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The transport of new make spirits through American white oak

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Abstract

Why was the work done: The reduction of maturation loss is a significant opportunity for increased revenue in aged spirits and varies through several factors. This work aims to better understand maturation loss by isolating and measuring spirit flow through wood.
How was the work done: Bourbon stave disks were fabricated by computer numeric control milling and loaded into a sealed module consisting of flanges holding the stave disk over a liquid filled pipe. The modules were filled with new make spirit at 50, 62.5 or 70% ABV, with either liquid or vapour contact with the stave disk. Further, the grain angle was measured for each sample. Samples were weighed each month to measure flux through the wood, with measurement of initial and final ABV and liquid mass to differentiate between ethanol or water loss.
What are the main findings: The initial alcohol content had a statistically significant (p value ≤ 0.05) effect on spirit diffusion, with the highest initial alcohol content exhibiting a 6.9 g reduction in total mass loss over the initial alcohol content. Based on the change in alcohol content, the change in mass loss is attributed to increased water uptake. Liquid versus vapour contact showed similar monthly rates of loss of mass and a statistically significant difference in total mass loss, though the magnitude of the difference is small (5.2 g, p value = 0.049), due to increased ethanol loss with liquid contact. Grain angle had no significant effect on spirit diffusion. A predicted average annual liquid loss of 1.2 ± 0.3% was calculated for non-leakage losses from a standard bourbon barrel (200L) matured in Kentucky.
Why is the work important: While the transport of water and alcohol through solid wood has been previously observed, this is the first study to investigate the diffusion of high proof alcohol through undamaged barrel staves. Maturation loss is a complex, unavoidable, and important aspect of ageing spirits, and this work establishes a lower level for maturation loss for spirit matured in Kentucky, USA.

Keywords

diffusion, spirit transport, bourbon, maturation loss, barrel, oak wood

Introduction

American white oak (*Quercus alba* L.) is the most used species of wood in cooperage due to its resilience, flexibility, relative impermeability to liquids, and unique flavour contribution to distilled spirits (del Alamo-Sanza and Nevares 2018). The process of maturation in a white oak barrel contributes significantly to the flavour, colour, and volume of the spirit (Mosedale and Puech 1998). As the barrel cycles in temperature, the liquid expands and penetrates the staves of the barrel and then flows back out of the wood. Transport of spirits through the wood is critical to the ageing process, as the liquid flowing out of the wood carries wood constituents that give bourbon its flavour, aroma, and colour (Gollihue et al. 2018; del Toro et al. 2019). However, this same flow of liquids during maturation also results in the loss of spirit known as the 'Angel's share'. Depending on the location, 2-5% proof gallons are lost in a barrel each year (Gallagher et al. 1942; Boruff and Rittschof 1959; Baldwin and Andreasen 1974). Although some volume loss drives the beneficial concentration and extraction of flavours from the wood, a reduction in the extent of maturation loss is a significant opportunity for increased revenue in ageing spirits (Singleton 1995).

Losses during maturation are a combination of diffusion through sound wood and losses at the joints between staves. Oak wood is a porous solid that acts as a 'semi-permeable membrane' that allows evaporation of spirit and migration of air into the barrel. Transport of fluids through wood occurs by two basic physical mechanisms (Siau 1984; Hansmann et al. 2002). The first is bulk flow of fluids through interconnected voids of wood under the influence of a pressure gradient (Siau 1984; Hansmann et al. 2002; del Alamo-Sanza and Nevares 2018). Here, permeability is only possible if the voids are interconnected with the openings. The second mechanism is diffusion. This occurs via intergas diffusion through the air in the cell lumen and bound diffusion inside the cell walls of the wood (Siau 1984; Hansmann et al. 2002; del Alamo-Sanza and Nevares 2018). During the process of ageing in an oak wood barrel, both mechanisms occur simultaneously. As a bulk flow spirit penetrates into the first millimetres of wood, where the voids are interconnected due to the hydrostatic pressure of the liquid, and water vapour and ethanol from the spirit diffuse through the wood due to the concentration gradient between the inside and outside of the barrel (del Alamo-Sanza and Nevares 2018; Junqua et al. 2021; Dussaut et al. 2024). The anatomical characteristics of American white oak limit the transport of fluids through the wood. This includes abundant 'tyloses', which are balloon-like outgrowths of parenchyma cells into the lumen of xylem vessels (Kim et al. 2024). Tyloses significantly reduce permeability, as they completely occlude the conducting vessels (Siau 1984; del Alamo-Sanza and Nevares 2018; Kim et al. 2024). White oak is also characterised by its wide multiseriate rays, which run radially across the trunk from the pith to the bark (Singleton 1995; del Alamo-Sanza and Nevares 2018). When the rays remain parallel to the inner side of the staves - they will be in contact with the spirit - and form a barrier to the diffusion of the liquid (del Alamo-Sanza and Nevares 2018).

Losses during maturation depend on several external factors (e.g. humidity and temperature), as well as internal factors relating to properties of the wood and liquid, such as porosity, density, stave preparation, morphology of the wood fibre, and alcoholic strength (Mosedale 1995; Singleton 1995; Mosedale and Puech 1998; del Toro et al. 2019). Strategies to limit the Angel's share include temperature and humidity controlled warehouses and sealants coating the outside of the barrel (English 2017; del Toro et al. 2019). Different models have been explored to describe the evaporation of liquid from barrels based on wood drying studies. It has been reported that the diffusion of bound water controls the rate of water drying from wood (Penvern et al. 2020) and this, and an earlier study (Baronas et al. 2001), found that models based on Fick's second law can predict the movement of water in drying wood. Both the Boltzmann transport equation and Fick's second law of diffusion have been used to fit experimental data for maturation losses based on the temperature and relative humidity (Ruiz De Adana et al. 2005; del Toro et al. 2019). While these studies provide some insight on the transport of water and alcohol through wood, the impact of wood and liquid properties on the transport of high proof alcohol through barrel wood have received less attention.

This work seeks to better understand maturation loss by isolating and measuring spirit flow through wood. While the transport of water and alcohol through solid wood has been observed in many industries, data on the rate of transport of high proof alcohol through undamaged barrel staves is unavailable. Here, American white oak stave disks were loaded into a sealed system where spirit transport is limited to the oak wood. This allowed investigation of the effects of alcohol concentration, vapour versus liquid contact with the barrel, and grain angle on non-leakage loss. This work provides the first measurement of 1.2% mass loss per year from spirit diffusion through wood, which provides a definitive lower boundary for maturation loss, as this is the theoretical minimum loss that is possible from a barrel without joints and leaks.

Materials and methods

Machining of bourbon stave disks

Bourbon staves were provided by Independent Stave Company, with at least three months of seasoning and a Level 4 barrel 'alligator' char (most intense standard charring level). The staves were cut into rectangular stave blanks using a compound mitre saw and machined into stave disks using a computer numeric control (CNC) router table (PRS Alpha, ShopBot Tools Inc) (Figure 1). Three dimensional (3D) printed jigs were used to secure the stave blanks to the router table surface during machining.

The outer surface of the stave blank (non-charred side) was secured to the jig using wood screws outside of the stave disk. Dimensions for the jig were determined by modelling a stave using computer aided design (CAD) software (Solidworks 2021) to approximate the curvature required between the stave and jig interface. The jigs were fabricated from acrylonitrile styrene acrylate (ASA) plastic on a filament 3D printer (F170, Stratasys). Computer aided manufacturing (CAM) software (VCarve Pro 9.519, Vectric Limited) was used to create the machining tool path. The toolpath left small tabs between the stave disk and stave blank to facilitate machining. These tabs were removed by hand from the stave disk using a random orbital sander.

Two sizes of stave disks were fabricated to probe edge and scaling effects. Stave disk sizes of 7.62 cm and 10.16 cm were used to match conventional three and four inch pipe fittings in the United States. The stave disks featured a step edge at the charred surface for seating against a PVC pipe of the same nominal size. The depth of the step edge was 0.3175 cm for both stave disks. The diameter of the step edge was 7.54 and 10.08 cm for the 7.6 and 10.2 cm stave disks, respectively. The outer circular profile of the stave disk had a diameter of 8.81 and 11.35 cm for the 7.6 and 10.2 cm staves. The slightly reduced diameters provided 0.04 cm of clearance between the stave disks and the diffusion module assembly to facilitate sealing. The step edge and the circular profile were cut using a 0.25 inch (0.635 cm) spiral flute end mill with downward chip removal. The downward chip removal provided compression against the charred surface of the stave during machining to prevent tear out.

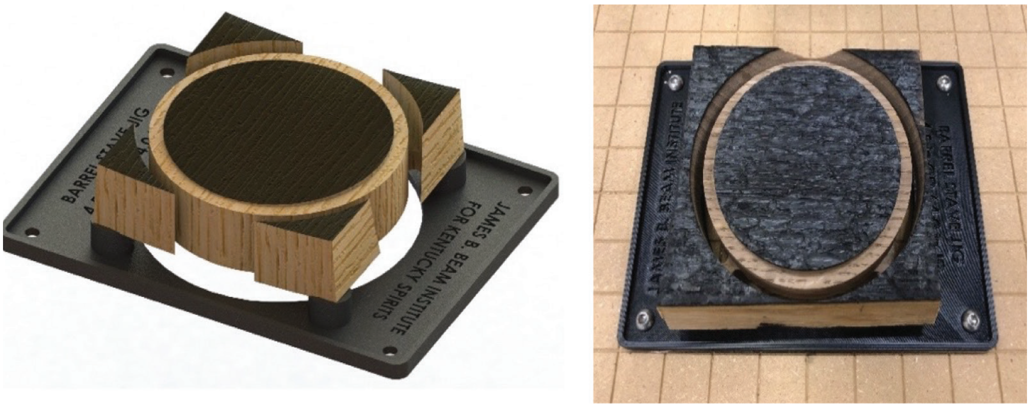


Figure 1. CAD rendering (left) and fabricated (right) stave disks secured to a 3D-printed jig for machining on a computer numeric control router table.

Diffusion module fabrication

Bourbon stave disks were loaded into a sealed module to investigate maturation loss through sound wood. Each sample is a stack of pipe, where flanges and bolts hold a wood disk over the liquid filled pipe (Figure 2A-B). The three inch (7.62 cm) and four inch (10.16 cm) diameter schedule 40 PVC pipes (793EG8, Grainger) were cut to 4.13 and 5.08 cm in length, deburred, cleaned with tap water, and dried with cotton towel. One end of the PVC pipe was sealed with clear silicone caulk (108311, Gorilla Glue Inc.) to a schedule 80 blind flange (1VFR2, Grainger) and left to cure for 24 h. Distillate was added to approximately 75%, which was 120 mL for 7.6 cm samples and 270 mL for 10.2 cm samples. Stave disk edges were sealed with silicone caulk to a schedule 80 slip-on flange (2PLW6, Grainger), and the other end of the pipe was sealed to the slip-on flange to hold the stave disk over the end of the pipe. Hex head screws (22RY03, Grainger) were secured in place with hex nuts (2FE47,

Figure 2. (A) From top to bottom, slip-on flange, wood stave disk, PVC pipe, and blind flange used to create the sealed modules. (B) Assembled module holding wood disk under liquid filled pipe and using hex head cap screws to secure the system.

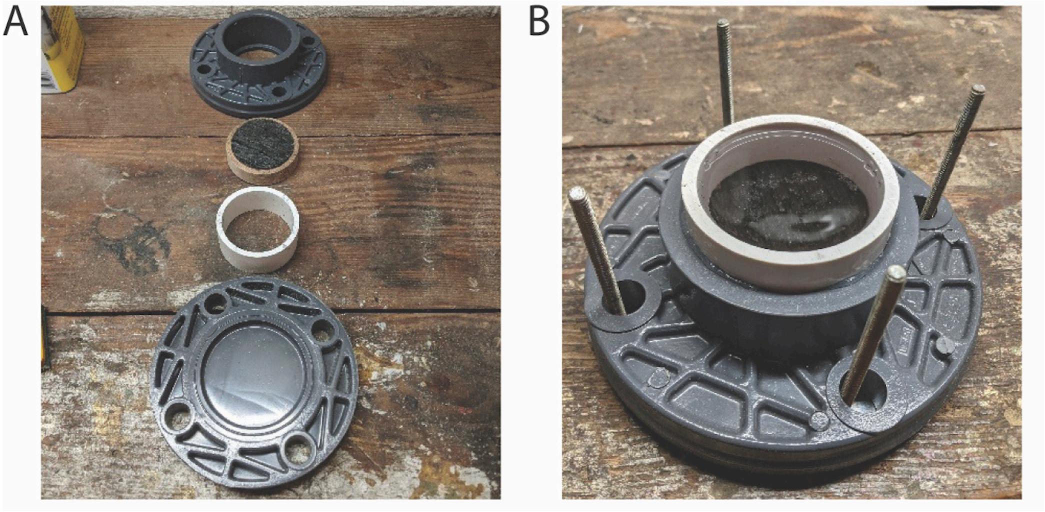
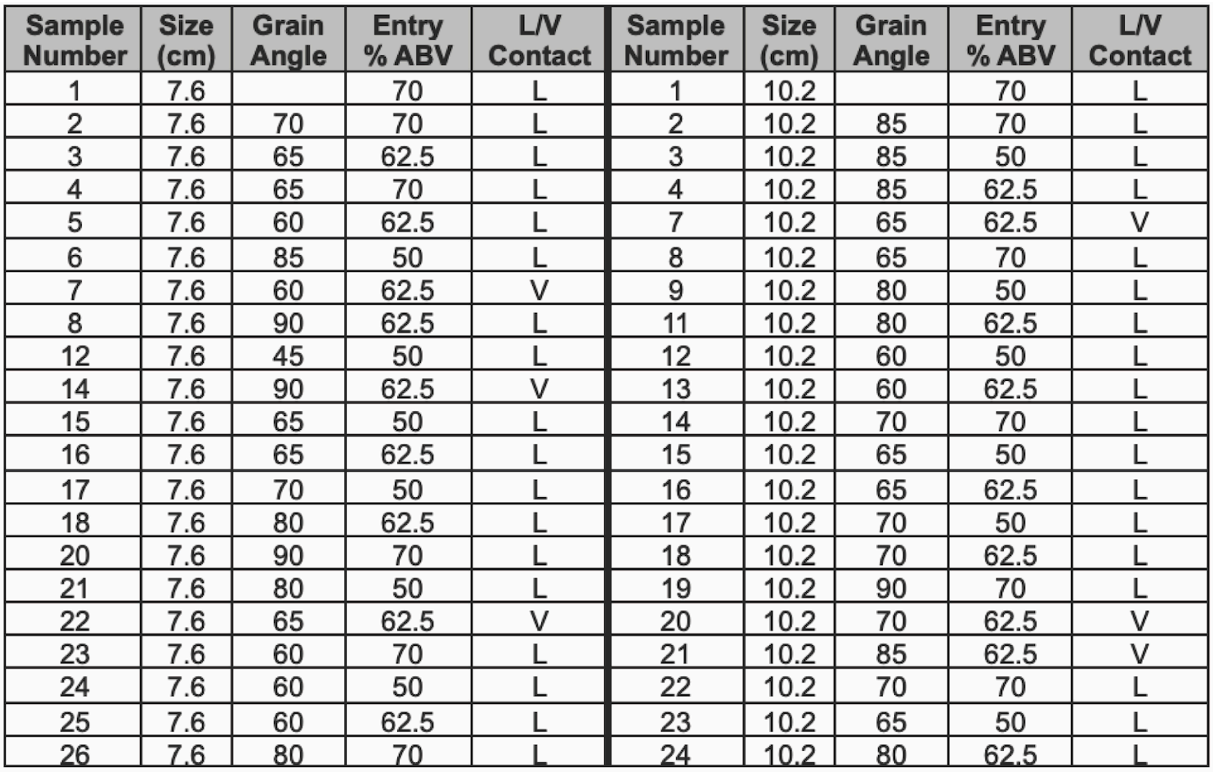


Figure 2C. Size, grain angle, entry % ABV, and liquid (L) or vapour (V) contact for each sample.



Sample Number	Size (cm)	Grain Angle	Entry % ABV	L/V Contact	Sample Number	Size (cm)	Grain Angle	Entry % ABV	L/V Contact
1	7.6		70	L	1	10.2		70	L
2	7.6	70	70	L	2	10.2	85	70	L
3	7.6	65	62.5	L	3	10.2	85	50	L
4	7.6	65	70	L	4	10.2	85	62.5	L
5	7.6	60	62.5	L	7	10.2	65	62.5	V
6	7.6	85	50	L	8	10.2	65	70	L
7	7.6	60	62.5	V	9	10.2	80	50	L
8	7.6	90	62.5	L	11	10.2	80	62.5	L
12	7.6	45	50	L	12	10.2	60	50	L
14	7.6	90	62.5	V	13	10.2	60	62.5	L
15	7.6	65	50	L	14	10.2	70	70	L
16	7.6	65	62.5	L	15	10.2	65	50	L
17	7.6	70	50	L	16	10.2	65	62.5	L
18	7.6	80	62.5	L	17	10.2	70	50	L
20	7.6	90	70	L	18	10.2	70	62.5	L
21	7.6	80	50	L	19	10.2	90	70	L
22	7.6	65	62.5	V	20	10.2	70	62.5	V
23	7.6	60	70	L	21	10.2	85	62.5	V
24	7.6	60	50	L	22	10.2	70	70	L
25	7.6	60	62.5	L	23	10.2	65	50	L
26	7.6	80	70	L	24	10.2	80	62.5	L

Grainger) to assemble the module. The silicone caulk was allowed to cure for 24 h. Six samples of each were loaded with new make distillate from a bourbon mash diluted to 50, 62.5 or 70% alcohol by volume (ABV) for both 7.6 and 10.2 cm groups with the stave disk on the bottom to have contact between the wood and liquid. Three additional 62.5% ABV samples were added for each size with the stave disk at the top to have contact between the wood and vapour. Grain angle was recorded for each sample and was measured to the nearest 5° by photoshopping a digital protractor over the centre of the stave disks in the photos included (Supplementary information, Figures S1 and S2). The sample parameters with the size, grain angle, entry % ABV, and liquid or vapour contact for each sample are shown in Figure 2C.

Data collection

Samples were placed on the first floor of a 58,800 barrel, rick-style warehouse built by Buzick Construction (Bardstown) and located in Frankfort, Kentucky. Samples were weighed monthly on a levelled, calibrated balance (10205-008, VWR, accuracy 0.1 g). Data was collected over 26 months providing two years of seasonal variation with an initial three months of set up, two months of equilibration, and one month of take down and analysis. At the end of the study, the alcohol content and mass of each 10.2 cm liquid sample were measured. Weather data was obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centres for Environmental Information (NCEI) weather station at Frankfort Capital City Airport, as environmental data was not available for the location of the modules in the warehouse.

Data analysis

Monthly flux was calculated using the below equation (Eqn 1).

$$J = \frac{-(m_i - m_{i-1})}{At}$$

where J is the flux in g/m^2/d, m_i is the mass of the system on the month being recorded, m_{i-1} is the mass of the previous month, A is the area of the stave disk, and t is the number of days between recordings of mass.

The initial ABV (%) of the samples was measured using a hydrometer (accuracy 0.1% v/v), with the final ABV measured using a DMA 4501 and Alcolyzer 3001 (Anton Paar, accuracy 0.01% v/v). The initial and final mass and alcohol content, total mass loss, ethanol loss, and water loss for each sample were calculated. An initial liquid mass for a standard bourbon barrel of 181.7 kg was estimated from a 200 L initial liquid volume and a density for 62.5% ABV spirit of 0.13229 wine gallons per pound (1.1 L/kg) at 60°F (15.6°C) from Table 4 of the Alcohol and Tobacco Tax and Trade Bureau (TTB) Gauging Manual (Alcohol and Tobacco Tax and Trade Bureau 2003). The surface area of a standard bourbon barrel of 2.23 m^2 was estimated by creating an approximate barrel surface in CAD based on the barrel specification for the head diameter, stave length, and barrel circumference. Based on the initial liquid mass, the monthly liquid flux, barrel surface area, and the liquid loss over time for each sample, the predicted barrel liquid weight was calculated.

Statistical analysis

Data were subjected to an ordinary one-way ANOVA, two-way ANOVA, mixed-effects analysis, or unpaired t-test using GraphPad Prism 10. Means were separated using a Tukey's Multiple Comparison Test at alpha = 0.05. Results were considered statistically significant with a p-value less than 0.05.

Results

Impact of initial alcohol content on spirit diffusion

To determine the impact of the initial alcohol concentration on spirit loss through barrel wood, stave disk modules loaded with 50, 62.5 or 70% ABV distillate, with the mass measured monthly over 17 months (August 2022-January 2023). Over this period, 12 months exhibited a statistically significant reduction in flux for 70% ABV compared to 50% ABV. Seven months had a significant reduction in flux for 70% ABV compared to 62.5% ABV (Figure 3A, Supplementary information Table S1). There was a reduced total mass loss with higher initial ABV (Figure 3B). There were similar losses in total mass between 50 and 62.5% ABV, while samples at 70% ABV had significantly less loss than each of those groups (Figure 3B). Ethanol loss was similar for the

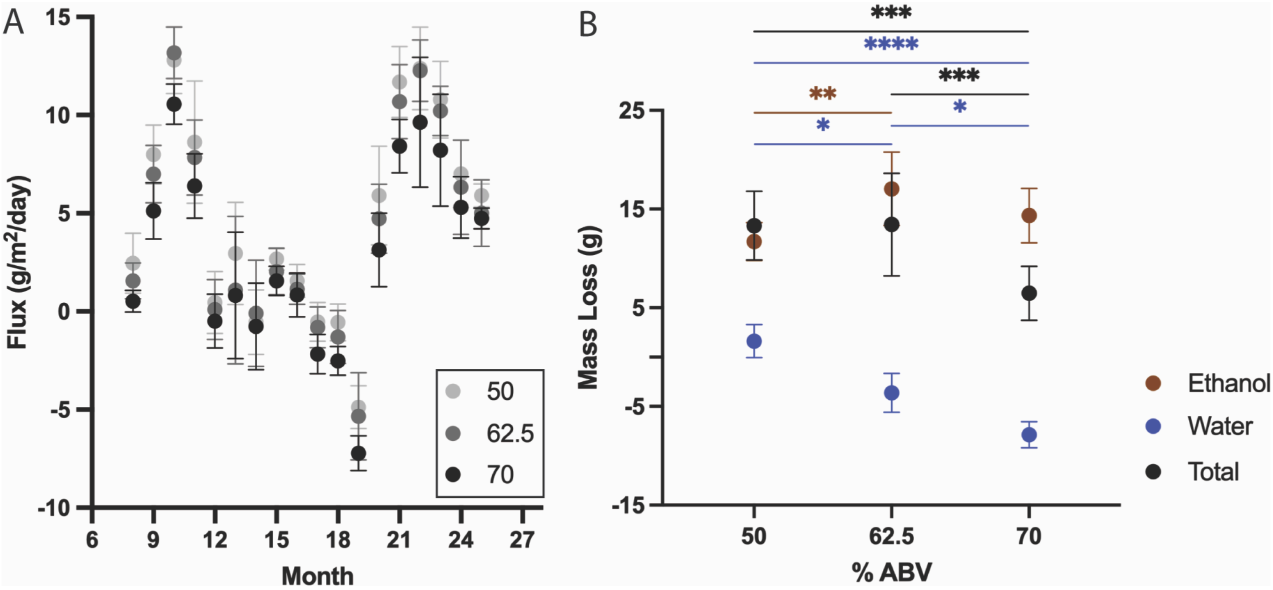


Figure 3. (A) Monthly flux of spirit through barrel wood with an initial ABV of 50, 62.5, and 70%. (B) Total mass loss, ethanol mass loss, and water mass loss from the modules over two years with an initial ABV of 50, 62.5, and 70%.

62.5 and 70% ABV samples, but there was increased water uptake with increasing ABV (Figure 3B).

Impact of liquid versus vapour contact on spirit diffusion

To determine the impact of liquid versus vapour contact on spirit loss through barrel wood, stave disk modules loaded with 62.5% ABV distillate were positioned with either the stave disk on the bottom to have liquid contact with the wood or stave disk on the top to have vapour contact with the wood. The mass was measured over the same 17-month period as above. There were similar rates of monthly mass loss from liquid and vapour contact, with only two of the 17 months exhibiting significant differences in the monthly flux (Figure 4A, Supplementary information Table S2). There was a significant difference in the total mass loss between liquid and vapour contact over the 17 months of the experiment, though the magnitude of the difference was small (5.2 g) (Figure 4B). However, liquid contact had significantly greater ethanol loss (Figure 4B) with similar water uptake, leading to a significant increase in ABV loss from liquid contact compared to vapour contact (Figure 4C).

Impact of grain angle on spirit diffusion

Figure 5A shows samples with of 60 and 90˚ grain angles, which is the angle at which the growth rings are oriented with respect to the inner side of the stave. The effect of grain angle on spirit diffusion was determined. No significant trends for spirit diffusion with grain angle were observed. Indeed, grain angle has no effect on the two year gain in ABV (Figure 5B) nor the total mass loss over 17 months (Figure 5C-E).

Measurement of annual non-leak losses

Using monthly flux measurements, the initial liquid mass and the surface area of the barrel, the predicted liquid mass for each month and the predicted annual liquid loss were calculated (Figure 6A). After the initial ‘drink-in’ (flavour absorption from the charred wood) in month 7, the predicted average annual liquid loss from a standard bourbon barrel was 1.2 ± 0.3% (Figure 6B). To investigate the 'drink-in', three stave disks were placed in the warehouse and their mass was measured over three months (October 2024-January 2025) (Supplementary information Table S3).

Module scaling validation and seasonal fluctuation

As shown in Figure 7A, the monthly flux for the 7.6 and 10.2 cm modules is roughly equal, which validates the module scaling. Figure 7B shows the average monthly temperature from the local weather station in Frankfort (KY) from April 2022-January 2024.

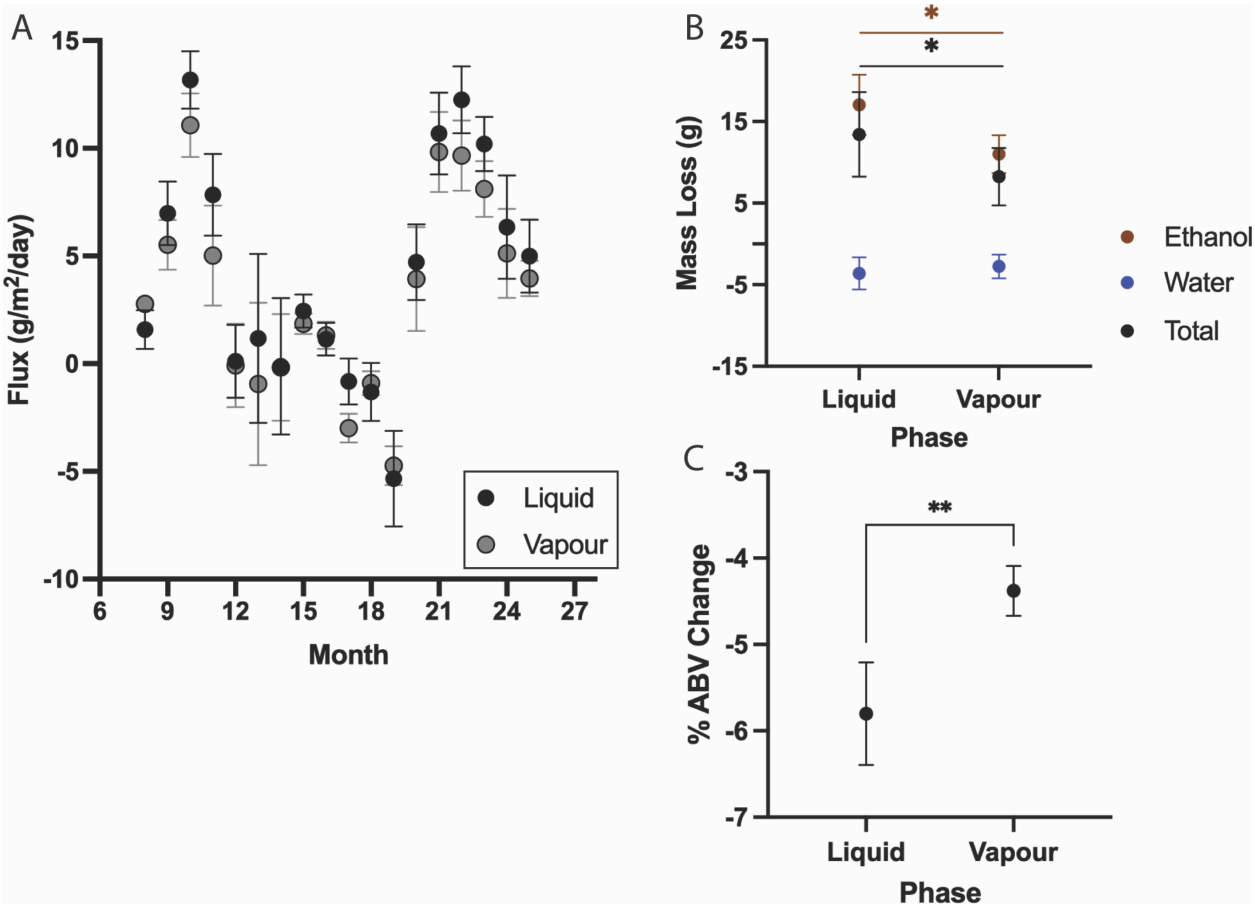


Figure 4. (A) Monthly flux of spirit through barrel wood for liquid and vapour contacting stave disks, (B) Total mass loss, ethanol mass loss, and water mass loss from the modules over the two year period for liquid and vapour contacting stave disks, (C) % ABV gain of spirit in the modules over two years, with stave discs in contact with the liquid and vapour.

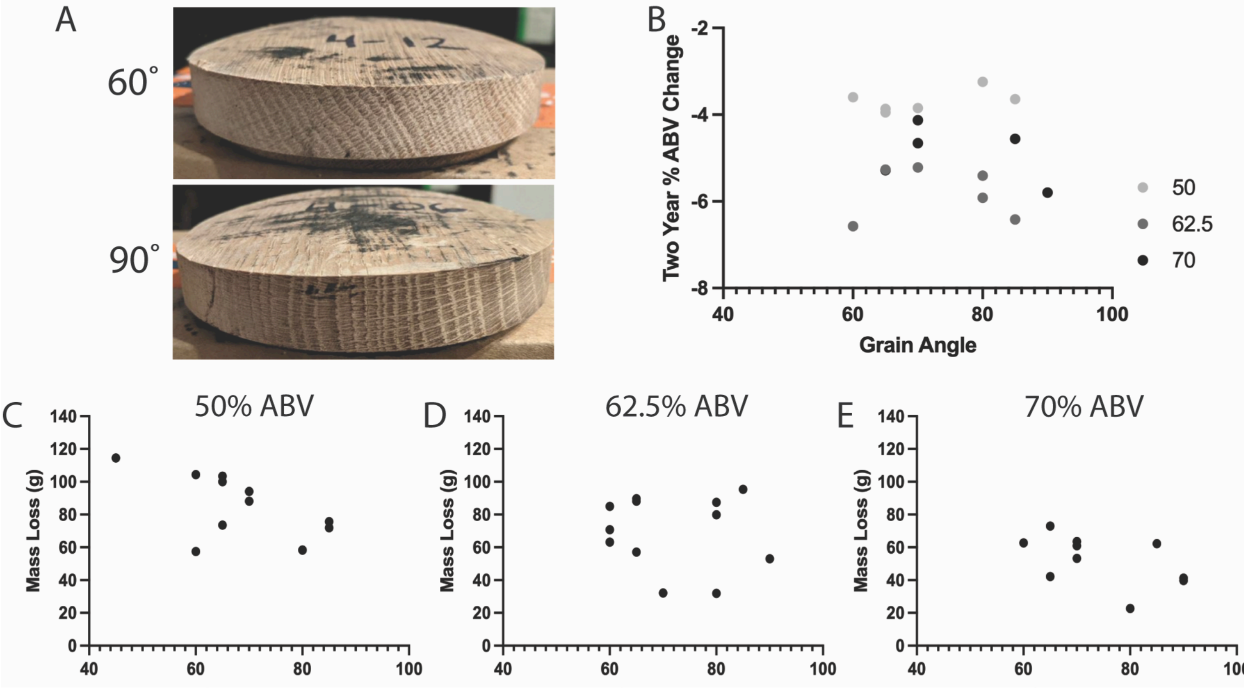


Figure 5. (A) View of staves with 60˚ and 90˚ grain angle, (B) % ABV gain of spirit in the modules over two years for all initial alcohol contents at each grain angle, (C-E) total mass loss from the modules over the two years at each grain angle for (C) 50% ABV initial alcohol ($R^2 = 0.40$), (D) 62.5% ABV initial alcohol ($R^2 = 0.011$), and (E) 70% ABV initial alcohol ($R^2 = 0.26$).

Discussion

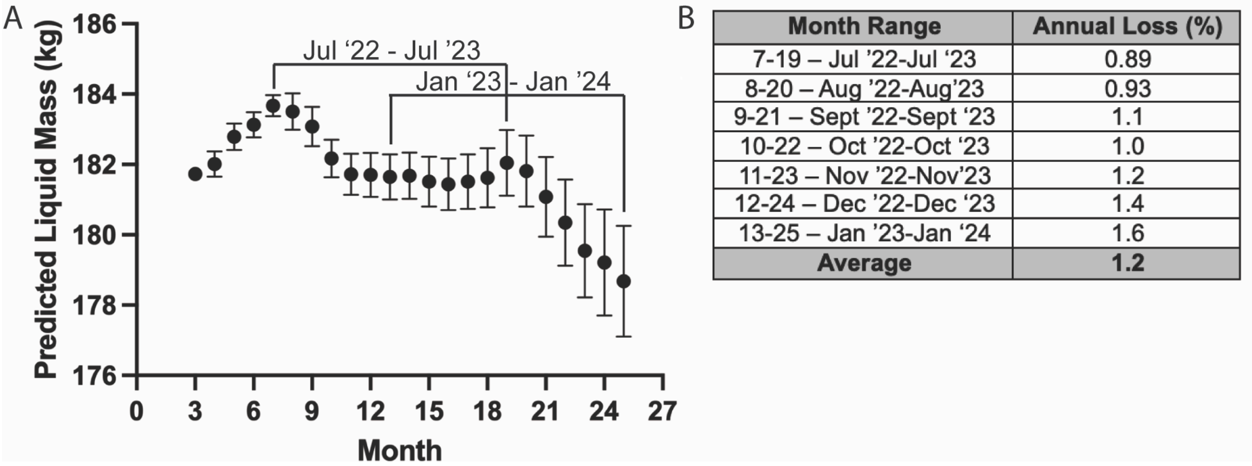
Barrel entry alcohol content has a significant impact on production economics and flavour development (Boruff and Rittschof 1959). However, the impact of the initial alcohol content on spirit diffusion through sound wood has not been investigated. This work shows a significant reduction in the monthly flux with increasing entry ABV (Figure 3A, Supplementary information Table S1) and in the total mass loss between 50 and 70% ABV, and between 62.5 and 70% ABV (Figure 3B).

The main factor in decreased mass loss was the significant increase in net water uptake with increasing ABV (Figure 3B). As diffusion is molecular mass flow under the influence of a concentration gradient (Siau 1984), Fick's first law represents the relationship between the flux and concentration gradient under steady state conditions (Eqn 2).

$$J = -D\, dc/dx$$

where J is flux (g/m^2/d), D is the diffusion coefficient (m^2/d), and c is the concentration (g/mL) (Siau 1984). 50% ABV corresponds to a concentration of water of 0.559 g/mL contacting the inside surface of the stave, 0.432 g/mL for 62.5% ABV, and 0.352 g/mL for 70% ABV. This results in an altered concentration of water at the inner wood surface, which creates a difference in the concentration dependent driving force for water diffusion into the module. The Alcohol and Tobacco Tax and Trade Bureau (TTB) regulate the maximum ABV for bourbon of 62.5% entering the barrel. Since 50 and 62.5% entry ABV had no significant difference on maturation loss (Figure 3B), the traditional metrics of flavour extraction and economics are more salient drivers for selecting the initial alcohol content.

The investigation of the effects of vapour contact with the stave on spirit diffusion, showed the final alcohol concentration (Figure 4C) and the total mass loss (Figure 4B) were different between the liquid and vapour contact groups. The decrease in alcohol concentration for both groups was expected from observations of the decreasing alcohol concentration of barrels stored on the lower floors of Kentucky maturation warehouses (Conner 2014). The net water gain in liquid and vapour contacting groups were comparable (Figure 4B), suggesting that water uptake is largely driven by a humid maturation environment coupled with a similar water activity on the inside surface of the stave between groups. The difference in ethanol flow is the clear driver in the net mass loss between liquid and vapour contacting groups (Figure 4B). Also, the difference in ethanol flow suggests a different magnitude of the diffusion driving force between the liquid and vapour contacting groups. Since the concentration of alcohol in the ambient warehouse air should be comparable for both groups, the major difference in flow must arise from a change in the concentration of ethanol on the wood surface inside the stave. The concentration of ethanol on the wood surface in the liquid contacting group is relatively constant for this study. The concentration of ethanol on the wood surface for the vapour contacting surface will vary



Month Range	Annual Loss (%)
7-19 – Jul '22-Jul '23	0.89
8-20 – Aug '22-Aug'23	0.93
9-21 – Sept '22-Sept '23	1.1
10-22 – Oct '22-Oct '23	1.0
11-23 – Nov '22-Nov'23	1.2
12-24 – Dec '22-Dec '23	1.4
13-25 – Jan '23-Jan '24	1.6
Average	**1.2**

Figure 6. (A) Liquid mass in a standard bourbon barrel without joints or leaks predicted from the monthly flux of liquid in the stave disks modules. (B) % annual liquid loss from a standard bourbon barrel without joints or leaks after the initial drink-in.

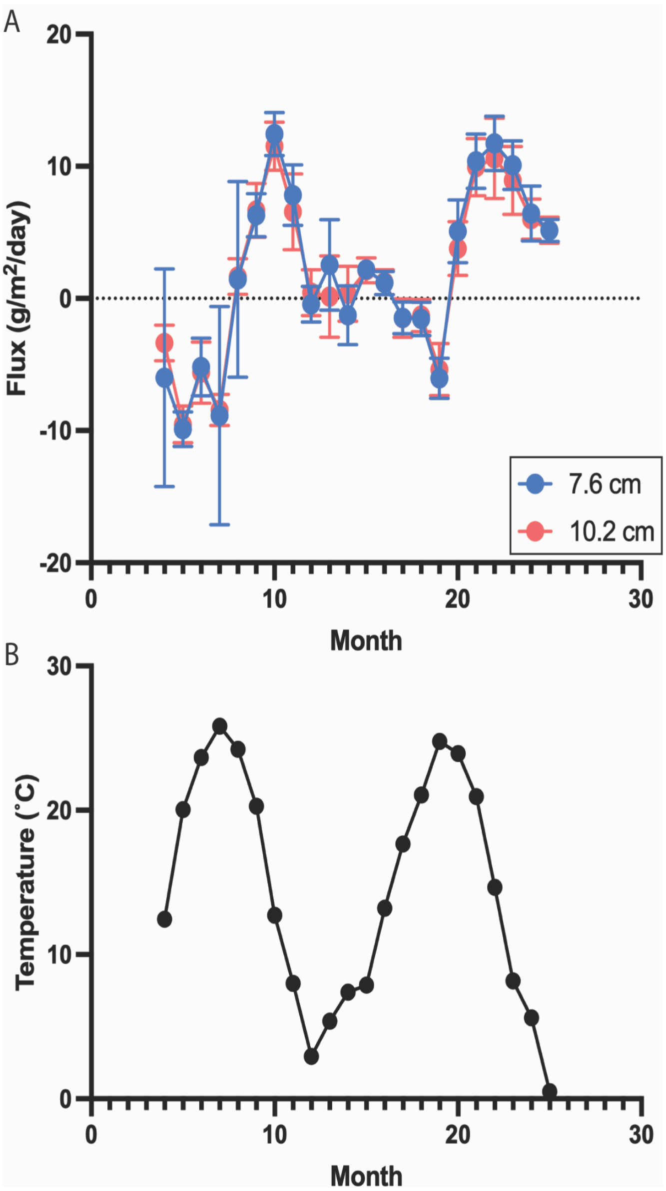


Figure 7. (A) Monthly flux of spirit through barrel wood for 7.6 and 10.2 cm stave disks. (B) Temperature from the local weather station in Frankfort, KY.

as the temperature changes over time. For a stable temperature or declining temperature, the saturated vapour phase will support a liquid layer on the inner wood surface that is like that seen in the liquid contact system. With a rapid rise in temperature, the vapour will briefly become unsaturated, reducing the ethanol concentration on the inner surface of the wood to levels lower than those in the liquid contact system. The small magnitude of the difference between liquid and vapour contacting groups is consistent with an intermittent difference in ethanol driving forces.

When using European oak to create barrels, the logs are split lengthwise along the grain to ensure the rays remain parallel to the inner side of the stave that will be in contact with the spirit (Chatonnet and Dubourdieu 1998; del Alamo-Sanza and Nevares 2018). However, with American white oak, logs are quartersawn in a way that does not follow the grain (Chatonnet and Dubourdieu 1998; del Alamo-Sanza and Nevares 2018). The reasoning for this, is that American white oak has abundant tyloses which obstruct the conducting vessels making the barrels impermeable to liquids (Kim et al. 2024). The lack of change in diffusion rate with oak grain angle results support this historical practice (Figure 5B-E). Quarter sawing utilises 40-50% of the log mass, while splitting utilises about 20%, resulting in the manufacture of about twice as many barrels from each cubic metre of sawn wood compared to split wood. This difference in manufacturing approach contributes to the lower cost of American white oak barrels (Chatonnet and Dubourdieu 1998; del Alamo-Sanza and Nevares 2018). The cost and resource effective method of quarter sawing American white oak staves is justified by the diffusive maturation losses being consistent regardless of grain angle.

From the predicted barrel liquid weight (Figure 6A), the average annual liquid loss from a standard bourbon barrel was calculated as 1.2 ± 0.3% (4.4 ± 1.4% proof gallons) (Figure 6B). This is the first measurement of maturation loss through sound wood. This provides a lower band for efforts to reduce maturation loss, as this is the non-leakage loss expected from a standard bourbon barrel. Any additional loss would be attributed to leaks at joints between the staves or leaks from the barrel. However, this annual liquid loss is also only valid for this specific location, pertaining to the wood and liquid properties that affect maturation loss. Any changes in external factors, including temperature, humidity, or location in the warehouse, will change the amount of loss (del Toro et al. 2019). Cooler climates such as Scotland will have lower rates of loss than in Kentucky, while hotter, drier climates such as Texas will result in increased maturation losses (Conner 2014). Further, within a warehouse, the lower floors will be cooler and more humid, with the temperature increasing and humidity decreasing with higher floors (Conner 2014). Although there are many factors that can affect maturation loss, an annual liquid loss of 1.2 ± 0.3% gives a measurement of spirit diffusion through wood in Kentucky. As seen in Figure 6A, the initial 'drink-in' results in the barrel gaining mass.

Stave disks placed in the warehouse gained approximately one gram of mass over the first month (Supplementary information Table S3), which corresponds to an increase of about 0.4 kg to a standard bourbon barrel. This increase in mass is explained by the wood pulling moisture from the humidity in the air and explains the initial increase in mass observed in Figure 6A.

Seasonal variation is evident in the monthly flux data (Figure 7A). The relationship between diffusion coefficient and temperature can be expressed by the Arrhenius equation (Kang and Hart 1997) (Eqn 3).

$$D = D_0 \exp\left(-E_a/RT\right)$$

where D is the diffusion coefficient (m^2/d), D_0 is a constant representing the maximal diffusion coefficient (m^2/d), E_a is the activation energy for diffusion (J/mol), R is the universal gas constant (J/mol/K), and T is the temperature (K).

Diffusive flux and temperature have a direct relationship, and this relationship is consistent with the flux data and the local temperature in Frankfort, KY (Figure 7B). As expected, the monthly flux typically follows the same trend, increasing or decreasing with temperature. However, there is a delay between an upward or downward temperature swing and the corresponding swing in the monthly flux. For example, the local temperature first peaks at month 7 (July 2022), while the flux peaks in month 10 (October 2022). The temperature then peaks again at month 19 (July 2023) while the flux peaks again in month 22 (October 2023). It is suggested that this delay is due to the environment of the first floor of the warehouse changing temperature more slowly than the surrounding air, as the thermal mass of over 58,000 barrels will slow the thermal response of these modules.

The diffusive flux is likely to fluctuate more in the experimental modules than in a 53 gallon (200 L) barrel. The liquid in a barrel has a greater thermal mass and requires more energy to change the temperature. So, with fluctuating ambient temperatures, the temperature of the liquid would be more consistent than the smaller volume of liquid in the stave disk modules. However, in this study, this is less of an issue with the modules located in the centre of the warehouse but would be a greater issue at the perimeter of the warehouse. Although the 10.2 cm modules have greater than 50% more mass loss than the 7.6-cm modules, the monthly flux is relatively equal for each size (Figure 7A). As noted in Equation 1, the flux represents the daily mass loss through a square meter of wood. Therefore, the module scaling is validated by the flux being equal for both sizes of diffusion stave systems.

Conclusions

Although losses are unavoidable in maturation, there are opportunities for increased revenue by reducing evaporative losses. This work shows that - excluding any losses from leaks in the joints between the staves - liquid losses of about 1.2% per year occur in a sealed bourbon barrel. Although this loss is unavoidable, it is a necessary aspect of the maturation process, with liquid loss linked to flavour development of the spirit. Compounds become more concentrated as the liquid volume in the barrel decreases. In addition, the outflow of liquid contributes to the influx of oxygen, resulting in oxidative reactions that contribute many of the flavours and aromas of the spirit.

This work reports the effects of the initial alcohol content, liquid versus vapour contact with the stave, and grain angle on spirit diffusion through wood. Of these, the initial alcohol content had the largest effect on maturation loss, with increasing alcohol content leading to the greatest decrease in the magnitude of loss. Although regulations for maximum ABV prevent the use of alcohol contents higher than 62.5%, a higher alcohol content may occur during maturation. Liquid and/or vapour contact is an inherent property of maturation, with vapour contact becoming more significant as the liquid level in the barrel decreases. The difference between the two is minimal, and is likely not a major factor in variations in maturation loss. Although the practice of quarter sawing American white oak has been in place for centuries, the effect of grain angle on spirit diffusion through wood had not yet been investigated. This study confirms that this practice is justified by the lack of impact of grain angle on losses.

There are many historic practices used by brands in the spirits industry, and changes in maturation loss will impact the flavour and aroma of the spirit. Accordingly, building on this work, the effect of wood and liquid properties on congener development should be investigated. Other properties of the barrel, such as charring, toasting, and seasoning which affect the structure and chemical composition of the wood, should be explored for their effect on maturation loss and flavour development. Although the effects of temperature and humidity on maturation loss have been observed over the years, experiments on the direct impact of temperature and humidity on spirit transport through wood are needed. In all, this work has shown that maturation loss is a complex and unavoidable aspect of aged spirits. A lower level of 1.2% loss per year has been established for maturation loss in Kentucky, which suggests that producing barrels that limit leaks is perhaps the most effective strategy for reducing excess maturation loss.

Author contributions

Taylor Scott: validation, formal analysis, investigation, data curation, writing (original draft), writing (review and editing), visualisation.
Jarrad Gollihue: methodology, investigation, writing (review and editing).
Michael Sama: methodology, investigation.
Michael Shaffer: methodology, investigation.
Brad Berron: conceptualisation, methodology, formal analysis, writing (original draft), writing (review and editing), project administration, funding acquisition.

Conflict of interest

The authors declare there are no conflicts of interest.

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