Received: 13 September 2018 | Revised: 31 January 2019 | Accepted: 14 February 2019

DOI: 10.1002/fam.2707

RESEARCH ARTICLE

WILEY

Relative humidity versus moisture content relationship for several commercial wood species and its potential effect on flame spread

Laura E. Hasburgh[1] | Steven T. Craft[2] | Ineke Van Zeeland[2] | Samuel L. Zelinka[1]

[1] Forest Products Laboratory, Madison, WI, USA

[2] CHM Fire Consultants Inc., Ottawa, Canada

Correspondence
Laura E. Hasburgh, Forest Products Laboratory, 1 Gifford Pinchot Drive, Madison, WI 53726, USA.
Email: lehasburgh@fs.fed.us

Funding information
Canadian Wood Council; U.S. Forest Service; American Wood Council, Grant/Award Number: NA

Summary

Recently, measured flame spread indices on commercial wood species tested per ASTM E84 were found to be lower than previously published data. One reason for this may be that the hygrothermal conditioning of the red oak calibrant required by the test standards for measuring flame spread was changed between 1973 and 1981. This paper examines how much variability there is in the moisture content of commercially important wood species at 50% relative humidity by collecting water vapor sorption isotherms. Additionally, the effect of moisture content on the flame spread was evaluated after conducting 14 tests with eastern white pine in accordance with CAN/ULC-S102 and four in accordance with ASTM E84 at four commercial test laboratories. For the sorption isotherms, it was found that the moisture contents at 50% relative humidity ranged from 6.8% to 11.4% moisture content and depended on the species and whether the specimens had been conditioned in absorption or desorption. The flame spread indices, as measured as different laboratories, also varied from 37% at 10.4% reported moisture content to 200% at 6.5% reported moisture content. The findings suggest that the wood moisture content and conditioning requirements of the standards are important test variables that affect the flame spread results.

KEYWORDS

flame spread, moisture content, sorption isotherm, wood

1 | INTRODUCTION

Two test methods are used in North America to determine the surface flammability characteristics of interior finish materials/products: CAN/ULC-S102 *Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies* used to regulate products in Canada and ASTM E84 *Standard Test Methods for Surface Burning Characteristics of Building Materials* used to regulate products in the United States.[1,2] The two standards are similar, placing materials in a 7.6-m-long tunnel that has gas burners at one end, which produce a steady heat release rate, and a fan to provide a known air flow. During the test, the flame propagates along the surface of the material. Windows along the tunnel allow the flame front to be measured as a function of time. The area under the flame-spread-distance-versus-time curve is used to calculate the flame spread index. The flame spread is calibrated so that the flame spread of cement board is 0 and so that the flame reaches the end of the tunnel in 5.5 minutes for red oak flooring conditioned to 7% moisture content (MC—calculated as m_{water}/m_{wood}). Table 1 provides a summary of the conditioning requirements for each standard. All tested materials are compared with the two reference materials, and the results provide what is termed the flame spread index (FSI). While the test methods are

TABLE 1 Summary of conditioning requirements in CAN/ULC-S102 and ASTM E84

Standard	Material	Requirement	Comment
CAN/ULC-S102	Red oak calibrant	Moisture content of 7% (±1%) determined using oven-dry method	A range of 6% to 8% MC is permitted, and there is no requirement to condition to equilibrium; therefore, moisture gradients can be present in the wood.
	Test sample	Conditioned to constant mass at 23 ± 2.8 °C and 50 ± 5% RH. Constant mass is defined as <1% change in 72 h	Equilibrium moisture content (EMC) at 23°C and 50% RH is approximately 9.2% for wood.[3]
ASTM E84	Red oak calibrant	Moisture content of 7% (±0.5%)	A range of 6.5% to 7.5% MC is permitted, and there is no requirement to condition to equilibrium; therefore, moisture gradients can be present in the wood.
	Test sample	Conditioned to constant mass at 23 ± 2.8°C and 50 ± 5% RH	Same temperature and relative humidity as CAN/ULC-S102. However, "constant mass" is not defined.

similar, the constant used in the equation to calculate flame spread index in ULC-S102 results in a 9% greater FSI value for a given area under the flame-spread-distance-versus-time curve when compared with the ASTM E84 FSI calculation method. It should be noted that the terminology between the standards does vary with the results being referred to as flame spread index in ASTM E84. CAN/ULC-S102 refers to the results from an individual test as the flame spread value (FSV) and a flame spread rating (FSR) when three tests are averaged. Here, for simplification, the term "flame spread index" is used.

At the vent end of the tunnel, a photoelectric device measures the opacity (density) of the smoke. This provides an indication of the amount of smoke released from the burning material. Similar to the calibration of the flame spread index, the smoke-developed classification is calibrated so that the inorganic reinforced cement board provides a classification of zero and red oak provides a classification of 100. All tested materials are compared with these two reference materials, and the results of the tests provide what is termed the smoke-developed index (SDI).

The MC of the material will affect the flame spread index; water within the wood near the exposed surface needs to be heated and then vaporized prior to wood combustion. Therefore, all other things equal, wood at a higher MC will require more energy input to reach combustion temperature and the flame spread index will be lower. Prior to 1973, ASTM E84 did not have a specified MC for the red oak calibration material or the test material, but rather stated that both materials be equilibrated in an environment at 21°C (70°F) and between 35% and 40% relative humidity (RH). By 1981, the standard had changed so that the red oak material was required to be equilibrated to a MC target (currently 7%), whereas the test material is not tested at a specific MC but is rather conditioned at 23°C (73°F) and 50% RH ± 5% RH. Because of this change, using the current method, the flame spread index of red oak as a test sample will likely be less than that determined during calibration since the wood MC of the test sample material will likely be greater than that of the calibration material. Furthermore, the interspecies variation in the hygroscopicity of wood will affect its MC in the test and, therefore, its flame spread index.

The relationship between the RH and the wood MC at a given temperature is referred to as the sorption isotherm.[3] Different wood species have a wide range of sorption properties; for example, Spalt reported a 22% difference in MC between basswood (*Tilia* sp) and white spruce (*Picea* sp) at 61% RH.[4] In addition to interspecies variation, sorption isotherms are also path dependent.[5-9] When wood is moved from a lower to higher RH (absorption), its equilibrium MC is less than if it were moved to the same RH but from a higher RH (desorption). Typically, two sorption isotherms are presented for wood: the "absorption isotherm" where the wood is equilibrated at higher RH from an oven-dry state and the "desorption isotherm" where the wood is equilibrated at lower RH from a wet initial state.[10-21] Although desorption isotherms are commonly plotted starting at an RH of 90% or 95%, true desorption isotherms need to be collected from a fully water-saturated state.[22] The absorption and desorption isotherms represent boundary MCs; if the RH is first increased, then decreased and then increased again, the actual MC will fall somewhere in between the two boundary isotherms.[6]

The fact that the sorption isotherms are both species dependent and hysteretic has implications for flame spread testing. Both CAN/ULC-S102 and ASTM E84 specify only the RH at which the specimens must be conditioned and not the actual MC. For wood, the result is that, in addition to the inherent variation in flame spread index between species, there will be an additional moisture effect because the samples will be tested at different MCs. Furthermore, the flame spread as measured by the two standard tests will also depend upon the previous conditioning/environmental history of the material. Lower flame spread indices will be obtained if the samples are placed in the conditioning chamber at a higher MC than targeted, as would be typical of kiln-dried lumber that commonly is dried to a target of 19%, to equilibrating at 50% RH.

In addition to inherent differences in the *equilibrium* MC caused by differences in species and conditioning, moisture variation between samples can also be caused by improper or incomplete conditioning. Even for small samples on the order of 20 mg, it takes many days for wood samples to reach true equilibrium after a change in RH.[23] Scaling upwards, the samples used in flame spread testing would require much longer to condition (eg, months) when they are a wood product. For ASTM E84, the samples are required to be conditioned to "constant mass," but there are no details given on the tolerance used to describe constant mass. While the CAN/ULC-S102 gives a

tolerance on the equilibrium criterion, "less than 1% change in total mass over 72 hours," this is greater than the maximum rate at which wood can absorb or desorb moisture at room temperature conditions, and so is not very useful for wood products. Guidance can be taken from ASTM D4933 *Standard Guide for Moisture Conditioning of Wood and Wood-Based Materials*, which states that the typical conditioning time required for 20-mm-thick solid wood specimen, initially at equilibrium at 50% RH and 20°C and exposed to 90% RH at 20°C, resulting in a MC increase from approximately 10% to 20%, would be approximately 60 days. As a rule of thumb, required conditioning time is proportional to the square of thickness.[24] Given the lack of details and rigor on the conditioning requirements within the standard for flame spread testing, the result is that in practicality, wood is not likely conditioned to true equilibrium, and therefore, the material will likely have a gradient in MC within its cross section. The gradient may be increasing or decreasing from the surface toward the middle of the material depending on whether the wood is decreasing or increasing in MC, respectively.

Moisture gradients affect both the flame spread and the reported test MC. Most fire test laboratories use handheld moisture meters to measure the MC.[25] These measurements rely on the relationship between conductivity and wood MC to estimate the wood MC. A gradient in MC of the wood over the depth at which the pins are inserted will result in a nonuniform electric field and bias the measurements, since more current can flow through the areas with higher MC. Thus, the resulting measurement is a value closer to the highest value of the gradient with which the pins are in contact. Similarly, using the oven-dry method results in an overall average MC that may be misleading depending on the steepness of the initial gradient in the MC within the sample before being oven dried.

The goal of this work was to quantify the differences in wood MC across five commercially important wood species. Sorption isotherms were collected in both absorption and desorption to give both interspecies variation and intraspecies variation based upon previous conditioning. Additionally, to better define the relationship between MC and flame spread indices, test results from 18 flame spread tests from four different commercial fire test laboratories were evaluated as a function of MC.

2 | MATERIALS AND METHODS

2.1 | Sorption isotherms

Five different wood species/species groups were examined: red oak (*Quercus* sp), redwood (*Sequoia/Sequoiadendron* sp), spruce, presumably black spruce (*Picea* cf. *mariana*), white pine group, presumably eastern white pine (*Pinus* cf. *strobus*), and southern yellow pine (*Pinus* sp). The samples were cut so that all oven-dry samples weighed at least 1.45 g (Figure 1).

Sorption isotherms were collected by conditioning the wood samples above either saturated salt solutions or by placing them inside a conditioning chamber. Six different saturated salt solutions were used: LiCl (11.3%), $MgCl_2$ (32.9%), K_2CO_3 (43.2%), NaBr (58.4%), NaCl (75.4%), and KCl (84.7%). All samples were also placed in a conditioning chamber at 50% ± 1% RH. In a couple of instances, the samples exposed to the LiCl and $MgCl_2$ solutions gave unusually high MCs in absorption caused by condensation on the samples. In these cases, new samples were dried and then reconditioned to similar relative humidities using a conditioning chamber. A total of 10 replicates were run for each RH level and sorption direction.

Samples were run in parallel in both absorption and desorption. Absorption samples were first oven-dried and then placed into a jar above one of the saturated salt solutions. Desorption samples were first conditioned at 90% RH until equilibrium was reached. Since these samples were not fully saturated in vacuum prior to the desorption isotherm, this represents a so-called "scanning" desorption isotherm.[22] This choice of scanning isotherm (rather than desorption from full water saturation) was justified as the goal of the study was to examine the range of potential MCs for standard flame spread tests where it is unlikely that the samples start from a fully water-logged state prior to testing. After equilibration at 90% RH, the samples were then placed above one of the saturated salt solutions (Figure 2).

Equilibrium was determined when successive mass readings taken at least 48 hours apart were within 0.5 mg or the mass change switched directions. Frequently, the equilibrium criteria for sorption measurements are presented as a change in MC as a function of time

FIGURE 1 Samples used to collect the isotherm while they were being oven-dried: (left, front) redwood, (right, front) eastern white pine [Colour figure can be viewed at wileyonlinelibrary.com]

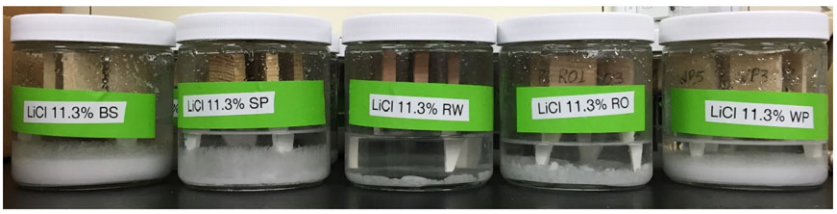

FIGURE 2 Wood samples above saturated salt solutions [Colour figure can be viewed at wileyonlinelibrary.com]

$(\frac{dM}{dt})$.[11,20,23,26] Given that the oven-dry masses of the samples were greater than or equal to 1.45 g, the equilibrium criterion used in this study is equivalent to a $\frac{dM}{dt} \leq 0.12\,\mu g_{water}\, g^{-1}_{dr\ wood}\ min^{-1}$. For reference, Glass et al have suggested a minimum dM/dt of 3 μg g^{-1} min^{-1}.[3] The samples were weighed on a balance with a precision of 0.1 mg, and that was recalibrated when a known 100-g weight was off by more than 0.2 mg.

The sorption models were fit to the so-called ABC isotherm

$$\frac{h}{m} = Ah^2 + Bh + C \quad (1)$$

where h is the fractional RH, m is the fractional wood MC, and A, B, and C are fitting parameters with no physical significance.[27] This sorption model, first used by Zelinka and Glass,[10] is mathematically equivalent to several commonly used isotherms derived from thermodynamics but whose ability to predict thermodynamic quantities, such as heat of sorption, is suspect.[27,28]

2.2 | Flame spread tests

All the tests were conducted on 19 mm (nominal 1 in.) thick by 140 mm (nominal 6 in.) wide eastern white pine shipped to four fire test laboratories. The historical flame spread value for eastern white pine was 85.[29] The boards were sourced from an Ottawa, Ontario, area distributer and shipped to each of the fire test laboratories. No special instructions were provided to the fire test laboratories with respect to conditioning and testing beyond the request to follow the respective standard.

A total of 14 tests were conducted in accordance with CAN/ULC-S102 and four tests in accordance with ASTM E84. The testing occurred between December 2014 and April 2015. The tests conducted are summarized in Table 3, providing the time in conditioning chamber, measured MC prior to each test (and method used to determine MC), and the flame spread results. The tests at lab 2 did not fully comply with the test standard since the room in which the tests were conducted was not conditioned prior to, or during, the tests. The test standard requires the air supply to be at 23 ± 3°C and 50 ± 5% RH; however, the test laboratory was 12°C with a RH likely significantly higher than 50% RH. This could have resulted in lower flame spread values; however, it is difficult to quantify to what degree. Additionally, the first test conducted at lab 4 was completed on eastern white pine that was shipped at the beginning of December and left in a nonconditioned area of the laboratory during December and January with a very low RH. A week prior to the test, the material was placed in the conditioning chamber.

3 | RESULTS

3.1 | Sorption isotherms

Figure 3 shows the absorption and desorption isotherms for the five species tested along with the fit from Equation 1. There are both interspecies differences between the amounts of water adsorbed (hygroscopicity) and differences between the absorption and desorption isotherms (hysteresis). For a given species, the difference between replicates was small; the error bars in Figure 3 are smaller than the symbols and thus not readily visible. At 50% RH, the largest difference between two replicates from the same species was 0.75% MC (southern yellow pine). The fit parameters used to generate the isotherms are given in Table 2. These can be used to estimate the wood MC for these species for wood at equilibrium with a given RH.

The interspecies variation in the isotherms can be better observed in Figure 4, which shows all of the absorption isotherms on one graph. Importantly, the MC at 50% RH varies between 6.8% (redwood) and 8.1% (black spruce); for reference, the MC of red oak was 7.3%. Therefore, even if all samples equilibrated in absorption, there would be a 19% difference in MC between species.

Figure 5 illustrates the hysteresis between absorption and desorption for each wood species at 50% RH. This is the amount of variation that may be possible within a given wood species based upon the prior conditioning. There is a 2% to 3% MC difference between the MC measured in absorption and desorption across wood species. The highest hysteresis was found for black spruce (3.3% MC difference), and the smallest was found for eastern white pine (2.3% MC

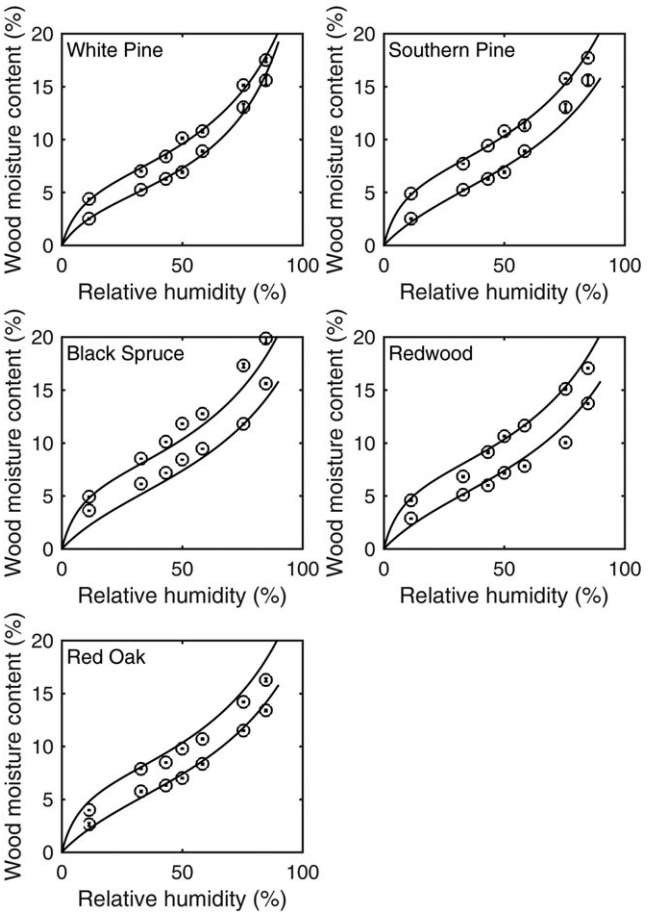

FIGURE 3 Adsorption and desorption isotherms for the five wood species tested. The error bars represent the standard error from five replicates

TABLE 2 Fit parameters (from Equation 1) that describe the absorption and desorption isotherms along with their correlation coefficient (R^2)

	Absorption				Desorption			
Species	A	B	C	R^2	A	B	C	R^2
Red oak	−11.95	14.30	2.73	0.95	−8.17	11.15	1.62	0.98
Redwood	−15.53	18.36	2.04	0.95	−8.17	10.92	1.54	0.90
Black spruce	−12.73	15.60	1.53	0.97	−7.28	9.66	1.36	0.98
Southern yellow pine	−8.73	9.51	4.21	0.88	−9.41	12.16	1.11	0.98
Eastern white pine	−14.78	15.19	2.98	0.94	−10.85	13.25	1.31	0.97

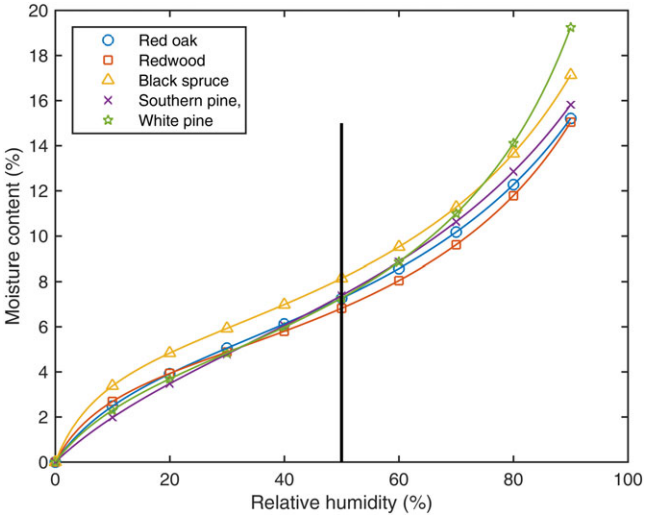

FIGURE 4 Comparison of absorption isotherms for each wood species. The solid black line represents the conditioning criteria for the ASTM E84 test [Colour figure can be viewed at wileyonlinelibrary.com]

difference). The MC of red oak in desorption was 9.7% MC—nearly 3% MC higher than the red oak calibration material. As a percentage of the total amount of moisture in the wood, the samples conditioned in desorption contained between 32% more water (eastern white pine) to 48% more water (redwood) than their absorption counterparts.

3.2 | Flame spread tests

Table 3 provides the FSR results for each test conducted. The CAN/ULC-S102 test results are plotted in Figure 6 and emphasize the potential range for data between laboratories as well as within a single laboratory. Since the ASTM E84 test results included only four data points from four different test laboratories, it is difficult to draw conclusions regarding the relationship between MC and flame spread because the variability between test laboratories (resulting from

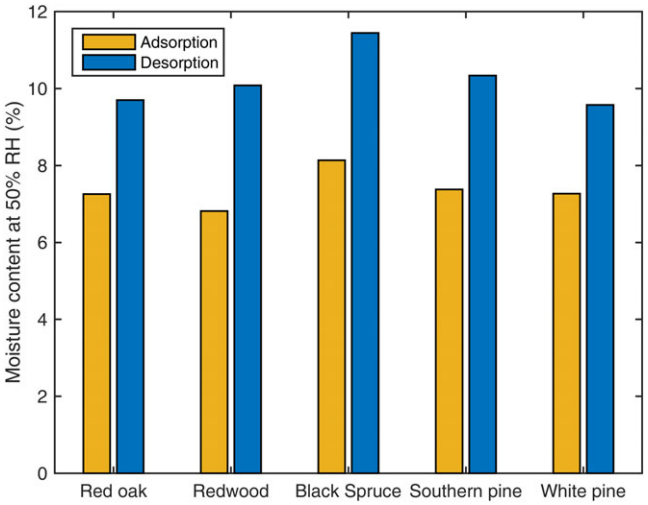

FIGURE 5 Comparison of moisture content for each wood species when previously conditioned in absorption and desorption at 50% relative humidity [Colour figure can be viewed at wileyonlinelibrary.com]

differences in calibration, etc) is likely a confounding factor that may also have affected the resulting FSI.

4 | DISCUSSION

4.1 | Sorption isotherms

Clear differences in wood moisture can be seen across the wood species within the conditioning limits established within ASTM E84. In the standard, the flame spread index is compared against a standard of red oak that is conditioned to a wood MC of 7 ± 0.5%. Based upon the data in Figure 1, the wood MCs for these species that were conditioned at 50% RH varied from 6.8% to 11.4%. Even for the red oak sample, the MC varied from 7.3% to 9.7%. These stated differences include both differences in how the specimens were conditioned and also interspecies variation. Of the two, the method of conditioning has the larger impact, and specimens conditioned in desorption had higher MCs that were further away from the red oak calibrant that was conditioned at 7% MC.

These differences in MC, both from conditioning as well as interspecies variation, will affect both the calibration of the test apparatus as well as the flame spread measured in the ASTM E84 test. In this regard, it is interesting to compare redwood, which has a flame spread index of 55 with black spruce that had a flame spread index of 45.[30] Our analysis suggests that redwood will actually be tested at a slightly lower MC than the red oak if both samples are conditioned in absorption. On the other hand, black spruce will have a MC of over 8% no matter how the sample is conditioned. It is likely that the low flame spread of black spruce can be at least partially attributed to its high hygroscopicity.

The ASTM E84 standard does not specify whether the samples must be conditioned in absorption or desorption. Rather, it only

TABLE 3 Flame spread test results

Laboratory	Test ID	Test Method	Moisture Content (Average from Handheld Meter)	Moisture Content (Gravimetric)	Flame Spread Index	Approximate Time in Conditioning Chamber
Lab 1	1a	S102	-	9%	129	1.5 weeks
	2a	S102	-	8%	106	
	3a	S102	-	8%	109	
	1b	E84	-	9.7%	71	1 week
Lab 2	1a	S102	10.2%	-	41	1.5 weeks
	2a	S102	10.4%	-	37	
	3a	S102	10.5%	-	40	
	1b	E84	11.8%	-	38	
Lab 3	1b	E84	7.3%	8.3%	60	9 weeks
	1a	S102	7.8%	7.7%	62	
	2a	S102	7.2%	8.7%	66	
	3a	S102	7.0%	7.8%	64	
Lab 4	1a	S102	6.4%	7.1%	200	1 week
	2a	S102	8.0%	8.1%	82	10 weeks
	3a	S102	8.9%	8.4%	74	8.5 weeks
	4a	S102	9.0%	8.4%	71	
	5a	S102	8.7%	8.4%	65	
	1b	E84	8.8%	8.4%	65	

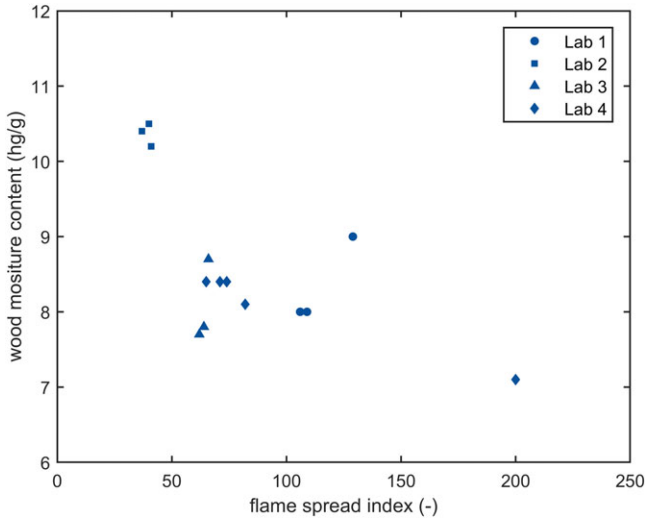

FIGURE 6 Eastern white pine flame spread (CAN/ULC-S102) test results as a function of moisture content [Colour figure can be viewed at wileyonlinelibrary.com]

specifies that the samples have achieved constant mass, which is not a defined term. The method of conditioning affects the wood MC and will affect the flame spread. The results suggest that higher MCs, obtained from conditioning samples in desorption, will result in lower flame spread indices, and in some cases may affect the flame spread index of the material. The results of the flame spread tests conducted on eastern white pine, discussed in the next section, highlight how dramatically small changes in MC can affect the flame spread index.

4.2 | Flame spread tests

The limited test data shows a trend between the MC of eastern white pine boards and flame spread indices such that lower MC leads to a higher flame spread value. The trend over a larger differential in MC is not expected to be linear since, at very high MCs, there is likely little change in flame spread causing the trend line to go near vertical at low flame spread values. It is difficult to predict what would happen at very low MC levels without any test data available. Using the tests conducted at lab 4, (Figure 7), a drop in reported MC from 8% to 7% results in approximately a doubling of flame spread value from 100 to 200. This large change also has implications for the calibration of the tunnels since the red oak calibrant is permitted to vary within 1% MC (7 ± 0.5%) in ASTM E84 and 2% MC (7 ± 1%) in CAN/ULC-S102. These tolerances are clearly very large in comparison with the impact on the test results (Figure 7).

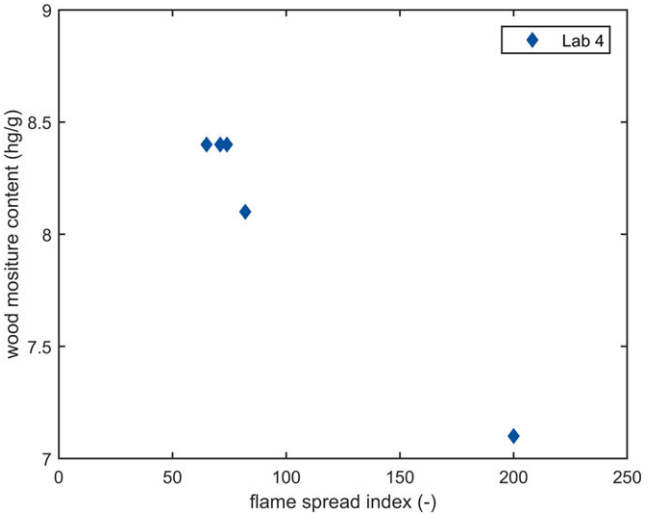

FIGURE 7 Eastern white pine flame spread (CAN/ULC-S102) test results from lab 4 as a function of moisture content [Colour figure can be viewed at wileyonlinelibrary.com]

In all tests completed, the test specimen material reached "constant mass in the conditioning chamber" as required by the test standard. The requirements in the CAN/ULC-S102 standard of not more than 1% total mass change over 72 hours is inadequate since typical flame spread testing samples (2.4 m or longer) will not change more than 1% during this short a period of time regardless of initial MC. Therefore, the result is that conditioning to meet the current standards will not be sufficient to significantly change the MC of the wood sample. This includes the test 1a completed at lab 4 in which the gravimetric MC was measured as approximately 7.1%, but where the material had dried significantly prior to being placed in the conditioning chamber for a week. Based on this experience, it is clear that the current method to determine "constant mass" is not sufficient to ensure consistent results in testing wood products, and the test methods may be improved by further specifying the conditioning method, requiring MC targets for both the calibration and test materials, or specifying a more stringent *dM/dt* criteria for equilibrium. The lack of a stringent *dM/dt* criteria could have an even higher potential impact on pressure-impregnated treated wood products, which may have relatively higher MCs when delivered to the test laboratory. Further data are required before developing more stringent *dM/dt* criteria.

Based on the published historic flame spread value of 85 for eastern white pine, it would appear that results now are lower than when that result was determined, regardless whether that result was based on CAN/ULC-S102 or ASTM E84. This is likely because of the change in test methods that lowered the MC requirement of the red oak calibrant. Given the relationship presented here on the impact a change in MC can have on the flame spread value for wood products, it is no surprise that a lowering of the MC requirement for the calibration deck would have the general effect of lowering the flame spread value on any given product tested.

5 | CONCLUSION

Sorption isotherms were collected on five commercially important wood species. The isotherms revealed that, depending on wood species and conditioning method, the MC of the wood conditioned to 50% RH may be as low as 6.8% MC to as high as 11.4% MC. By far, the largest effect was whether the samples were conditioned in absorption or desorption. In some cases, samples that were conditioned in desorption contained as much as 48% more moisture than the samples conditioned in absorption. These differences in MC will greatly affect the flame spread given that a reported MC difference of 1% resulted in a doubling of FSR from 100 to 200. These differences will also affect the calibrant, which is a critical component of the CAN/ULC-S102 and ASTM E84 test methods, since the surface flammability of the red oak calibrant determines the index of all products tested using the tunnel.

In order to draw any quantitative conclusions as to the influence of MC on the flame spread index, many more tests would be required at a single laboratory in an attempt to avoid introducing additional variables. However, it is clear that the MC has an impact on the flame spread index, and the wood MC is greatly affected by species and conditioning method. The conditioning of test specimens should require conditioning to equilibrium, on account of the high degree of sensitivity of results to the MC. The current equilibrium requirements in the CAN/ULC-S102 and ASTM E84 standard are inadequate and result in large variations in the tested MC of wood samples.

ACKNOWLEDGMENTS

The authors acknowledge funding from the Canadian Wood Council and the American Wood Council.

ORCID

Laura E. Hasburgh https://orcid.org/0000-0001-6637-2665

REFERENCES

1. *ASTM E84-18b Standard Test Method for Surface Burning Characteristics of Building Materials*. 2018, ASTM international: west Conshohocken, PA.
2. *CAN/ULC-S102–18 Standard Method of Test for Surface Burning Characteristics of Building Materials and Assemblies*. 2018, ULC Standards.
3. Glass SV, Zelinka SL. Moisture relations and physical properties of wood. In: Ross RJ, ed. *Wood Handbook. Wood as an Engineering Material*. U.S.: Department of Agriculture, Forest Service, Forest Products Laboratory; 2010.
4. Spalt H. The sorption of water vapor by domestic and tropical woods. *Forest Prod J*. 1957;7(10):331.
5. Derome D, Derluyn H, Zillig W, Carmeliet J. Model for hysteretic moisture behaviour of wood. 2008.
6. Peralta P. Moisture sorption hysteresis and the independent-domain theory: the moisture distribution function. *Wood Fiber Sci*. 1996; 28(4):406-410.
7. Frandsen HL, Svensson S, Damkilde L. A hysteresis model suitable for numerical simulation of moisture content in wood. *Holzforschung*. 2007;61(2):175-181.
8. Scheffler G. *Validation of hygrothermal material modelling under consideration of the hysteresis of moisture storage*. 2008, Technical University of Dresden
9. Engelund E, Thygesen LG, Svensson S, Hill CA. A critical discussion of the physics of wood–water interactions. *Wood Sci. Technol.* 2013;47(1):141-161.
10. Zelinka SL, Glass SV. Water vapor sorption isotherms for southern pine treated with several waterborne preservatives. *ASTM J. Test. Eval.* 2010;38(4):80-88.
11. Hill CAS, Norton A, Newman G. The water vapour sorption properties of Sitka spruce determined using a dynamic vapour sorption apparatus. *Wood Sci. Technol.* 2010;44(3):497-514.
12. Jalaludin Z, Hill CA, Xie Y, et al. Analysis of the water vapour sorption isotherms of thermally modified acacia and sesendok. *Wood Mater. Sci. Eng.* 2010;5(3):194-203.
13. Engelund ET, Klamer M, Venås M. *Acquisition of sorption isotherms for modified woods by the use of dynamic vapour sorption instrumentation: principles and practice*. in *41st Annual Meeting of the International Research Group on Wood Protection, Biarritz, France, 9–13 May* 2010.2010. IRG Secretariat.
14. Xie Y, Hill CA, Jalaludin Z, et al. The dynamic water vapour sorption behaviour of natural fibres and kinetic analysis using the parallel exponential kinetics model. *J Mater Sci*. 2011;46(2):479-489.

15. Ceylan Ö, Van Landuyt L, Meulewaeter F, De Clerck K. Moisture sorption in developing cotton fibers. *Cellul*. 2012;19(5):1517-1526.
16. Volkova N, Ibrahim V, Hatti-Kaul R, Wadsö L. Water sorption isotherms of Kraft lignin and its composites. *Carbohydr Polym*. 2012;87(2):1817-1821.
17. Williams DL, Hodge DB. Impacts of delignification and hot water pretreatment on the water induced cell wall swelling behavior of grasses and its relation to cellulolytic enzyme hydrolysis and binding. *Cellul*. 2013;21(1):221-235.
18. Popescu C-M, Hill CA, Curling S, Ormondroyd G, Xie Y. The water vapour sorption behaviour of acetylated birch wood: how acetylation affects the sorption isotherm and accessible hydroxyl content. *J Mater Sci*. 2013;49(5):2362-2371.
19. Kymäläinen M, Rautkari L, Hill CAS. Sorption behaviour of torrefied wood and charcoal determined by dynamic vapour sorption. *J Mater Sci*. 2015;50(23):7673-7680.
20. Hill CAS, Norton A, Newman G. The water vapor sorption behavior of natural fibers. *J Appl Polym Sci*. 2009;112(3):1524-1537.
21. Esteban LG, de Palacios P, Fernández FG, Martín JA, Génova M, Fernández-Golfín JI. Sorption and thermodynamic properties of buried juvenile Pinus sylvestris L. wood aged 1,170±40 BP. *Wood Sci. Technol*. 2009;43(7–8):679-690.
22. Fredriksson M, Thybring EE. Scanning or desorption isotherms? Characterising sorption hysteresis of wood. *Cellul*. 2018;25(8):4477-4485.
23. Glass SV, Boardman CR, Thybring EE, Zelinka SL. Quantifying and reducing errors in equilibrium moisture content measurements with dynamic vapor sorption (DVS) experiments. *Wood Sci. Technol*. 2018;52(4):909-927.
24. *ASTM D4933-16 Standard Guide for Moisture Conditioning of Wood and Wood-Based Materials; ASTM: West Conshohocken, PA, USA, 1999*.2016, ASTM: West Conshohocken, PA
25. James WL. *Electric moisture meters for wood*. Vol. 8.1963: US Dept. of agriculture, Forest Service, Forest Products Laboratory
26. Glass SV, Boardman CR, Zelinka SL. Short hold times in dynamic vapor sorption measurements mischaracterize the equilibrium moisture content of wood. *Wood Sci. Technol*. 2017;51(2):243-260.
27. Zelinka SL, Glass SV, Thybring EE. Myth versus reality: do parabolic sorption isotherm models reflect actual wood–water thermodynamics? *Wood Sci. Technol*. 2018;52(6):1701-1706.
28. Simpson W. Sorption theories applied to wood. *Wood Fiber Sci*. 1980;12(3):183-195.
29. Canadian Wood Council, *Fire safety design in buildings*. Ottawa, ON, Canada: CWC, 1996.
30. American Wood Council, *Design for Code Acceptance (DCA) 1 - Flame Spread Performance of Wood Products Used for Interior Finish*. 2016, American Wood Council: Leesburg, VA.

How to cite this article: Hasburgh LE, Craft ST, Van Zeeland I, Zelinka SL. Relative humidity versus moisture content relationship for several commercial wood species and its potential effect on flame spread. *Fire and Materials*. 2019;43:365–372. https://doi.org/10.1002/fam.2707