# Help for Kiln Model
# V 1.0

# About the Model

A model is a tool that allows you to predict what will happen given a set of inputs. Getting a perfect match between a model and the real world is very difficult. Perfect agreement, however, is not necessary. The important thing is that the model predicts trends correctly. We do not know the wood properties of every board in the kiln charge and we certainly do not know drying curves for every combination of wood properties. This is largely what prevents an exact board by board match for moisture content between the real kiln and the model. There are also some mechanical factors. For example, the model can exactly follow the drying schedule whereas there are time delays in real kilns due to heating limitations. Keeping these limitations in mind, the model should provide reasonable trends if the input data is accurate. Accurate input data falls upon the user.

Each of the four yellow tabs (four worksheets) in the workbook is a page for input. The areas in dull yellow can be changed. The hyperlinks take the user to the appropriate page in this file. Information is divided among the pages by topic.

*Kiln and stacking* worksheet is used to input information that is unlikely to change for a given mill or kiln.

- input and output units for model (decide on these first)
- kiln layout
- package construction

Package kilns can be accommodated by grouping the lumber onto tracks (even though there are no physical tracks present). How to do this is described in the help under “Tracks” and Units wide on a track.” Reheat coils between tracks are optional, but will occur between each track if they are present.

*Drying rate* worksheet is used to input information about how a single board behaves. It includes a graphical tool so the user can see the drying behavior.

*Wood properties* worksheet is used to tell the model about the wood that is in the kiln. In the lower part are tables of all the initial board properties.

*Schedule* worksheet is where the drying schedule is input. A few other program execution variables are set here.

Each of the two green tabs (two worksheets) in the workbook contains output.

*Output picture* worksheet shows the current moisture content of every board in the kiln, unit moisture contents, and track moisture contents.

*Output graphs* worksheet shows the trends from the start of drying to the current time.

The model is started using the gray button “Start simulation” that occurs on several pages. The model will pause at times you set on the schedule page. The “Resume simulation” button is used after a pause. These buttons are located in several locations. Changing the input requires a restart of the simulation.

The kiln is one package long and one package high. This might seem restrictive, but a long kiln is a series of short segments put together. To simulate variability along the length of a kiln, use multiple runs of the simulation setting kiln conditions that represent the variability along the length of the kiln. For example, to simulate a kiln with a hot zone on one end, run the program twice (once for each zone with slightly different schedules) and compare the results. Similarly, to simulate top packages getting more heat than bottom packages, run the program twice with two slightly different schedules. The capability to simulate this in a single simulation might get added to the program at a later date.

Unit and track numbering are from left to right as the user looks at all diagrams. The units showing initial properties on the *Wood properties* worksheet are in the same order as the units on the *Output picture* worksheet. The kiln width is limited to approximately 225 boards (depends on configuration). There can be up to six tracks and/or 24 units wide. A typical track kiln may have two tracks and a total of four units, so exceeding the limits of the model is unlikely.

## Kiln and stacking worksheet

This worksheet allows the kiln to be configured. The items on this page are things that you should be able to set once and then not need to reset each time you run the model. Examples are the number of tracks, number of units wide, package width, and maximum air velocity.

### Units for input:

Entry is restricted to “English” or “SI”

- Set this value before entering any other information. When this value is changed, the units on the inputs will change, but the entered values will not.

## Units for output

Entry is restricted to “English” or “SI”

-Set this value at any time before starting the simulation

English units include °F, inches, feet, BTUs, horsepower etc.  SI units include °C, meters, millimeters, Joules, etc.  Units can be mixed – input in English and output in SI – but all input or output is in one unit type..

## Tracks

For track kilns, enter the number of tracks (up to six).  See examples on next page.

For kilns without tracks (side loaders or package kilns), units that are close together should be considered to be on the same track.  If there are spaces large enough between some units for the air to mix (maybe a foot, use your judgment), then units are on separate tracks.

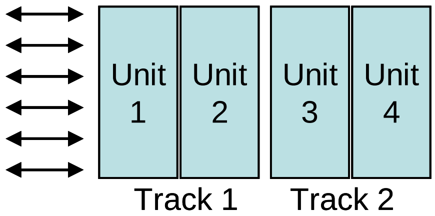
Even without reheat (center) coils, there is a subtle difference in program execution between, for example, four units on one track and two tracks each with two units.  The air entering a track will be at one temperature, humidity, and velocity and equal in all sticker slots.  Air moving from one unit to the next on a track will have the properties of the air leaving the corresponding sticker slot in the previous unit.  The difference is minor in most cases.

## Units per track

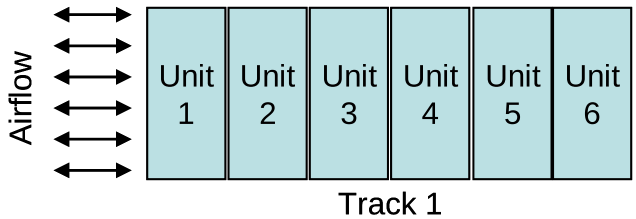
In a track kiln, this is the number of units wide on a track.  Most likely it is one or two, although some kilns have three.

For a package kiln, enter the number of adjacent units.  See examples on next page.

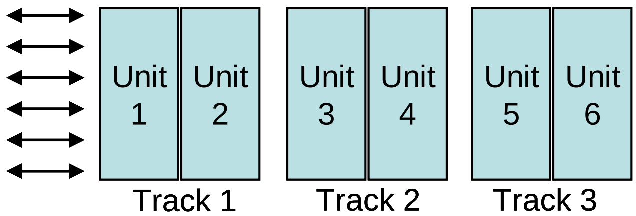
The units per track is limited to 24/(# Tracks).  So, 24 for 1 track, 4 for 6 tracks, etc.



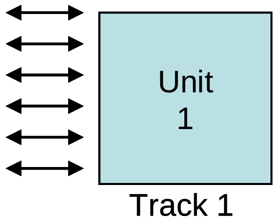

Double track kiln, two units per track OR Package kiln with a Reheat coil or space
Tracks = 2,
Units on a track = 2




Package kiln that is six units deep with no reheat coils or space
Tracks = 1,
Units on a track = 6




Triple track kiln OR Package kiln that is six units deep with two reheat coils or spaces
Tracks = 3,
Units on a track = 2




Crib-loaded single-track kiln OR Package kiln that is one unit deep
Tracks = 1,
Units on a track = 1

## Reheat coils

Entry is restricted to “Yes” or “No.”

If Yes – Reheat coils will be placed between each pair of adjacent tracks. When the program executes with entering-air control, the air will be heated to the setpoint temperature as it passes from one track to the next (with a constant absolute humidity). For exiting air control, the air will be heated to maintain the exiting temperature. The air is completely mixed between tracks so that the air entering each sticker slot in the next track has the same temperature.

If No – Reheat coils are not placed between tracks. The air is not heated. The air is completely mixed between tracks so that the air entering each sticker slot in the next track has the same temperature.

As a note – when the air passes between units on the same track, the air temperature entering each sticker slot of the next unit is not necessarily uniform. If the air temperature was higher leaving a sticker slot in the first unit, the air entering the adjacent sticker slot in the next unit is higher by the same amount. In other words – two or more adjacent units on a track are treated like one wide unit.

## Velocity at 100%

Enter the air velocity when the kiln's variable speed drive is set to 100%. A typical value would be 500-2000 ft/min (2.5-10 m/s).

This value is used to determine the air velocity at any point in the schedule. On the "Schedule" page there is a column for % fan speed. If you enter 90% for the % fan speed then the airspeed entering the load is 90% of the value you entered here.

Fan reversal times are handled in the "Schedule" page

## Package width

This is the width of the package in inches or meters. Typically this value is in the range of 8-12 boards, so 42" to 60". It might be as great as 96 inches for crib stacking or tracks that are one unit in width.

The number of boards in a unit is determined within the program by dividing the unit width by the width of a board and rounding down to the nearest whole number. If the unit width is 42" and the board width is 5.8" there will be 7 boards per unit (42/5.8 = 7.24).

The maximum number of boards across the width of the kiln is limited by the width of the Excel worksheet. The number of units across the kiln is

UnitsWideInKiln = Tracks x UnitsPerTrack

The maximum boards allowed in a unit is

$$\frac{240 - (3 \times UnitsWideInKiln)}{UnitsWideInKiln}$$

From this we can determine:

| Units wide in kiln (all tracks) | Max Boards in a unit |
|---|---|
| 1 | 237 |
| 2 | 116 |
| 3 | 76 |
| 4 | 56 |
| 5 | 44 |
| 6 | 37 |

### Package height

This is the height of a unit in inches or meters. 36 to 60” are typical values. The program handles up to 94 layers in a unit. The layers are calculated from the package height, sticker thickness, and board thickness.

Hint on unit height: You will probably get the same information from the program if the unit height is small or large. Consider setting it to 10 or 12, even if your actual unit height is greater. This will make the simulation run faster.

## Drying rate page

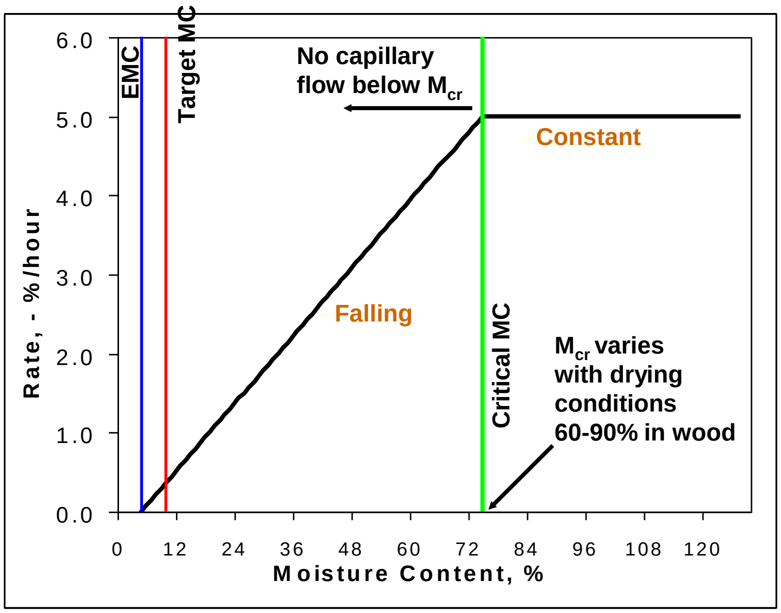
This page is used to describe how fast the wood species in the kiln dries at a certain temperature, humidity, and air velocity.

### Background on drying rates

The drying rates in the correlations are for individual pieces of lumber exposed to the specified conditions of temperature, humidity, and velocity. The simulation calculates the drying rate for the whole kiln after calculating the temperature, humidity, and velocity to which each board is exposed.

Several correlations can be selected in the drop down box. These are programmed in according what was presented by the authors in the paper cited. The custom drying rate (first selection in drop-down box) allows the user of the program to simulate any kind of wood. The parameters for some kinds of wood are already worked out and can be selected with buttons. The user can also fill in their values, although a reasonable understanding of what each value does is necessary. The link on each value contains this information. The overall theory is below.

The drying rate of the board is influenced by the temperature, humidity, and velocity of the air immediately around the board. The custom drying rates are based on drying theory which provides for two drying periods. These are separated by the “critical moisture content”. The critical moisture content is the point at which the surface moisture content of the board begins to decrease. The period above the critical moisture content is called the “constant rate period” and below is called the “falling rate period.” The graph below illustrates this concept.




During the constant rate period, the internal movement of free water (liquid water in the cell lumens) to the surface of the board is rapid enough to keep the surface wet. It becomes harder for water to move to the surface as the average moisture content of the board decreases. At some point the internal movement can no longer keep up with the surface evaporation and the surface moisture content decreases. Simultaneously, the surface temperature rises (much like a wet-bulb sock when it dries out), the rate of heat transfer decreases, the rate of drying decreases, and the end of the constant rate period is reached.

During the falling rate period, the surface of the board is drier while the interior might be quite wet. As drying progresses heat must move further into the board to reach the water and the water vapor must move further to get to the surface of the board. In addition, the wood is becoming less permeable due to internal structural changes (pit aspiration). This results in progressively slower drying until the board is at the equilibrium moisture content. Notice in the chart above that the drying rate is zero when the board reaches the equilibrium moisture content (EMC).

External factors control drying during the constant rate period. The board temperature is at the wet-bulb temperature and the board acts like a big wet-bulb sock. The rate of heat transfer from the air to the board is proportional to the temperature difference between the board's surface and the air. Thus, if the wet-bulb depression is doubled, the drying rate will double. Air velocity also has an effect that is proportional to the square root of the change in air velocity. Temperature plays very little role.

Internal factors control drying during the falling rate period. Diffusion of water through wood is very dependent on temperature. The drying rate during the falling rate period increases dramatically as the kiln temperature is raised because the wood temperature also increases. The EMC in the kiln is also important because the surface moisture content of the board approaches the EMC. A lower EMC causes a greater difference between the surface moisture content and the internal moisture content which causes the water the move faster. Velocity plays only a small role during the falling rate period because the air velocity is external to the board and can have no impact on the diffusion rate inside the board.

For materials such as sand, the transition from the constant rate to falling rate period is well defined as in the graph above. It is less defined for wood and other hygroscopic materials. The correlation will allow us to more smoothly from one curve to another.

Caveats on air velocity at low MC: First, increasing the air velocity probably brings the board to a slightly higher temperature, thus it may have a small effect on diffusion. Second, this discussion applies to an individual board. When a higher velocity passes between the first boards in a stack the temperature drop decreases if the drying rate is not changed. Thus the air passing between the second boards is slightly higher. This continues through the stack and the boards at the exiting side of the stack dry faster because they see a significantly higher temperature.

With that background, let’s see what the parameters in the model mean.

## Drying rate correlation

This selection determines the set of equations that are used to determine how fast a board loses water.

Selecting one (such as Southern pine, Milota and Tschernitz, 1990) will cause the custom values below to be ignored. The coefficients needed are elsewhere in the Excel program. Pick the one that matches your species or select custom and enter values below.

Selecting custom will cause the values further down the worksheet to be used. After selecting custom, the buttons can be used to enter some values that have been predetermined. The meaning of the values for a custom correlation are described below.

You can see the effect of your selections by entering dry-bulb and wet-bulb temperatures above the graph to the right and updating it.

## Behavior at high MC

The values in cells D27 to D30 affect how the board will dry at high moisture content. Essentially, these parameters determine the location of the horizontal black line in the figure above. This can be somewhat fictitious in some cases. For example, the starting moisture content of a species may not be high enough for the wood to dry on the horizontal line.

### Drying rate

This factor will determine the drying rate at a given wet-bulb depression. Increase the value to get a faster drying rate at high moisture content. This will not impact the drying rate at low moisture content.

The correlation in Milota and Tschernitz (1990) used the following to obtain a flux, Fcr (like a drying rate except in $lb/ft^2/hr$ or $kg \bullet m^{-2}s^{-1}$)

Fcr = (0.01208 + 0.006797 * (Td - Tw) - 0.00002482 * (Td - Tw) ^ 2) * fv

where fv is a velocity factor discussed later.

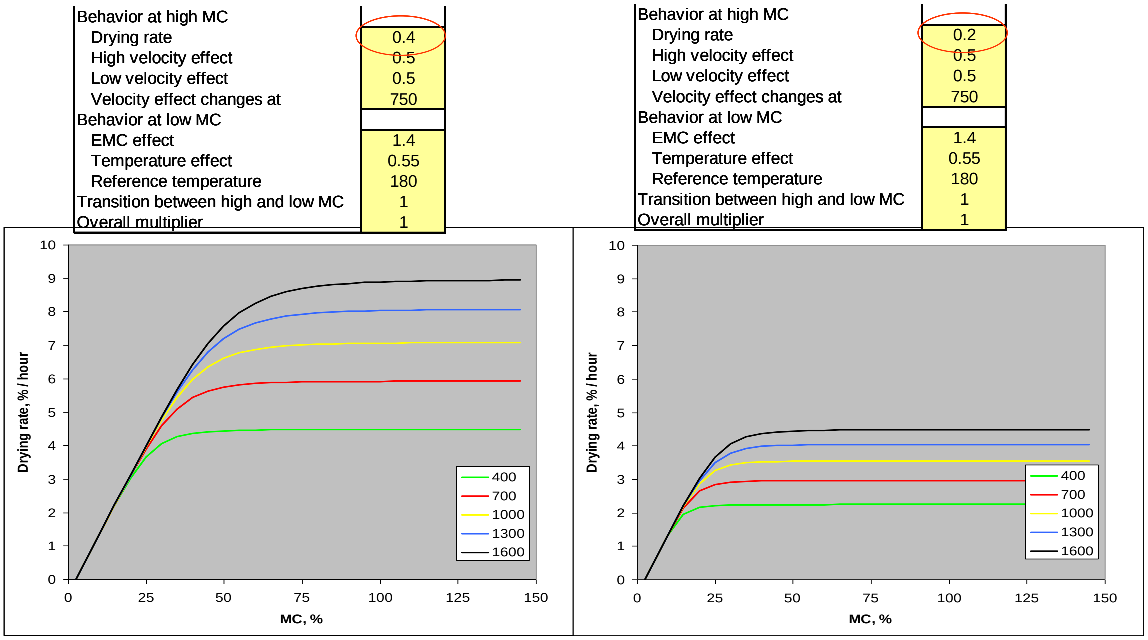
This was modified within the program so that the flux is expressed as

Fcr = (HighMCRate/1.2) *
(0.01208 + 0.006797 * (Td - Tw) - 0.00002482 * (Td - Tw) ^ 2) * fv

The drying rate at high moisture content will equal that in the southern pine correlation if 1.2 is used for the drying rate at high moisture content. When trying to guess a value from scratch, starting with a lower value (0,2 to 0.8) is suggested.

The logic in using the 1990 southern pine correlation for this is that the southern pine dried was almost 100% sapwood and was more likely to have a constant rate period than other species.

The graph below illustrates the effect of this parameter. Notice that the rate at lower MC is unaffected while the rate at high MC changes in proportion to the parameter.




### High velocity effect

### Low velocity effect

This is the power to which velocity affects the drying rate from a board at high moisture content. For example, if the VelocityEffect = 0.5, then if air velocity increases by a factor of 2, the drying rate changes by a factor of $2^{0.5} = 1.41$. Numerically, this is expressed as

For V > ChangeV; $fv = (\text{Velocity} / \text{ChangeV})^{\text{HighVelocityEffect}}$

For V ≤ ChangeV; $fv = (\text{Velocity} / \text{ChangeV})^{\text{LowVelocityEffect}}$

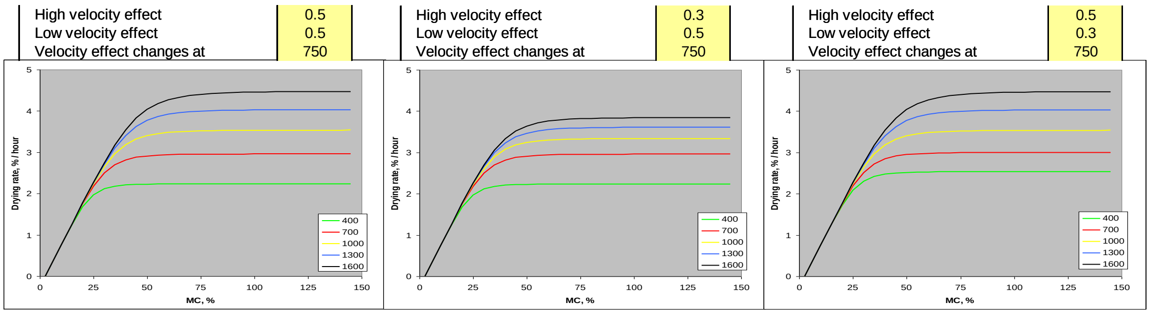
where fv is a velocity factor. Drying during the constant rate period is proportional to this factor (see previous section)

A value of 0.5 is a good starting point for the VelocityEffect coefficients. An expected range might be 0.3 to 0.7. Berberovic (2007) used 0.5 for both for hemlock. Milota and Tschenitz (1990) use 0.5 (high) and 0.3 (low) with a change at 1361 ft/min.

Increasing the value of HighVelocityEffect causes the rate at high moisture content to increase for velocities greater than ChangeV. The lines on the graph will spread further apart.

Increasing the value of LowVelocityEffect causes the rate at high moisture content to decrease for velocities less than ChangeV. The lines on the graph will spread further apart.

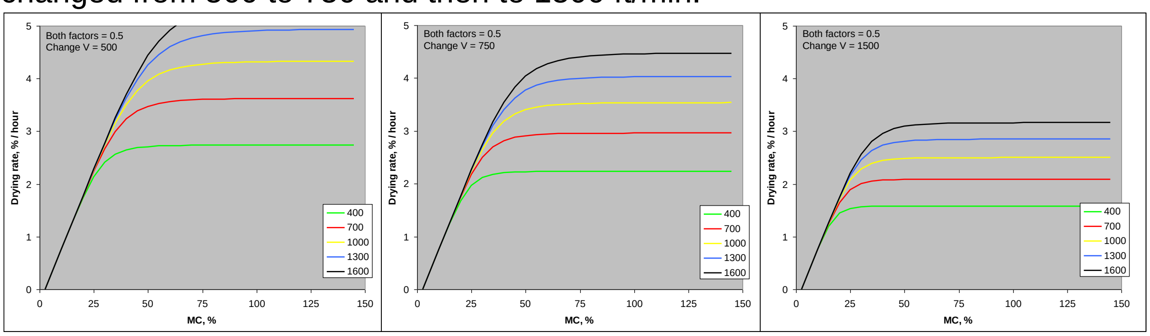
In the center chart below, the upper lines are closer together than in the left chart because the HighVelocityFactor was reduced. In the right chart below, the lower lines are closer together because the LowVelocityFactor was reduced.




### Velocity effect changes at

ChangeVelocity is the dividing point between when the Low and High VelocityEffects are used. Selecting a value in the mid-range of the velocities at which the model will run works.

Note that even if HighVelocityEffect=LowVelocityEffect (both 0.5 for example), the selection of ChangeVelocity will affect the results. If ChangeVelocity is lowered, the drying rates will increase and there will be more difference due to velocity. This can be observed in the charts below as ChangeVelocity is changed from 500 to 750 and then to 1500 ft/min.




## Behavior at low MC

The values in cells D32 to D34 affect how the board will dry at low moisture content. Essentially, these parameters determine the slope of the black line in the figure above that intersects EMC.

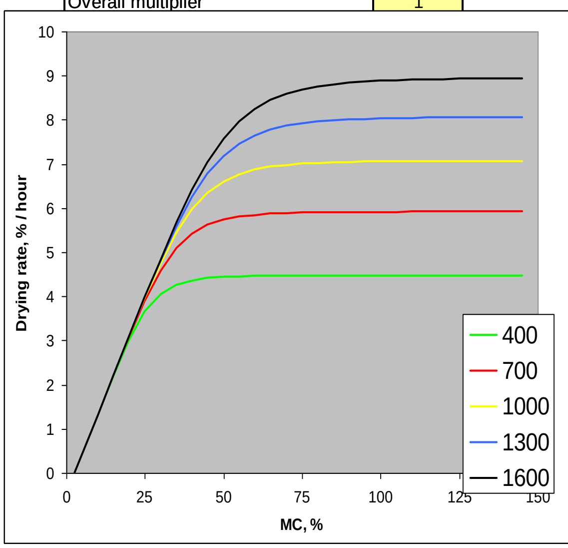
## EMC effect

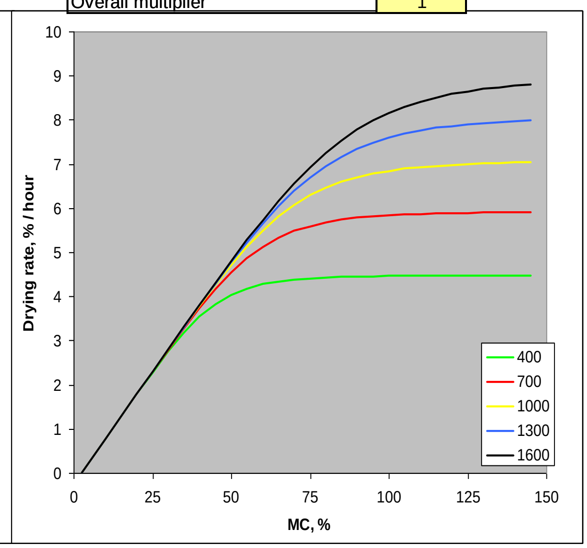
This controls how the drying rate changes at low moisture content. It directly affects the slope of the line in the falling rate period. Doubling the value of this coefficient

This chart below illustrates this for a change from 1.4 to 0.8.

| | |
|---|---|
| Behavior at high MC | |
| Drying rate | 0.4 |
| High velocity effect | 0.5 |
| Low velocity effect | 0.5 |
| Velocity effect changes at | 750 |
| Behavior at low MC | |
| EMC effect | 1.4 |
| Temperature effect | 0.55 |
| Reference temperature | 180 |
| Transition between high and low MC | 1 |
| Overall multiplier | 1 |

| | |
|---|---|
| Behavior at high MC | |
| Drying rate | 0.4 |
| High velocity effect | 0.5 |
| Low velocity effect | 0.5 |
| Velocity effect changes at | 750 |
| Behavior at low MC | |
| EMC effect | 0.8 |
| Temperature effect | 0.55 |
| Reference temperature | 180 |
| Transition between high and low MC | 1 |
| Overall multiplier | 1 |




## Temperature effect

## Reference temperature

These parameters affect how the drying rate at low MC varies with temperature. In general, the drying rate will increase with temperature. This factor allows the temperature effect to be different for different species.

An Arrhenius-type relationship is used to describe how diffusion varies with temperature. The temperature effect, TFactor, multipies this effect so that

$$\text{Rate} \propto \text{TFactor} * (\text{Exp}(T_{dry} / T_{ref}) - 2.71828) + 1$$

where the right hand side is equal to 1 for $T_{dry}$ = $T_{ref}$. The rate increases exponentially for $T_{dry}$>$T_{ref}$ and decreases exponentially for $T_{dry}$<$T_{ref}$. (Exp in the equation is the exponential function)

To use this factor, you need to know the drying behavior of the wood at two temperatures. Set Tref to be in between the two temperatures. Then adjust TFactor so the drying behavior is modeled at both temperatures. 2.5 is probably a good starting value for wood dried at higher temperatures. Lower values may work better for woods dried at lower temperatures.

There's no convenient way to show this in a chart but the following table shows the effect. The wet-bulb depression is 30°F for each dry-bulb temperature

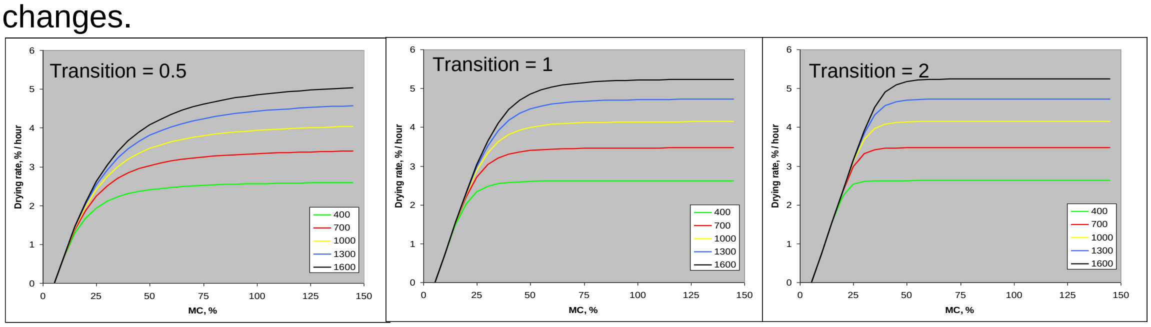
| | | | Drying rate at 50% MC | | |
|---|---|---|---|---|---|
| EMC Effect | Temper-ature Effect | Reference temperature | Td = 160°F | Td = 180°F | Td = 210°F |
| 0.5 | 1.5 | 180 | 2.12 | 2.41 | 2.71 |
| 0.5 | 2 | 180 | 2.02 | 2.41 | 2.80 |
| 0.5 | 2.5 | 180 | 1.92 | 2.41 | 2.89 |
| 0.75 | 2.5 | 180 | 2.81 | 3.43 | 3.95 |

In the first three rows, TemperartureEffect was increased and the drying rates at the higher and lower temperature became further apart. The rate decreased below the reference temperature and increased above it. In the last row, the EMC effect was increased by 50%. Notice how each rate also increased by a little less than 50%. (it's not exactly 50% because of the transition factor).

## Transition

This value (cell D35) controls the shoulder of the curve. Instead of the drying rates suddenly changing from a horizontal line to a sloped line at the critical moisture content, an increasing value of this factor causes a smoother change. A high value (5) means the shape of the rate versus MC relationship makes a sharp turn from the constant rate period to the falling rate period.

The following chart illustrates a transition of 0.5, 1.5, and 5. Notice how the rate at high MC and the rate at low MC are not changed. The shape of the transition changes.



Changing the transition can have an affect the drying rate because the curves have lower values in the mid-MC range.   This can be compensated for by increasing the OverallMultipier.

Changing the transition will cause the velocity effect will extend to lower moisture contents.

### Overall multiplier

This value (D36) is a fudge factor.  If the all the other factors are set correctly, then this can be used to increase or decrease the drying rate.  It simply multiplies the calculated drying rate by the value in the cell.  Run the model and if it dries too fast, reduce this value.   Always set this to one when developing all the other parameters and use it when you are pulling your hair out and give up.

## Graph

The graph will show what the model will use for drying rates of individual boards. It plots drying rate versus moisture content for several air velocities.

Enter the temperatures at the top in dull yellow and press the update button.  The graph will update to reflect the correlation selected in cell C4.  The values in the table are used if “Custom” is selected.

The graph is for an individual board.  Each board in the kiln will be exposed to a different dry-bulb temperature, wet-bulb temperature, and perhaps air velocity. Each board may have a different moisture content.  The model steps through time and calculates these things each board, then makes the same calculation as is shown on this graph to get the drying rate for each face of each board.  When the two faces of a board are exposed to different conditions (especially in the top and bottom layers) there will be a different moisture loss at each face.  In this case, them model calculates only one moisture content for a board for the next time step in the program.

## Wood properties page

This page is used to describe the properties of the wood in the kiln. The tables in the lower part show the initial values used in the most recent simulation for initial MC, specific gravity, initial temperature and thickness. Each cell is a property for one board. Scroll down the page to see the different properties. Scroll across to the right to see the values for each unit. Unit 1 is on the left side of the left track in the kiln, unit 2 is to its right, etc. If there are two units per track, then units 1 and 2 are on the left track in the kiln and units 3 and 4 are on the next track to the right, etc. Tracks and units per track were entered on the "Kiln and Stacking" page. Fans in the forward direction means the air moves from left to right through the units.

In the upper part of the page (yellow cells), an average and standard deviation are entered for each property. Clicking the large gray button will cause the tables in the lower part of the page to be filled in (the simulation will do this when it executes if the button is not pushed) based on the values (means and standard deviations) in the upper part of the page. They are normally distributed and assigned randomly. The normal assumption may not be valid and someday the assignment of properties might be improved. Also, the assignment of one property is independent of the others. For example, basic specific gravity has no impact on the distribution of moisture content; whereas, in reality boards with higher specific gravity often have lower initial moisture content.

Uncheck any the four boxes to disable standard deviation (make SD = 0). This will make the initial moisture content for every board equal to the mean (setting standard deviation = 0 would do the same thing). Having no wood variability makes these things easier to see in the results when looking at effects due to the kiln, stacking geometry, and schedules.

Board width is the same for all boards (no variability). Board length is not used in the simulation (it's there to make you feel good).

When the "Do not overwrite values below" box is checked, the large gray button is non functional and the simulation will not change the initial values. The box is used to run the simulation more than once with exactly the same wood data. If the tracks, units per track, unit width, or unit height is changed, the box must be unchecked before running the simulation. If the grey button is pushed, the box can be rechecked. This ensures that the information on the wood propeties page matches the kiln configuration.

You can custom-enter values for the data in the lower part or cut and paste them from another program. In this case only the value for board width is used from the top of the page. Read the section on custom entering prior to trying this.

## Moisture content

Values are in %.  The upper value is the mean moisture content on a dry basis for the wood in the kiln.  Dry basis means that at 50 percent moisture content, 1/3 of the mass is water and 2/3 is bone dry wood.  At 100% dry-basis moisture content, the mass of the bone dry wood and the water it contains are equal.  For unsorted coastal Douglas-fir, 65% is a good value.  For unsorted Hem-fir, 90 to 120% is a good value.

The lower value is the standard deviation of moisture content in %.

Unchecking the box will cause all boards to start at the mean moisture content (standard deviation = 0).

## Specific gravity

Values are unitless.  The upper value is the mean basic specific gravity for the wood in the kiln.  This is the mass of the bone dry wood divided by the mass of a volume of water equal to the wood when it is the fully swollen (green) condition. Values can be found in the *Dry Kiln Operators' Manual* or the *Wood Handbook.* For Douglas-fir, 0.45 is a good value.  For unsorted Hem-fir, 0.42 is a good value.

The lower value is the standard deviation of specific gravity.  10% of the value of specific gravity is not a bad guess.  So 0.045 for Douglas-fir, etc.

Unchecking the box will cause all boards to have the same specific gravity (standard deviation = 0).

## Temperature

Values are in °F or C as indicated in cell D8.  The energy change from ice to water is not accounted for so model will not simulate the thawing of ice in wood.

The upper value is the initial temperature for the wood in the kiln.  Enter the ambient temperature for your region unless some other value seems better.

The lower value is the standard deviation of temperature.  Zero or one are probably good values.

Unchecking the box will cause all boards to have the same initial temperature (standard deviation = 0.

## Thickness

Values are in inches or millimeters as indicated in cell E8.

The upper value is the thickness of the boards in the kiln. Enter the rough green target size.

The lower value is the standard deviation of thickness.

Unchecking the box will cause all boards to have the same thickness (standard deviation = 0.

### Width

Values are in inches or millimeters.

This is the width of the boards in the kiln. All boards are the same width so the standard deviation of width is zero.

### Length

This value is not used in the simulation. To simulate lumber of different lengths in different units, it would be necessary to input the wood properties for each unit (because wood of different lengths will have different properties) or run the simulation more than once with different wood proporties.

### How to custom-enter values for wood properties

You can custom-enter (type in or cut and paste) values for the data in the lower part of the wood properties worksheet. Check the "Do not overwrite values below" box to prevent the simulation from overwriting what you entered.

Before custom-entering data,

1. Uncheck the box "Do not overwrite values below".
2. Make sure all setting on the "Kiln and Stacking" page are correct.
3. Click on the large gray button to format the wood properties page.
4. Check the "Do not overwrite values below" box to prevent the simulation from overwriting your custom-entered values.
5. Type MC, SG, Temperature, or Thickness directly in for each board or cut and paste from another program.

You can mix and match – use the large gray button to set the values (when you do step 3 above), then modify the boards you want to change.

## Schedule page

This page is used to describe the drying schedule and a few other things that happen during the simulation. The type of schedule (MC or time), how the kiln changes temperature (step or ramp between set points), and whether the control is based on the entering- or leaving-air temperature.

When all the worksheet pages with bright yellow tabs (bottom of screen) have been filled in, the gray button can be used to start the simulation.

## Schedule type

There are two types of drying schedules in common use – *time*-based schedules and *moisture content*-based schedules. A time schedule is most common for softwoods. Some headings will change when you change the schedule type.

Time schedule – When this is selected, the desired values for dry- and wet-bulb temperatures and fan speed change based on the times entered. Cell B11 will automatically set to time=0. Following times must be in increasing order.

Moisture content – When this is selected, the desired values for dry- and wet-bulb temperatures and fan speed change based on the moisture content of the wood. When the wood moisture content decreases to the value in the schedule, desired values change. Cell B11 will automatically set to MC=500 which may be confusing. An example may help. In moisture content-based schedule below, 140/120 will be held from green to 50%, 160°F/135°F from 50% to 40%, 170°F /135°F from 40% to 30% etc.

| | | | |
|---|---|---|---|
| Schedule type | MC | (set before entering schedu | |
| Set point change | Step | | |
| Side measured | Entering | | |
| Kiln Schedule | Interval | | |
| Step | MC | Dry-bulb | Wet-bulb |
| | % | °F | °F |
| 1 | 500 | 140.0 | 120.0 |
| 2 | 50 | 160.0 | 135.0 |
| 3 | 40 | 170.0 | 135.0 |
| 4 | 30 | 180.0 | 140.0 |
| 5 | 20 | 180.0 | 140.0 |
| 6 | 15 | 180.0 | 160.0 |

Only stepped schedules (no temperature ramping in cell B6) work with moisture content-based schedules.

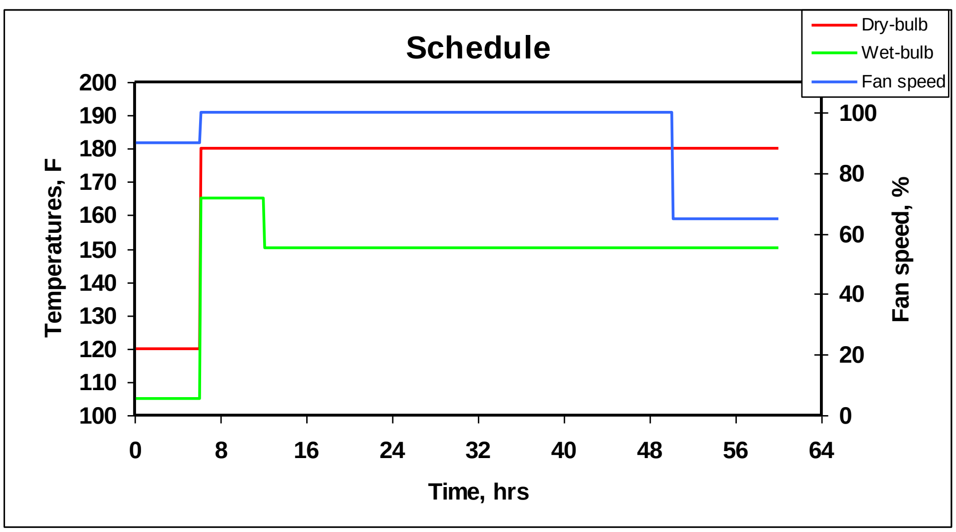
The simulation does not support hybrid schedules in which the first part of the schedule is time-based and the second part is moisture based.

## Set point change

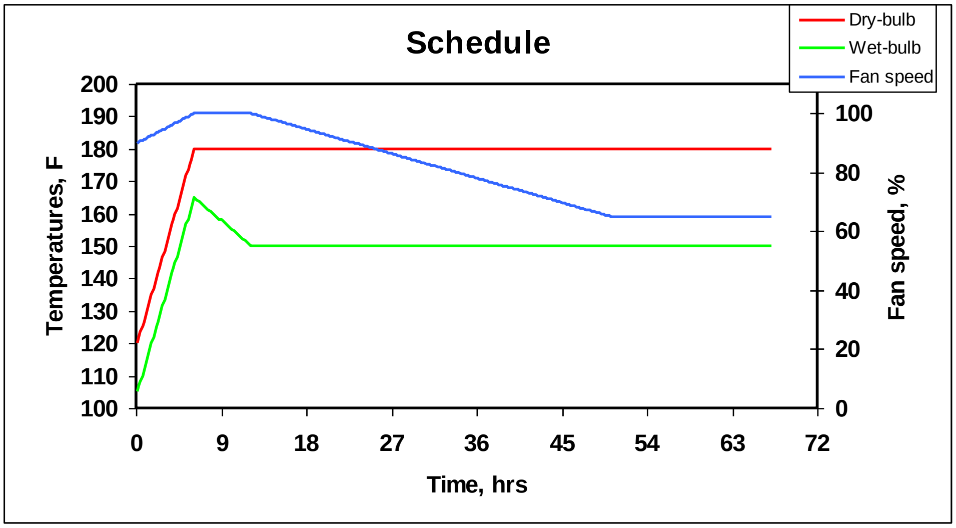
Set points are the desired values for the dry-and wet-bulb temperatures. These change during drying and there are two ways the change is commonly made – stepped or ramped. The following schedule is used for the example graphs below.

| Step | Time hrs | Dry-bulb °F | Wet-bulb °F | Fan speed % |
|---|---|---|---|---|
| 1 | 0 | 120.0 | 105.0 | 90 |
| 2 | 6 | 180.0 | 165.0 | 100 |
| 3 | 12 | 180.0 | 150.0 | 100 |
| 4 | 50 | 180.0 | 150.0 | 65 |

Step – When this is selected the desired values are constant throughout a schedule step.




Ramp - When this is selected desired values change gradually and reach the values for the next schedule step at its start.

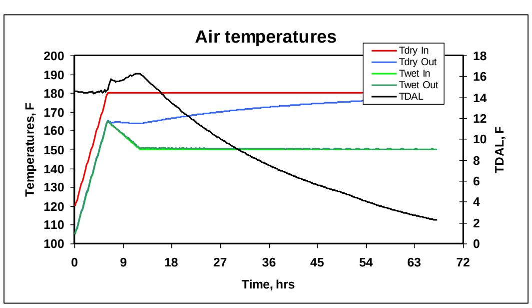


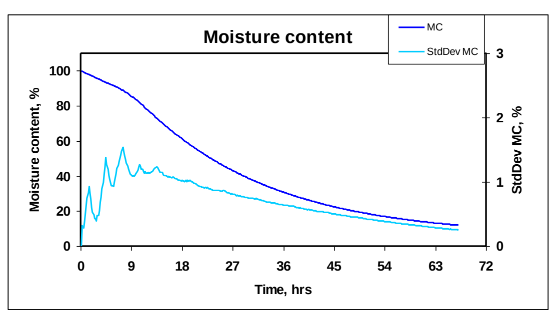

## Side measured

The dry-bulb temperature can be measured on the side where the air enters a track of lumber or where it exits a track. The examples below are for the following schedule (ramped).

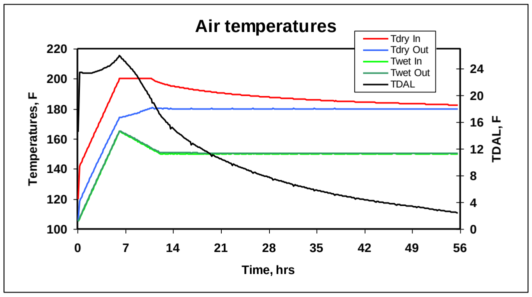
| Step | Time hrs | Dry-bulb °F | Wet-bulb °F | Fan speed % |
|---|---|---|---|---|
| 1 | 0 | 120.0 | 105.0 | 90 |
| 2 | 6 | 180.0 | 165.0 | 100 |
| 3 | 12 | 180.0 | 150.0 | 100 |
| 4 | 50 | 180.0 | 150.0 | 65 |

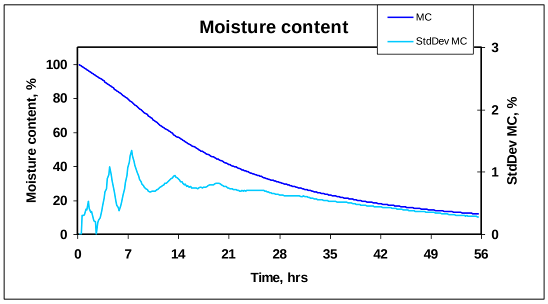
Entering – In this case the air entering a track will be at the set point temperature. Note how the red line (entering air temperature) follows the dry-bulb set point while the blue line (exiting-air temperature) rises with time because the drying rate slows at lower moisture content and the temperature drop across the load decreases.



Exiting – In this case the air entering the track will be higher than the setpoint so that the air leaving the track is at the set point. Note how the blue line (exiting-air temperature) follows the dry-bulb set point while the red line (entering-air temperature) decreases as the drying rate decreases.




Also notice that even though the written schedule is the same, the choice of entering- or exiting-air control makes a large difference in how the kiln operates.

## Interval

The values entered will be different depending if a MC- or time-based schedule is selected in cell B5. The headings in B9-B10 will change to match your entry in Cell B5.

Time based – the first value will be set to zero. All other values should be greater than the previous value.

> Step schedule - When the time reaches the value, the set point will be used.
>
> Ramp schedule - In a ramp schedule, the set point will change linearly between values. For example, if the times 12 and 24 hours have temperatures of 100 and 200F, then the setpoint will be 100°F at 12 hours, 125°F at 15 hours, 150°F at 18 hours, 175°F at 21 hours and 200°F at 24 hours.

MC-based – the first value is set higher than the wood MC (it is set to 500%), then the values you enter should decrease. When the average wood MC reaches the value, the corresponding setpoints will be used. Ramp schedules are not valid with MC-based schedules.

## Dry-bulb

This is the desired temperature for the dry-bulb temperature. It is the entering or leaving-air temperature, depending on what was selected in cell B7.

## Wet-bulb

This is the desired temperature for the wet-bulb temperature in the kiln. The wet-bulb temperature does not change much from one side of the kiln to the other so no distinction between the entering and leaving wet-bulb temperature is made. The simulation will calculate small changes in the wet-bulb temperature across the load during warm up and due to reheat coils.

## Fan speed

Enter the fan speed as a percent. This will give an airflow through the load that is based on the maximum air speed the kiln can achieve (cell B31 on the "Kiln and Stacking" page). If you entered 1500 ft/min in cell B31 and 50% for the fan speed, then the airspeed through the load will be 750 ft/min.

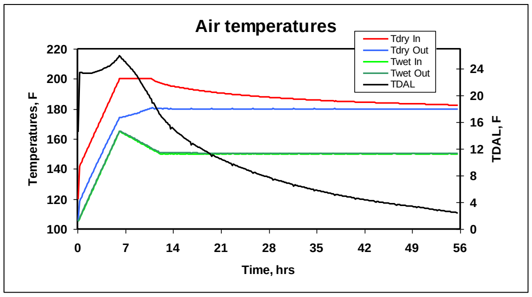
## Max Dry-bulb

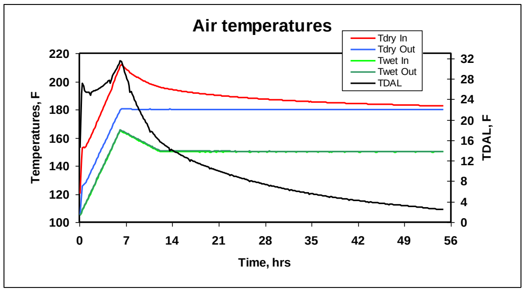
This is the maximum dry-bulb allowed on the entering side of the kiln. This value should be set on exiting-air schedules to prevent the entering air temperature from exceeding reaching a value higher than is possible in your kiln (because of steam supply or coil size, etc). It is also used in kiln controllers to prevent a high entering air temperature from damaging the lumber. This value has no effect when the control is based on entering air. Set the values large to disable them. For example, 500°F or 300°C for maximum dry-bulb temperature.

The effect of limiting the maximum dry-bulb temperature can be see in the chart below which was run with the following schedule.

| Kiln Schedule | | | | | Max | Max |
|---|---|---|---|---|---|---|
| Step | Time | Dry-bulb | Wet-bulb | Fan speed | Dry-bulb | Tw depr |
| | hrs | °F | °F | % | °F | °F |
| 1 | 0 | 120.0 | 105.0 | 90 | 140.0 | 35.0 |
| 2 | 6 | 180.0 | 165.0 | 100 | 200.0 | 35.0 |
| 3 | 12 | 180.0 | 150.0 | 100 | 200.0 | 50.0 |
| 4 | 50 | 180.0 | 150.0 | 65 | 200.0 | 50.0 |

At hour 7, note how the entering dry-bulb stays at 200°F in the chart on the left. The chart on the right show the entering temperature reaching over 210°F at 7 hours when the limits were set to 500°F.




## Max Tw depr

This is the maximum wet-bulb depression allowed on the entering side of the load. It is used in some kiln controllers when controlling on the exiting air to prevent a large wet-bulb depression from damaging the lumber. This value has no effect when the control is based on entering air. Set the values large to disable them. For example, 100°F or 50°C for wet-bulb depression.

## Ending MC

Cell N9. The simulation will stop when the lumber reaches this moisture content unless it reaches the ending time first.

## Ending time

Cell N10. The simulation will stop when the drying time reaches this value unless the ending MC is reached first. Set this value high if you want the simulation to run to a certain ending MC.

## Upper MC limit

Cell N13. Boards with a moisture content higher than this value will be counted as wet. They will appear green in the output

## Lower MC limit

Cell N14. Boards with moisture content lower than this value will be counted as overdried. . They will appear red in the output Boards in between the two MC limits will be counted as correctly dried and appear black in the output.

## Initial fan direction

Cell N17. Select “Forward” or “Reverse”. Forward will cause the air to go from left to right through the lumber.

## Fan change times

Cells N18 to N22. These are the times at which the first five fan reversals will occur. These are not time intervals – they are times in the simulation. See example below.

## Interval to end

After the first five fan direction changes, fan reversals will occur at the interval entered in cell N23. See example below.

Fan example - the following input will cause the fans to start in forward, change to reverse at 1.5 hours, change to forward at 4.5 hours, and continue to charge every 3 hours.

| | | |
|---|---|---|
| Initial fan direction | Forward | |
| Fan change 1 | 1.5 | hr |
| Fan change 2 | 4.5 | hr |
| Fan change 3 | 7.5 | hr |
| Fan change 4 | 10.5 | hr |
| Fan change 5 | 13.5 | hr |
| Interval to end | 3 | hr |

## View results at

These are the times at which the simulation will pause and the results up to the time indicated can be viewed. After the first five selections, the simulation will stop at regular intervals. This works the same as the fan settings.

The following input will cause the simulation to stop at 1, 4, 8, 16, 25, 35, 45, etc hours.

| | | |
|---|---|---|
| View results at | 1 | hr |
| View results at | 4 | hr |
| View results at | 8 | hr |
| View results at | 16 | hr |
| View results at | 25 | hr |
| Interval to end | 10 | hr |

After stopping to view the results, restart the simulation with the resume button (right below). This will continue the simulation as if no disruption occurred.

Do not change values in the Excel cells if you intend to continue the simulation. This will either have no effect or it might cause unexpected results.

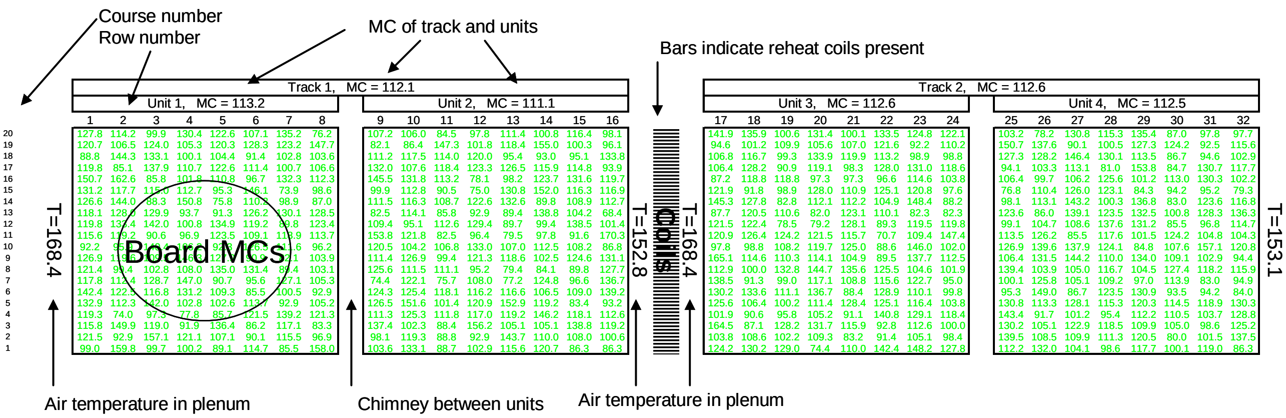
Pressing the left button will restart the simulation at time = 0. If the ending time or moisture content has been reached, pressing the Resume button will result in a message to this effect.

| | |
|---|---|
| Start simulation at time = 0 | Resume Simulation |

For those familiar with Excel – each button above starts a macro. When the time to view results is reached, the macro stops after all of the dryer settings, temperatures, moisture contents, etc are saved to a hidden worksheet page. The resume button causes a macro to read all the settings and continue the simulation.

## Output Picture

This page is updated each time program execution stops and will display a picture of the kiln cross section.  For example, the output below shows a double track kiln with the lumber placed two units wide each track.   The picture adusts to the dimensions input on the Kiln and Stacking page.




The average MCs for each track and unit are marked.

The MC values for each board are shown.  These are diplayed in green if above “upper MC limit” on Schedule page and in read if they are below the “lower MC limit”  on Schedules page.  Blue is used for values between within the desired MC range.

The air temperatures in the plenums are shown.

The stripes or bars appear when coils are present as set on Kiln and Stacking page.

## Output Graphs

This page is updated each time program execution stops and displays graphs of interest.  These include

Drying schedule

MC and standard deviation of MC versus time
Average board MC across load
Average MC vertically (by layer)
Histogram of board moisture contents

Air temperature versus time (Td and Tw in and out and TDAL)
Air temperature versus time (Td in left and right plenums and TDAL)
Average air temperature across load