DEWALD ACADEMY OF DRYING

Enthalpy Evaporation Evaluation – *A Case for the E3 Drying Metric*
White Pages | Chuck Dewald III

The Foundation of E³

Water loss mitigation requires controlled removal of various types of water. There is often bulk liquid water to be sucked-up by a pump and soaked items which can be removed. Beyond this, there is water held within the building materials of the structure. This water can be held as free water or as bound water. Free water is held in liquid form within the tiny pores that exist in porous materials, while the bound water is held to the materials by weak but effective forms of chemical bonding.

Both types of held water require breaking chemical bonds for the water to evaporate, but the balance and number of bonds is different between the two. Because of that, the rate mechanics and energy factors controlling their evaporation are very different. The composition of the energy content in the ambient air plays a major role in determining whether and how quickly these bonds break.

To evaluate this evaporative energy transfer process, you must employ metrics that evaluate how the energy transfer values can change as you apply drying efforts. We have discovered 3 conditions that, when taken together in the proper distribution, fully determine relative evaporation rates of water from construction materials. All 3 of these are extremely important to predicting the evaporation rate of water from a wet material but each has a slightly different role.

> 1. Ambient Condition Energies
> 2. Dew Point Temperature Energies
> 3. Wet Bulb Temperature Energies

The formulas for sensible and latent ambient energy (enthalpy) content of air at sea level are:
- $(Ta)*(0.24 \text{ btu/lb.-F}) + gpp/7000*((0.45 \text{ btu/lb.-F})*(Ta)) =$ Sensible energy in btu/lb
- $gpp/7000*(1,061 \text{ btu/lb.}) =$ Latent energy in btu/lb

Where:
Ta = dry bulb temperature, °F
1,061 = average Btu requirement to evaporate 1 lb. of water
0.24 = average Btu requirement to raise 1 lb. of air by 1°F
0.45 = average Btu requirement to raise 1 lb. of water vapor by 1°F
The total enthalpy (H) of air= sensible energy + latent energy

Similar energy content formulas for the Dew point energies:
- $(Tdp)*(0.24 \text{ btu/lb.-F}) + gppdp/7000*((0.45 \text{ btu/lb.-F})*(Tdp)) =$ dp sensible energy in btu/lb
- $gppdp/7000*(1061 \text{ btu/lb.}) =$ dp latent energy in btu/lb

Where:
Tdp = Dew point temperature, °F
Gppdp/7000 = dew point humidity ratio (same as ambient humidity ratio)
Other factors are same as the ambient formula

This dew point energy composition will be different from the ambient composition, but the dew point energy composition is controlled by the ambient composition.

And the energy content formulas for the Wet bulb energies:
- (Twb)*(0.24 btu/lb.) + gppwb/7000*((0.45 btu/lb.)*(Twb)) = wb sensible energy in btu/lb.
- Gppwb/7000*(1061 btu/lb.) = wb latent energy in btu/lb.

Where:
Twb = Wet bulb temperature, °F
Gppwb/7000 = wet bulb humidity ratio (calculated from drop in wet bulb sensible)
Other factors are the same as the ambient formula

The wet bulb sensible + latent energy total must equal the sensible + latent total of the ambient condition; it will just have different sensible and latent values.

E³ Formula

The restoration industry has never had a singular metric to evaluate the drying or evaporation rate. This has been a huge problem in the restoration industry since its inception. We needed a metric that could evaluate any ambient condition and provide a proportionate drying or evaporation rating. E³ provides this metric.

E³ evaluates any ambient conditions and predicts the relative drying or evaporation rate that will be created on the wet materials by the ambient air. The system performs a thorough energy evaluation and provides a proportionate number—meaning an E³ number of 200 would dry or evaporate water from all materials twice as fast as an E³ number of 100.

You will notice the free water (Fw) section of the formula evaluates the ambient sensible and latent contents as well as the wet bulb sensible and latent contents in several different ways. This section of the formula had some historical help because even before E³ some insights and comparisons could be made about free water evaporation by looking at the difference between the ambient and wet bulb temperatures. The relationship between the ambient and wet bulb temperature by itself was not enough, though, to completely quantify all aspects of evaporation from free water. The rest of the relationships listed in the free water (Fw) part of the E³ equation came from hours of empirical testing (drying and weighing of wet materials) and tweaking the formula to develop a tighter relationships with the results.

$$\left[\left(\frac{A_{(s)} \div A_{(L)}}{Dp_{(s)} \div Dp_{(L)}}\right) \times \left(\frac{A_{(s)} - Dp_{(s)}}{Dp_{(s)}}\right) \times (0.5)\right]_{B_{(w)}} + \left[\left(\frac{A_{(s)} \div A_{(L)}}{Wb_{(s)} \div Wb_{(L)}}\right) \times \left(\frac{A_{(s)} - Wb_{(s)}}{Wb_{(s)}} + \frac{Wb_{(L)} - A_{(L)}}{Wb_{(L)}}\right) \times (0.5)\right]_{F_{(w)}}$$

A$_{(s)}$: Ambient Sensible Energy = (0.24 btu/lb -°F)(Ta°F) + Wa [(0.45 btu/lb -°F)(Ta°F)]

Dp$_{(s)}$: Dew Point Sensible Energy =(0.24 btu/lb -°F)(Tdp°F) + Wdp [(0.45 btu/lb -°F)(Tdp°F)]

Wb$_{(s)}$: Wet Bulb Sensible Energy =(0.24 btu/lb -°F)(Twb°F) + Wwb [(0.45 btu/lb -°F)(Twb°F)]

A$_{(L)}$: Ambient Latent Energy = Wa (1061btu/lb)

Dp$_{(L)}$: Dew Point Latent Energy = Wdp (1061btu/lb)

Wb$_{(L)}$: Wet Bulb Latent Energy = Wwb (1061btu/lb)

- Ta°F: Ambient Temperature
- Tdp°F: Dew Point Temperature
- Twb°F: Wet Bulb Temperature
- Wa°F: Ambient Humidity Ratio, Ambient gpp/7000gpp=lb/lb
- Wdp°F: Dew Point Humidity Ratio, Dew Point gpp/7000gpp=lb/lb
- Wwb°F: Wet Bulb Humidity Ratio

Energy Evaluation of the Ambient Air

The bound water (Bw) section of the formula evaluates the ambient sensible and latent energy contents as well as the dew point sensible and latent energy contents in several different ways. Unlike the free water section there was no existing data on how to address evaporation of bound water in building materials from an energy standpoint. This section took years to finalize. The dew point temperature quantifies condensation which is the opposite of evaporation, and I used the dew point temperature energy compositions to complete the bound water (Bw) section of the formula.

After countless hours of testing, I was able dial in both the bound water and free water formulas with remarkable accuracy.

I realized my testing alone would not be enough to gain the acceptance and validation of E³. The best way to eliminate all doubt would be to compare E³ predictions to third party published testing. I lay out these comparisons in the next sections.
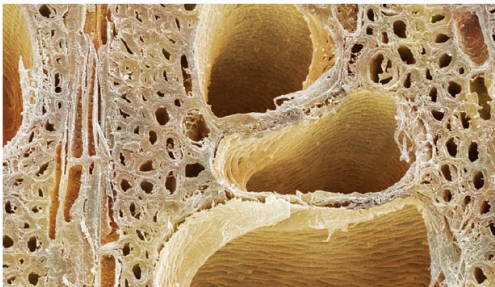
Comparison 1

>> RESTORATION

The Role of Vapor Pressure and Enthalpy in Drying Wood-Based Products

Using the second law of thermodynamics and data gathered from the lumber industry as a guide, the author examines the drying processes of water-damaged wood.

>> by Jerry Blaylock

This study investigates water vapor pressure as measured in inches of mercury (inHg) and enthalpy (h) within ambient air and water-damaged wood-based building products. Water vapor pressure and enthalpy differentials between ambient air and wood building products below fiber saturation point were analyzed using the Energy Transfer Rate (ETR) model. SPF (spruce, pine, fir) framing lumber and red oak hardwood flooring were tested and assessed.

It was determined that the largest moisture content reduction resulted from the largest vapor pressure and enthalpy differential. Importantly, it was determined that the reduction of the humidity ratio — expressed in grains per pound — within the environment was not the most significant contributing factor in moisture content reduction.

Introduction
In drying water-damaged structures, understanding and applying the equilibrium moisture content (EMC) chart (figure 1) can be instrumental in evaluating drying efficiency. In this paper the science of EMC from the wood-drying industry is integrated into the services provided by restoration professionals. A topic of importance as an educator, researcher and consultant is to evaluate the role of vapor pressure and enthalpy differentials within the ambient air and within wood-based building materials. By understanding the thermodynamics involved in EMC, and the movement of moisture within wood, we find that vapor pressure and enthalpy differentials are key metrics that reveal the forces at work in drying efficiency.

The second law of thermodynamics
The second law of thermodynamics states that in an isolated system, concentrated energy will disperse to lower energy. In regards to the restoration in-

This published study on evaporation came from within the restoration industry and was published in the IICRC Journal (2014) by Jerry Blaylock. It looked at the moisture evaporation rates from wood materials—spruce, pine, and fir framing lumber and red oak hardwood flooring. Blaylock added water to these wood materials until he got the moisture content well above 20%MC. He then exposed this wet wood to 3 different ambient conditions for 24 hours and measured the resulting moisture content change. Whichever condition dropped the moisture content the most was deemed the best for drying or evaporating water and the one the least was the worst for drying or evaporation. This testing involved both free and bound water. His results were summed up in his chart below:

Energy Transfer Rate - wood samples of SPF and Red Oak submerged in water for a 24 hour period prior to testing. 3 different conditions and impact on materials.

	Materials		V.P.	Enthalp	Environment		V.P.	Enthalpy		Δ	Δ	Δ
	Temp	% MC	inHg	BTU's	Temp	RH	inHg	BTU's	% EMC	inHg	Enthalpy	% EMC
start	78	23.7	0.91	39.6	70	35	0.26	22.5	6.9	0.65	17.0	16.8
24 HRS	70	13.2	0.52	28.4	70	35	0.26	22.5	6.9	0.27	5.9	6.3
start	78	24.2	0.91	39.6	90	25	0.35	29.5	5.1	0.56	10.1	19.1
24 HRS	90	10.5	0.83	40.6	90	25	0.35	29.5	5.1	0.48	11.1	5.4
start	78	26.5	0.94	40.3	115	18	0.52	39.3	3.5	0.41	0.9	23.0
24 HRS	115	9.5	1.71	67.4	115	18	0.52	39.3	3.5	1.19	28.1	6.0

Test 1	Materials 0 Hours Temp	%MC	24 Hours Temp	%MC	Δ
SPF w/ Airflow	78	21.8	70	13.8	37%
SPF	78	21.6	70	13.4	38%
Oak w/ Airflow	78	25.3	70	12.5	51%
Oak	78	26.2	70	13.1	50%
Average	78	23.7	70	13.2	44%

Air: 70F/38 GPP

Test 2	Materials 0 Hours Temp	%MC	24 Hours Temp	%MC	Δ
SPF w/ Airflow	78	22.8	90	12.0	47%
SPF	78	24.1	90	11.8	51%
Oak w/ Airflow	78	25.2	90	8.4	67%
Oak	78	24.8	90	9.7	61%
Average	78	24.2	90	10.5	56%

Air: 90F/52 GPP

Test 3	Materials 0 Hours Temp	%MC	24 Hours Temp	%MC	Δ
SPF w/ Airflow	78	24.7	115	10.4	58%
SPF	78	28.1	115	10.5	63%
Oak w/ Airflow	78	27.2	115	7.9	71%
Oak	78	26.0	115	9.2	65%
Average	78	26.5	115	9.5	64%

Air: 115F/77 GPP

Test 1 - MC% of 13.2% and reduction of 44%, Δ .27 inHg, Enthalpy Δ 5.9
Test 2 - MC% of 10.5% and reduction of 56% Δ .48 inHg, Enthalpy Δ 11.1
Test 3 - MC% of 9.5% and reduction of 64% Δ 1.19 inHg, Enthalpy Δ 28.1

Airflow was provided via 3,000+ cfm air mover placed 6' from material.

All the wet materials started at 78°F and then were exposed to the 3 different conditions:
- Condition 1 = 70°F/35%RH at 38 gpp
- Condition 2 = 90°F/25%RH at 52 gpp
- Condition 3 = 115°F/17.3%RH at 77 gpp

Average Starting Moisture Content values in each condition:
- Condition 1 = 23.7%MC
- Condition 2 = 24.2%MC
- Condition 3 = 26.5%MC

Moisture Content after 24 hours under each condition:
- Condition 1 = 13.2%MC
- Condition 2 = 10.5%MC
- Condition 3 = 9.5%MC

Drop in Moisture Content for each condition:
- Condition 1 = 23.7 - 13.2 = d10.5%MC points
- Condition 2 = 24.2 - 10.5 = d13.7%MC points
- Condition 3 = 26.5 - 9.5 = d17%MC points

Condition 3 performed best; Condition 2 second best, and Condition 1 the worst.

E^3 matches the results of Jerry's testing. Here are the E^3 Values for each test condition:
- Condition 1 = 131
- Condition 2 = 171
- Condition 3 = 211

E^3 Comparisons to the actual results:
- E^3 Condition 2 vs Condition 1 = 171/131 = 30.5% prediction on Condition 2 doing better than Condition 1 (actual result = 30.5% better = **0% off)**
- E^3 Condition 3 vs Condition 2 = 211/171 = 23.4% prediction on Condition 3 doing better than Condition 1 (actual result = 24.1% better = **0.7% off**)
- E^3 Condition 3 vs Condition 1 = 211/131 = 61.1% prediction on Condition 3 doing better than Condition 1 (actual result = 61.9% better = **0.8% off**)

E^3 and the test results agree within an average of **0.5%**.

Comparison 2

Temperature Discontinuity at an Evaporating Water Interface

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ABSTRACT: Evaporative mass flux is governed by the interfacial state of liquid and vapor phases. For closely similar pressures and mass fluxes of liquid water into its own vapor, the discontinuity between interfacial liquid and vapor temperatures in the range of 0.14–28 K is reported. This controversial discontinuity has resulted in an obstacle to understanding and theoretical modeling of evaporation. Here, through the study of vapor transport by the Boltzmann transport equation solved through the direct simulation Monte Carlo Method, we demonstrated that the measured discontinuities were strongly affected by boundary conditions on the vapor side of the interface and do not reflect the interfacial state. The temperature discontinuity across the evaporating interface is ≤0.1 K for all of these studies. To accurately capture the interfacial state, the vapor heat flux should be suppressed.

■ INTRODUCTION

Evaporation phenomenon is the governing pillar of a wide range of disciplines ranging from atmospheric sciences to energy and biology. Kinetic of evaporation is described by the molecular dynamics (MD)-based simulations and various theories including diffusion[1-4] Hertz–Knudsen (HK),[5-7] statistical rate theory (SRT),[8-10] nonequilibrium thermodynamics (NET),[11,12] and molecular dynamics (MD) simulations.[13-15] In all of these theories, the kinetic of evaporation is governed by the interfacial thermodynamic properties (i.e., temperature and pressure), which are difficult to measure. Fang and Ward[16] conducted an accurate measurement of interfacial temperature of liquid and vapor at an evaporating water interface and found that a temperature discontinuity exists across the interface with the magnitude of up to 7.8 K. This was in contrast to all the previous measurements that considered approximately local equilibrium condition at the water interface.[17] This contrast in temperature discontinuity brought an unprecedented hurdle on a fundamental understanding of evaporation. Possible factors affecting the measurement of the interfacial temperature discontinuity, including radiation and evaporative cooling of the thermocouple bead, were closely examined and concluded to be negligible. Various scientists conducted these experiments and reported temperature discontinuity of 0.14–28 K.[7,16,18-42] Although the majority of experiments indicated that the liquid side of the interface is colder than the vapor side, few experiments[33,34] showed the opposite direction of temperature discontinuity. This temperature discontinuity at an evaporating water interface remains still a mystery.

Here, we propose a molecular insight on the evaporation phenomenon and elucidate source of the mystery. This insight explains all of the contradicting measurements conducted by various groups and provides a platform for further advancement of evaporation theories. The interface is only a few-molecular-length thick, and determination of the thermodynamic state on each side of the interface is difficult. One way to avoid the experimental challenges is to computationally analyze vapor transport in the Knudsen layer (Kn) and the vapor phase. This layer forms during evaporation between a liquid surface and the bulk vapor phase, Figure 1. By definition, the Knudsen layer is an adjacent layer to the liquid surface, where the escaping vapor from the surface is in a state of thermodynamic nonequilibrium, i.e., the vapor molecules do

Figure 1. Schematic of a planar evaporating interface, zoomed into the scale of the Knudsen layer. There are indeed three regions consist of the liquid phase, the Knudsen layer, and the bulk vapor phase. The thickness of the Knudsen layer is equal to a few molecular mean free path. T_i^l and T_i^v are temperatures at the liquid and vapor sides of the interface, respectively.

A

This came from The Journal of Physical Chemistry, December 2019. Three PhD's (Jafari, Amritkar, Ghasemi) at the University of Houston did a study, "Temperature Discontinuity at an Evaporating Interface". This paper evaluated evaporation rates (kg/m2-s) from a liquid interface at bulk vapor (ambient air) temperatures ranging from 13°F to 175°F in 31 different tests. The study evaluated 4 sets of test data (Kasemi, Jafari, Fang & Ward, & Badam) at different ambient and liquid temperatures as well as different vapor pressure or humidity ratio values. Below are their raw data and their results summary:

Table 1. Summary of All Simulations at Different Vapor Boundary Conditions

| $\dot{m}_d \times 10^4$ (kg/(m² s))	$P_{exp} \pm 13$ Pa	P_{sim} (Pa)	T_B (K)	T_I^v (sim) (K)	T_I^v (exp) (K)
		Kazemi et al.[22]			
3.97	266	268	264.58	262.6	262.69
3.88	303	308	266.38	264.3	264.33
3.08	435	444	271.02	268.96	268.90
2.35	545	533	273.82	272.0	271.75
0.65	815	820	279.15	276.6	277.37
		Jafari et al.[18]			
3.61	374	373	270.15	267.15	267.15
2.53	436	430	272.15	269.2	269.15
3.40	526	520	273.95	271.6	271.55
2.24	541	533	274.8	272.4	272.05
2.18	636	631	277.45	273.9	274.15
0.72	755	744	278.55	277.1	276.55
1.77	913	911	281.4	279.0	279.25
		Fang and Ward[16] and Duan et al.[46]			
2.40	194	198	286.38	268	266.40
0.87	196	193	300.07	263.1	263.67
0.56	583	595	301.25	275.9	275.25
0.31	591	602	294.73	275.5	275.03
1.04	625	630	302.97	275	275.33
		Badam et al.[20]			
7.20	213	220	353.15	275.11	275.40
7.15	288	288	353.15	275.5	277.80
7.52	388	401	353.15	280.5	280.92
7.42	569	565	353.15	283	284.00
7.80	744	780	353.15	287.8	286.83
7.60	855	894	353.15	287.5	288.05
8.15	946	972	353.15	288.3	289.10
7.50	1076	1090	353.15	291.1	291.00
7.28	215	210	343.15	273.15	274.78
7.10	290	295	343.15	274.5	276.40
6.76	389	381	343.15	278	278.70
6.5	573	590	343.15	283	282.75
6.91	747	753	343.15	285.57	285.50
6.96	850	876	343.15	287.2	286.50
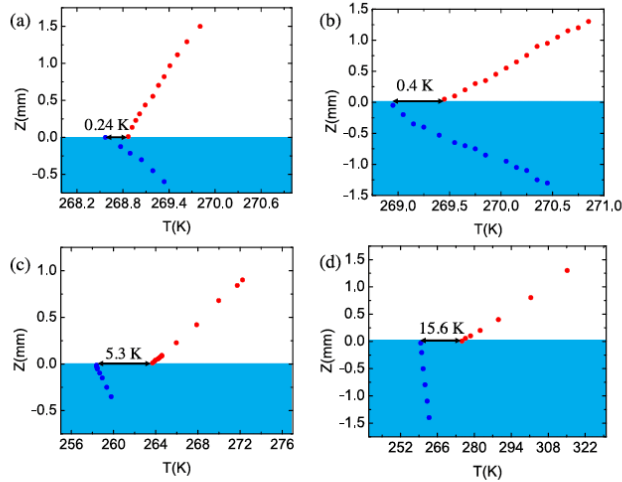
Figure 2. Temperature profile in the liquid and vapor phases of an evaporating water into its own vapor from four independent groups. All of these temperature profiles are measured at the centerline of the liquid−vapor system. Due to the symmetry at the centerline, the role of convection is negligible. (a) Kazemi et al.,[22] (b) Jafari et al.,[18] (c) Duan et al.,[43] and (d) Badam et al.[20] In (a)−(c) studies, there was no direct heating element in the vapor phase, while in study (d), the authors used a mounted heating element with a temperature of 80 °C above the free liquid surface.

We will evaluate their test data in two ways. First let's look at what the average evaporation rate was from the liquid in the different tests, the average bulk vapor temperatures, and vapor pressure (humidity ratio) values, as well as the temperature discontinuity values:

- Kasemi = 2.41 kg/m2-s, 271K(29°F), 435 Pa (+/-13 Pa), 19 gpp, 0.24K Discontinuity
- Jafari = 3.1 kg/m2-s, 274K(34°F), 446 Pa (+/-13 Pa), 20 gpp, 0.4K Discontinuity
- Duan = 8.65 kg/m2-s, 297K(76°F), 176 Pa (+/-13 Pa), 7 gpp, 5.3K Discontinuity
- Badam = 12.3 kg/m2-s, 349K(170°F), 213 Pa (+/-13Pa), 10 gpp 15.6K Discontinuity

The authors mentioned that as the temperature discontinuity (difference) increased between the liquid and bulk vapor phase so did the margin of error in predicting or comparing the evaporation rates. Nowhere in this paper were the authors trying to predict evaporation rates using a new formula or method, they were focused on how the evaporation rate was influenced by the temperature difference between the liquid and the bulk vapor phase. I plugged their results into E³ to see how well E³ predicted the evaporation rates they measured, while correcting for the temperature discontinuities.

First, since they were only looking at free water, I applied their data to only the Free Water (Fw) section or component of E³. I then applied it to the full E³ formula (both free and bound water components). These evaluations used the summary (average) values of the raw data and considered the temperature difference between the liquid and bulk vapor phase. Lastly, I plugged their results into an evaporation formula derived in 1802 by John Dalton (known here for his Law of Partial Pressures) that is supposed to evaluate evaporation from a liquid interface by looking solely at vapor pressure differentials between the liquid and the water vapor.

Here is the first evaluation, using only the Free Water (Fw) component of the E³ formula. Free Water E³ values were obtained using the average bulk vapor temperatures and vapor pressures (gpp) from the 4 sets of tests (31 overall) in this study:

Free Water E³ Correction for TK Discontinuity Between Tests *All Text Compared to Badam E³ Value and Evap Rate*							
TK Dis	Badam E³	Evap Rate	Dis Corr	E³ Comp	Predicted	Error	Error
15.6	6,638	12.3	425.5128	34.59454	12.3	0.00%	0.00%
5.3	1,600	8.56	301.8868	34.59454	8.726429	0.88%	0.88%
0.4	44	3.1	110	34.59454	3.179693	2.51%	2.57%
0.24	20	2.41	83.33333	34.59454	2.408858	0.05%	0.05%
					Avg	0.86%	0.88%
					TAvg	0.87%	

Average Free Water E³ values for each set of tests:
- Kasemi = 20
- Jafari = 44
- Fung & Ward & Duan = 1,600
- Badam = 6,638

As mentioned by the authors of this study, to have a chance at predictable modeling for evaporation the temperature difference between the liquid and bulk vapor phase must be compensated for. This is what I did in the above calculations. A correction calculation was made by dividing the free water E³ value by the temperature discontinuity; essentially providing an E³ per one degree value. For instance, the average free water E³ value for Badam tests was 6,638...this gets divided by the 15.6K temperature discontinuity to give a corrected E³ value of 425.5. Each of the tests was compared this way below:

- Badam = 6,638 E3/15.6K = 425.5 E3 Corrected
- Fung, Ward, Duan. = 1,600 E3/5.3K = 301.9 E3 Corrected
- Jafari = 44 E3/0.4 = = 110 E3 Corrected
- Kasemi = 20 E3/0.24 = 83.3 E3 Corrected

Once we do this, we can directly compare the corrected Fw E³ values to the actual measured evaporation rates. First though, we need to get the actual evaporation rate per incremental unit of E³; a calibration factor, so, to get the first comparison we need to divide the Corrected E³ value of any one test by its tested evaporation rate (kg/m2-s). We used the Badam tests to get our calibration factor. 425.5 E3/12.3 kg/m2-s equals a calibration factor of 34.59 that will be divided into the remaining 3 test's E³ values to predict what their evaporation rates should be:

- Badam = 425.5 E3/34.59 CF = 12.3 kg/m2-s predicted rate (12.3 actual tested)
- Fung, Ward, Duan = 301.9 E3/34.59 = 8.72 kg/m2-s predicted rate (8.65 actual)
- Jafari = 110 E3/34.59 = 3.18 kg/m2-s predicted rate (3.1 actual)
- Kasemi = 83.3 E3/34.59 = 2.41 kg/m2-s predicted rate (2.41 actual)

As you can see from these numbers, the Free Water E³ component was within **0.87%** of predicting the tested evaporation rates.

The second comparison from this study was done using the complete E³ formula (free and bound water). Below is a list of the average temperature differences between the liquid and bulk vapor phase and the average listed raw vapor pressures (gpp) in each of the tests:

- Kasemi = 2.1K difference, 473 Pa (+/-13 Pa), 21 gpp
- Jafari = 2.6K difference, 596 Pa (+/-13 Pa), 26 gpp
- Fung, Ward, Duan = 25.6K difference, 438 Pa (+/-13 Pa), 19 gpp
- Badam = 66.5K difference, 582 Pa (+/-13 Pa), 25.5 gpp

By using the same average temperatures of the bulk vapor phase as before I was able to calculate average E3 values for each of the tests. Below is a listing of these values:

		Predictions Using E³ (bound free water- full formula) compared to average Vp and temp differnece in all test								
		Avg Vp were calculated for each test as well as average temperature difference between Tb and Ti E³ values were calculated for these Vp and Temp Values for each condition and compared to to Evap rate								
	Avg VpPa	Tp Diff	Avg Tk(b)	E³ Values	T Diff Corr	Evap Rate	E³ Comp	Predicted	Error	Error
Kazemi	473	2.1	271	13.7	6.52381	2.41	2.706975	2.41	0.00%	0.00%
Jafari	596	2.6	275.5	22	8.461538	3.1	2.706975	3.125828	0.83%	0.83%
Duan	438	25.6	297.1	602	23.51563	8.65	2.706975	8.687049	0.43%	0.43%
Badam	582	66.55	249	2100	31.55522	12.3	2.706975	11.65701	5.23%	5.52%
								Avg	1.62%	
								TAvg	1.66%	

Average E³ values for each of the tests:

- Kasemi = 13.7
- Jafari = 22
- Fung, Ward, Duan = 602
- Badam = 2,100

Again, we are going to compensate for the temperature differences between the liquid and vapor by calculating a corrected value, thereby eliminating the temperature difference. For instance, Kasemi E³ value was 13.7 divided by the measured temperature difference of 2.1K gives us 6.52.

- Kasemi = 13.7 E3/2.1K = 6.52 E3 Corrected
- Jafari = 22 E3/2.6K = 8.46 E3 Corrected
- Fung, Ward, Duan = 602 E3/25.6K = 23.5 E3 Corrected
- Badam = 2,100 E3/66.55K = 31.56 E3 Corrected

Next, just like in the last comparison we take an E³ corrected value from any test and divide it by the actual measured evaporation rate (kg/m2-s). Again, it doesn't matter which test we chose to get our calibration factor. In this case I chose Kasemi taking an E³ corrected value of 6.52 divided by the measured evaporating rate of 2.41 kg/m2-s to give a calibration factor of 2.707. This factor was then applied to each test to get a predicted evaporation rate and then compared to the actual measured evaporation rate:

- Kasemi = 6.52 E3/2.707 = 2.41 kg/m2-s predicted rate (2.41 actual)
- Jafari = 8.46 E3/2.707 = 3.13 kg/m2-s predicted rate (3.1 actual)
- Fung, Ward, Duan = 23.5 E3/2.707 = 8.69 kg/m2-s predicted rate (8.65 actual)
- Badam = 31.6 E3/2.707 = 11.7 kg/m2-s predicted rate (12.3 actual)

As you can see, E³ (the complete formula) was within **1.66%** of matching the evaporation rates in all the tests from this study.

Comparison 3

Here I compare John Dalton's formula that evaluates (as mentioned previously) vapor pressure differentials from the liquid and vapor to predict free water evaporation. His formula was only designed for free water but people in our industry commonly use it for both free and bound water. The reason I show the information below is to demonstrate that it does not even work well on free water:

Predictions Using Vapor pressure Comparisons to actual Evap Rate						
TDiff	Badam VpDiff to Evap Rate			Predicted	Error	Error
65.576923	1023	12.3	83.17073	12.3	0.00%	0.00%
76.226415	404	8.65		4.857478	43.84%	78.08%
462.5	185	3.1		2.22434	28.25%	39.37%
215.41667	51.7	2.41		0.621613	74.21%	287.70%
				Predicted	36.57%	101.29%
				Predicted	68.93%	

Predictions using Vapor pressure comparisons to actual Evap rate										Avg
Badam VpDiff to Evap Rate			Predicted	Error	Error	TDiff Corr	TDiff Comp	Predicted	Error	Error
654	12.3	53.17073	12.3	0.00%	0.00%	9.827198	0.7989592	12.3	0.00%	0.00%
142	8.65	53.17073	2.670642	69.13%	223.89%	5.546875	0.7989592	6.942627	19.74%	24.59%
34.7	3.1	53.17073	0.652615	78.95%	375.01%	13.34615	0.7989592	16.70443	81.44%	438.85%
13.9	2.41	53.17073	0.261422	89.15%	821.88%	6.619048	0.7989592	8.284588	70.91%	243.76%
			Avg	59.31%	355.20%			Avg	43.02%	176.80%
			TAvg	207.25%				TAvg	109.91%	

No matter how you evaluate the vapor pressure differentials of the liquid versus the bulk vapor phase Daltons formula was 68% – 207% off from the results of the tests in this study. Looking only at vapor pressure differentials will never predict evaporation. It can never work because it is only partially evaluating energy composition. All the energy components must be correctly factored in.

Third Party Testing Summary

To sum up the evaluations of E³ on these two third party published studies, E³ was 0.50%, 0.87%, and 1.66% off predicting or evaluating exactly what happened, which is right at the 1.0% margin of error that I had seen in the tests I carried out developing E³. We can now start to effectively evaluate our drying chambers and perform our setups based upon the equipment being used, class of loss, day of loss, and outside conditions. We have a number that gives meaning and purpose to our drying logs.

We now have a metric that gives us the EVAPORATION ABILITY OF THE AIR. And as this paper has shown it is backed up and proven by not only my personal testing but other third party published studies.
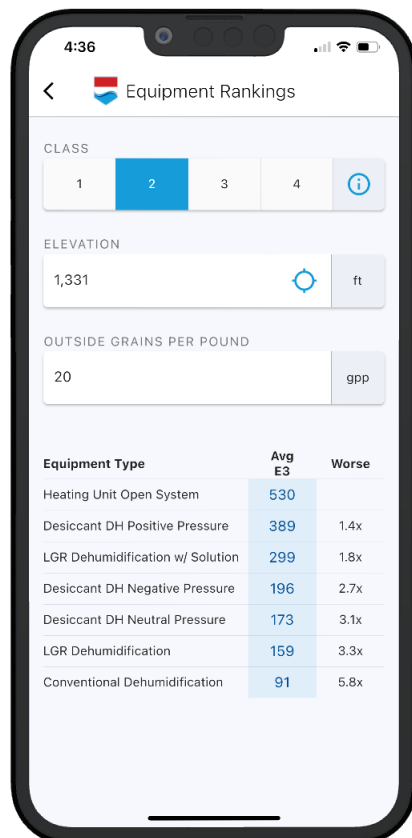
E³ extensions

It is important to note that E³ was never designed to give an exact evaporation rate (kg/m2-s for instance). But what it does accomplish, equally importantly, is tell us that no matter what the job, or materials, or amount of water, that a drying condition with an E³ value of 200 will always dry that building twice as fast as a condition with an E³ value of 100. Having said that, with more development E³ could be used to predict exact evaporation rates. Of course, to do this, jobs would have to be divided into many different categories to get average rates at similar E³ values. This is coming and I have plenty of data to start doing this, but I am cautious to do so until it is perfected so it can be well-accepted by insurance companies and third-party evaluators.
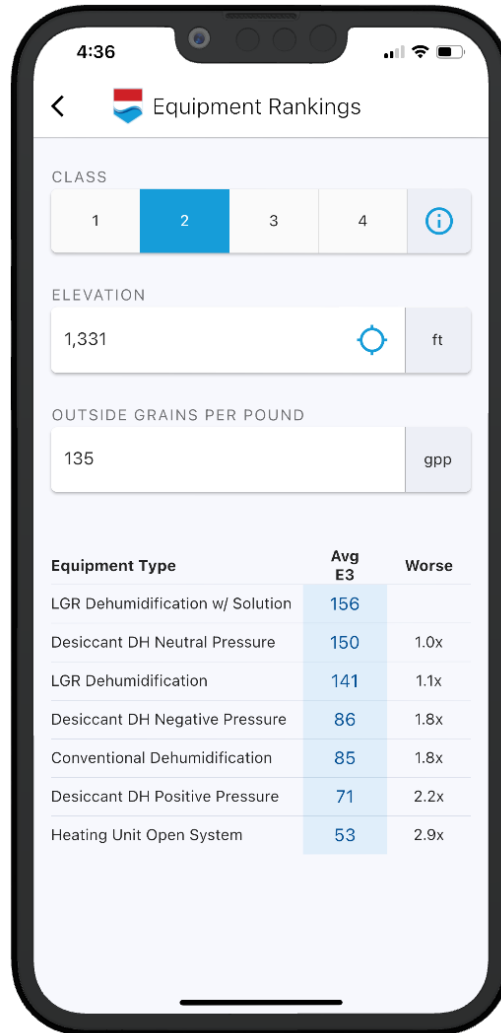
E³ and Drying Equipment

The most important use of E³ came when I was able to apply E³ targets to all types of jobs, classes of losses, types of equipment, day of the loss, and outside conditions. E³ took a long time to develop but what took even longer was developing the chamber E³ daily targets throughout a loss for all different types of drying equipment.   What will dry better between LGRs, Desiccants, or Heating Units? Before E³ this could not be scientifically answered, it could not be quantified. Now with E³ it can be.

This page in the E³ app (Equipment Rankings) shows, once we provide the class of loss, elevation, and outside gpp, exactly which equipment would dry the fastest and exactly how much faster. It compares all the drying equipment, from the beginning of the loss onward, to let the restorer know which would work best if they had multiple types of equipment. As this E³ page shows, with the outside gpp at 20 on a class 2 loss the Heating Unit in an Open System would work the best. It then ranks the equipment from best to worst and exactly how much worse. This screen also shows that LGR dehumidification would take 3.3x longer to dry the same building compared to properly using an Open Heating System.

Equipment Type	Avg E3	Worse
Heating Unit Open System	530	
Desiccant DH Positive Pressure	389	1.4x
LGR Dehumidification w/ Solution	299	1.8x
Desiccant DH Negative Pressure	196	2.7x
Desiccant DH Neutral Pressure	173	3.1x
LGR Dehumidification	159	3.3x
Conventional Dehumidification	91	5.8x

Now if the outside gpp goes up to 135 gpp on the same Class 2 loss, look what happens to the performance of the Open Heating System—it falls all the way to the bottom. Desiccant dehumidification on neutral pressure, or LGR's would now work best. This lays out exactly how the equipment will perform in comparison.

Equipment Type	Avg E3	Worse
LGR Dehumidification w/ Solution	156	
Desiccant DH Neutral Pressure	150	1.0x
LGR Dehumidification	141	1.1x
Desiccant DH Negative Pressure	86	1.8x
Conventional Dehumidification	85	1.8x
Desiccant DH Positive Pressure	71	2.2x
Heating Unit Open System	53	2.9x

Next are the Daily E^3 targets for all drying chambers. These daily E^3 targets for all possible types of drying equipment, classes of loss, days of loss, and outside conditions took a lot of time and testing to dial in. I did extensive testing to define the maximum E^3 value that any equipment could achieve during any classification and all outside grain loads, I then determined how long it took to achieve this maximum E^3 value throughout the progression of the loss.

For instance, if using LGR dehumidification on a Class 2 loss with an average outside 75 gpp and an elevation at 1,300 feet, the highest possible E^3 value of this set-up is 225-230 (75°F/25%RH - 34 gpp). At maximum (100%) performance it takes 3-4 days to reach this E^3 value of 225-230. So, the progression of the maximum E^3 value was established for each day of the loss to reach this maximum E^3 value.

Day 0 is the day the loss is set up, or when drying is officially started. Because of this there is no E^3 target for Day 0. Day 1 is the next day on the loss (not necessarily 24 hours later). Day 2 is the day after that and so on.

Using the previous example with the LGRs (Class 2, outside gpp of 75 gpp, 1,300 feet), this would be what the E^3 values would look like each day if that set up was working at 100% performance:

- Day 0 = n/a
- Day 1 = 143
- Day 2 = 188
- Day 3+ = 225

It is important to note that this does not mean that the building should be dry in 72-96 hours. This is the time frame it should take to get to these max E^3 values if the setup is working at 100% efficiency and effectiveness. It may take another 2-4 or more days for the building to dry, but what E^3 shows and proves is that the equipment and chamber are maximized for evaporation (drying). The restorer did their job. It justifies the set up.

Now, of course, I do not expect the restorer to perform at 100% efficiency or effectiveness on every loss, but this had to be established first to provide a baseline for a reasonable daily E^3 target. The daily E^3 targets are set at 80% of maximum performance, giving a 20% buffer for field issues.

 So, going back to the example before with LGR dehumidification (Class 2, outside moisture 75 gpp, 1,300 feet) this is what the daily E^3 targets would look like and where they came from (compared to 100% maximum performance):

E^3 Values (100%)
- Day 0 = n/a
- Day 1 = 143
- Day 2 = 188
- Day 3+ = 225

E^3 Targets (80%)
- Day 0 = n/a
- Day 1 = 114
- Day 2 = 150
- Day 3+ = 180

This means with this set up, the E³ value within the drying chamber on Day 1 should be at 114 or higher, Day 2 should be 150 or higher, and from Day 3 on it should be 180 or higher. If these E³ targets are hit each day, the restorer (and all parties involved) knows that their chamber is set up efficiently and effectively and that they did their job. If the E³ target was achieved each day and it took 7-8 days for the building to dry, then the restorer should be paid in full for these drying days. Likewise, if an E³ target is not achieved on a certain day it immediately lets the restorer (and all parties involved) know there is a problem that needs to be addressed. E³ also provides a list of potential problems (checklist) a restorer could be experiencing if an E³ target was not achieved. Again, these E³ targets give purpose to drying logs and scientific justification for a set up. This is how it looks in the E³ app:
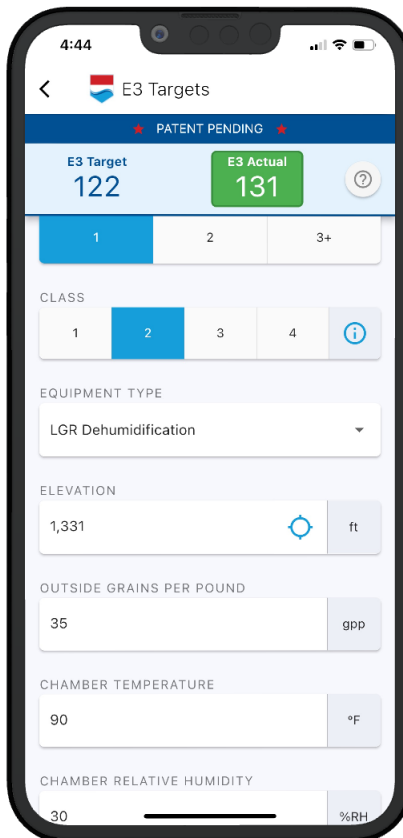
It is simple to use, asking for the day of the loss, Class of loss, elevation is figured for you, type of equipment used, and outside grain load. On this example we used Day 1, Class 2, LGR Dehumidification, Elevation 1,338 ft. and outside grains at 35 gpp. Once this data is in, the daily E³ target is set. Next you enter in the actual conditions in the chamber and for this example I used 90°F at 30%RH which is 66 gpp. At the top is displayed an easy-to-read comparison of what the daily minimum E³ target should be (122) versus what the E³ value is in the chamber (131). If the Actual chamber E³ value is greater than the daily E³ target you are good...that is why the number shows in green. Your chamber is efficiently set up. If you hit your E³ target every day and yet it took that building 8 days to dry you should get paid 8 days for drying and no one can or could argue. You did the best you could with the available equipment.

15
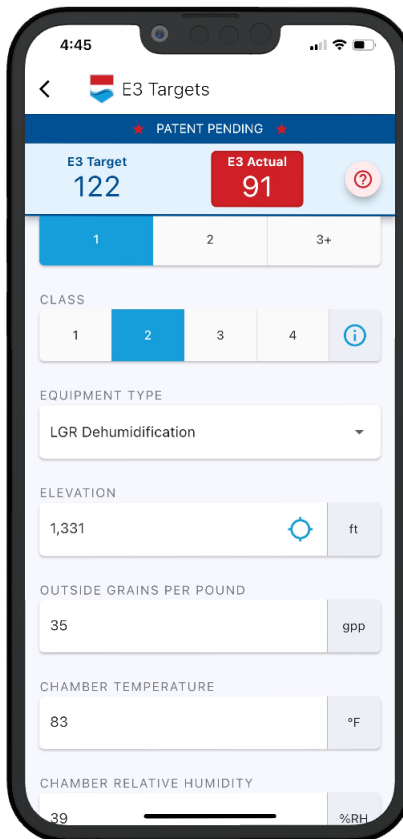
On the other hand (like in the above example), if your actual chamber E³ value (91) is less than the daily E³ target value (122) then you are made aware that there is a problem. You know there is a problem, and you need to go find it and fix it. If the problem is not found the job will lag and the likelihood of hitting any daily targets goes to almost 0%. We made it easy as well to help find the potential problems if the targets are not achieved. You hit the red question mark button in the right-hand corner, and it provides you a list like this:
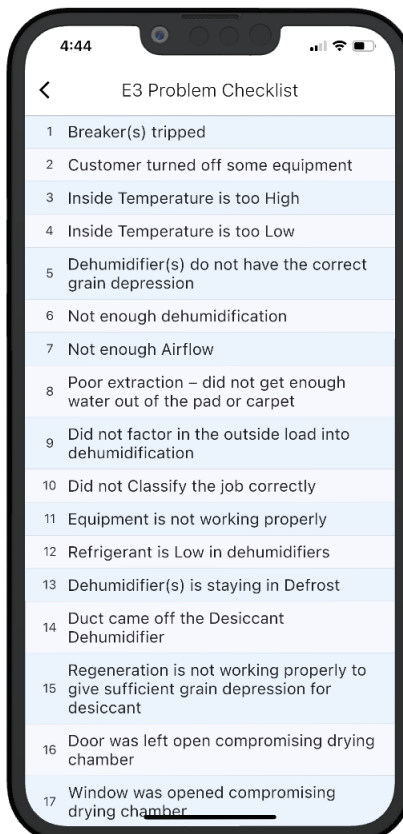
The list is longer (I cut it off) but you get the idea. One of these issues will be the reason why you missed your E³ target, go find it and fix it.

E³ may not be perfect in every possible temperature and humidity ratio value but for the drying world it is darn close. It has been proven over and over to be within 1% accuracy of predicting drying rates in temperature ranges from 13°F – 175°F and humidity ratios of 5gpp – 170 gpp. This covers any conditions that should be seen on property water mitigation losses. If you are drying a wet building above 175°F I will go ahead and tell you that you will have problems and will ruin the building. Could this formula be dialed in more for extreme values outside of these listed ranges? Yes, it could, and I am open to that, even though those won't be seen in our industry an extended range may help other industries. I am always open to input or critique. I am simply asking that our industry be willing to look at the proof of E³ and consider the many ways that it can add value to the restoration industry.

Energy Correlations Between E³, Dew Point Temperature, & Wet Bulb Temperature. Predicting Dew Point & Wet Bulb Temperatures Using E³ to Evaluate Ambient Enthalpy Values

In addition to the proven unbiased testing results (in the above portion of this white paper) validating E³ from an empirical standpoint, this next section of the white paper will further validate E³ from a theoretical and energy relationship basis. E³ will be shown and proven to exactly correlate to the Dew Point and Wet Bulb temperatures for any and all conditions simply by evaluating the different energy compositions for these conditions.

For more than 20 years I have known that all psychrometric values were tied together and correlated to the composition of any condition's energy content. Everything comes down to energy and this correlation should be no different. Given any ambient condition, you should be able to break down the energy composition (latent energy, sensible energy, and total enthalpy values) of this condition to correlate it to the energy compositions of the Dew Point Temperature and Wet Bulb Temperature for this given condition. In other words, there is a reason why the Dew Point and Wet Bulb Temperatures are what they are for all possible ambient conditions. Why are the Dew Point and Wet Bulb Temperatures what they are for all conditions and why does the Dew Point and Wet Bulb take place?

I have spent many years trying to figure out this correlation between any condition's ambient energy content to the energy contents of the dew point and wet bulb temperatures calculated for any condition. I have evaluated the combination of any conditions Sensible, Latent, and Total Enthalpy contents in every possible way I could think of to try and find this energy association that I knew had to exist.

I had to first be asked and answer, "why does condensation take place at the Dew Point Temperature and what causes the Wet Bulb temperature to be what it is?" This paper will explain and, for the first time, define both processes by using the E³ metric.

Dew Point Temperature

Almost all definitions of the Dew Point Temperature correlate this temperature to the point at which the relative humidity is 100% or the air is saturated. This is incorrect in a couple of ways.

First off, the relative humidity being 100% is not why the Dew Point is taking place and it is not taking place because the air is "saturated." The Dew Point temperature is the point at which condensation will take place but, why is it taking place? Condensation, just like evaporation and the boiling point, is governed by an energy transfer process between two systems. In nature one of the strongest properties in physics is that all systems are trying to equalize in terms of their respect energy contents. High energy is always seeking low. Condensation, evaporation, and the boiling point can be no different and must be looked at from this point of view. Knowing that condensation and evaporation are governed by the energy transfer process, in order to accurately evaluate both, we must evaluate them with a metric that possess energy values. The problem with using relative humidity to evaluate condensation or evaporation (or any process for that matter) is that there is no energy value that can be applied to relative humidity. It is not a part of the enthalpy equation in any way. This means that it has no role in either of these processes.

Secondly, condensation is not taking place because the air is "saturated" or cannot hold any more water. There is no magic holding capacity of air. Warm air does not "hold" more water than colder air. More water vapor is seen in air at higher temperatures because of its higher energy content for evaporation (and can be exactly correlated to that) and not its "holding capacity". Using the saturation of the air to describe or define the Dew Point temperature is also wrong because the relative humidity can be higher than 100% and is seen so often in nature. Theoretically, the relative humidity could be as high as 300%, based on the fact that the relative humidity values on the psychrometric chart were determined over a flat surface of liquid and not the much higher surface are value of the water droplet that is seen in nature. If the relative humidity can be higher than 100% then the Dew Point temperature (and the resulting visible condensation) it's not taking place because the air is some how "saturated" or can't hold anymore water.

So why does the Dew Point Temperature and the resulting condensation at this point take place and what is governing and defining this process. As mentioned, before it must be defined by metrics that possess energy values as well as evaluating the specific combination of these energy values. Condensation, and the Dew Point temperature that defines this point of condensation, takes place because two systems are trying to equalize in their total energy contents. When looking at the two systems of the air and any material exposed to this air, the latent, sensible, and total enthalpy contents of these two systems are constantly trying to equalize. The larger the difference between the energy contents of these two systems, the more energy is transferred between the two to reach this equilibrium. Visible condensation at the Dew Point Temperature takes place in nature because the total energy difference (at specific latent, sensible, and total enthalpy combinations) between the air and material has gotten so large that nature developed as a way to maximize energy transfer between these two systems in order to reach equilibrium quicker. Visible condensation drastically increases the surface area of the material which means there is more surface area allowing more energy to be transferred between the air and material. The boiling point of a liquid is no different. Due to the large energy differences between the liquid and air around it, the boiling point takes place which drastically increases the surface area of the liquid with the bubbles. This allows for maximum energy transfer between the liquid and air. The point of this paper to be able to define this energy difference and combinations at which the Dew Point temperature takes place.

Some generic energy comparisons (many more could be laid out in this paper):

- The higher the latent energy content at the same sensible energy content, the less sensible and total energy required to be removed by the material to reach this point of condensation (and the higher the dew point temperature).
- The lower the latent energy content at the same sensible energy content, the more sensible and total energy required to be removed by the material to reach this point of condensation (and the lower the dew point temperature.

For example:
- *Condition 1 – 85F/45%RH = 85 gpp*
- Total Enthalpy = 33.8 Btu/lb
- Sensible Energy = 20.9 Btu/lb
- Latent Energy = 12.0 Btu/lb
- Dew Point Temperature = 61°F
- Sensible Energy Difference between Ambient (20.9 Btu/lb) and Dew Point (14.9 Btu/lb) = 6 Btu/lb removed to reach visible condensation point

For example:
- *Condition 2 – 86F/25%RH = 48 gpp*
- Total Enthalpy = 28.0 Btu/lb
- Sensible Energy = 20.9 Btu/lb
- Latent Energy = 7.1 Btu/lb
- Dew Point Temperature = 46°F
- Sensible Energy Difference between Ambient (20.9 Btu/lb) and Dew Point (11.6 Btu/lb) = 9.3 Btu/lb removed to reach visible condensation point

- The same total enthalpy value (Btu/lb) of the air, the higher the sensible to latent energy value (Se/Le), the more sensible and total energy required to be removed by the material to reach this point of condensation (lower dew point temperatures).

For example:
- *Condition 1 – 75F/35%RH = 48 gpp*
- Total Enthalpy = 25.5 Btu/lb
- Sensible Energy = 18.2 Btu/lb
- Latent Energy = 7.3 Btu/lb
- Sensible Energy/Latent Energy ratio = 2.506 Btu/lb
- Dew Point Temperature = 45°F
- Sensible Energy Difference between Ambient (18.2 Btu/lb) and Dew Point (11.0 Btu/lb) = 7.2 Btu/lb removed to reach visible condensation point

For example:
- *Condition 2 – 70F/49%RH – 56 gpp*
- Total Enthalpy = 25.5 Btu/lb
- Sensible Energy = 17.0 Btu/lb
- Latent Energy = 8.5 Btu/lb
- Sensible Energy/Latent Energy ratio = 2.00 Btu/lb
- Dew Point Temperature = 51°F
- Sensible Energy Difference between Ambient (17.0 Btu/lb) and Dew Point (12.4 Btu/lb) = 4.6 Btu/lb removed to reach visible condensation point

There are many other generic comparisons between the Ambient Sensible Energy value and the Sensible Energy (drop in total Enthalpy) that must be removed by the material to reach visible condensation point of the Dew Point temperature, but none of these comparisons (I tried hundreds and hundreds of these evaluations) could be used to define or calculate this exact drop in Sensible Energy from the Ambient Enthalpy content to reach the Dew Point Value. Should I say none of them could until now. The E³ white paper proved the effectiveness of predicting the evaporation ability of any ambient condition from liquid water or from wet building materials to within 1% accuracy (proving that it works). E³, of course, evaluates the energy content of the air in several different ways (factoring in the Ambient Sensible and latent contents, Dew Point Sensible and latent contents, and Wet Bulb Sensible and latent contents) and was successful in predicting evaporation. I finally had the idea to apply E³ to help solve for this energy relationship between the Ambient and Dew Point to see if E³ could also be used to predict or define the condensation point just like it did for evaporation. Once I had the idea to use E³ to find this seemingly impossible relationship (after countless times of trying any and all possibilities without E³), it did not take long at all to find the correlation that I had been looking for all those years. And here it is:

{(E³/6.6) ÷ Am(Se/Le)} = ΔDpSe(Btu/lb)
- **E³** = E³ value for any given Ambient Condition (unitless)
- **6.6** = Constant division factor
- **AmSe** = Ambient Sensible energy (Btu/lb)
- **AmLe** = Ambient Latent energy (Btu/lb)
- **ΔDpSe(Btu/lb)** = Change in Sensible Btu/lb from Ambient Sensible energy to Dew Point Temperature Sensible energy value

Now that we can accurately measure or calculate **ΔDpSe(Btu/lb)**, we can now predict the Dew Point Temperature by only knowing the Ambient E³ Value, Sensible Energy value, and Latent Energy Value. The energy composition of any ambient condition can now be evaluated to predict the exact amount of energy it takes to be removed to cause visible condensation (or the Dew Point), and E³ was the answer.

AmSe(Btu/lb) - ΔDpSe(Btu/lb) = DpSe(Btu/lb)
- **DpSe** = Sensible Energy value (Btu/lb) at the Dew Point Temperature
- **AmSe** = Ambient Sensible Energy value in (Btu/lb)

DpSe ÷ ((0.24Btu/lb-°F)+(gpp/7000 x 0.45Btu/lb-°F)) = DpT°F
- **DpTF** = Dew Point Temperature in °F
- **0.24 Btu/lb-°F** = Specific heat capacity of air in Btu/lb per °F
- **Gpp/7000** = Ambient grains per pound converted to humidity ratio (lb/lb)
- **0.45 Btu/lb-°F** = Specific heat capacity of water vapor in Btu/lb per °F

Proof Using E³

Condition – 75F/45%RH – 58 gpp
- Ambient Sensible Energy = 18.3 Btu/lb
- Ambient Latent Energy = 8.8 Btu/lb
- Ambient Total Enthalpy = 27.1 Btu/lb
- Ambient Sensible Energy ÷ Latent Energy = 2.08 Btu/lb
- E³ Value = 76

$\{(E^3/6.6) \div Am(Se/Le)\} = \Delta DpSe(Btu/lb)$

$\{(76/6.6) \div (2.08)\} = \Delta 5.54$ Btu/lb

18.3 - Δ5.54 Btu/lb = 12.76 Btu/lb

12.76 Btu/lb ÷ ((0.24Btu/lb-°F)+(58/7000 x 0.45Btu/lb-°F)) = 52.4°F(predict Dew Point)

Measured Dew Point Temperature = 52.2°F

Accuracy = 0.38%

This newly developed correlation has been tested against hundreds of different ambient conditions ranging from 10-150°F and grain counts of 10-200 gpp and it has shown a remarkable accuracy of only having an average margin of error of 0.65% (predicted Dew point temperature versus calculated Dew Point temperature). This means that, just like in predicting the evaporation ability of the air (from both free and bound water), E³ can also predict the point of visible condensation by evaluating the energy composition of any ambient condition. This adds even more value and credibility to the E³ metric.

Wet Bulb Temperature

Over the years the wet bulb temperature has been difficult to calculate requiring look up charts and correction factors for certain conditions. Let's first look at what the Wet bulb temperature is and what is being calculated. The wet bulb temperature has been measured by using two different thermometers in different ambient conditions by blowing this air across the two thermometers. One thermometer is left alone to measure the dry bulb (or actual air temperature) temperature, and the other thermometer is wrapped in a wet wick and both are exposed to the same air stream (temperature and water vapor content). The thermometer with the wet wick will be cooled down by the evaporation of the water from the wick by this air stream. The better the air is at evaporating free water, the more evaporation from the wetted wick thus the more the temperature of the second thermometer is lowered due to evaporative cooling. The lowest possible temperature of this second thermometer (with wet wick) in this air stream will equate to the wet bulb temperature measurement. The greater the drop between the dry bulb (first thermometer) and wet bulb (second thermometer), the greater the evaporation rate of free water.

It is also important to note that in this relationship the total enthalpy of the air stream being delivered to both thermometers does not change. The total enthalpy in Btu/lb is constant since energy cannot be destroyed or created. Energy is just being changed between Sensible and Latent values. This is called an adiabatic process. This means that the drop in the Sensible energy of the air stream from the Ambient Sensible content to the Wet Bulb temperature Sensible content must offset by an increase of the exact amount in the Latent energy content. This means that if the Sensible energy drop from ambient to wet bulb is -Δ5 Btu/lb, that means +Δ5 Btu/lb must be added to the Ambient Latent content which can be seen in the increased gpp content of this air stream once passing the wet wick.   This also means that once the wet bulb temperature can be calculated, its drop in Sensible energy can be calculated, meaning we now know the exact increase in the Latent energy content must be the same in order for this to be the adiabatic process it is.

Knowing this about how the wet bulb temperature is calculated, just like we asked regarding the dew point temperature, what dictates this measured drop in the sensible energy value (and added latent energy value) from the ambient air stream to the wet bulb temperature? It must be controlled by something. We know why it is dropping in temperature and sensible energy from the air stream to the wet bulb temperature (evaporative cooling), but what determines the exact sensible energy drop (latent energy increase) for all possible ambient conditions.

For example:

- Condition – 75°FF/45%RH – 58 gpp
- Wet Bulb Temperature = 61.3°F
- Ambient Total Enthalpy = 27.1 Btu/lb
- Ambient Sensible Energy = 18.3 Btu/lb
- Ambient Latent Energy = 8.8 Btu/lb
- Wet Bulb Sensible Energy = 15.0 Btu/lb
- Wet Bulb Latent Energy = 12.1 Btu/lb
- Wet Bulb Total Enthalpy = 27.1 Btu/lb
- -ΔSensible Energy from Ambient to Wet Bulb = -Δ3.3 Btu/lb
- +ΔLatent Energy from Ambient to Wet Bulb = +Δ3.3 Btu/lb

As shown above this is the break down in energy content from the ambient air to the wet bulb temperature values. Why at this specific condition does the Sensible energy drop 3.3 Btu/lb and the Latent energy increase 3.3 Btu/lb? Just like with the drop in sensible energy from the ambient to the dew point temperature, there is something controlling this exact change. Also, just like with the dew point temperature evaluation, we must look to the energy composition of any given ambient condition to be able to calculate this exact change.

Just like trying to solve for the energy change between the ambient and dew point values, I had no luck in being able to find an exact correlation in the ambient conditions energy composition to be able to answer this question until E³ was brought into the mix. Similar to the dew point temperature energy evaluations, E³ was also able to break the code in defining the correlation between ambient and wet bulb temperature energy changes.

Here it is:

$\{(E^3) \div (Am(Se/Te) \times 16 \times Am(Se/Le))\} = \Delta WbSe(Btu/lb)(\text{-}Se\ \&\ +Le)$

- **E^3** = E^3 value for given ambient condition
- **AmSe** = Ambient Sensible Energy value (Btu/lb)
- **AmTe** = Ambient Total Enthalpy value (Btu/lb)
- **16** = Constant multiplier
- **AmLe** = Ambient Latent Energy value (Btu/lb)
- **$\Delta WbSe(Btu/lb)(\text{-}Se\ \&\ +Le)$** = Change (-Se, +Le) in Sensible & Latent energy values from Ambient to Wet Bulb

Now that we can accurately measure or calculate ΔWbSe(Btu/lb)(-Se & +Le), we can now predict the Wet Bulb Temperature by only knowing the Ambient E^3 Value, Sensible Energy value, Latent Energy Value, and Total Enthalpy value. The energy composition of any ambient condition can now be evaluated to predict the exact amount of energy removed by evaporative cooling to approach the wet bulb temperature and thus predict the evaporation of free water (or the Wet Bulb Temperature). With this information we can also predict or calculate the exact added gpp (from latent energy increase) at the Wet Bulb Temperature, and E^3 was again the answer.

AmSe(Btu/lb) - ΔWbSe(Btu/lb)(-Se & +Le) = WbSe(Btu/lb)
- WbSe = Sensible Energy value (Btu/lb) at the Wet Bulb Temperature
- AmSe = Ambient Sensible Energy value in (Btu/lb)

AmLe(Btu/lb) + ΔWbSe(Btu/lb)(-Se & +Le) = WbLe(Btu/lb)
- WbLe = Sensible Energy value (Btu/lb) at the Wet Bulb Temperature
- AmLe = Ambient Latent Energy value in (Btu/lb)

WbSe ÷ ((0.24Btu/lb-°F)+(gpp/7000 x 0.45Btu/lb-°F)) = WbT°F
- WbTF = Wet Bulb Temperature in °F
- 0.24 Btu/lb-°F = Specific heat capacity of air in Btu/lb per °F
- Gpp/7000 = Ambient grains per pound converted to humidity ratio (lb/lb)
- 0.45 Btu/lb-°F = Specific heat capacity of water vapor in Btu/lb per °F

WbLe(Btu/lb) ÷ 0.1516(Btu/lb÷gpp) = Wbgpp
- 0.1516(Btu/lb÷gpp) = Conversion to solve for gpp (gpp/7000)x(1061 Btu/lb) from latent energy content
- Wbgpp = Grain content (gpp) at the Wet Bulb temperature

Proof Using E³

Condition – 75F/45%RH – 58 gpp

- Ambient Sensible Energy = 18.3 Btu/lb
- Ambient Latent Energy = 8.8 Btu/lb
- Ambient Total Enthalpy = 27.1 Btu/lb
- Ambient Sensible Energy ÷ Latent Energy = 2.08 Btu/lb
- Ambient Sensible Energy ÷ Total Enthalpy = 0.675 Btu/lb
- E³ Value = 76

$\{(E^3) \div (Am(Se/Te) \times 16 \times Am(Se/Le))\} = \Delta WbSe(Btu/lb)(-Se \ \& \ +Le)$

$\{(76) \div (0.675 \times 16 \times 2.08)\} = \Delta 3.38 \ Btu/lb$

$18.3 - \Delta 3.38 \ Btu/lb = 14.9 \ Btu/lb$

$14.9 \ Btu/lb \div ((0.24 Btu/lb\text{-}°F) + (58/7000 \times 0.45 Btu/lb\text{-}°F)) = 61.2F(\text{predicted Wet Bulb})$

Measured Dew Point Temperature = 61.3°F

Accuracy = 0.16%

This newly developed correlation has been tested against hundreds of different ambient conditions ranging from 10-150°F and grain counts of 10-200 gpp and it has shown a remarkable accuracy of only having an average margin of error of 0.72% (predicted Wet Bulb temperature versus calculated Wet Bulb temperature). This means that, just like in predicting the overall evaporation ability of the air (of both free and bound water) and the point of visible condensation (Dew Point Temperature), E³ can also predict the Wet Bulb temperature energy compositions thus predicting the amount of free water evaporation by evaluating the energy composition of any ambient condition. This again adds even more value and credibility to the E³ metric.

Conclusion:

The combination of the E³ white paper along with the comparisons made in this document should put to rest any questions regarding the validity of the value that E³ provides. This metric has been proven (through unbiased and third-party testing) to accurately evaluate evaporation of both free and bound water to within 0.5-1.0% accuracy, evaluate the point of visible condensation to within 0.6% accuracy, and ultimately predict ALL energy components of the psychrometric chart to within 0.6-0.72% accuracy. There are probably many other uses and industries (HVAC, Lumber drying, any drying of any product, weather predictions) in which this metric would show to even more predictions and accurate explanations of processes that have yet to be defined. It has shown to be a crucial energy content evaluation and I can't wait to explore other areas and fields in which this metric can be applied.

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