UNIT V--FUEL MOISTURE

The fuel, moisture content in natural fuels is such an important factor to fuels availability for fire ignition and combustion that we have devoted an entire unit to the subject. Most fuel complexes contain a combination of dead and live fuels; thus, a wide range of moisture contents occur within these fuels. Since all fuels may not be involved in a flaming front or be consumed, by fire, our analysis of fuel complexes must determine which fuels will be responsible for the propagation of fire.

The purpose of this unit is to help you make estimations of moisture content in various dead and live fuels, to identify those fuels which can burn, and to assess the chances of ignition from firebrands landing in new fuels or of fire spreading by preheating fuels ahead of a flaming front. You will also recognize that fuel moisture content is a very important input toward making fire behavior calculations and predictions.

Before starting the unit, be sure you have read the instructions to students on page 1 of your workbook. On page 2, you will find the unit objectives on which you will be tested at the end of this unit. Please study these objectives, then return to this text.

The first section, starting on page 3, deals with natural fuels and their moisture contents. Fuel complexes vary greatly by areas or regions; with extremes from sparsely vegetated deserts, to rain forests with lush vegetation, to parched timber lands. If we view each as a potential fire environment, our immediate assessments must include fuel loadings and fuel moisture contents. We would expect desert fuels to be dry for extended periods, but is there enough fuel to carry fire? The rain forest has abundant fuels which are generally too wet or too green to burn, but infrequently these areas do have fires. Extended summer drought periods occasionally make our timber lands extremely dry, sometimes to the point of being "explosive", should fires occur.

We can generalize at this point and say that when fuel moisture content is high, fires ignite and burn poorly, if at all; and when it is low, fires start easily, and spread and burn rapidly. These simple deductions might satisfy some fire managers, except that fuel moisture contents are frequently some place between the two extremes and fluctuate with changes in weather. During normal fire seasons, these same fire managers have experienced times when rapidly spreading fires suddenly stop, perhaps even go out, due to changes in their fuels and moisture contents. These fuels may have been on a different aspect, had a later curing date, or experienced a sudden change in relative humidity.

How does one measure fuel moisture content and then anticipate what changes will take place over time and space? First of all, fire managers have agreed upon a common description and unit of measure for fuel moisture content. This is the amount of water in a fuel, expressed as a percent of the oven dry weight of that fuel. If there were no moisture at all in the fuels, as if dried in an oven, the fuel moisture content would be zero percent. Fuels can be weighed before and after drying in an oven, and percent can be determined by dividing the difference between the original and dry weights by the dry weight. There are other, more practical ways of estimating fuel moisture percents in the field, and these will be discussed in this unit.

Our next concern is how to anticipate what changes will take place over time and space. Turn to page 4. Fire managers are concerned with fire danger on a daily basis and make calculations of fuel moisture contents for fire danger-rating purposes. Some of the factors which are considered in the daily calculations are live to dead ratios of fuels; the stage of the growing cycle; the size classes of fuels; the daily weather elements; and the effects of accumulative weather on various fuel complexes.

Fire danger ratings have been designed for, and are usually adequate for general planning purposes, but do not provide enough data for fire behavior predictions about ongoing fires. In such cases, observed onsite data can help you refine estimates of fuel moisture percents. We will take you, step-by-step, through the process of estimating fuel moisture contents, given specific site data.

In estimating fuel moisture contents, you must remember that part of the fuel may be living vegetation, and part cured or dead vegetation. The two have different water retention mechanisms and different responses to the weather. Live vegetation has much higher moisture contents that fluctuate on a seasonal rather than a daily basis.

Living fuel includes both herbaceous plants and woody plant material. Herbaceous plants are either perennials, which sprout from the base, or annuals, which develop from seed each year. Herbaceous plants are relatively soft or succulent and do not develop woody, persistent tissue. The woody plant material that we are concerned with is small enough to be consumed in the flaming front of a fire. Mostly, this includes leaves, needles, and twigs. Herbaceous plants die each year, thus producing more dead, fine fuels. In grasses, perennials usually cure out later than the annuals; this is an important factor in assessing fire danger.

In living woody vegetation, the high fuel moistures are primarily in the foliage, and in new shoots or stems. In these fuels, the moisture content normally decreases as the growing season progresses, with lowest amounts occurring by late summer or autumn. Deciduous plants produce dead, fine fuels; whereas, most evergreen plants that retain their needles or leaves more than one season may have substantially reduced moisture contents.

Figure 2 illustrates the usual moisture content in live conifer foliage by season. The dashed line shows old foliage or needles gaining moisture in spring and early summer, then decreasing into the fall season. New growth or new foliage initially has very high moisture contents in early summer but decreases rapidly as the summer progresses.

Under item A, page 5 you should note the approximate fuel moisture ranges in natural fuels: Living fuels--about 30 percent to over 300 percent. Dead fuels--about 2 percent to 30 percent. Why the big difference? Well, living cells have the capability of holding large amounts of water, while dead fuels have been found to be fiber saturated at approximately 30 percent and can absorb little more water.

Even though live fuel moisture content can be accurately determined by oven drying and weighing procedures, fire considerations are usually satisfied with a good estimate. Figure 3 provides a table that gives approximate moisture content percents for six stages of vegetative development. These stages and their average moisture contents are a contributing factor to determining fire propagation. Study this table since you will be required to know the six stages and their percent moisture contents.

Now let's do question 1. Mark your choice or choices, then return to the text.

You should have marked all of the choices under question 1. These are all things that can bring about abnormal fire seasons or burning conditions by decreasing moisture contents in live fuels and/or producing additional dead fuels within a fuels complex.

Annual herbaceous vegetation, such as grasses, is a primary contributor to fire problems in many areas of the country. The amount of vegetation and the time of curing usually vary from year to year. One such species is Bromus tectorum, commonly called cheatgrass or annual brome. Although most common on dry areas of the West, it can be found in almost every state and is present in most continents of the world. Cheatgrass is a primary contributor to, and usually dictates, the severity of fire seasons on range lands in the Great Basin area of the United States. Here cheatgrass stands normally cure out by early summer to produce abundant, fine, flashy fuels, which are frequently termed "explosive" when fuel moistures are very low.

Figure 4, page 6 illustrates the annual growth period and moisture contents of cheatgrass during various stages of its short growth cycle. Coloration of the plant is an excellent indicator of its stage of development and probable moisture content range. As cheatgrass goes into its curing stage, it turns from green to purple; then, finally, it develops a straw color as it cures and its moisture content declines and fluctuates with changing weather factors.

The moisture contents in the three stages for cheatgrass would appear to be somewhat lower than those indicated in figure 3 on the preceding page. Actually there will be some variation by species, and figure 3 should be used as a general guide only.

Now do question 2, then return to the text.

In question 2, you should have noted fuel moisture in the living stage--above 100 percent, the curing or transition stage--30 to 100 percent, and the dead stage--below 30 percent. Fire will not ordinarily carry through cheatgrass until it reaches the cured stage and moisture contents drop below 30 percent.

We will now move from a discussion of live fuel moisture to dead fuel moisture. The first and most important factor is fuel moisture exchange with the atmosphere. (See figure 5 on page 7.)

Fuels are constantly exchanging moisture with the surrounding air. During periods of high humidity and precipitation there is a net gain in fuel moisture. However, when the air is dry, with low humidity, fuels are giving up more moisture to the air than they receive. Several factors influence the rate of moisture exchange between fuels and the air. Under item B list the following: Difference in water vapor pressure between each, presence or absence of wind, size of fuels, compactness of fuels, and proximity of fuels to damp soil.

If the moisture content in the atmosphere remained constant for a period of time, the fuels and the air would eventually achieve equal vapor pressures. This we call equilibrium moisture content, which occurs when there is no net gain or loss of moisture between fuels and the surrounding air. This can occur in small, fine fuels, but rarely occurs in larger fuels, as the time required to reach equilibrium in larger fuels is much longer.

On page 8, figure 6, we have diagrammed various environmental factors which influence fuel moisture. We will be discussing each of these factors in this unit. Note that -fuel moisture is directly influenced by temperature, relative humidity, and precipitation. Wind helps to speed up the exchange of moisture between the fuels and the air.

Other site factors of weather and topography influence atmospheric temperatures and relative humidity. Each of these site factors indirectly affects fuel moisture and must be considered in making estimations of fuel moisture content.

For example, figure 7 illustrates how shade versus sunlight affects fuel temperatures. During sunny daylight hours, temperatures at the earth's surface can reach 160° F. That temperature decreases very rapidly a few feet above the surface where air is mixing. At 5 feet above the surface, the air temperature may be 85° as observed in a weather instrument shelter. Relative humidity is much lower where temperatures reach 160°; thus, in this example, fine fuel moisture at the surface will be considerably lower--3 percent in the open, exposed area, as opposed to 8 percent in a shaded area.

On page 9, figure 8 illustrates the effects of aspect by time of day. Let's follow the curves through the 24-hour period shown. South slopes obviously receive more heating during the daytime than north slopes; thus temperatures are higher, relative humidity is lower, and fuel moisture ordinarily is lower on the south slopes. When darkness comes, temperature differences on various aspects diminish, and by early morning, temperature, relative humidity, and fine fuel moisture values have mostly stabilized

You should also note that east aspects reach their lowest fuel moisture contents by early afternoon; whereas, southwest aspects have the lowest afternoon fuel moisture contents.

Now do question 3; mark your choice or choices.

In question 3, statements 2, 3, and 4 are true. Number 3, you will note, states that level ground receives about the same intense heating as south aspects. We're usually talking about valley bottoms here. Also remember that at night, temperatures on south slopes and valley bottoms may be much different due to-surface inversions and thermal belt effects.

On page 10, we see more topographic effects on fuel temperatures. Time of the year influences the amount of solar heating received, thus affecting ground surface and air temperatures. Figure 9 gives the amount of solar heat received at Boise, Idaho, by average day of month. For example, during March, this area receives about 1,250 BTUs per average day per square foot of horizontal surface. July receives the highest amount of solar heating at almost 2500 BTUs per average day per square foot. The average day in July receives twice as much solar heat as an average day in March.

Now let's look at September. It receives about 1,700 BTUs per square foot on an average day. You may have noted that although solar equinoxes; that is, equal days and nights, occur during the months of March and September, September receives considerably more solar heating than March. Why is this? Well, the reason is that there are more cloudy days at Boise during March than September. Actually, when the sun is shining, March 21 should receive about the same amount of solar heating as September 21. The point that we want to make here is that time of year has considerable influence on fuel temperatures and fuel moisture contents.

Latitude, or distance north of the equator, also has some effect on the amount of solar heating received. Although heating values will vary by locality, the shape of the Boise curve is mostly representative of that of the contiguous states. The curve will be considerably different for Alaska and northern Canada.

How about elevation? Figure 10 illustrates the accepted "normal" temperature lapse rate of about 3-1/2° decrease per 1,000 feet of elevation rise. Note that as temperature decreases with elevation, the relative humidity increases. We have determined fuel moisture percents for the given temperatures and relative humidities as listed at the right. In this example, with an elevation rise of 5,000 feet, dead fuel moisture contents have increased from 4 percent to 8 percent. Together with later curing dates and higher green to dead fuel ratios at higher elevations, the overall fuel moisture differences can be very significant to fire ignition and spread-rates.

On page 11, question 4 is about elevation. Please mark your choice or choices.

In question 4, you should have marked statements 1, 3, and 4. Each of these definitely affects fuel moisture contents. Obviously, number 2 should state that snow melt dates are later at higher elevations, which also makes curing dates later in the season.

The steepness of slopes is a factor in the amount of solar radiation received on various aspects, and this affects the fuel moisture content of fuels on various slopes. (See figure 11.) You should note that surfaces perpendicular to incoming radiation receive considerably more heating than slopes that are almost parallel to these heat rays. The angle at which solar radiation hits various surfaces changes throughout the day and with the time of year. The steepness or percent slope on north aspects is particularly important, as there may be times of the year when such slopes receive no direct solar heating at all.

Next, we recognize wind as a factor influencing fuel moisture from the standpoint of helping fuels to reach equilibrium moisture content with the atmosphere at a faster rate. Here's how wind speeds up the drying or the evaporation process: During calm air conditions, the air next to the fuels tends to become saturated with water vapor, decreasing the evaporation rate of moisture from the fuel. Wind removes this saturated air, continually replacing it with drier air and thus speeding up the evaporation process.

Wind can also speed up the wetting or absorption process. Moist air moving over dry fuels provides a continuous supply of moisture for fuel moisture increase.

Precipitation can raise dead fuel moisture more rapidly than any other factor. (See page 12.) Both the amount and duration of the precipitation are considerations when predicting fuel moisture increases in various size fuels. Fine, dead fuels react very rapidly to precipitation and reach their saturation points quickly. Additional rainfall has little effect on the fuels. However, there are some feelings that more rainfall can be responsible for wetting the soils in contact with fuels, thus keeping those fuels damper for a longer period and prolonging the effects of the rainfall.

Heavy, dead fuels react more slowly to precipitation, since much of the rain may run off the fuel. Fuels continue to absorb moisture throughout the duration of precipitation; thus duration is more important than amount.

Figure 12 illustrates the effects of duration of precipitation on fuels of three size classes. The horizontal axis represents hours of continuous precipitation, while the vertical axis is fuel moisture content in percents. The dashed line representing 1-hour time lag fuels starts at 5 percent, rises rapidly, and reaches 30 percent moisture content within the first hour. The broken diagonal line representing 10-hour time lag fuels starts at 8 percent and increases at a slower rate, but reaches 30 percent moisture content after 6 hours. The solid line which represents 100-hour fuels starts at 12 percent and only reaches 20 percent after 16 hours of continuous precipitation. The data used to prepare this chart represent average western fuel situations with standing and down, dead fuels.

Now do question 5; mark your choice-or choices.

In question 5, statements 1, 2, and 4 are valid reasons. Statement 3 is not necessarily correct, but heavy rains do penetrate vegetative canopies better to reach understory fuels. It should also be noted that a wetting rain will penetrate fuels better than high relative humidity in the air. Having free water on the surface of fuels induces a higher absorption rate than high humidities in the air.

Before introducing the next section of the unit, we would like to re-emphasize some points on the environmental factors affecting the drying of dead fuels. Please do exercise 1 on page 13. When you have finished, return to the text.

For exercise 1, you should have checked your answers with those on page 29. We hope that this first section of the unit has given you a better under-standing of the natural factors affecting the fuel moisture and the complexity of predicting changing over time and space.

The next topic is fuel moisture time lag. On page 14, we have two definitions for time lag. In simple terms, it is an indication of the rate a fuel gains or loses moisture due to changes in its environment. The more technical definition is the time necessary for a fuel particle to gain or lose approximately 63 percent of the difference between its initial moisture content and its equilibrium moisture content. You may use either of these definitions for time lag.

This gain or loss of moisture does not occur at a constant rate. When conditions change, fuels respond quickly at first. The change in moisture content becomes slower as the fuel moisture gets closer to the equilibrium moisture content. In nature, fuel takes five time lag periods for 95 percent of the change to occur, but most of the change occurs in the first time lag period.

The time lag of fine fuels is short, and they reach their equilibrium moisture content quickly. Heavy fuels have a longer time lag. They will usually not reach an equilibrium moisture content since environmental conditions do not stay constant. However, it is still worthwhile to classify fuels ac-cording to their time lag.

Remember, time lag is related to fuel size. This is illustrated in figure 13. On the horizontal axis, we have the size of branchwood in inches of diameter. The vertical axis gives us time lag in days. Fuels of 1.4 inches in diameter have a time lag of 48 hours or 2 days. Fuels 2 inches in diameter have a time lag of 4 days, and so on. This means that if the air was kept at a constant point drier than the fuels, it would take 4 days, time for 2-inch branchwood to lose 63 percent of the difference between its initial weight and the equilibrium moisture content.

Now do question 6; mark your choice.

In question 6, you should have marked choice number 3.

Figure 14 on page 15 illustrates the time lag concept by showing the reaction times of two different size fuels to wetting and drying. The fuels are 1/2-inch sticks and a 12-inch log. During a typical fire season with a week of dry weather, the fuel moisture in 1/2-inch dead fuels will be consider-ably less than the moisture content of a 12-inch log. This is because the time lag period is much shorter in the 1/2-inch sticks.

If the fuels experience a day with precipitation, the moisture content of both will go up, but note the rates at which they absorb moisture. The 12-inch log is still gaining moisture after the rain has stopped, perhaps because of free water and wet soils resulting from the rainfall. The 1/2-inch sticks gain moisture rapidly but also lose it rapidly when temperatures and relative humidity return to normal.

See question 7; mark your choice or choices.

In question 7, the correct choices are statements 1 and 4. The reason for number 1, which states that the reaction time for drying is less in the sticks is number 4, the surface area to volume ratio is greater in the smaller fuels.

As discussed earlier, wildland fuels come in many shapes and sizes, and we will never see a fuel complex of homogenous fuel. A pure grass stand comes closest to being a homogenous fuel. The wide variety of fuel components and changes in the weather make it virtually impossible for an entire complex to be at equilibrium moisture content at the same time.

Turn to page 16. For the purpose of predicting fire behavior, it is accept-able to use estimates for the moisture content of the fuel sizes which contribute most to fire spread. Dead fuels are grouped into four size classes based on time lag: 1-hour fuels which are up to 1/4-inch in diameter; 10-hour--1/4 to 1-inch in diameter; 100-hour--1- to 3-inches in diameter; and 1000-hour--3- to 6-inches in diameter. Thousand hour fuels are used in the National Fire Danger Rating System, but not for making fire behavior predictions.

To give you an example of how the groupings were made, let's look at the 100-hour category. It includes fuels from l- to 3-inches in diameter. The midrange fuel size is 2-inches. Go back to page 14, figure 13, and view the time lag on the fuel size relationship chart. The time lag for 2-inch diameter fuels is 4 days. Four days is approximately 100 hours.

Although it's helpful to have current estimates of fuel moisture in each of the four categories, we are most concerned with the 1-hour group, which includes all fine or small fuels up to 1/4-inch in diameter. This is the group that mostly determines whether a fire will start and continue to spread. This is also the group that is constantly changing with changes in relative humidity. It is possible to predict these changes, and thus fire behavior, for different periods of the day and night.

Figure 15 shows the daily relationship of relative humidity to fine, dead fuel moisture. With no major airmass changes, relative humidity typically rises during the night with lowering temperatures until it reaches the highest humidity just about sunrise. Relative humidity then usually starts to drop with rising temperature until the lowest humidity is reached during midafternoon. The fine, dead fuel moisture curve follows the relative humidity curve with a short time lag of about 1 hour. Before you have finished this unit, you will be able to estimate fine, dead fuel moisture content for various times of day or night, given atmospheric conditions and other site factors.

Now do question 8; mark your choice or choices.

You should have marked choices 1, 3, and 4. These are valid reasons for slower reaction times in surface litter.

We have covered natural fuel complexes and their ranges of fuel moistures, environmental factors affecting fuel moisture, and the fuels time lag concept. We're now ready to discuss methods of determining dead fuel moistures and lead you through the steps to making your own calculations. See page 17.

Here are some ways in which fuel moisture contents can be determined for each of the time lag categories. Note the following under item C: One-hour time lag fuels--fuel moisture charts, National Fire Danger Rating System nomograms, and drying oven and scales, for 10-hour time lag fuels--fuel moisture sticks, NFDR or National Fire Danger Rating System nomograms, and drying oven and scales; for 100-hour time lag fuels--NFDR System nomograms; and for 1000-hour time lag fuels--NFDR System nomograms.

Determining fuel moisture percents for 100-hour and 1,000-hour time lag fuels gives managers an indication of drought conditions and overall severity of a fire season. 10-hour fuels are much more important in making fire behavior predictions than 100-hour fuels, but not nearly as important as 1-hour fuels. One-hour fuels are the primary carrier of the fire. We will there-fore work primarily with 1-hour time lag fuels in this course.

On the following pages, you will be introduced to tables which can give you acceptable estimates of 1-hour time lag dead fuel moistures under a variety of conditions. Before leaving page 17, we want to discuss briefly how the tables are to be used. First of all, you will determine a reference fuel moisture for day or night by entering dry bulb temperature and relative humidity into a table. Next, you will determine a fuel moisture correction value from the tables by considering the month, time of day, aspect, and fuel exposure to sun or shade. The correction value is then added to the reference fuel moisture to get the adjusted dead fuel moisture.

Now turn to pages 18 and 19. There are a series of nine steps that will direct you to the proper tables. You may not need to use all the steps. For example, in step 2, there are two different conditions of which you will select one. You then go on to the step under that selection. You will go only to those steps to which you are directed.

On pages 20 through 22 are five tables referred to in the nine steps. Let's look at table 1 on page 20. This table is for reference fuel moisture during daytime hours. You must enter both dry bulb temperature and relative humidity from your site. Notice the ranges of temperatures on the left, and ranges of humidities across the top of the table. You are to select the appropriate ranges in which your values are included. With the appropriate temperature range, move horizontally until you intersect with the column for the appropriate humidity range at the top. At this intersection you have a reference fuel moisture content percent.

Now look at table 2. It gives you correction values for the months of May, June, and July. Notice that there are two sections to the table. The top section is for clear and/or no canopy, while the bottom part is for cloudy and/or canopy. The steps will tell you when to use each. You have choices of north, east, south, and west aspects for your site.

Across the top are time periods of 2 hours each. After making the proper selections of lines on the right and columns from the top, you will find a correction value at the point of intersection. These values are added to the reference fuel moistures to obtain adjusted fuel moistures.

Please turn to page 23. Exercise 2 requires that you use the steps and tables on the preceding pages to determine dead fuel moisture contents. Complete the exercise; then return to the text.

If you had any problems in completing exercise 2, please seek help. It's important that you are able to accomplish this portion of the unit.

On page 24, exercise 3 relates relative humidity and precipitation to fuel moisture. Carefully read the instructions; then complete the exercise.

The last section of this unit, starting on page 25, is intended to make fuel moisture information more meaningful to fire managers. First, we can relate fuel moisture content directly to probability of ignition. Probability of ignition is a rating of the probability that a glowing firebrand will cause a fire, providing it lands on receptive fuels. It is not related to the likelihood of a firebrand being produced, from torching trees for example.

Figure 16 gives probability of ignition as a function of fuel temperature and moisture content. Here's how it works. On the horizontal axis, we have fine fuel moisture content expressed in percent. On the vertical axis, probability of ignition is also expressed in percent. There are three curves representing three different fuel temperatures. Fuels on the ground surface can easily reach 130° on warm sunny days. You will select a temperature curve closest to your site situation. If fine fuel moisture is 10 percent, and fuel temperature is 90°, you will look for the intersection of the 10 percent vertical line with the middle curve. Then go horizontally to the left to obtain a percent ignition probability. In this example, it is approximately 35 percent, which represents the chances of a firebrand causing a fire if it lands on receptive fuels. You will use this graph in an exercise a little later in this unit. In a later unit, you will learn to use a table to estimate probability of ignition from fine fuel moisture, dry bulb temperature, and shading of fuels.

On page 26, we continue our discussion of fuel moisture contents as they relate to fire spread. Fire spreads as a result of fuels ahead of the fire being preheated to their ignition point. Heat is required to drive moisture from fuels before they can support combustion. At some point, fuel moisture content can slow combustion and the preheating of new fuels; thus ignition temperature in new fuels is not reached. The intensity of the fire, then, determines whether moist fuels can be dried and preheated to their ignition temperature.

Natural fuel complexes generally contain a combination of live and dead fuels. A fire passing through a fuels complex may or may not burn the live fuels. When the live fuels are not consumed, there must be enough dead, dry fuels to support the fire. Also, some live fuels will burn although their moisture contents may be 100 percent or higher. One example is green pine needles that have volatile substances.

What is that point where dead fuel moisture discourages combustion and fire spread? We call it the moisture of extinction, and it is defined as the fuel moisture content at which a fire will not spread, or spreads only sporadically and in a nonpredictable manner.

At what percent do we reach the moisture of extinction? Here we can only give you some guidelines and factors to consider. The moisture of extinction varies by fuel situation. The moisture of extinction is dependant on various fuels characteristics such as fuel loading, fuel size, arrangement, and chemical content. Moisture of extinction is lowest (around 12 percent) for light porous grasses such as cheatgrass, and tends to be higher (around 30 percent) for more compacted fuels such as needle litter.

On page 27, figure 17 gives the moisture of extinction for the 13 fire behavior fuel models. These can be used as a guide when predicting fire behavior activities. The presence or absence of fuel classes within the fuel models is also shown for your use as a reference.

Exercise 4 on page 28 deals with probability of ignition, moisture or extinction, and fire spread. Read the instructions; then complete the exercise. When you have finished, check your answers with those on page 29. This will conclude the unit. Prepare to take the unit test by going back and reviewing the unit objectives and the materials presented in this unit as you feel necessary.