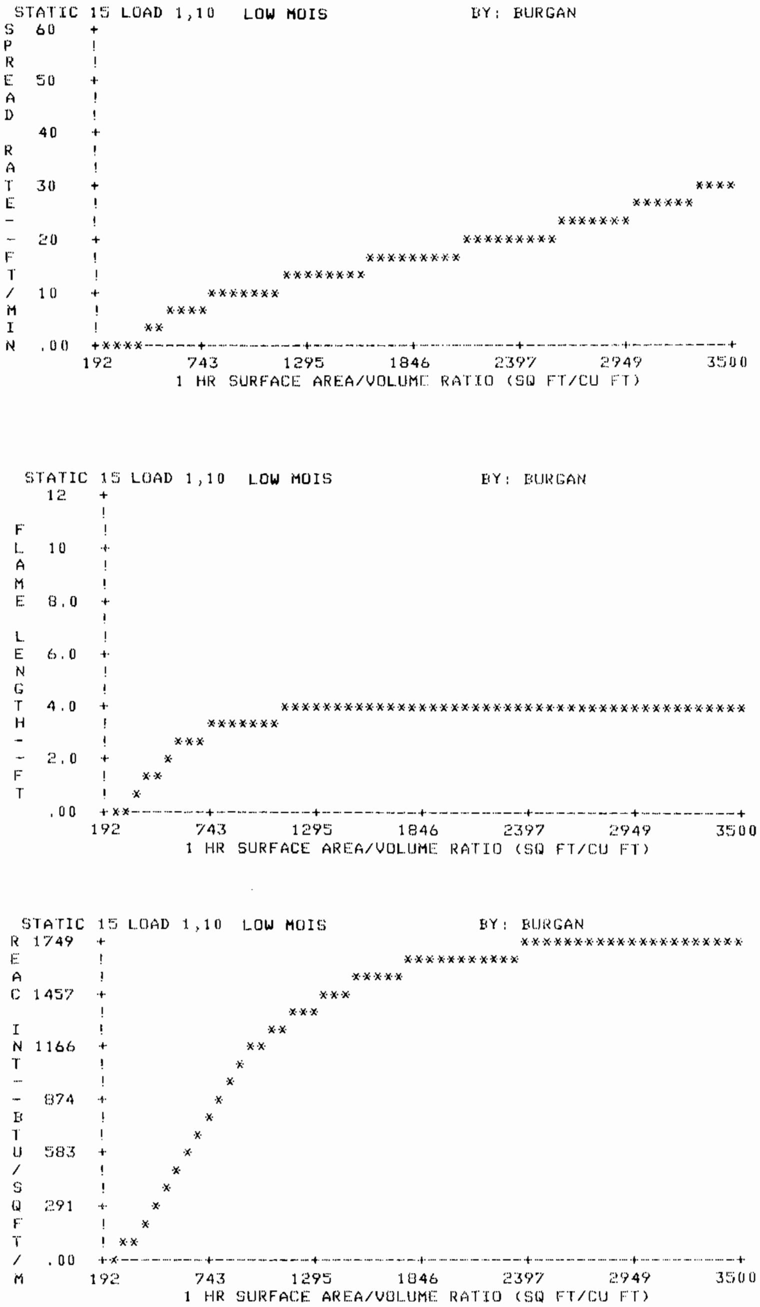

Figure 15—One-hour surface area/volume ratio, example 2.

S/V Effects—Reaction intensity, propagating flux ratio, wind, and slope coefficients all increase as the S/V ratio increases; that is, all the parameters in the numerator increase. The heat sink (denominator) will also increase because a larger proportion of each fuel particle is heated to ignition temperature when flaming combustion starts. In general, the effects in the numerator will dominate so the spread rate, flame length, and reaction intensity tend to increase (fig. 15). But in a model that has a low load of fine dead fuels (at a relatively low moisture content) and a heavy load of live fuels (at a relatively high moisture content), an increase of the live fuel S/V ratio may actually decrease spread rate, etc., because the heat sink effects could dominate in that case.

Extinction Moisture, Heat Content Effects—The effects of extinction moisture and heat content are similar to example 1 and so will not be discussed.

Example 3

Example 3 has a load of 1 ton/acre in each of the 1-, 10-, and 100-h classes as shown in the following tabulation:

```
Fuel Model Test Run—User-Defined Environmental Inputs
Static 16. Load 1, 10, 100                                     By: Burgan
    Load (T/AC)            S/V Ratios                Other
_________________________________________________________________________
1 HR          1.00   1 HR        2000.   Depth (feet)               0.50
10 HR         1.00   Live herb      0.   Heat content (Btu/lb)     8000.
100 HR        1.00   Live woody     0.   Ext moisture (%)            25.
Live herb     0.00   Sigma       1876.   Packing ratio           0.00861
Live woody    0.00   S/V = (sqft/cuft)   PR/OPR                     1.23
                                    Fire Behavior Results
                       __________________________________________________
    Environmental
        Data               Fire                 Midflame Wind
____________________     Variable          0.         4.         8.
1 HR FM           3.   ______________   ______     ______     ______
10 HR FM          4.
100 HR FM         5.   ROS (ft/m)          3.        11.        27.
Live herb FM     70.   FL (ft)             2.         3.         5.
Live woody FM    70.   IR (Btu/sq ft/m) 1649.      1649.      1649.
                       H/A (Btu/sq ft)   338.       338.       338.
Slope (%)        30.   FLI (Btu/ft/sec)   16.        64.       150.
_________________________________________________________________________
```

The optimum packing ratio for this model is 0.0070 and the optimum loading is 2.44 tons/acre.

Load Effects (1-h and 10-h)—The effects of increasing 1-h (fig. 16) and 10-h (fig. 17) fuel loads are very similar to example 2 and for the same reasons, so these will not be discussed further.

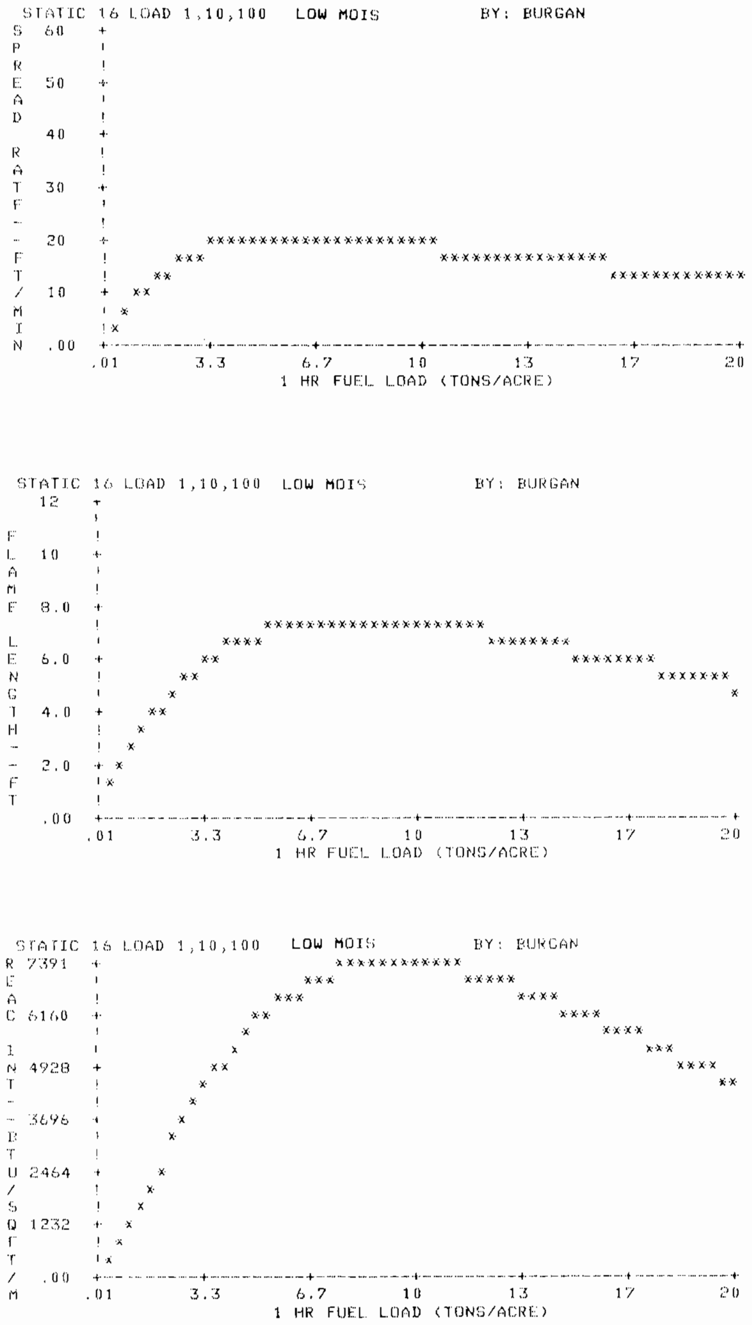

Figure 16—One-hour fuel load, example 3.

```
 STATIC 16 LOAD 1,10,100   LOW MOIS           BY: BURGAN
S   60    +
P         !
R         !
E   50    +
A         !
D         !
    40    +
R         !
A         !
T   30    +
E         !
-         !
-   20    +
F         !xx
T         !  x
/   10    +   xxxxx
M         !        xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
I         !
N  .00    +---------+---------+---------+---------+---------+---------+
         .00       3.3       6.7       10        13        17        20
                          10 HR FUEL LOAD (TONS/ACRE)
```

```
 STATIC 16 LOAD 1,10,100   LOW MOIS           BY: BURGAN
   12     +
          !
F         !
L   10    +
A         !
M         !
E  8.0    +
          !
L         !
E  6.0    +
N         !
G         !
T  4.0    +x                       xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
H         ! xxx         xxxxxxxxxxx
-         !    xxxxxxxxx
-  2.0    +
F         !
T         !
   .00    +---------+---------+---------+---------+---------+---------+
         .00       3.3       6.7       10        13        17        20
                          10 HR FUEL LOAD (TONS/ACRE)
```

```
 STATIC 16 LOAD 1,10,100   LOW MOIS           BY: BURGAN
R 3649    +                                   xxxxxxxxxxxxxxxxx
E         !                              xxxxx                 xxxxxxx
A         !                          xxxx                             x
C 3041    +                       xxx
          !                    xxx
I         !                  xx
N 2433    +               xxx
T         !             xx
-         !          xxx
- 1825    +      xxxx
B         !xxxxxx
T         !
U 1216    +
/         !
S         !
Q  608    +
F         !
T         !
/  .00    +---------+---------+---------+---------+---------+---------+
M        .00       3.3       6.7       10        13        17        20
                          10 HR FUEL LOAD (TONS/ACRE)
```

Figure 17—Ten-hour fuel load, example 3.

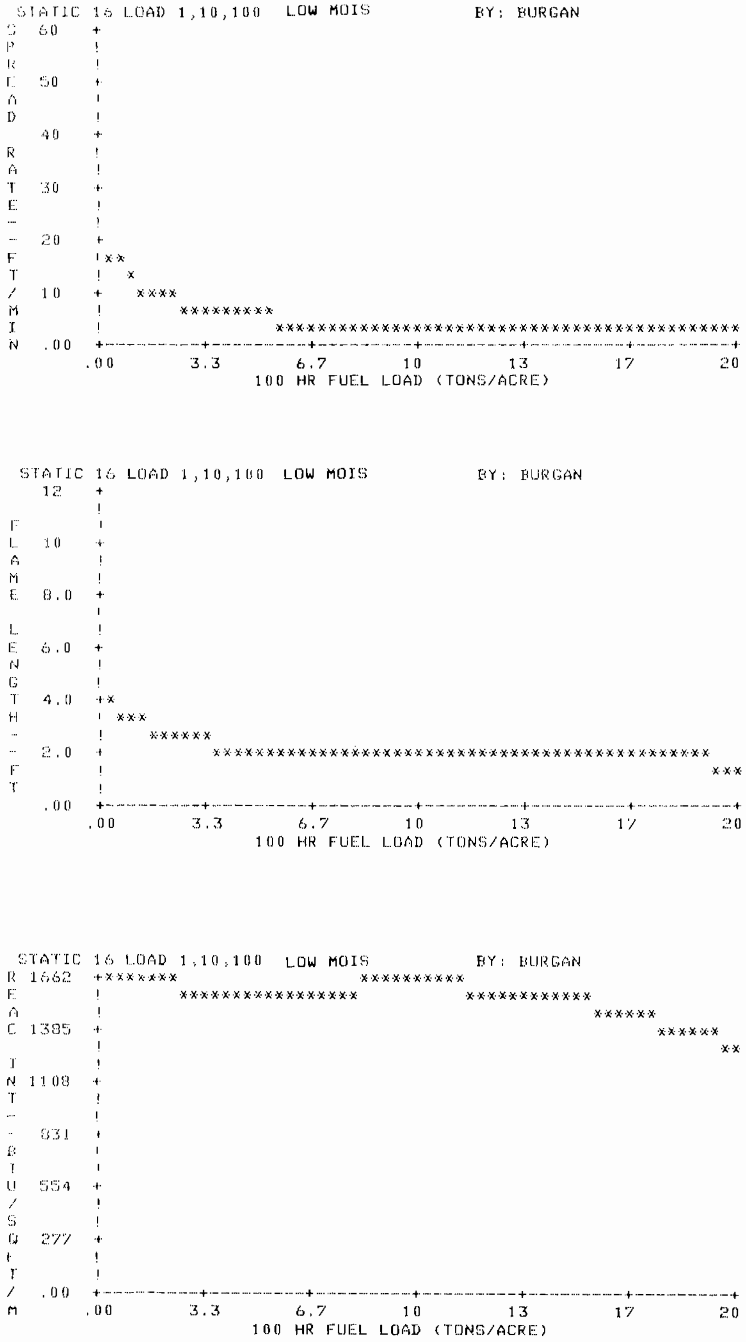

Figure 18—One hundred-hour fuel load, example 3.

Load Effects (100-h)—The effect of adding 100-h fuel to any model is similar to that of adding 10-h fuel. Spread rate and flame length decrease (fig. 18) primarily because the low S/V ratio of the 100-h fuels decreases the characteristic S/V ratio for the model as a whole. This also shifts the peak reaction velocity toward high packing ratios. In this case, the 100-h fuel has only slight effect on the reaction intensity (fig. 18) until so much 100-h load is added that the fuel bed becomes tightly packed and the reaction intensity begins to decline.

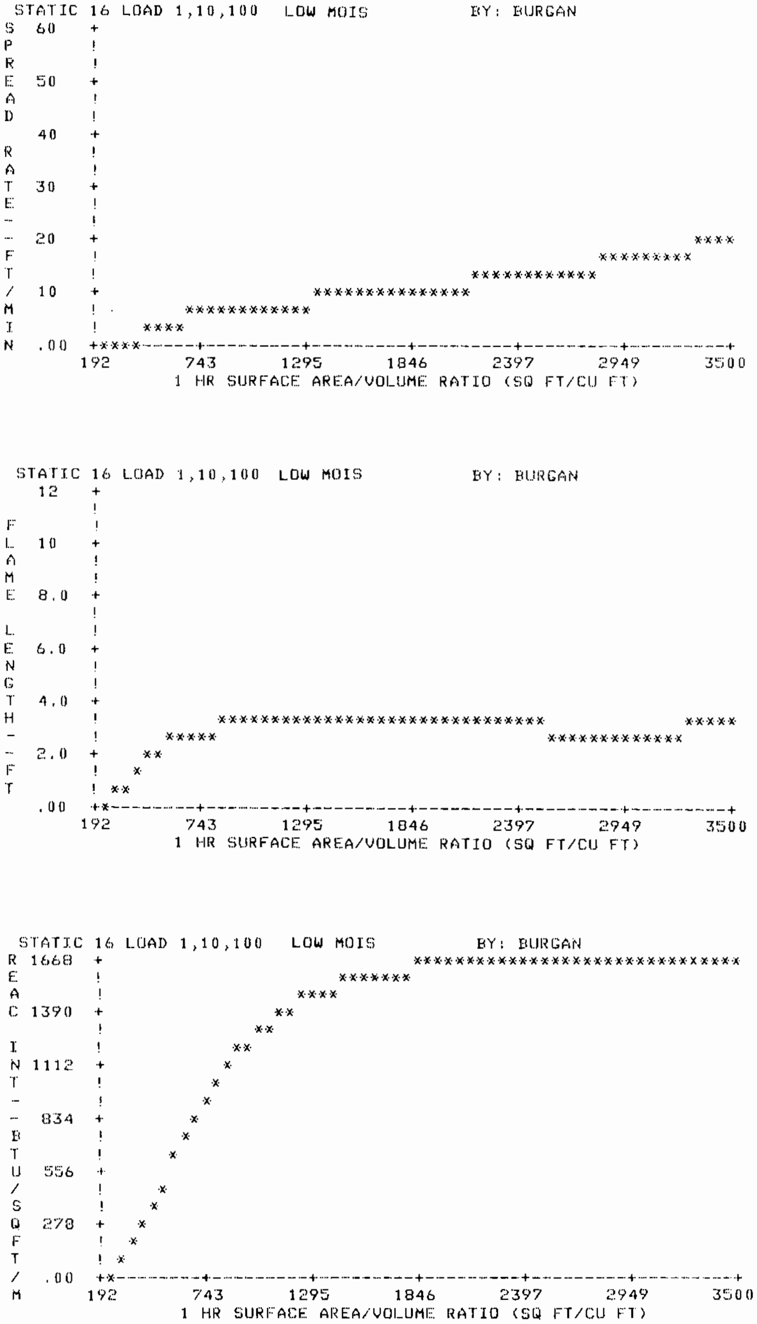

Figure 19—One-hour surface area/volume ratio, example 3.

S/V Ratio Effects—Increasing the S/V ratio of 1-h fuels has the same effect on a fuel model that has 100-h fuel in it as one that does not. That is, predicted fire behavior outputs generally increase (fig. 19).

Example 4

For the fourth example, 1 ton/acre of herbaceous fuel is added. Note that this is a static model. The data are given in the following tabulation:

```
Fuel Model Test Run—User-Defined Environmental Inputs
Static 17. Load 1, 10, 100, herb                                By: Burgan
   Load (T/AC)            S/V Ratios                  Other
1 HR          1.00     1 HR         2000.     Depth (feet)              0.50
10 HR         1.00     Live herb    2000.     Heat content (Btu/lb)    8000.
100 HR        1.00     Live woody      0.     Ext moisture (%)           25.
Live herb     1.00     Sigma        1936.     Packing ratio          0.01148
Live woody    0.00     S/V = (sqft/cuft)      PR/OPR                    1.69
                                        Fire Behavior Results
   Environmental
       Data                 Fire                       Midflame Wind
1 HR FM          3.       Variable               0.        4.        8.
10 HR FM         4.
100 HR FM        5.    ROS (ft/m)                2.        7.       16.
Live herb FM    70.    FL (ft)                   2.        3.        5.
Live woody FM   70.    IR (Btu/sq ft/m)       2993.     2993.     2993.
                       H/A (Btu/sq ft)         594.      594.      594.
Slope (%)       30.    FLI (Btu/ft/sec)         17.       66.      157.
```

The optimum packing ratio is 0.0068 and the optimum loading is 2.37 tons/acre.

Load Effects (1-h Varies)—The addition of 1-h load increases spread rate, flame length, and reaction intensity until the packing ratio gets so high the reaction velocity starts to decrease. Then these fire behavior predictors also decrease (fig. 20).

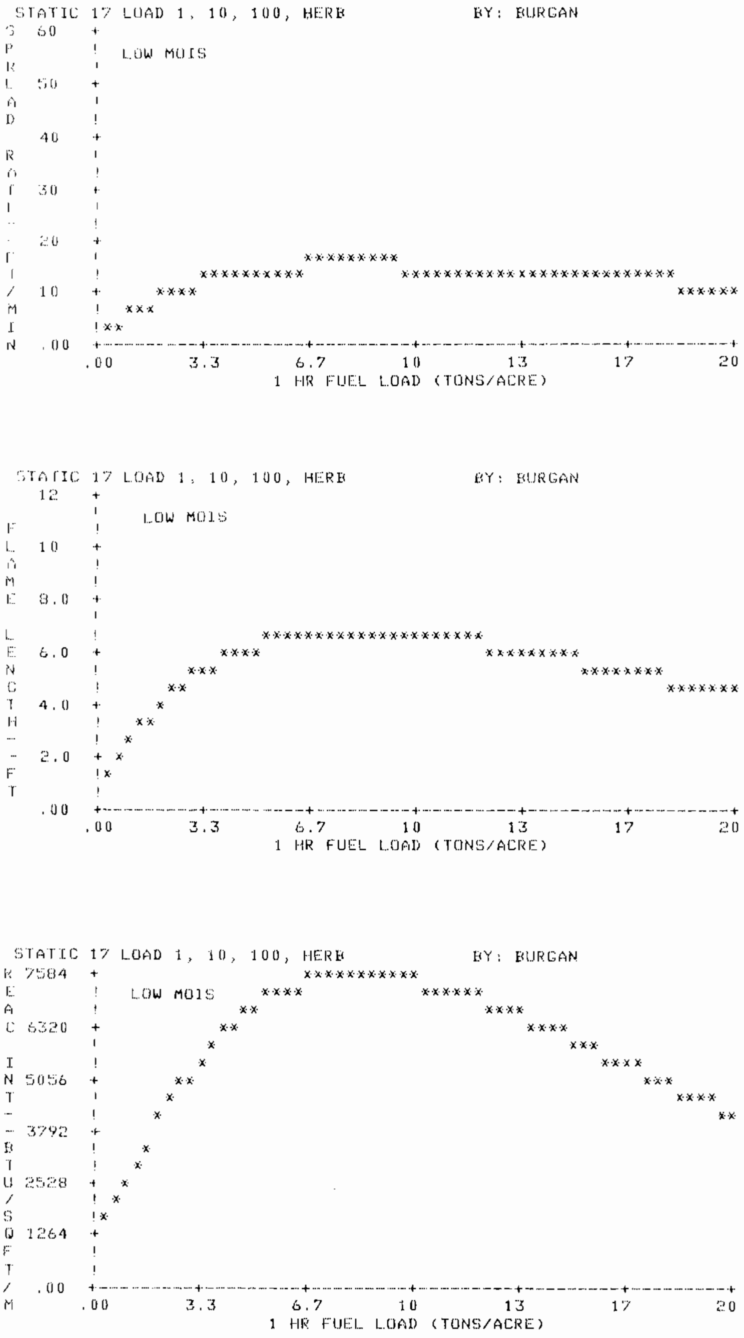

Figure 20—One-hour fuel load, example 4.

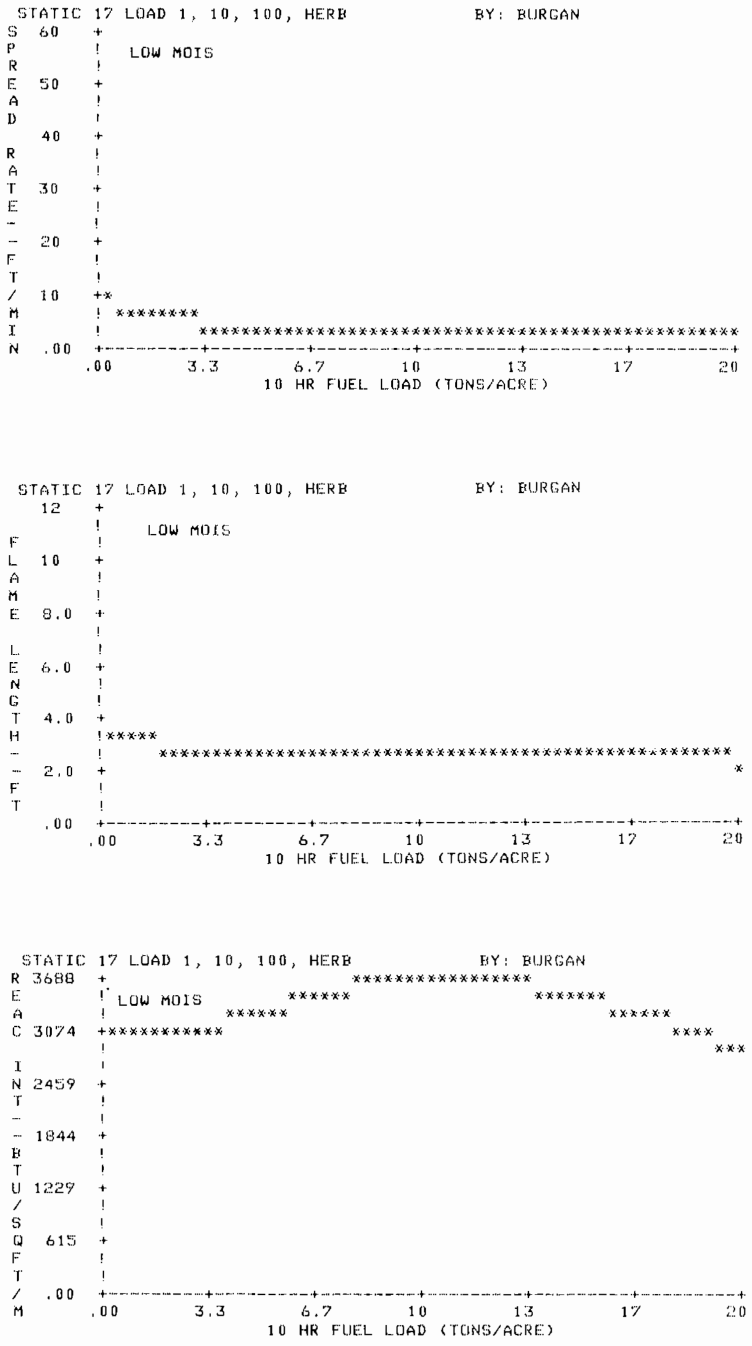

Figure 21—Ten-hour fuel load, example 4.

Load Effects (10-h Varies)—Again, addition of 10-h fuel decreases spread rate because it decreases the S/V ratio of the model and thus ϕ_w, ϕ_s and the reaction velocity (fig. 21).

The reaction intensity increases to a maximum at a rather high load of about 10 tons/acre because the characteristic S/V ratio is decreasing; thus the optimum packing ratio advances to a rather high fuel load.

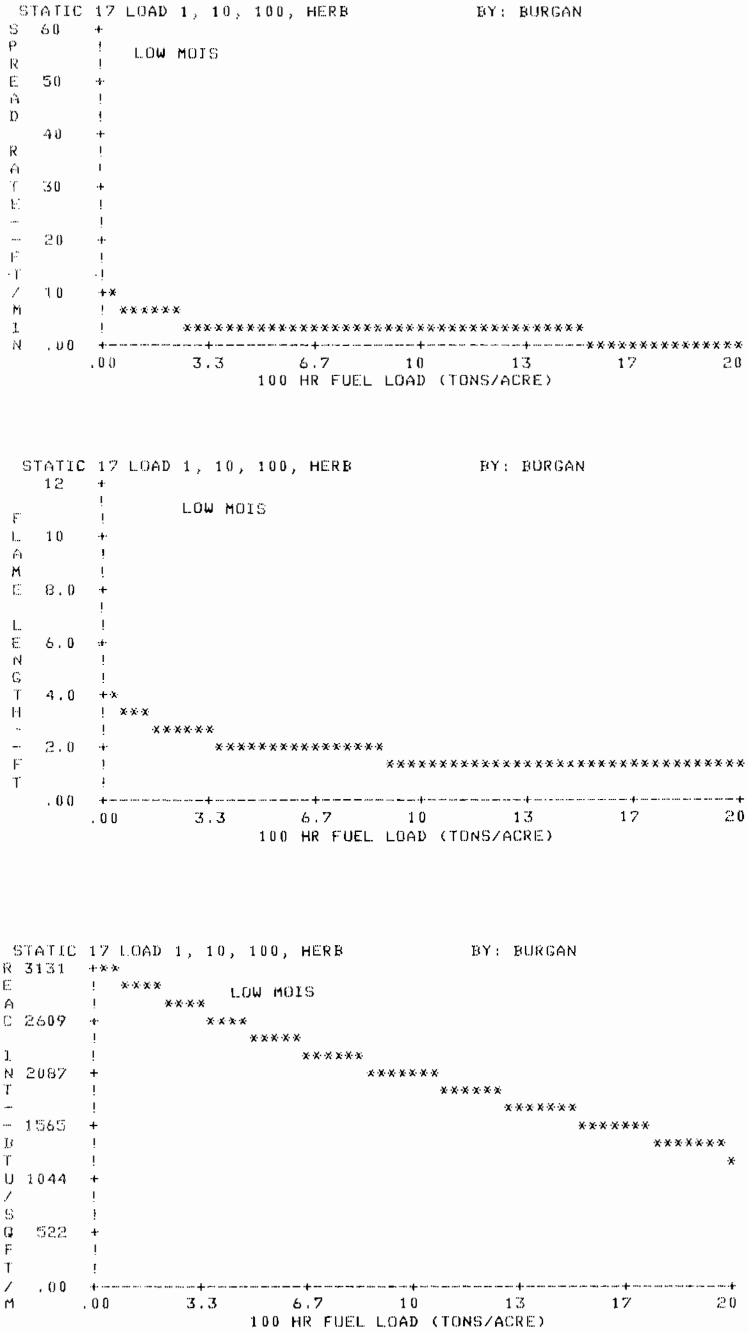

Figure 22—One hundred-hour fuel load, example 4.

Load Effects (100-h Varies)—Again, addition of 100-h fuels decreases the S/V ratio for the model and thus the fire behavior outputs (fig. 22).

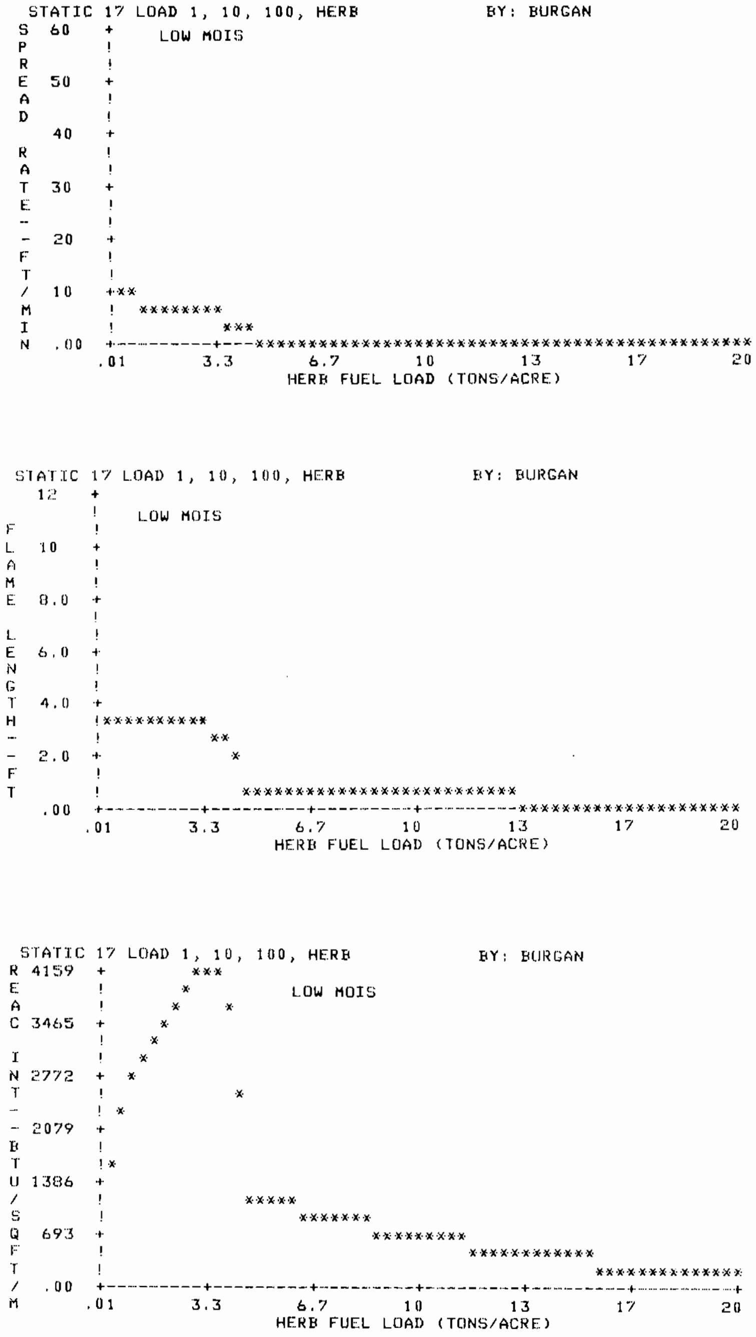

Figure 23—Herbaceous fuel load, example 4.

Load Effects (Herb Varies)—Spread rate decreases because an increasing amount of live fuel, which has a high moisture content, is being dumped into the model (fig. 23). The heat sink is increasing fast.

Reaction intensity increases for a time because the dead fuels generate enough heat to ignite the live fuels, which also contribute to the rate of combustion. At about 4 tons/acre, the live fuels suddenly stop becoming a heat source and serve entirely as a heat sink, so the reaction intensity decreases rapidly (fig. 23).

The decline in flame length results from a decrease in both spread rate and, particularly, reaction intensity (fig. 23).

```
 STATIC 17 LOAD 1, 10, 100, HERB               BY: BURGAN
S  60    +     LOW MOIS
P        !
R        !
E  50    +
A        !
D        !
   40    +
R        !
A        !
T  30    +
E        !
-        !
-  20    +
F        !*
T        ! ****
/  10    +     *******
M        !            ************************************************
I        !
N  .00   +---------+---------+---------+---------+---------+---------+
        192       743      1295      1846      2397      2949      3500
                HERB SURFACE AREA/VOLUME RATIO (SQ FT/CU FT)
```

```
 STATIC 17 LOAD 1, 10, 100, HERB               BY: BURGAN
   12    +
         !     LOW MOIS
F        !
L  10    +
A        !
M        !
E  8.0   +
         !
L        !
E  6.0   +
N        !**
G        !  ****
T  4.0   +      *********
H        !               ************************
-        !                                       *********************
-  2.0   +
F        !
T        !
   .00   +---------+---------+---------+---------+---------+---------+
        192       743      1295      1846      2397      2949      3500
                HERB SURFACE AREA/VOLUME RATIO (SQ FT/CU FT)
```

```
 STATIC 17 LOAD 1, 10, 100, HERB               BY: BURGAN
R 3593   +**
E        !  ****   LOW MOIS
A        !      *********
C 2994   +               ******************************************
         !                                                         ***
I        !
N 2395   +
T        !
-        !
-  1796  +
B        !
T        !
U 1198   +
/        !
S        !
Q   599  +
F        !
T        !
/   .00  +---------+---------+---------+---------+---------+---------+
M       192       743      1295      1846      2397      2949      3500
                HERB SURFACE AREA/VOLUME RATIO (SQ FT/CU FT)
```

Figure 24—Herbaceous surface area/volume ratio, example 4.

S/V Ratio Effects (1-h and Herbaceous)—An increase of 1-h S/V ratio acts in this model as in the previous ones—it increases the fire behavior predictions. It is more interesting to look at the effect of increasing the S/V ratio of the herbaceous fuels. Remember in example 2 it was noted that increasing the S/V ratio for high moisture content live fuels could **reduce** rather than **increase** the fire behavior predictions? Why? Primarily because as the live fuel particle size decreases, the proportion of the live fuel that must be heated to ignition increases. And this stuff is wet! So the heat sink goes up and the fire behavior goes down (fig. 24).

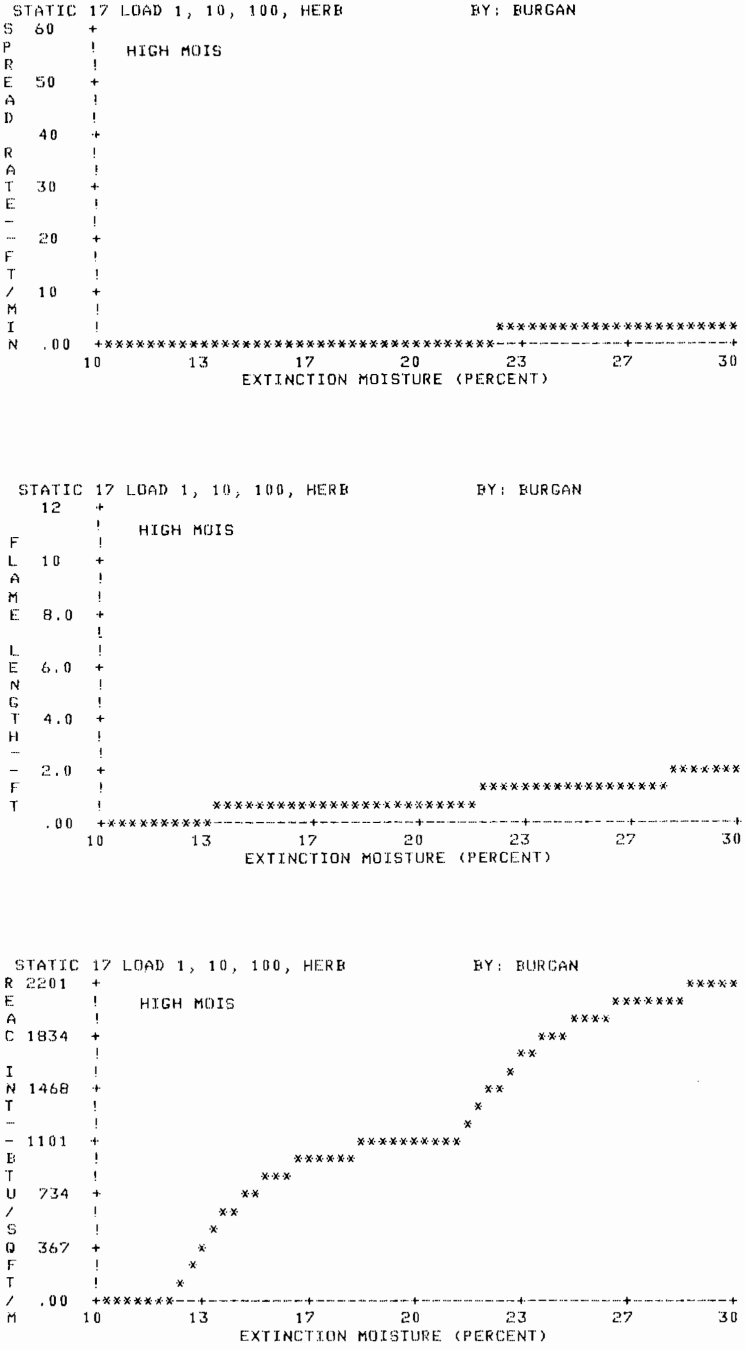

Figure 25—Extinction moisture, example 4.

Extinction Moisture Effect—When the extinction moisture for dead fuels is changed, the moisture damping coefficient (η_m) does **not** remain constant as we suggested earlier. Increasing the moisture of extinction moves us to the left on the moisture damping curve (fig. 6). Since η_m is a multiplier, the closer it is to 1, the less the damping effect. Increasing the extinction moisture (M_x) reduces the ratio of M_f/M_x, where M_f is the moisture fraction of the actual fuels. The reaction intensity curve has the same general S shape as the moisture damping curve (fig. 25).

Example 5 (1-h, Herb-static) and Example 6 (1-h, Herb-dynamic)

These two examples are discussed together so the effects of static vs. dynamic models can be easily compared. Note that there is now 1 ton/acre in just the 1-h and live herbaceous classes. The only difference between the models is that one is static and one is dynamic. They are presented in the following tabulation:

```
Fuel Model Test Run—User-Defined Environmental Inputs
Static 18. Load 1, herb                                          By: Burgan
   Load (T/AC)            S/V Ratios                  Other
1 HR          1.00    1 HR        2000.    Depth (feet)             0.50
10 HR         0.00    Live herb   2000.    Heat content (Btu/lb)   8000.
100 HR        0.00    Live woody     0.    Ext moisture (%)          25.
Live herb     1.00    Sigma       2000.    Packing ratio         0.00574
Live woody    0.00    S/V = (sqft/cuft)    PR/OPR                   0.87
                                  Fire Behavior Results
   Environmental
       Data                 Fire                Midflame Wind
                           Variable          0.        4.        8.
1 HR FM          3.
10 HR FM         4.
100 HR FM        5.       ROS (ft/m)             3.       14.       35.
Live herb FM    70.       FL (ft)                2.        4.        7.
Live woody FM   70.       IR (Btu/sq ft/m)    3058.     3058.     3058.
                          H/A (Btu/sq ft)      587.      587.      587.
Slope (%)       30.       FLI (Btu/ft/sec)      33.      138.      338.
```

```
Fuel Model Test Run—User-Defined Environmental Inputs
Dynamic 18. Load 1, herb                                         By: Burgan
   Load (T/AC)            S/V Ratios                  Other
1 HR          1.00    1 HR        2000.    Depth (feet)             0.50
10 HR         0.00    Live herb   2000.    Heat content (Btu/lb)   8000.
100 HR        0.00    Live woody     0.    Ext moisture (%)          25.
Live herb     1.00    Sigma       2000.    Packing ratio         0.00574
Live woody    0.00    S/V = (sqft/cuft)    PR/OPR                   0.87
                                  Fire Behavior Results
   Environmental
       Data                 Fire                Midflame Wind
                           Variable          0.        4.        8.
1 HR FM          3.
10 HR FM         4.
100 HR FM        5.       ROS (ft/m)             6.       23.       57.
Live herb FM    70.       FL (ft)                3.        6.        9.
Live woody FM   70.       IR (Btu/sq ft/m)    3455.     3455.     3455.
                          H/A (Btu/sq ft)      663.      663.      663.
Slope (%)       30.       FLI (Btu/ft/sec)      61.      258.      630.
```

The optimum packing ratio is 0.00066; the optimum loading is 2.3 tons/acre.

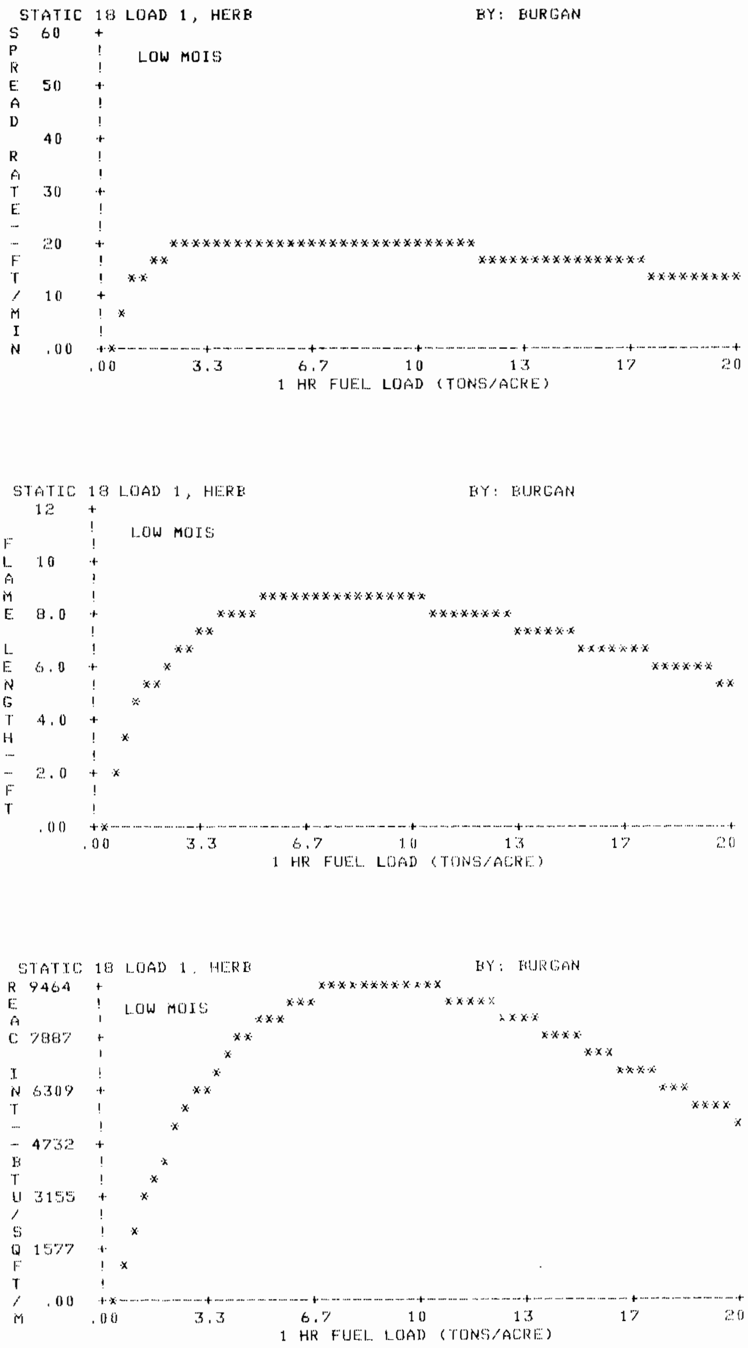

Figure 26—One-hour fuel load, example 5.

Load Effects (1-h, Static)—In this case, the spread rate stops increasing at about the optimum loading (2.3 tons/acre) (fig. 26). Above this load, the reaction velocity is decreasing. Also ϕ_w and ϕ_s are decreasing because the packing ratio (β) is increasing, as is the heat sink. These effects prevent the spread rate from increasing even though the reaction intensity continues to increase for some time because of the added fuel.

Flame length is a function of both spread rate and reaction intensity, so peaks at a load somewhere between the loads at which these two parameters peak (fig. 26).

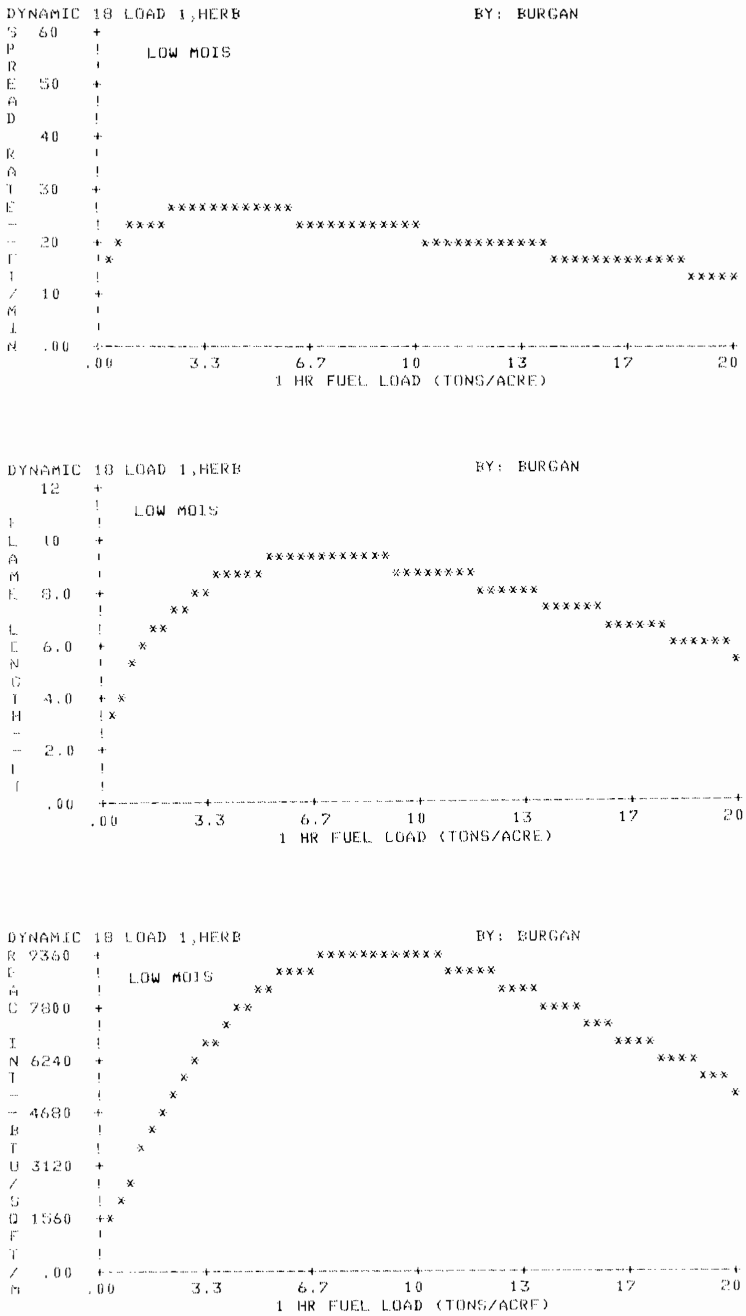

Figure 27—One-hour fuel load, example 6.

Load Effects (1-h, Dynamic)—Because the herbaceous moisture is 70 percent, part of the live herbaceous fuel is transferred to the 1-h class. Thus we do not have a model with 1 ton/acre of 1-h load and 1 ton/acre of herb load as advertised, but rather one with 0.55 ton/acre of herb load transferred to the 1-h class. The percentage transferred from the live herbaceous to the 1-h class is:

$(-0.0111 * \text{HFM} + 1.33) * 100$

In our case HFM = 70 percent so the percent transferred is:

$(-0.0111 * 70 + 1.33) * 100 = 55$ percent

Thus, with a higher 1-h load to start with (1.55 tons/acre), a comparison of figure 27 with figure 26 shows the dynamic model predicts greater spread rates, flame lengths, and reaction intensity than does the static model.

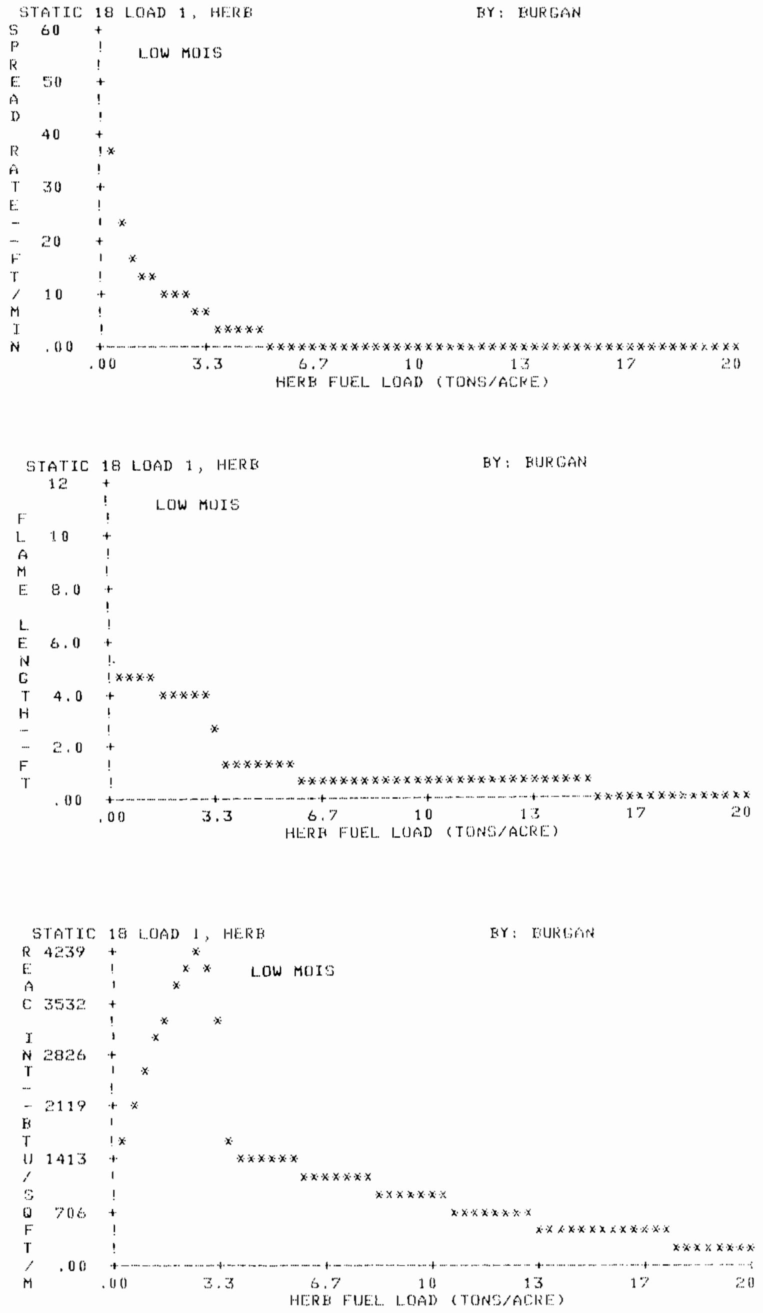

Figure 28—Herbaceous fuel load, example 5.

Load Effects (Herb-static)—The addition of herbaceous fuel to this static model has the same effect as described in example 4 and for the same reasons (fig. 28).

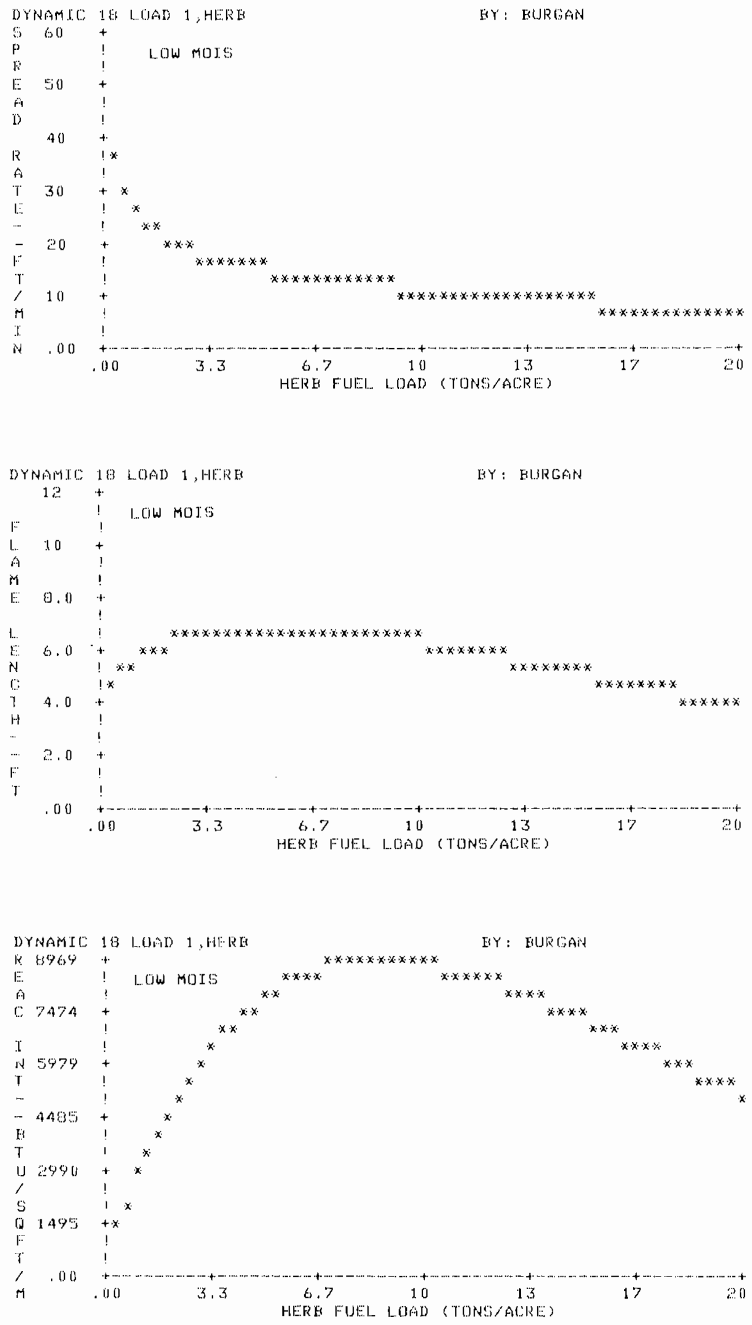

Figure 29—Herbaceous fuel load, example 6.

Load Effects (Herb-dynamic)—Because this is a dynamic model, the addition of herbaceous fuels (with a moisture content less than 120 percent) means that we are also adding to the 1-h fuel load. Thus the reaction intensity curve (fig. 29) is similar to the first example (1-h load only) except that reaction intensity peaks a little sooner because of the influence of some live (and wet) herbaceous fuel.

Spread rate decreases (fig. 29) for the same reasons given in example 1 (decreasing ϕ_w and ϕ_s and increasing heat sink).

Flame length reacts similarly (fig. 29) to example 1.

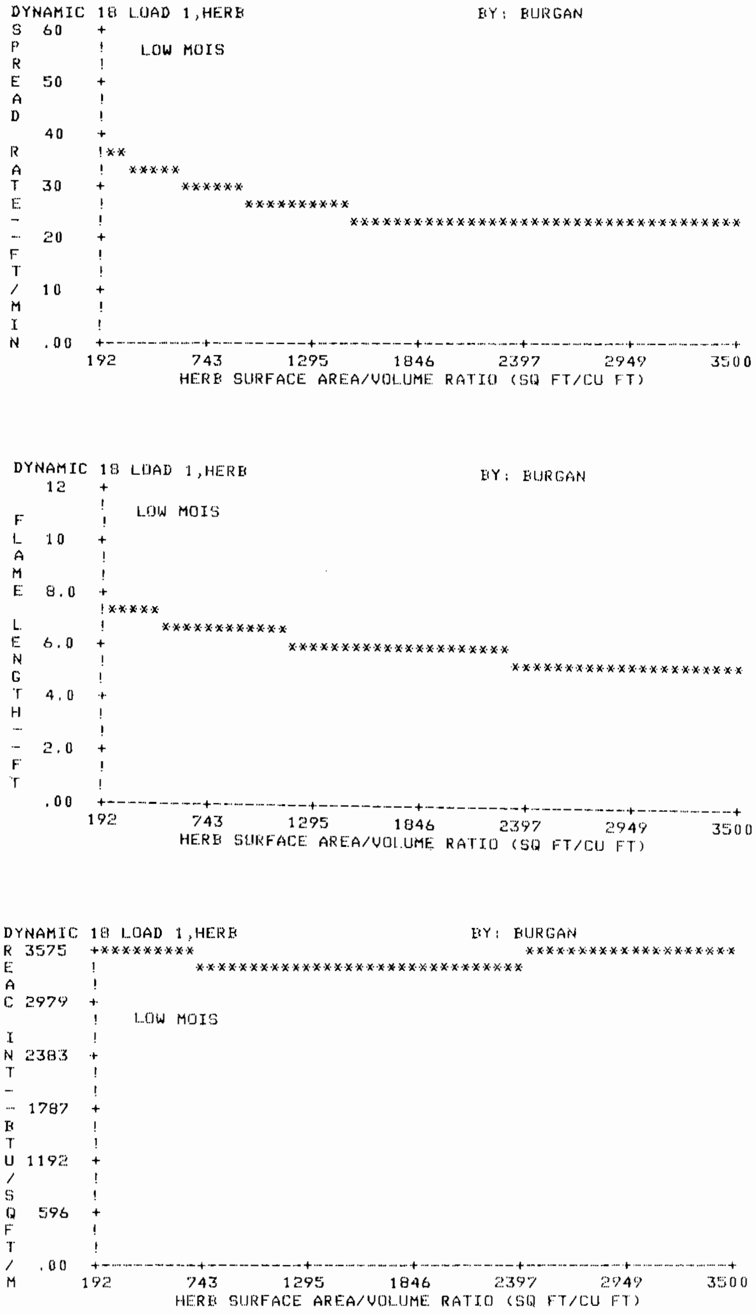

Figure 30—Herbaceous surface area/volume ratio, example 6.

S/V Ratio Effects—Again, increasing the S/V ratio of these relatively wet fuels increases the heat sink enough to overpower the effect of an increasing σ on ϕ_w, ϕ_s and Γ'. Note, however, that the predicted fire behavior for the dynamic model (fig. 30) decreases more slowly than for the static model (fig. 31). This is because there are actually 1.55 tons/acre of 1-h fuels and 0.45 ton/acre of live herbaceous fuels in the dynamic model when the herbaceous moisture is 70 percent.

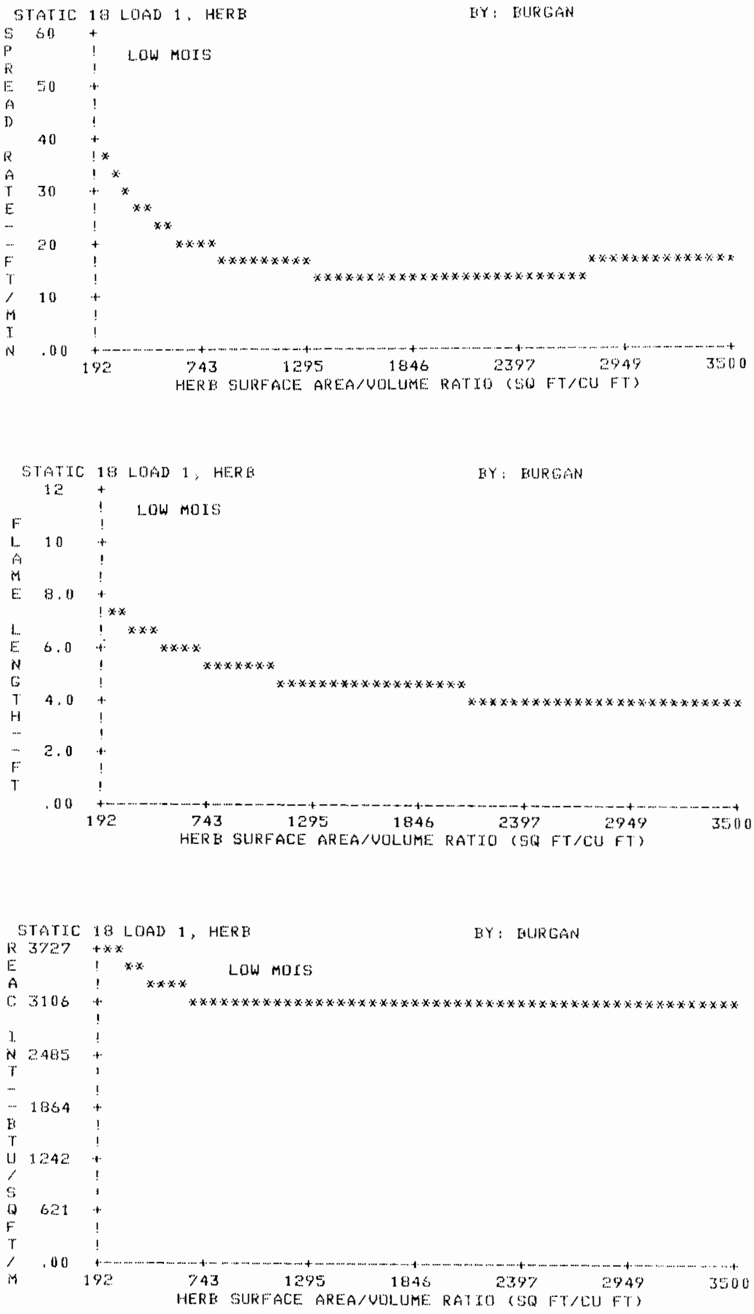

Figure 31—Herbaceous surface area/volume ratio, example 5.

FUEL MODELING EXERCISE

Although the local fire manager must develop models to represent specific fuels, an exercise is presented here to help reinforce the fuel modeling concepts discussed earlier. This exercise grew out of a need to model a particular shrub type, but the approach to the problem may be applicable to other vegetation types that have a large component of living vegetation.

The specific vegetation is a bitterbrush/chaparral type, with a negligible amount of grass. The bitterbrush has a total load of 13.84 tons/acre, of which 19.9 percent is 1-h, 28.9 percent is 10-h, 7.3 percent is 100-h, and 43.9 percent is live. The chaparral has a total load of 3.10 tons/acre, of which 16.1 percent is 1-h, 16.1 percent is 10-h, 0.0 percent is 100-h, and 67.8 percent is live. The bitterbrush has a significantly lower S/V ratio than the chaparral.

```
CURRENT USER DEFINED ENVIRONMENTAL PARAMETERS

STATIC 21. MANZ\BITTBRSH                       BY: BURGAN

          MOISTURES (%)                        OTHER
          -----------------          ----------------------------
          1 HR          6.           MIDFLAME WIND (MPH)      4.
          10 HR         7.           SLOPE.(PERCENT)         30.
          100 HR        8.
          LIVE HERB   120.
          LIVE WOODY  120.
```

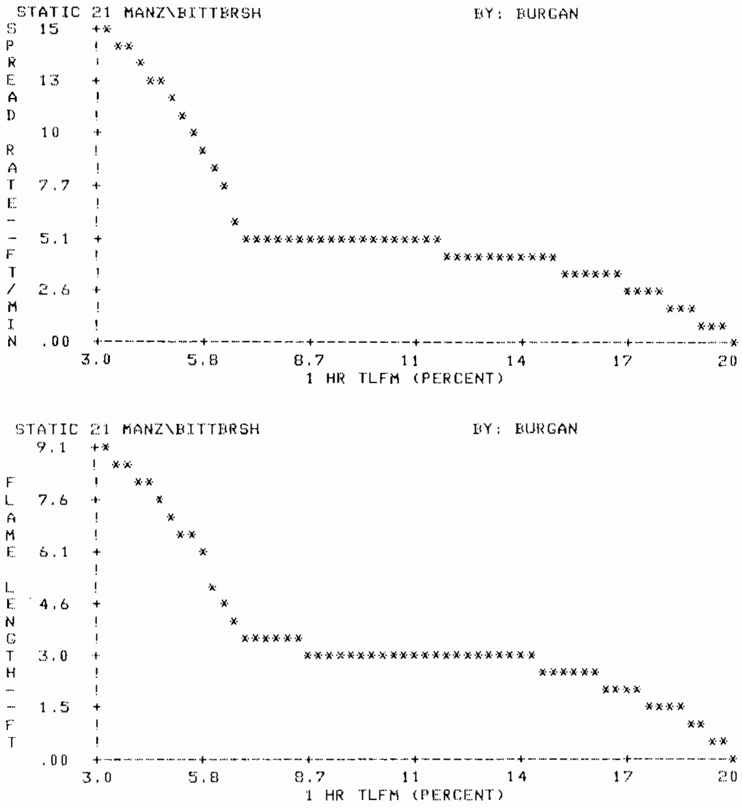

Figure 32—Fuel modeling exercise.

Your task is to produce a fuel model for this type such that its predicted fire behavior approximates that shown in the following tabulation and in figures 32 and 33. Use the environmental inputs provided with the tabulation and the figures. You will have to be innovative to match the solution.

Environmental Data	
1 HR FM	3.
10 HR FM	4.
100 HR FM	5.
Live herb FM	70.
Live woody FM	70.
Slope (%)	30.

Fire Behavior Results			
	Midflame Wind		
Fire Variable	0.	4.	8.
ROS (ft/m)	7.	28.	61.
FL (ft)	7.	13.	19.
IR (Btu/sq ft/m)	13836.	13836.	13836.
H/A (Btu/sq ft)	3341.	3341.	3341.
FLI (Btu/ft/sec)	379.	1553.	3377.

Environmental Data	
1 HR FM	6.
10 HR FM	7.
100 HR FM	8.
Live herb FM	120.
Live woody FM	120.
Slope (%)	30.

Fire Behavior Results			
	Midflame Wind		
Fire Variable	0.	4.	8.
ROS (ft/m)	2.	8.	17.
FL (ft)	3.	5.	7.
IR (Btu/sq ft/m)	5777.	5777.	5777.
H/A (Btu/sq ft)	1395.	1395.	1395.
FLI (Btu/ft/sec)	45.	183.	398.

```
                 CURRENT USER DEFINED ENVIRONMENTAL PARAMETERS

STATIC 21. MANZ\BITTBRSH                              BY: BURGAN

           MOISTURES (%)                         OTHER
           ---------------------       ----------------------------
           1 HR            6.          MIDFLAME WIND (MPH)      4.
           10 HR           7.          SLOPE (PERCENT)         30.
           100 HR          8.
           LIVE HERB     120.
           LIVE WOODY    120.
```

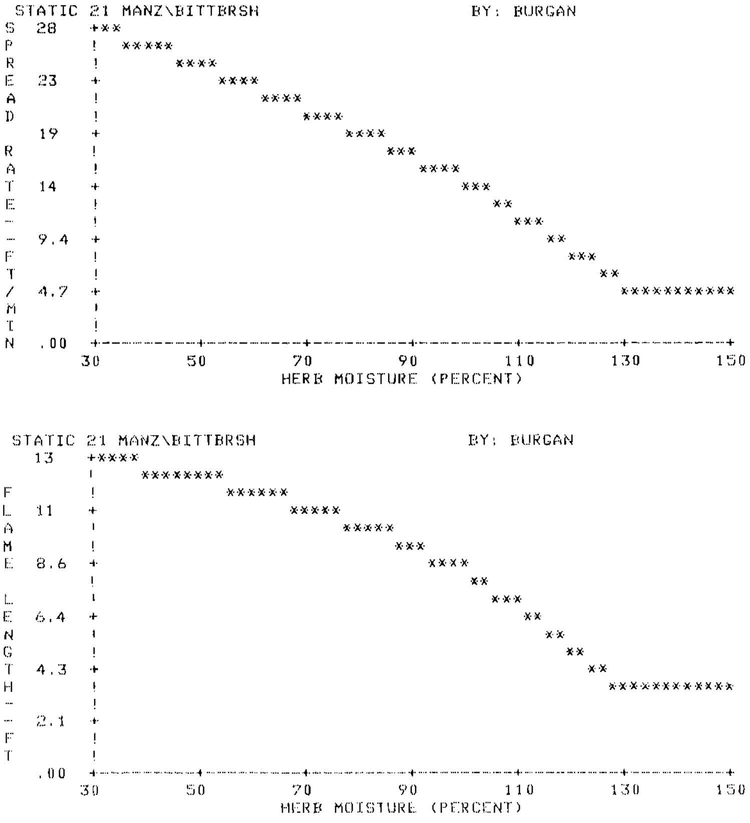

Figure 33—Fuel modeling exercise, continued.

The problem in modeling this fuel type is that because the two shrub types have significantly different surface-area-to-volume ratios, they should be put in separate live fuel classes. Fire behavior fuel models do permit two live fuel classes—conventionally named live herbaceous and live woody. Because the live herbaceous load is negligible, the load and S/V data for one of the shrubs can be put in this fuel class. But the model **must** be "static" because the shrub load placed in the live herbaceous class is **not** going to cure and be transferred to the 1-h class as does the live herbaceous load in a dynamic model.

The solution is given in the following tabulation. The live bitterbrush component was placed in the live herbaceous class and assigned an S/V ratio of 1,250 ft^2/ft^3. The live chaparral load was placed in the live woody class and assigned an S/V ratio of 1,800 ft/ft^3.

Fuel Model Test Run—Standard Environmental Inputs

Static 21. Manz/Bittbrsh By: Burgan

Load (T/AC)		S/V Ratios		Other	
1 HR	3.26	1 HR	1986.	Depth (feet)	2.50
10 HR	4.50	Live herbaceous	1250.	Heat content (Btu/lb)	7575.
100 HR	1.00	Live woody	1800.	Ext moisture (%)	19.
Live herbaceous	6.08	Sigma	1590.	Packing ratio	0.00972
Live woody	2.10	S/V = (sqft/cuft)		PR/OPR	1.22

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Expands upon the basic concepts of fuel modeling to provide a more complete discussion of the technical details of constructing site-specific fire behavior fuel models.

KEYWORDS: fuels, fire, fire behavior, modeling

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