COURSE: Prescribed Fire Planning and Implementation

TOPIC: Smoke Management (Unit 5B)

LESSON B: Quantifying and Achieving Smoke Management Objectives

SUPPLEMENTAL MATERIAL 2: Fuel Combustion and Consumption

THE COMBUSTION PROCESS

Most observers of forest fires distinguish between flaming and smoldering combustion. Flaming combustion is characterized by the movement of a visible flame through the fuel; smoldering combustion is more general and loosely defined term associated with the "die-down" of a fire after the flame front has passed. The burning process, however, is more complicated than this. It is more logical to consider it in four phases: pre-ignition, flaming, smoldering, and glowing. The prescribed fire manager and burn boss should understand this process to appreciate how the various smoke components are produced.

FOUR PHASES OF COMBUSTION

A. Pre-ignition Phase (Distillation and Pyrolysis Predominating)

In this phase, fuel elements ahead of the fire are heated; this causes water vapor to move to the surface and escape. As the fuel dries and its internal temperatures rise, certain components of the wood decompose, releasing a stream of combustible organic gases and vapors. This process is called pyrolysis. Because these gases and vapors are very hot, they ignite when mixed with oxygen. This brings the process to its second phase, flaming combustion.

B. Flaming Phase (Rapid Oxidation of Gases Predominating)

At the beginning of this phase, the fuel temperature rises rapidly. Pyrolysis accelerates and is accompanied by rapid oxidation (flaming) of the combustible gases, which are now increasing in greater and greater quantities. The products of flaming combustion are predominately carbon dioxide (CO_2) and water vapor. This water vapor is not the result of fuel dehydration (pre-ignition phase), but rather a product of the combustion reaction. Temperatures in this phase range between 600 and 2,500 degrees Fahrenheit. Some of the pyrolyzed substances cool and condense without passing through the flame zone; others pass through the flames but are only partially oxidized, producing a great variety of emissions.

C. Smoldering Phase (Slow, Flameless Combustion Predominating)

In this phase, the overall reaction rate of the fire has diminished to a point at which the concentration of combustible gases above the fuel is too low to support a persistent flame envelope. Consequently, the temperature drops and the gases condense. The resulting condensates appear as visible smoke as they escape into the atmosphere. Emissions from a smoldering fire are at least twice that for flaming fire. The heat release rate of a smoldering fire is seldom sufficient to sustain a convective column because the smoke stays near the ground and persists in relatively high concentrations, thereby compounding the impact of the fire on air quality.

D. Glowing Phase (Solid Oxidation Predominating)

In the glowing combustion phase, all the volatile material in the fuel has been driven off. Oxygen in the air can now reach the fuel; the surface of the charcoal begins to burn with a characteristic yellow glow. There is not visible smoke. Carbon monoxide and carbon dioxide are the principal products of glowing combustion. This phase continues until the temperature drops or until only noncombustible, gray ash remains.

It is important to recognize that combustion in forest fires, even in the most favorable circumstances, is not a chemically efficient process. First, moisture contained in the fuel absorbs some of the heat energy, thereby reducing the combustion temperature. Second, considerable heat is subsequently lost to the soil and surrounding air. Third, fresh air movement in and around the fire cools the combustion zone. Also, the oxygen required for optimal combustion is sometimes insufficient, resulting in more visible smoke.

IMPORTANCE OF FUEL CONSUMPTION

Burning in the conversion of cellulose woody material to ash, heat, and atmospheric gasses through the process we know as combustion. Fuel consumption is the amount of woody material converted during the combustion process. Fuel consumption is usually a primary or secondary objective of all resource management burning, and can also be an undesirable consequence of wildfire. Estimating fuel consumption is important for two reasons:

1. A prescribed fire planner can "test" and adjust a burn prescription to make a preliminary determination on the probable success of achieving the burn plan fuel consumption objective, and;

2. A prescribed fire manager or burn boss can make an estimate of the amount of emissions produced by a prescribed burn under current or predicted site conditions.

Emission production (smoke) is directly related to two aspects of burning:

1. The total amount of fuel consumed by the fire, and;

2. The efficiency of the combustion process as represented by an emission factor.

The ability to estimate fuel combustion, therefore, enables us to also estimate emissions production. We can then determine the acceptability of the burn from a smoke management standpoint. If estimated emission production is unacceptable, then one way to "manage" smoke could be to limit the amount of fuel consumed during the burning. To successfully accomplish this we must know what factors affect fuel combustion and consumption.

FACTORS AFFECTING COMBUSTION AND CONSUMPTION

Fuels can only be involved in the combustion process if they meet availability requirements. For fuels to be "available" to burn, they need to be in sufficient quantity, dry enough and arranged in a way that supports continued combustion. There are several factors that affect fuels availability to burn, including:

1. Fuel Loading. More fuel on site results in more fuel being available to burn if all other factors support combustion. Under many burning scenarios, only partial consumption is possible and/or desirable. Even in these situations, however, more total fuel loading will equate to more fuel consumed.

2. Fuel Size. Smaller diameter fuels have a greater surface area-to-volume ratio. Combustion usually takes place at the fuel/atmosphere interface (surface), and is much more efficient with smaller fuel sizes. Also, the relative availability of smaller fuels tends to be more dependent on current weather conditions. Larger fuels tend to be less dependant on current weather factors. Availability is influenced more by long term climatic conditions and the availability of smaller fuels to initiate and sustain combustion.

3. Fuel Arrangement. The structuring of fuel particles and air space within the fuel bed can either enhance or retard fuel consumption during burning by altering fuel availability or combustion efficiency. A loosely packed fuel bed results in inefficient heat transfer between burning and adjacent unburned fuel particles. Many particles cannot be heated to ignition

temperature and are made "unavailable" for combustion. A tightly packed fuel bed severely restricts oxygen availability but increases heat transfer efficiency resulting in incomplete combustion and reduced fuel consumption.

4. Fuel Bed Continuity. Discontinuity isolates portions of the fuel bed from ignition. The isolated fuels are not available for combustion and are not consumed.

5. Fuel Moisture. Fuel moisture content is the most influential single factor in the combustion and consumption processes. Live fuel moisture content has an extremely influential effect in some fuel types; and relatively little in other fuel types, but it is important to combustion and consumption in all fuel types.

   Heat is required to remove the water from a fuel before the dried out material can be raised to flame temperature and ignited. To do this, heat is required to:

   1. Raise the temperature of water in the fuel to boiling.

   2. Separate the bound water from the fuel.

   3. Vaporize the water in the fuel.

   4. Heat the fuel to ignition temperature.

   Of these, only #2 and #3 are really heat losses. Drawing from Davis (Brown and Davis, Forest Fire Control and Use, 2nd Ed., 1973, p. 162), we can see the heat requirements needed for combustion of one pound of wood at different moisture contents are shown in the table.

   When wood (fuel) is heated, the water within the wood must be brought to boiling point before it can be vaporized. The greater the amount of water within the wood, the more heat energy it takes to vaporize the water. The heat lost during this process causes less complete oxidation, thus less efficient combustion.

   Because the products of the combustion reaction must share part of their heat within the inert moisture vapor, there is a reduction in flame temperature; which has a significant effect in reducing the rate of spread. Measurements have shown that flame temperatures may be as high as 1,800-2,000 degrees Fahrenheit for dry fuels and as low as 1,600 degrees Fahrenheit for fuels above 40 percent moisture content. So water in fuels is extremely influential in not only the degree of consumption (how much burns), but the rate at which it burns. Dry fuels burn more completely, and burn up in a hurry. Wetter fuels burn incompletely, and burn slowly, giving off much more visible smoke.

CONSUMPTION RELATED TO COMBUSTION PHASE

Fuel consumption occurs at different rates for each phase of combustion. Consumption resulting from the pre-ignition and glowing phases of combustion are generally insignificant in wildland fuels. The flaming and smoldering phases cause the majority of fuel consumption. Since flaming combustion is more efficient than smoldering combustion, consumption rate and duration for these two phases can be quite different, requiring separate estimates of consumption for each phase and sometimes each fuel size class.

Flaming combustion results in exterior diameter reduction of round wood material. Consumption generally occurs at the rate of 8 mm/inch of diameter reduction. For example, a dry limb 3" in diameter would take approximately 24 minutes for complete consumption, if it sustained flaming combustion for the entire time period. This is an average rate that varies depending on the factors influencing combustion described above.

Smoldering combustion generally occurs at a much slower rate, and longer duration, than flaming combustion, taking place over several minutes to several hours. Consumption is not at a constant rate that makes prediction difficult.

Smoldering and flaming combustion phases occur simultaneously when a whole fire area is considered. Modeling the rate of fuel consumption, heat release rate, and emission production rate requires modeling the rate for the area that is flaming at any instant and the area that is smoldering, then adding the two together.

ESTIMATING FUEL CONSUMPTION

Processes for estimating fuel consumption based on pre-ignition site and weather data are still being developed and perfected. Existing processes focus on a specific component of the fuel bed. Most of the research in this area has concentrated on the consumption of large woody material (>3" diameter) and the litter/duff layer. Processes for estimating consumption of small woody fuels (<1" diameter) and live fuels are still in the developmental stage. Much of the research data supporting these processes is specific to an area, region, and fuel type. However, many of these processes can be applied to areas outside of where the data collection occurred when similar fuels and moisture regimes exist.

No algorithms exist to predict fuel consumption for fuels less than 1" in diameter.

Most models assume 100 percent consumption if the fuels are dry enough to ignite. We know from experience that this is not always the case. Fuel consumption of small woody fuels under high fuel moisture or high humidity conditions can produce a very uneven burn mosaic. The best consumption estimates in these situations will come from the local experience base.

Consumption of larger diameter woody material (1-3" and >3" diameter material), and the litter/duff layer, can be estimated using a variety of charts, graphs, and computer applications. Most of these tools correlate consumption estimates to a pre-ignition weather or fuel moisture value. Estimates for large woody fuel consumption use 10- and/or 1,000-hour fuel moistures either from measurements on site or calculated values from representative NFDRS weather station data.

Research on fuel consumption for 3" and larger diameter material has shown that there is a close correlation between the diameter reductions of the burned material to the pre-burn 1,000-hour fuel moisture level. This is because a fuel moisture gradient usually exists in larger fuels with the surface layer being drier than the center position. The fire burns away surface material during the flaming phase of combustion until the interior fuel moistures will no longer support flaming combustion. Tons of fuel consumed can then be determined by the estimated diameter reduction expected to occur at a given 1,000-hour fuel model level.

Fuel consumption of 1-3" diameter material has been correlated to the burn site 10-hour fuel moisture. This is based on actual fuel sampling and must be adjusted if 10-hour fuel stick is used.

Litter/duff consumption estimates are determined using factors such as duff moisture, estimated large fuel consumption, 1,000-hour fuel moisture, Keetch-Byram drought index and/or days since significant precipitation.

Consumption of live fuels is best estimated using local data gathered from previous prescribed fire projects in a similar fuel type.