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SIMULATION OF WOOD COLOUR DEVELOPMENT AND ENERGY USE IN KILN DRYING OF SOFTWOOD TIMBER

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Abstract: A computer model was developed to simulate energy use and wood colour change in kiln drying of softwood timber. The model has been applied for a temperature range from 50°C to 70°C and an airspeed from 3m/s to 9m/s. The model is based on theoretical analysis and contains components such as kiln configuration and practical operations. From the model simulation, optimised drying schedules for minimising colour change and energy use are recommended.

Keywords: colour change, wood drying, kiln brown stain, energy use, computer model

INTRODUCTION

The wood colour change (darkening) during drying is a major issue for producers of high value appearance grade timber. The development of surface discolouration such as kiln brown stain (KBS) can cause significant economic loss and is particularly problematic in high temperature drying.

There are a number of potential methods to reduce the KBS problem from the previous research. Methods such as sap displacement (Dieste and Williamson, 2002; Kreber et al, 2001), biological treatment (McCurdy et al., 2002) have been tested as a way to reduce the concentration of reactants and therefore colour formation. These methods have been successful in the laboratory scale but are not viable for a commercial operation. Methods such as compression rolling (Kreber and Haslett, 1997) and chemical inhibitors (Kreber et al., 1999) also show benefits but are also not commercially viable.

Some studies have shown that vacuum drying (Wastney et al., 1997) and modified drying atmospheres (Pang and Li, 2005) can reduce the formation of kiln brown stain. These methods require specialist drying equipment that many operators may be reluctant to adopt or the owners are unable to invest in. Further research is being performed in this area to develop most viable drying medium as reported by Pang and Li (2006).

The simplest solution to kiln brown stain is to reduce the temperature of the wood during the drying process, through the use of lower temperature drying schedules. The reduction in temperature however comes at a cost, with lower production levels and higher energy use for drying the same volume of timber. Previous studies have suggested that slower straight drying schedules are not commercially viable (Kreber and Haslett, 1998) but with better understanding of the KBS formation and quantification of the affecting factors (McCurdy et al. 2003; 2005), optimised drying schedules can be possible in producing bright coloured wood at acceptable drying costs. It is therefore worth determining the most efficient way of designing drying schedules to minimise colour development.

The recent development of an equation describing colour development in *Pinus radiata* (McCurdy et al., 2005) has made it possible to quantify the development of colour. The objective of the work presented in this paper is to develop a computer model that can include the energy use, drying time and colour changes for various drying schedules, thus can be used to optimise low temperature drying schedules for appearance grade timber. In this way, drying schedule can be selected in order to achieve maximum economic gains by analysing added value of bright coloured wood and costs of energy use and drying time.

METHODS

The model is based on the kiln design as shown in Fig 1 and comprises three main parts: the stack model, the kiln energy model and the colour development model. Various schedules which are likely to be used in commercial drying were simulated and analyzed using the model developed in this work with MatLab software.

The stack model simulates the moisture content, humidity and temperature change through the stack during drying based on the schedule conditions. The humidity and temperature data from this model are input into the kiln energy model to determine the energy requirements. In the meantime, the temperature data is input into the colour change model to determine the wood colour during drying.

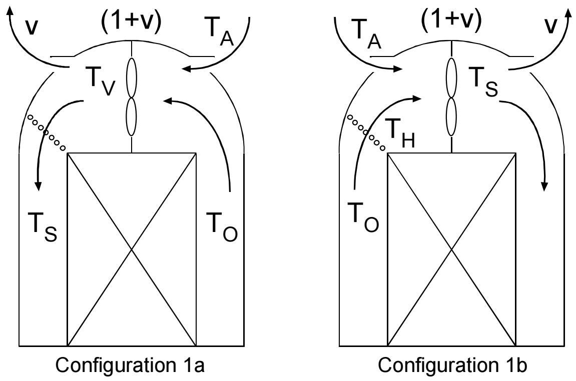

Fig 1. Kiln configuration showing both airflow directions. (1a). Humid air is exhausted before heating coils; (1b). Humid air is exhausted after heating coils.

Stack Model

The stack simulated had a total timber volume of 40m^3 made up from 40mm thick boards. The computer model for simulating the drying of the wood stack used the lumped parameter approach based on van Meel's batch drying equations (van Meel, 1958). The form of the batch drying equations was based on those proposed by Pang (1994) and Nijdam (1998). However, the model used in this work used different relationships to describe the characteristic drying curve as it was used to simulate lower temperature drying.

The characteristic drying curve equation in this work was derived from single board drying data from previous drying experiments (McCurdy et al, 2003) in the temperature range being simulated. This resulted in a two stage quasi-linear falling rate curve as shown in Fig. 2. This diagram shows that for low temperature drying the characteristic drying curve is concave up and for higher temperatures it is concave down.

As for high value grade timber, low temperature schedules are normally used, and thus the concave up curves are employed. The equations that describe the characteristic drying curves (*f*) are:

$$f(\Phi) = \frac{(1 - f_{0.4})}{0.6} \cdot (\Phi - 0.4) + f_{0.4} \quad (0.4 \le \Phi \le 1)$$
$$f(\Phi) = \frac{f_{0.4}}{0.4} \cdot \Phi \quad (\Phi < 0.4) \qquad (1)$$

Where the curves change the form at the normalised moisture content (Φ) of 0.4 and this change point for the drying curve ($f_{0.4}$) is determined by:

$$f_{0.4} = 0.0078 e^{0.05 T_{DB}} + 0.35(\psi - 0.54) \qquad (2)$$

In this equation T_{DB} is the dry bulb temperature of the drying schedule (°C) and ψ is the relative humidity of the drying schedule.

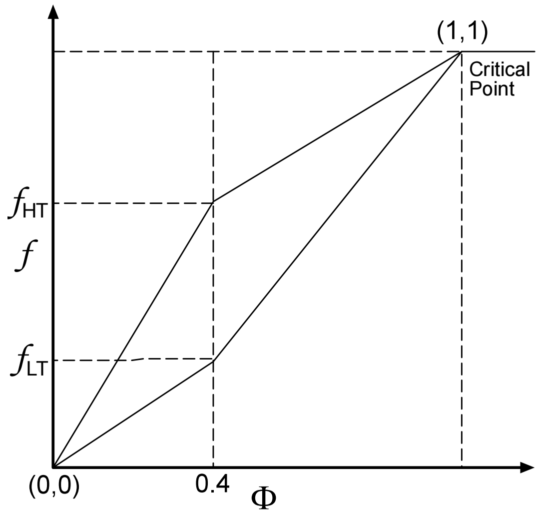

Fig. 2. Two stage quasi-linear characteristic drying curves for wood drying in the falling drying rate periods. The concave up curves are for low temperature drying and the concave down curves for high temperature drying.

Kiln Energy Model

Two kiln configurations as shown in Fig.1 were considered in this study, the first of which had a heating coil on one side of the kiln and the other had two heating coils that could be switched depending on the air flow. The energy requirements in the kiln drying considered in this model were the process heat required to maintain the schedule, the process heat required to cover the heat loss and the electricity required to drive the fans

The diagrammatic representation of the first configuration is shown in Fig.1 for both directions of airflow. The second configuration is effectively the same as configuration Fig.1a for both airflow directions where the humid air is always exhausted before heating coils. In these diagrams v is the venting ratio, which is the proportion of the stream passing through the stack that is vented. This is determined from a mass balance on the airstreams to give the following:

$$v = \frac{Y_{GO} - Y_{GS}}{Y_{GS} - Y_{GA}} \qquad (3)$$

Where Y_{GO} is the air humidity at the stack outlet, Y_{GS} is the air humidity at the stack inlet and Y_{GA} is the ambient air humidity. The venting ratio is the same for both of the configurations regardless of airflow directions.

The temperatures of the airstreams in (T_S) and out (T_O) of the stack are determined by the stack model and the schedule being tested. The temperatures T_V

and T_H and the process heat requirements to maintain the kiln schedule are calculated from a heat balance. For configuration shown in Fig.1(a), the temperature of the vented air, T_V, is calculated from the following balance:

$$T_V = \frac{C_{PYO}T_O + vC_{PYA}T_A}{(1+v)C_{PYV}} \tag{4}$$

Where T_A and T_O are the ambient and stack outlet temperature respectively. C_{PY} is the humid heat of the airstreams.

With the venting temperature determined the heat required to maintain the conditions in the kiln is simply the heat required to raise the temperature of the air from T_V to the dry-bulb temperature set point T_S:

$$Q_S^{1a} = C_{PYS}T_S - C_{PYV}T_V \tag{5}$$

Substituting Eq. (4) into Eq. (5) yields:

$$Q_S^{1a} = \frac{1}{1+v}\left[(C_{PYS}T_S - C_{PYO}T_O) + v(C_{PYS}T_S - C_{PYA}T_A)\right] \tag{6}$$

The heat supply for configuration shown in Fig. 1(b) can be calculated more directly as:

$$Q_S^{1b} = (C_{PYS}T_S - C_{PYO}T_O) + v(C_{PYS}T_S - C_{PYA}T_A) \tag{7}$$

Heat loss from a kiln makes up a small part of the total energy demand of the kiln so a number of assumptions have been made to simplify the model. It has been assumed that the kiln is perfectly sealed so that there are no fugitive emissions and that the heat loss from outside the kiln is only due to natural convection. The internal conditions inside the kiln are assumed to be uniform and at the schedule set point throughout the kiln. This will slightly over-estimate the internal heat transfer coefficient. Heat transfer through the floor of the kiln is assumed to be negligible. Finally it is assumed that the radiation heat loss is transferred to the immediate surroundings at the same ambient temperature used for the external convection calculations. This assumption means that the radiation heat transfer can be estimated with a radiation heat transfer coefficient analogous to the convective heat transfer coefficient.

The heat loss was calculated iteratively by solving the following equations:

$$Q_{loss} = \frac{T_S - T_A}{1/h_iA_e + \Delta x_w/k_wA_e + 1/(h_e+h_r)A_e} \tag{8}$$

$$T_{Wi} = T_S - \frac{Q_{loss}}{h_iA_e} \tag{9}$$

$$T_{We} = T_{Wi} - \frac{\Delta x_w Q_{loss}}{k_wA_e} \tag{10}$$

The heat transfer coefficients were calculated using standard heat transfer correlations (Holman, 1992). The external and radiation heat transfer coefficients were recalculated on every iteration due to their dependence on the external wall temperature.

The fan energy requirements were based entirely on the pressure drop through the stack, ignoring the pressure drop in the rest of the kiln. The pressure drop was calculated using Bernoulli's equation:

$$p_S - p_O = \left(K_c + \frac{4fw_S}{D_H} + K_e\right)\rho\frac{u_f^2}{2} \tag{10}$$

The head loss due to contraction and expansion were assumed to be K_c=0.4 and K_e=1, respectively, based on the work of Nijdam (1998). The friction factor, f, was taken as 0.02 based on the work of Langrish and Keey (1996). The energy used by the fan to generate the required pressure drop is given by:

$$P_{Shaft} = \frac{(p_S - p_O)Q}{\eta_{fan}} \tag{12}$$

Where the fan efficiency η_{fan} was assumed to be 0.8 and the volumetric flow was given by:

$$Q = h_s l_s u_f \varepsilon (1+v) \tag{13}$$

Colour Change Model

The colour change model used was an empirical model based on colour change measurements (McCurdy et. al, 2005). The main assumption made in this model was that the important temperature for determining colour change is the wet-bulb temperature of the drying schedule when the normalised moisture content of the board is above Φ=0.4 and the dry-bulb temperature below this point. This simplification is based on experimental observation and it avoids the need to calculate the temperature at the evaporative front. The colour equation used is therefore:

$$\begin{aligned} \Phi \geq 0.4 &: \Delta E = f_{\Delta E}(T_{WB})\cdot \Delta t \\ \Phi < 0.4 &: \Delta E = f_{\Delta E}(T_{DB})\cdot \Delta t \end{aligned} \tag{14}$$

Where T_{GW} and T_{GD} are the wet-bulb/dry-bulb temperatures of the air adjacent to the wood surface, both in K. The colour change function is given by:

$$f_{\Delta E}(T) = a_4T^4 + a_3T^3 + a_2T^2 + a_1T + C \tag{15}$$

This equation is a 4th order polynomial fit to experimental data with the coefficients given in Table 1. This equation is valid over the temperature range 50-70°C and is plotted in Fig. 3.

Cost Calculations

The running costs of the schedules were determined from the cost of electricity (NZ$22/GJ), process heat (NZ$5/GJ) and depreciation (NZ$5000 p.a.) based on an operational time of 7000h/year.

Table 1. Coefficients for colour change in Eq.(6)

Coefficient	Magnitude
a_4	4.36×10^{-6}
a_3	-5.682536×10^{-3}
a_2	2.77672739
a_1	-6.02893983×10^{2}
C	4.90766422×10^{4}

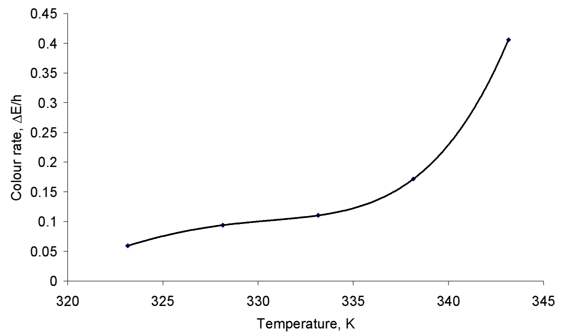

Fig. 3. Plot of colour rate function (Eq.15) between 50°C and 70°C.

RESULTS AND DISCUSSION

The computer model was run for a number of schedules with a dry-bulb temperature range of 50-70°C and an airspeed range of 3-9m/s with reversals every 6 hours. The schedules were initially analysed based on two criteria to reduce the number of schedules being tested. Firstly the total colour change produced in the wood during the schedule had to be less than ΔE=15 and secondly the moisture content variation across the stack had to be less than 20% (with a target moisture content of 10%). The schedules simulated that met both criteria are shown in Table 2.

Schedule Effects

The plot in Fig. 4 shows how the wet-bulb depression affects the level of colour change and the moisture content variation for schedules with a 70°C dry-bulb and 5m/s air speed. In the Figure, the colour change values can be found from the left-hand side y axis and the MC variation can be found from the right-hand side y axis, as indicated by the arrows. The simulations suggest that the effect on the moisture content variation is linear and the variation increases with decreasing humidity. This is due to the greater humidity and consequential drying rate variations through the stack that means the boards on the edge of the stack dry much more quickly than those in the centre.

The cause for the effect of the wet-bulb depression on the colour change is the drying time. Low humidity schedules dry the wood faster so there is less exposure to heat and therefore a shorter reaction time. There is a diminishing return on this effect as there is a diminishing gain in drying rate with increasing wet-bulb depression due to the effects of humidification through the stack.

Table 2. Simulated schedules that produced low colour development and moisture content variation

Schedule	DB (°C)	WB (°C)	Air Speed, (m/s)	Drying Time (h)
A	70	50	9	35
B	70	60	9	54
C	65	50	5	74
D	65	55	5	92
E	60	50	9	71
F	60	50	7	85
G	60	50	5	107
H	60	50	3	145
I	60	45	3	129
J	60	45	5	95
K	60	45	7	75
L	60	45	9	62
M	50	45	5	212
N	50	40	7	125
O	50	40	9	104
P	50	40	5	159
Q	50	40	3	218

The effect of the wet-bulb depression can also be explained by the wood surface temperature. Lower wet-bulb depression (higher wet-bulb temperature at a given dry-bulb temperature) means that in the early stages of drying the wood surface temperature is higher thus the colour change rate is higher. However, this effect is relatively less significant compared to the colour change occurring during the later stages of drying.

In these simulations the airspeed seems to have a minimal effect on the moisture content variation. It does however affect the both the colour change and the total schedule cost as shown in Fig. 5 for a 60/45°C schedule. In the Figure, the colour change values can be found from the left-hand side y axis, as indicated by the arrow.

Increased airspeed reduces colour change. This is similar to the effect of lower humidity in that the higher airspeed reduces the drying time. There is a slight diminishing return at high airspeeds but the effect is still strong.

The total schedule cost increases as the airspeed increases. This is mainly due to the increased electricity requirements from the fan motor. The relationship between airspeed and fan energy is non-linear and an examination of Eqs. (11) and (12) show that the energy increases with the cube of the airspeed. This means electricity costs increase rapidly as the airspeed is increased. This can be seen in the concave upward shape of the total schedule cost curve in Fig. 5 with values of schedule cost shown on the right-hand side y axis. There is a small effect from the depreciation component in this curve. This is due to the sorter drying time reducing the depreciation cost at higher airspeeds. This is the reason why there is little change in cost going from 3m/s to 5m/s.

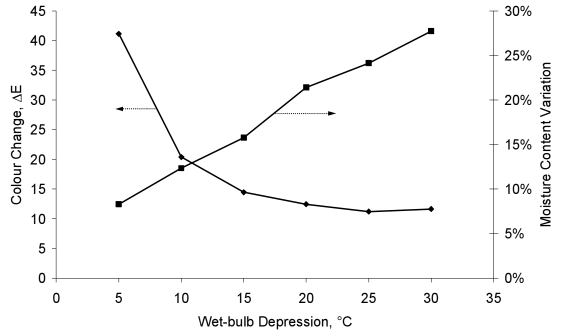

Fig. 4. Colour change and MC variation with wet-bulb depression for 70°C dry-bulb schedules at 5m/s.

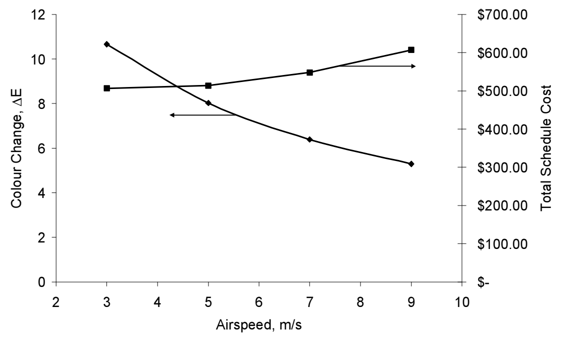

Fig. 5. The effect of airspeed on colour change and total schedule cost for a 60/45 schedule.

Kiln Configuration Effects

A comparison of the two kiln configurations simulated is shown in Fig. 6-8 in which the effects of wet-bulb depression, dry-bulb temperature airspeed on the cost difference between kiln configurations 1 and 2 are illustrated. As it was found that the total schedule cost for configuration 2 was always lower than that for configuration 1, the difference shown in the figures is the costs of configuration 1 being subtracted by the cost of configuration 2.

The wet bulb depression comparison is based on the schedules with 70°C dry bulb temperature and airspeed of 5m/s. The airspeed comparison is based on the 70/50°C schedules and the dry bulb comparison is based on a wet bulb depression of 10°C and airspeed of 5m/s.

The first thing to note about the effect of kiln configuration is that it is very small. With a total schedule cost of around NZ$500 a difference between configurations of NZ$15 is less than 5%. For this reason there is no justification for retrofitting existing kilns. There may also be no justification for having switching heating coils in new kilns due to the added capital cost. The best recommendation is to have heating coils either side of the fan in new kilns.

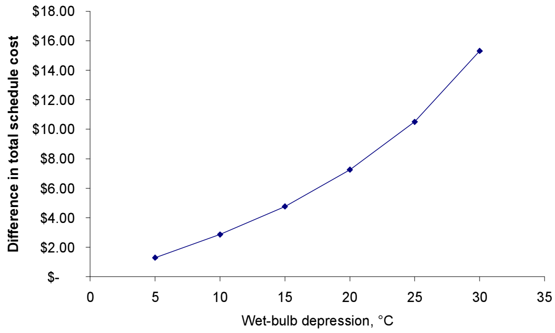

Fig. 6. Effects of wet-bulb depression on the cost difference between kiln configurations 1 and 2.

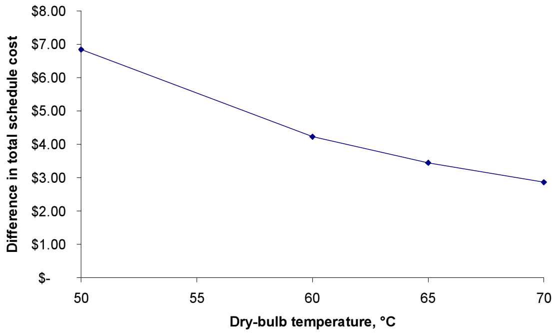

Fig. 7. Effects of dry-bulb temperature on the cost difference between kiln configurations 1 and 2.

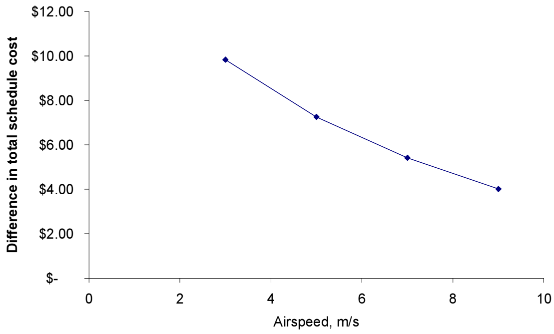

Fig. 8. Effects of airspeed on the cost difference between kiln configurations 1 and 2.

Putting the significance of the cost savings aside the results show that the configurations perform differently over the range of schedules. Increasing the wet-bulb depression increases the advantage of configuration 2. This is due to the greater venting requirements of low humidity schedules where more heating is required so the heating inefficiency of configuration 1b becomes more significant.

Increasing the airspeed reduces the difference between the schedules. This is probably due to two effects. Firstly the drying time is reduced so inefficiencies will accumulate over a shorter period of time and will therefore be lower. Secondly the humidification of the air passing through the stack will be lower at higher airspeeds so the venting ratio will be lower.

The effect of dry-bulb temperature is most likely due to the lower moisture carrying capacity of the lower temperature air meaning that more venting is required to maintain low temperature schedules. There may also be an effect of the fixed wet-bulb depression meaning the schedules relative humidity is actually different.

Best Schedules

The best performing schedules of those simulated are shown in Table 3. The annual profit shown is relative only and is calculated by subtracting the total schedule cost per m^3 of wood from a premium of NZ\$20/m^3 for high quality wood. The profit is affected by the total schedule cost and the drying time (which determines the annual volume dried).

Table 3. Performance of the simulated schedules.

DB (°C)	WB (°C)	u_f (m/s)	Profit p.a.	ΔE	Final MC (kg/kg)
70	50	9	$137,228	8.4	8.3-10.1
65	50	5	$67,800	9.2	8.6-10.2
60	45	7	$61.765	6.4	8.3-10.0
60	45	5	$51,304	8.0	8.3-9.9

CONCLUSIONS

The results of this work have shown that for a standard batch wood drying kiln design with overhead fans and heating coils, the placement of the heating coils only has a minor affect on the efficiency of the kiln. The model does however provide a basis for testing other kiln configuration against the standard design.

Some recommendations can be made for schedule design within the range of conditions tested. Firstly, high airspeed reduces colour change, though very high airspeeds will probably show diminishing returns and high costs.

In order to achieve the maximum economic benefits, a dry-bulb temperature of 60°C to 70°C is recommended with a wet-bulb depression of 15°C to 20ºC.

NOMENCLATURE

A_e	external surface area of kiln	m^2
C_{PY}	humid heat	kJ/(kg K)
D_H	hydraulic diameter	m
f	friction factor	
f	relative drying rate	
$f_{\Delta E}$	colour change function	ΔE/h
$f_{0.4}$	relative drying rate at Φ=0.4	
h_e	external convective heat transfer coefficient	$W/(m^2 K)$
h_i	internal convective heat transfer coefficient	$W/(m^2 K)$
h_r	external radiation heat transfer coefficient	$W/(m^2 K)$
h_s	stack height	m
k_w	thermal conductivity of kiln wall	$W/(m^2 K)$
K_c	head loss due to contraction	
K_e	head loss due to expansion	
l_s	stack length	m
p	pressure	Pa
P_{Shaft}	fan shaft power	kW
Q	volumetric flow of fan	m^3/s
Q_{Loss}	heat loss	kW
Q_S	heat supplied to kiln	kW
Δt	time interval	s
T	temperature	°C or K
u_f	fillet space velocity	m/s
v	venting ratio	
w_s	stack width	m
Y	humidity	kg/kg
Δx_w	kiln wall thickness	m

Greek letters

ε	void space	
Φ	normalised moisture content	
η_{fan}	fan efficiency	
ρ	air density	kg/m^3
ψ	relative humidity	

Subscripts

DB	dry-bulb
WB	wet-bulb
A	ambient
G	gas
H	heater
O	stack outlet
S	stack inlet
V	vent

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