A METHOD OF COMPUTING FINE FUEL MOISTURE CONTENT THROUGHOUT THE DIURNAL CYCLE

by

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Abstract

A method is presented for computing fine fuel moisture content at hourly intervals around the clock. It is derived from the standard daily Fine Fuel Moisture Code used in the Canadian system of forest fire danger rating. It produces diurnal cycles of fuel moisture content that match the behaviour of real pine litter fairly well. It also progresses from day to day at rates similar to the standard Fine Fuel Moisture Code. Equations are included, and possible applications discussed.

Résumé

L'auteur présente une méthode pour calculer le coefficient d'humidité des combustibles fins 24 heures sur 24. Elle est dérivée de l'Indice du combustible léger calculé quotidiennement, qu'emploie le Système canadien d'indice des dangers d'incendie. Elle produit des cycles diurnes de l'humidité contenue dans les combustibles fins, assez bien appareillés à la réalité touchant la litière d'aiguilles de Pin. De plus, elle progresse quotidiennement à des taux similaires à ceux de l'Indice du combustible léger. L'auteur inclut des équations et suggère les applications possibles de la méthode.

A Method of Computing Fine Fuel Moisture throughout the Diurnal Cycle

C.E. Van Wagner[1]

Introduction

The Canadian Forest Fire Weather Index (Anon. 1976) provides, through weather observations at noon LST, a daily measure of fire danger throughout the afternoon. The Fire Weather Index (FWI) and the subsidiary indexes and moisture codes are computed only once daily, and this single measurement is deemed valid for a period of several hours at least, say 1200 to 1600 hr. But the degree of fire danger obviously varies greatly throughout the 24-hr diurnal cycle, and there are many occasions when a measurement at some other time of day would be useful. The main problem in round-the-clock fire danger measurement is the estimation of fine fuel moisture content, represented in the Canadian system by the Fine Fuel Moisture Code (FFMC).

The first means of accounting for diurnal variation in fire danger in Canada was a table produced by Beall in 1939 based on work done several years earlier (Beall 1934). It was in terms of the fire danger index itself (the former 16-unit version), and based on an assumed normal diurnal weather trend. Within the present Canadian fire danger system, one method of estimating FFMC at various times of day has been published (Van Wagner 1972, based on work by Muraro *et al*. 1969). It is a table using as starting point the last noon determination of FFMC, and based mainly on a single standard daily cycle of temperature and humidity. Its ability to use current weather readings is very limited, and, not least important, the table is hard to cast in a smooth mathematical form. This report describes a more flexible procedure, based on equations that lend themselves easily to computer calculation. Some familiarity with the Canadian fire danger rating system on the part of the reader is presumed.

Development

The present standard FFMC was derived as described by Van Wagner (1974) from original work by Wright (1937), and standard equations for the present version are listed by Van Wagner and Pickett (1975). They are in two routines, a rain effect and a dry weather effect. If rain has been measured, the rainfall routine is first applied; the dry weather routine is in any case applied every day. Since the rain effect is based on amount rather than duration, the rainfall routine can be readily introduced whenever rain is measured. The difficulty lies rather in the dry weather routine.

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The basic reason for this difficulty is that the moisture content (MC) of fine fuel in Canadian fire danger rating is assigned a finite rate of change. If fine fuel MC remained in continuous equilibrium with weather, i.e., at equilibrium moisture content (EMC), then round-the-clock estimation would be simple. Real fuel MC, however, depends both on some past value and on the weather during the intervening period. With slow-drying fuels such as those represented by the Duff Moisture Code (DMC) and Drought Code (DC), the rate of moisture change is slow enough that the range in MC during any one diurnal period is not great enough to be important. The fine fuel represented by the FFMC, however, dries (and wets) quickly enough to undergo a substantial diurnal MC cycle superimposed on the larger day-to-day cycle. This diurnal trend was bypassed by the empirical field methods and analysis used in developing the FFMC, which claims only to represent fine fuel MC during a limited afternoon period.

Moisture change in the FFMC is exponential; that is, the difference between actual MC and current EMC decreases exponentially, calculated day by day according to the slope of the semilog graph of free MC versus time. This slope is called the log drying (or wetting) rate, and is quoted in logarithim to base 10 per day. In the FFMC, both the EMC and the log drying rate vary with weather.

The simplest solution to the problem is to calculate moisture content at regular intervals throughout the daily cycle, with the moisture content at the end of the previous period as the starting point, and assuming that each period's weather is adequately represented by observations at its end. The standard FFMC equations for moisture change must then be adjusted to the length of the period. The present method was developed for hourly computation from hourly weather data, but other intervals are equally feasible; it was at first in terms of percent fuel MC, conversion to FFMC being a later consideration.

The first step was to make proper provision for atmospheric wetting, as occurs in a regime of rising humidity. The standard FFMC employs a simple constant rate of change in this situation, which is of minor importance in day-to-day estimation. In hourly computation, however, wetting is just as important as drying, and needs a log wetting rate that varies realistically with changing environment. This was accomplished by simply reversing the humidity effect in the existing drying equations so that fuel MC increases whenever the EMC is above actual MC.

The second step was to set the hourly log drying and wetting rates so that, even while producing realistic hour-to-hour trends, they would still yield the desired day-to-day trend, especially after rain. This was accomplished by trial and error, testing the daily rate of change against the standard FFMC, and the hourly trends against some round-the-clock experimental fuel moisture runs of several days duration. After balancing these two features as well as possible, rates of change equal to 1/8 of the standard daily rates appeared to yield the best compromise. This is to say, in effect, that an entire normal 24-hr cycle is deemed the equivalent of 8 hr of drying weather as defined by noon observations.

The last step was to convert the percent MC values to code form, i.e., FFMC. The standard conversion equation is FFMC + MC% = 101, a relation known to be unrealistic but used traditionally for expediency. It limits MC to a maximum of 101%, whereas real litter may achieve MC's of 200% or more. A more realistic conversion, the F-scale, was used in the earlier diurnal scheme (Van Wagner 1972); it provides an upper limit of 250% and was constructed from actual jack and lodgepole pine litter data. Since the present method was also calibrated with actual moisture content data, the same F-scale was adopted for this hourly FFMC method. It appears as Equations 1 and 6 in the next section.

Equations

Below are listed the equations and basic instructions for the dry weather routine to be used in the hourly computation of the FFMC. The rainfall routine remains as given by Van Wagner and Pickett (1975). A computer program, written in Fortran for the DEC PDP-11 by T.L. Pickett[1/] is available on request from this Station. Weather values are in SI units.

$$(1) \quad m_o = \frac{205.2\ (101-F_o)}{82.9 + F_o}$$

$$(2a) \quad E_d = 0.942H^{0.679} + 11e^{(H-100)/10} + 0.18(21.1-T)\ (1-e^{-0.115H})$$

$$(2b) \quad E_w = 0.618H^{0.753} + 10e^{(H-100)/10} + 0.18(21.1-T)\ (1-e^{-0.115H})$$

$$(3a) \quad k_a = 0.424\ [1-(H/100)^{1.7}] + 0.0694W^{0.5}\ [1-(H/100)^{8}]$$

$$(3b) \quad k_d = 0.0579\ k_a\ e^{0.0365T}$$

$$(4a) \quad k_b = 0.424\ [1-(\frac{100-H}{100})^{1.7}] + 0.0694\ W^{0.5}\ [1-(\frac{100-H}{100})^{8}]$$

$$(4b) \quad k_w = 0.0579\ k_b e^{0.0365T}$$

$$(5a) \quad m = E_d + (m_o - E_d)e^{-2.303k_d}$$

$$(5b) \quad m = E_w - (E_w - m_o)e^{-2.303k_w}$$

$$(6) \quad F = \frac{82.9(250-m)}{205.2 + m}$$

[1/] Computer Programmer, Petawawa Forest Experiment Station. Program F-5G, Hourly FFMC calculation.

where m_o - initial fine fuel MC

m - final MC

F_o - initial FFMC

F - final FFMC

E_d - EMC for drying

E_w - EMC for wetting

k_a and k_b - intermediate steps to k_d and k_w

k_d - log drying rate for hourly computation, log to base 10

k_w - log wetting rate for hourly computation, log to base 10

H - relative humidity, %

W - wind, km/h

T - temperature, °C

The hourly FFMC is worked out as follows:

```
Previous hour's F becomes $F_o$.
If rain observed, apply rain routine and compute new $F_o$.
Compute $m_o$ by (1).
Compute $E_d$ by (2a).
     If $m_o > E_d$, compute $k_d$ by (3a) and (3b).
          Compute m by (5a).
     If $m_o < E_d$, compute $E_w$ by (2b).
          If $m_o < E_w$, compute $k_w$ by (4a) and (4b).
               Compute m by (5b).
          If $m_o = E_d$ or $E_w$, $m = m_o$.
          If $E_d > m_o > E_w$, $m = m_o$.
Compute F by (6).
```

Tables 1 and 2 illustrate the computer output in dry and wet weather respectively, listing day, hour (LST), temperature, relative humidity (RH), wind speed, rain, EMC, MC, and FFMC. The program can be run with a given diurnal cycle repeated any number of times, or with a series of different cycles. It can be started and stopped any time of day. It is arranged to accept weather data in either English or SI units, but calculations and printout are in SI units only.

If wind data are not available, the more or less normal wind trend shown in Table 1 can be used to give reasonable results, otherwise say 10 to 12 km/h during daylight and 4 to 6 km/h at night. The effect of wind is minor except just after rain.

Results

Two kinds of tests are illustrated in the accompanying tables and figures. Those of the first kind were attempts to match by hourly computation the actual MC trends of samples of jack pine litter exposed in the forest for some days under clear plastic shelters. Rain being excluded, the samples responded to atmospheric conditions only. Fig. 1 shows one of these trials, a run of ten days in August 1966, during which sample weight and weather were measured manually every two hours. Fig. 2 shows another, a run of ten days in August 1970 during which the sample was weighed automatically every half-hour; weather was recorded on chart instruments. In each case the fit is reasonably good, both in terms of absolute value and in terms of the amplitude between daytime minima and nighttime maxima. Jack pine litter is a fine fuel to which the FFMC is considered well suited.

Tests of the second kind were comparisons of the hourly and standard FFMC's using diurnal weather cycles representative of the weather in this region. Starting at saturation (250% MC on the F-scale), hourly MC's were computed for successive identical days until equilibrium for the entire cycle was reached. Five such results are presented here, based on diurnal cycles of the following types:

(1) Spring - very low afternoon RH with a short period of 100% at night.

(2) Early summer - low afternoon RH, and low overnight maximum RH, well below 100%.

(3) Moderate cycle typical of mid-summer.

(4) Moist cycle typical of rainy weather (but rain excluded).

(5) Late fall - low afternoon RH, but short daylength and long period of 100% RH at night.

Fig. 3 shows the computed MC trends for repeated days of all five cycles, starting at high MC and, except (4), reaching equilibrium within several days. Table 3 contains data on the five cycles and deserves some explanation.

The section of Table 3 called "Weather cycle data" describes the individual weather cycles in terms of their warm-dry and cool-humid extremes, with times of occurrence, and the noon temperature and RH needed for computing the standard FFMC. The next section lists the minimum and maximum MC's resulting from each weather cycle after the whole MC cycle has reached equilibrium. These are given with their times of occurrence, as well as the MC's at 1600 hr, the traditional time of day for the correlation of fuel MC and fire behaviour in Canadian fire research.

The final two sections of Table 3 draw comparisons between the hourly version of the FFMC and the standard daily version. "Days to equilibrium" is the number of repeated identical days required until the FFMC shows no further change within 0.1 unit. "Equilibrium FFMC" is the value then reached. In the case of the hourly FFMC, it is the 1600-hr FFMC converted from the 1600-hr MC by the F-scale. In the case of the standard FFMC, it is 101 minus the standard EMC computed from noon temperature and RH. THe standard FFMC's and days to reach them were calculated by equation; the tables would give approximately the same values but not to the desired level of accuracy for present purposes. The agreement between the hourly and standard FFMC's in afternoon equilibrium and its rate of approach is fairly good, and will be commented on later.

Discussion

The main requirements of a scheme for computing the FFMC hour by hour are that it follow reasonably well (1) the actual diurnal moisture trend of a fine fuel typical of those on which the FFMC is based, and (2) the day-to-day trend of the standard FFMC when drying down from a wet state after rain.

Figures 1 and 2 show evidence that the first requirement is met. These results were not formally analyzed, but the visual evidence simply accepted that the match between actual and computed moisture trends is good enough for practical purposes.

Evidence for the second requirement is mainly in Table 3, comparing the hourly and daily forms of the FFMC as they behave in repeated diurnal cycles of identical weather starting at saturation. The two main aspects of the comparison are rate of approach to equilibrium and the FFMC value finally reached, treated in turn in the next two paragraphs.

The day-to-day progressions of 1600-hr MC taken from the hourly test cycle calculations produce fairly straight lines when plotted (minus EMC) on semilog paper. This fact is in itself a worthwhile vindication of the exponential drying principle underlying the early empirical work of Wright and Beall on fine fuel moisture content. However, comparison of log drying rates with the standard version is complicated by the difference in MC scales. For this reason, the number of days to within 0.1 point of equilibrium was chosen as a better yardstick of drying rate for the present comparison. The published FFMC tables (Anon. 1976) give almost the same lengths of time. The hourly FFMC stabilizes a little sooner than the standard FFMC, but the difference would be unimportant in practice.

The use of the F-scale to convert between moisture content (MC) and code (FFMC) in the hourly version also complicates the comparison of afternoon equilibrium code values. However, if actual MC is to be simulated as well as the FFMC itself, then the F-scale is needed. One reason is that in the hourly calculations the MC never actually reaches the minimum EMC of the cycle; for example, the 1600-hr MC stabilizes at a pseudo-EMC somewhat above true 1600-hr EMC. The standard FFMC, on the other hand, is intended to apply to the afternoon period up to 1600 hr, and stabilizes after several days at the EMC calculated from noon temperature and RH. The F-scale conversion used in the hourly FFMC helps to offset this difference, and also provides for realistically high MC's after rain.

The nature of the individual test cycles also affects the comparison of equilibrium FFMC values. Thus, Cycles 1 and 2, which have either low night RH or a short-duration peak to 100%, yield 1600-hr FFMC's a point or so higher than the standard. Cycles 3 and 5, with longer periods of high night RH, match the standard FFMC more closely. Considering the wide variety of weather among the five test cycles, all these differences seem reasonable.

Two potential uses for the hourly FFMC come to mind. One is in direct fire control operations. If automatic weather stations should become common enough, it would be feasible to feed their output directly into a computer and to produce the FFMC plus associated other codes and indexes every hour on the hour. Such a procedure would be of particular interest during periods of intense fire activity for use as part of a computerized fire management system.

The other potential use is in simulating the effects of various patterns of diurnal weather on afternoon fine fuel moisture content. Any cycle suspected of being substantially different from the normal cycle embedded in the standard FFMC could be tested. Of interest might be the seasonal variation in diurnal weather, the effect of high latitudes, or the special cycles typical of seacoast or mountains.

A point worth noting is that the minimum MC during fine weather may occur as late as 1800 or 2000 hr, considerably after the mid-afternoon time of maximum temperature and relative humidity. This feature was observed both in the field results and in the simulations. However, since by this time of day the wind has often decreased considerably below its maximum, the conventional 1600-hr is probably still a fair choice as time of maximum fire danger.

The method developed here is not restricted to hourly intervals. Calculation say every 2, 4, 6 or more hr could be carried out by simply adjusting the multiplier coefficients in Equations (3b) and (4b). As the period lengthens, however, the assumption that average weather during each period can be represented by one set of observations becomes less and less tenable, and the value of the output data decreases.

The equations presented here are intended to represent the MC of the natural fuel on which the original FFMC was based, e.g., pine litter. However, such "standard" fine fuel is by no means particularly fast-drying as fine fuels go. Hardwood litter, grass, and reindeer lichen are examples of other fine fuels, of special interest in some areas, that dry (or wet) considerably faster than pine litter. Neither the standard FFMC nor this hourly version of it may represent such material to best advantage. Special versions of either the standard or the hourly FFMC are quite feasible; appropriate adjustment of the drying rates and rain effects would generally suffice, while some modification of the EMC equations might also be necessary. It is apparent that the present version is only one of many possible variations that could be devised if sufficient need should arise, based on experimental determination of EMC's and rates of moisture change for the fuel in question.

One final point remains to be discussed, namely the question of which version of the FFMC to accept as the standard daily record when both are operated concurrently. It can be expected that they should not agree perfectly, since the actual hour-to-hour weather may on any given day differ considerably from the normal diurnal cycle embedded in the standard FFMC. Presumably, in case of difference, the hourly computation should give the truer answer, provided the assumptions and adjustments on which it is based match the reality of nature. Complete verification would require much field-testing. Meanwhile, on the limited evidence presented here, the hourly computation of FFMC provides a useful means of simulating the effects of various diurnal weather cycles on fine fuel moisture content, and a basis for round-the-clock estimation of total forest fire danger.

Acknowledgement

Much credit is due to T.L. Pickett, who devised the computer program for the method and carried out the many runs necessary during its testing, and to J.W. Bell who performed the field work and most of the compilations.

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Table 1. Example of computer output for diurnal weather cycle no. 3 of Table 3 at equilibrium.

Symbols are:

T - temperature °C
H - relative humidity %
W - wind km/h
R - rain mm
E - equilibrium moisture content %, F-scale
M - moisture content %, F-scale
F - Fine Fuel Moisture Code

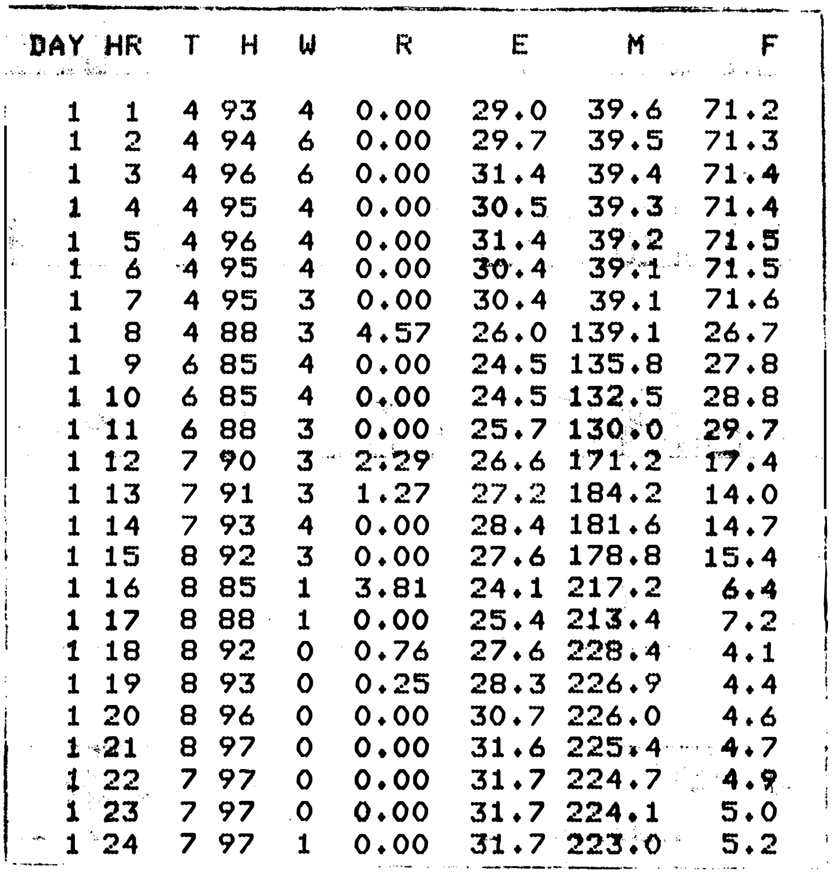
```
DAY HR  T  H  W     R      E      M      F

  1 17 24 54 11  0.00   13.6   16.1   87.6
  1 18 23 62 11  0.00   15.4   16.0   87.7
  1 19 21 68 11  0.00   15.2   16.0   87.7
  1 20 19 80  9  0.00   18.5   16.4   87.4
  1 21 17 90  9  0.00   22.8   17.3   86.7
  1 22 15 94  8  0.00   25.5   18.4   85.9
  1 23 14 96  6  0.00   27.2   19.5   85.1
  1 24 13 97  4  0.00   28.2   20.5   84.3
  1  1 13 98  4  0.00   29.2   21.5   83.6
  1  2 12 99  4  0.00   30.3   22.4   82.9
  1  3 12100  3  0.00   31.5   23.4   82.2
  1  4 11100  3  0.00   31.6   24.2   81.6
  1  5 11100  3  0.00   31.6   25.0   81.0
  1  6 12100  3  0.00   31.5   25.7   80.5
  1  7 15 90  4  0.00   25.1   25.7   80.6
  1  8 17 68  8  0.00   17.7   24.9   81.1
  1  9 20 68  8  0.00   17.2   24.1   81.6
  1 10 22 60  9  0.00   15.3   23.0   82.4
  1 11 23 55 11  0.00   14.1   21.8   83.4
  1 12 24 52 12  0.00   13.4   20.5   84.3
  1 13 24 51 12  0.00   13.1   19.3   85.2
  1 14 25 50 12  0.00   12.8   18.3   86.0
  1 15 26 49 12  0.00   12.5   17.3   86.7
  1 16 25 50 12  0.00   12.8   16.6   87.3
```

Table 2. Example of computer output: the effect of rain on a wet day.

Symbols are:

T - temperature °C
H - relative humidity %
W - wind km/h
R - rain mm
E - equilibrium moisture content %, F-scale
M - moisture content %, F-scale
F - Fine Fuel Moisture Code



```
DAY HR  T  H  W    R      E      M     F

  1  1  4 93  4  0.00   29.0   39.6  71.2
  1  2  4 94  6  0.00   29.7   39.5  71.3
  1  3  4 96  6  0.00   31.4   39.4  71.4
  1  4  4 95  4  0.00   30.5   39.3  71.4
  1  5  4 96  4  0.00   31.4   39.2  71.5
  1  6  4 95  4  0.00   30.4   39.1  71.5
  1  7  4 95  3  0.00   30.4   39.1  71.6
  1  8  4 88  3  4.57   26.0  139.1  26.7
  1  9  6 85  4  0.00   24.5  135.8  27.8
  1 10  6 85  4  0.00   24.5  132.5  28.8
  1 11  6 88  3  0.00   25.7  130.0  29.7
  1 12  7 90  3  2.29   26.6  171.2  17.4
  1 13  7 91  3  1.27   27.2  184.2  14.0
  1 14  7 93  4  0.00   28.4  181.6  14.7
  1 15  8 92  3  0.00   27.6  178.8  15.4
  1 16  8 85  1  3.81   24.1  217.2   6.4
  1 17  8 88  1  0.00   25.4  213.4   7.2
  1 18  8 92  0  0.76   27.6  228.4   4.1
  1 19  8 93  0  0.25   28.3  226.9   4.4
  1 20  8 96  0  0.00   30.7  226.0   4.6
  1 21  8 97  0  0.00   31.6  225.4   4.7
  1 22  7 97  0  0.00   31.7  224.7   4.9
  1 23  7 97  0  0.00   31.7  224.1   5.0
  1 24  7 97  1  0.00   31.7  223.0   5.2
```

Table 3. Day-to-day drying rates and equilibrium values of hourly and standard FFMC's, compared for five different diurnal weather cycles.

Item	Diurnal cycle				
	No. 1	No. 2	No. 3	No. 4	No. 5
Time of year	Early May	Mid-June	Late July	July-August	Late October
Weather cycle data					
Max. temp. (time)	25 (1600)	21 (1530)	26 (1500)	16 (1400)	21 (1600)
Min. RH	17	28	49	86	37
Min. temp. (time)	4 (0500)	9 (0500)	11 (0430)	12 (2400)	1 (0730)
Max. RH	100	64	100	100	100
Noon temp.	23	19	24	16	18
Noon RH	27	32	52	87	56
MC's at equilibrium					
Max. MC (time)	16.2 (0600)	12.8 (0800)	25.7 (0600)	30.9 (0600)	27.6 (0900)
Min. MC (time)	7.7 (2000)	10.4 (2000)	16.0 (1800)	28.5 (1600)	17.8 (1800)
1600-hr MC	8.9	10.7	16.6	28.5	19.0
Days to equilibrium					
Hourly FFMC	3	4	4	11	5
Standard FFMC	4	5	5	14	7
Equilibrium FFMC					
Hourly FFMC, 1600 hr	93.4	91.9	87.3	78.5	85.4
Standard FFMC	92.5	90.7	87.6	77.5	85.8
Difference					
Hourly minus Standard	+0.9	+1.2	-0.3	+1.0	-0.4

FIGURE 1

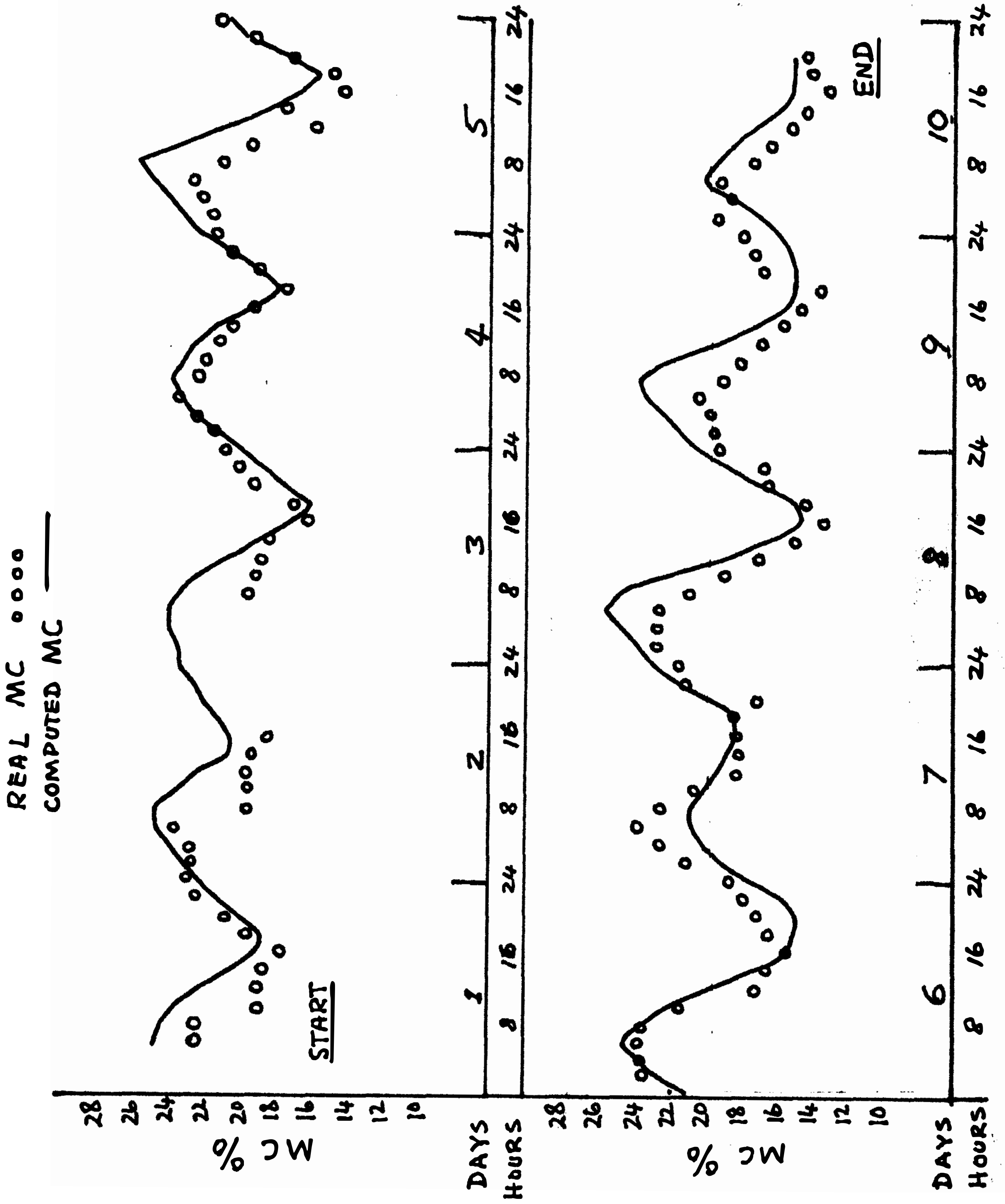


Figure 1. Graph of real moisture content of sample of jack pine litter plus moisture content computed hourly from weather records. Ten days in August 1966. Rain excluded.

FIGURE 2

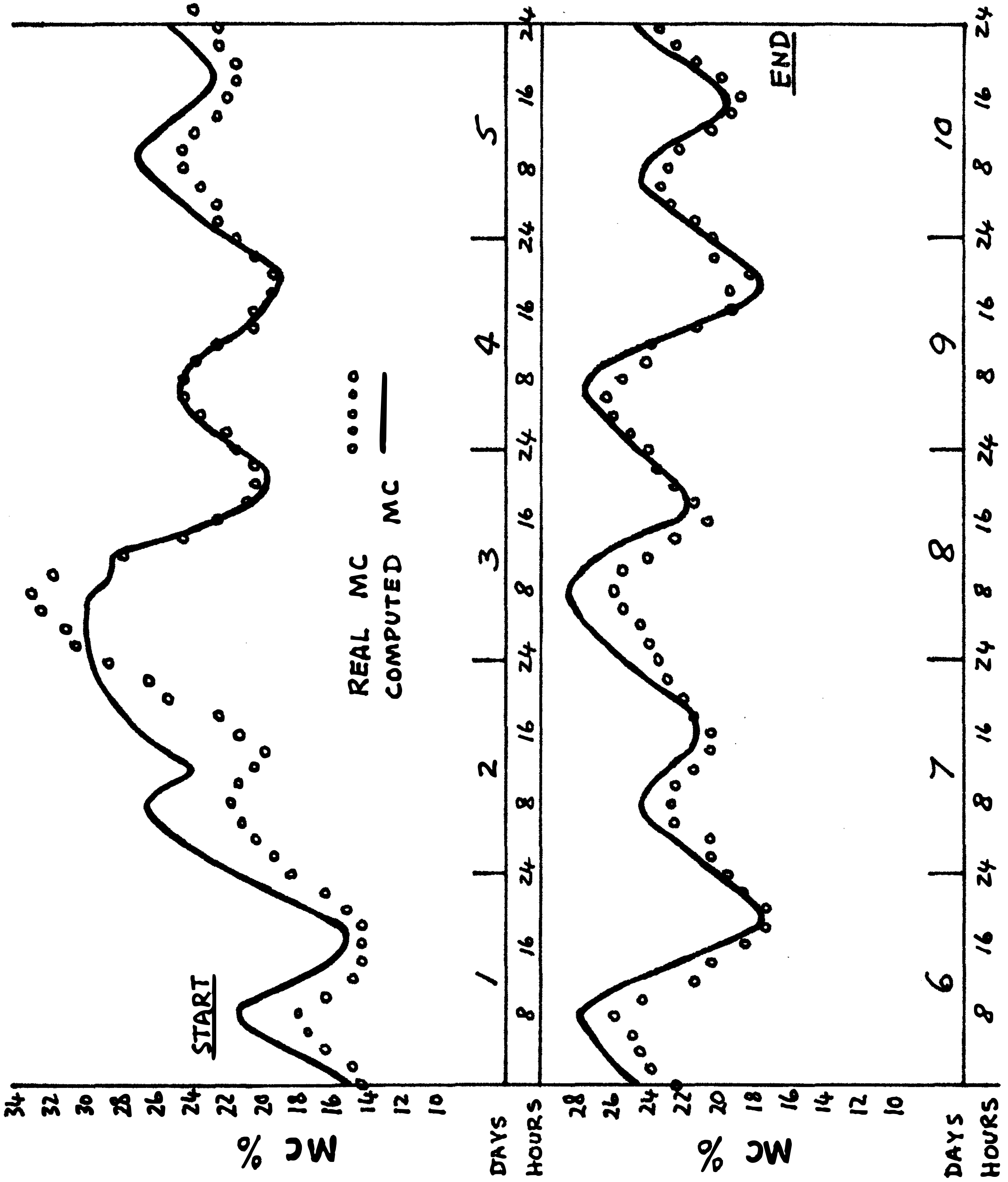


Figure 2. Graph of real moisture content of sample of jack pine litter, plus moisture content computed hourly from weather records. Ten days in August 1970. Rain excluded.

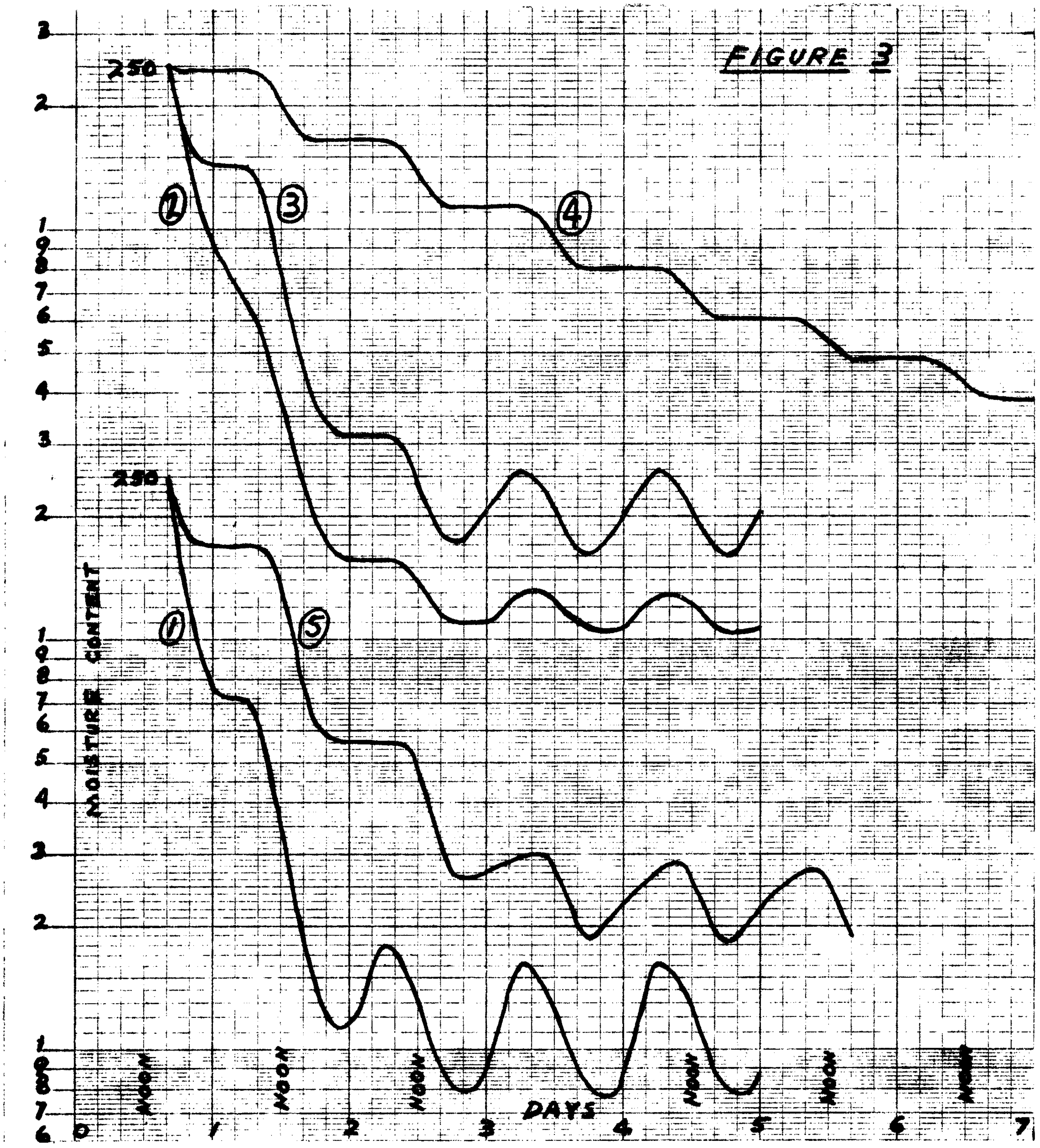


Figure 3. Hypothetical moisture content trends for repeated days of the fire weather cycles described in Table 3. Numbered as in Table 3. Number "250" indicates starting MC. Interpret each decade of MC scale accordingly.