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(***The goal of this paper is to introduce to non-technically-minded construction professionals fundamental 'real-world' aspects of the properties of water in a manner that minimizes consideration of esoteric mathematical formulas. The first iterations of this 'Water 101' paper were crafted in the early-2000's in Seattle while I trained as a building envelope consultant under Colin Murphy's tutelage at Exterior Research & Design, LLC (now Trinity|ERD) --- Colin's guidance and assistance remain much appreciated.***)

Water 101 – Contractor's Introduction to the Properties of Water

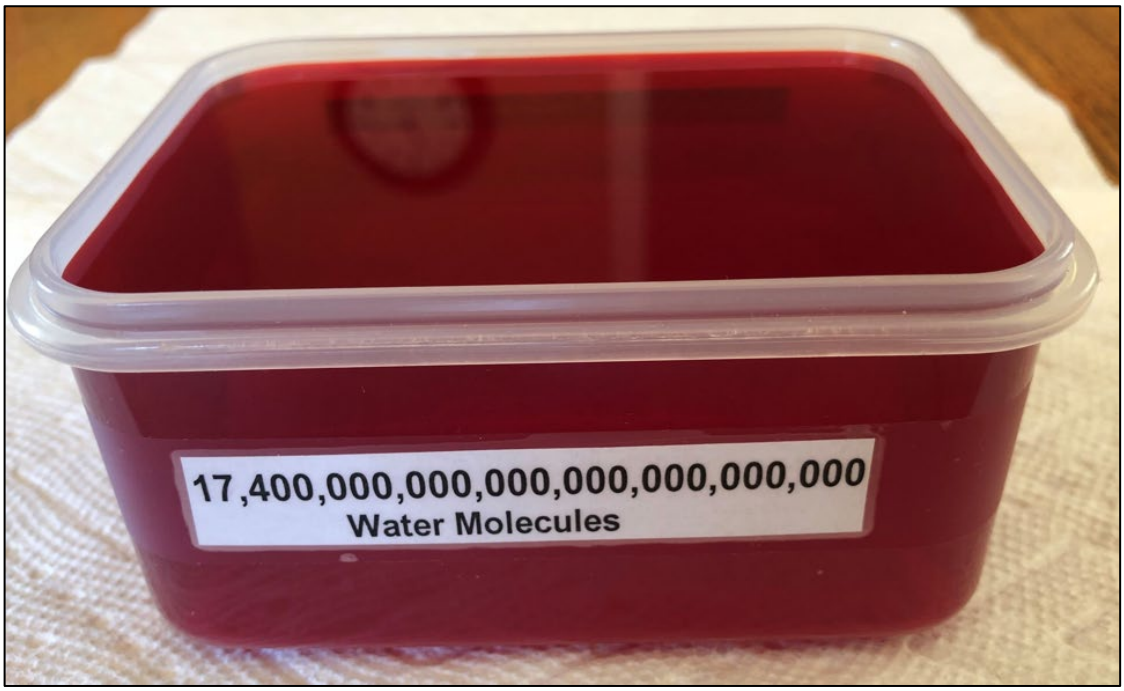
➢ Part A – Fundamental (Non-Technical) Concepts

Arguably, most participants in the building construction and design trades tend to lack sufficient knowledge of those properties of water that promote problematic moisture accumulation in exterior walls and roofs. Seven basic (non-technical) concepts to better understand such potentially destructive processes are outlined below:

1. Water molecules are very small.

The water molecule (H_2O) consists of two hydrogen atoms and one oxygen atom. A snowflake may contain 180 billion (180,000,000,000) water molecules. One cubic inch of water contains about 600 sextillion (600,000,000,000,000,000,000,000) water molecules.

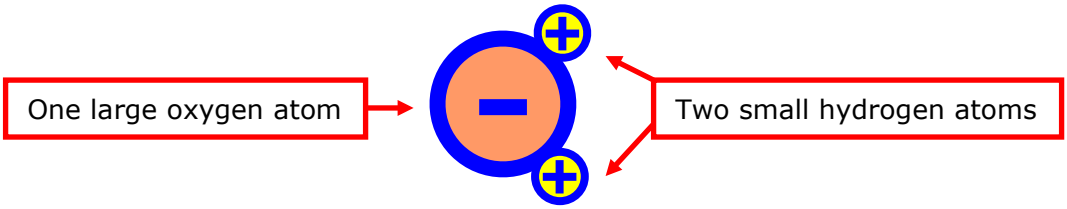
The 16.6 fluid ounce container seen in this photo holds 17.4 septillion (17,400,000,000,000,000,000,000,000) water molecules.



There are 17.4 x 10^{24} water molecules within this 16.6 fluid ounce container.

2. Water molecules are 'polar'.

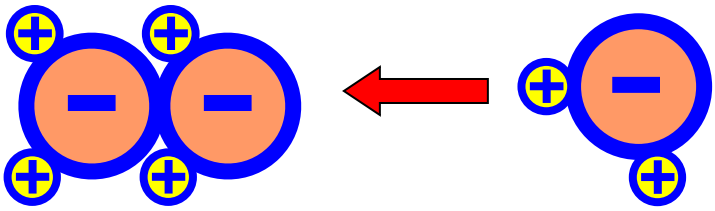
The water molecule is both ***asymmetrical*** and ***polar***. In simple terms, the electronic charge of these molecules is unevenly distributed. The relatively large oxygen atom has a partial negative electrical field and the two smaller hydrogen atoms have a partial positive field.



(Many common molecules are ***polar*** – demonstrating electrical field differentials of varying strength; however, there also are many others that are ***nonpolar*** – the electronic charge is evenly distributed.)

3. Water molecules are 'sticky'.

Similar to the commonly observed interactions between magnets, the attractive/repulsive forces (i.e., 'opposites attract' and 'likes repel') between a water molecule's positively charged hydrogen atoms and the negatively charged oxygen atoms of other polar molecules (not just water) are relatively strong. Through a process known as ***hydrogen bonding***, polar molecules tend to attract and stick to each other unless stronger forces (gravity, for example) sunder these bonds.



What happens when you exhale close to a glass surface? The glass 'fogs up' – many of your exhaled water molecules have become stuck to the available oxygen atoms at the glass surface, in a fashion similar to throwing Velcro-hooked balls at a Velcro-looped wall.

The asymmetrical shape of the water molecule provides an endless variety of these hydrogen-bonded configurations – including countless one-of-a-kind crystalline snowflakes.

The ability of these water vapor molecules to stick to many material surfaces, such as the gypsum wallboard in your living room, is called ***adsorption*** (not to be confused with ***absorption***, which describes capillary movement of moisture inside of a material).

What does a nonsmoker notice after departing a gathering of cigarette smokers? The nonsmoker's clothes, hair, and body reek of cigarettes due to the smoke molecules having become stuck (***adsorbed***) to other polar molecules.

4. Water molecules are exceptional little bundles of energy.

As Albert Einstein famously reported, all matter (from molecules to rocks to plants to animals to planets, and far beyond) is comprised of particular levels of ***energy***. Energy can be described as the capacity to do ***work***, which consists of the transfer, transformation or organization of energy.

Energy's many forms can be transformed via work into alternate forms of energy. As an example, increased *thermal energy* (heat) can be transformed into increased *kinetic energy* (speed or momentum) for water molecules or automobiles or spaceships.

All molecules have the potential for accomplishing work; however, due to their sticky nature (*i.e., their exceptional ability to form strong hydrogen bonds*), water molecules have an exceptionally high heat capacity (*that is, a greater ability to hold thermal energy prior to transformation into an organized form of energy*) that makes them particularly efficient workers. Acting in concert, the 'gazillions' of water molecules that we construction professionals encounter every day have the capacity for prodigious work.

Water, like all carriers of energy, always moves from areas of high energy potential to areas of low. ***Fundamentally, every condition we encounter with water is due to energy flowing from an area of greater concentration to an area of lesser***. If there is an accessible route, no matter how small, ***wet*** moves toward ***dry***, and ***warm*** moves toward ***cold***, and ***more*** moves toward ***less***.[1]

[1] As further reviewed below, reference the Second Law of Thermodynamics, which describes the one-way flow (from *more* to *less*) of energy in a closed system: https://en.wikipedia.org/wiki/Second_law_of_thermodynamics.

5. Vapor, liquid and ice simply represent three distinct stages of energy transfer.

Every action of water (from evaporation and condensation to powering the turbines of hydroelectric plants to the melting of the polar icecaps to the deterioration of wood framing) is explained by ***energy transfer***.

- At the range of ambient temperatures suitable for human life, water is the only substance that we can observe in the three fundamental stages of energy transfer: ***gas*** (vapor), ***liquid***, and ***solid*** (ice).

All around us, water molecules are moving (*kinetic energy*) at varying speeds that increase or decrease as the ambient temperature (*the pool of thermal energy that powers these vapor molecules*) rises and falls.

The velocity of each molecule varies in dependence to its energy level and to the overall supply of energy; however, at room temperature the average speed of these numerous molecules is more than 1,000 miles per hour.[2]

Like ricocheting billiard balls, at such velocities most of these highly speedy water molecules simply have too much momentum to 'stick' (*adsorption via hydrogen bonding*) to other molecules (*or to walls and ceilings*) during such collisions, and therefore remain actively dispersed as water ***vapor***.

At the slowing molecular speeds that result from cooler temperatures, some of these interacting water molecules create loosely associated groups that constantly form, break and reform their hydrogen bonds within the groups. These clumped molecules tend to have sufficient energy/momentum to avoid a fixed bond with other water molecules within the group but most cannot escape from the overall cohesive attraction of the pack.

Even though the continual bonding and rebonding process at this state is best described as 'flickering', the total quantity of hydrogen-bonding simultaneously occurring within large groups at any point in time is sufficient to produce the familiar ***liquid*** form of such vibrating masses of water molecules.

[2] The actual distance traveled by these speedy little water molecules is very substantially impacted by their numerous ricocheting collisions with other molecules.

As we see when pouring a morning cup of coffee, these flickering bonds provide a tremendous flexibility (fluidity) to this ever-shifting mass of interconnected molecules – allowing this group to match the shape of virtually any container.

As the liquid water cools even further, the hydrogen-bond connections between the slowing molecules will be maintained for longer periods before breaking and later reforming. The density of the cooling liquid increases as the compressive forces of the more stable hydrogen bonds tend to condense these molecules into a tighter mass.

- In short, *cold* liquid water is far denser than *warm* liquid water. Similar to warm air rising to the top of a room, warm water will float atop cold water.

Finally, at about 39° F, the cooling liquid reaches its maximum possible density, at which point a highly interesting event occurs – the water molecules reorganize into the innumerable crystalline structures that comprise solid water (***ice***).

Due to the asymmetrical shape of these water molecules, a hexagonal three-dimensional crystal shape is the most efficient form of the hydrogen-bonding process that leads to ice formation. Ice is less dense than liquid water (*ice floats*) due to the empty spaces within these rigid hexagonal three-dimensional crystal formations.

In ice, these once energetic and freely roaming water molecules have transformed much of their remaining energy into their fixed hydrogen bonds.[3]

- Importantly, as liquid water freezes into ice (containing empty space), its volume will expand.
- Professionals working in northern climes may well experience the destructive ***freeze-thaw*** expansion/contraction effects that can occur at the transitional zone between liquid and solid water.

You can easily test these forces by putting a full glass of water into a freezer – the ensuing ice will expand above the top of the glass and can be sufficiently powerful to break a closed container.

[3] Until the surrounding temperature drops down to 0º Kelvin (-459º F or -273º C) – aka "absolute zero" – these fixed ice molecules still continue to experience some degree of flickering movement or vibration within the limits of their bonds.

All of this collective *work*, transforming individual vapor molecules into a solid mass, is the result of *energy transfer* between water molecules.

- What happens if we then supply a source of additional energy (perhaps from a nearby fire) to the ice? Reenergized molecules, both individually/very small groups (as *vapor*) and larger clusters (as *liquid*), will strive to break free from their hydrogen bonds.
- *Radiant energy* from the fire has transformed into *kinetic energy*, allowing the molecules to escape from their icy prison.

6. Water is the 'universal solvent'.

What happens when you put a cube of sugar into liquid water? The sugar dissolves because the positively charged hydrogen ends of the water molecules have sufficient strength to pull the slightly polarized sugar molecules apart from the sugar cube. The result is a *solution* in which water is the *solvent* and the sugar molecules are the *solute*.

- In short, the adhesive pull of the polar water molecule is greater than the cohesive forces binding the polar sugar molecules in their original cubic form.

Water often is called the ***universal solvent*** because it can pull apart so many substances, whether comprised of polar molecules or charged ions (salt, for example). Water can dissolve more substances (albeit, in a generally less spectacular manner) than can sulfuric acid.

7. Water and oil (or wax) (or silicone) don't mix.

What happens when you put a chunk of paraffin wax into water? The simple answer is 'not much'. The wax consists of nonpolar molecules that remain unaffected by the pull of the positively charged hydrogen wings of the many water molecules. The general rule of thumb is '*like dissolves like*'. To dissolve the nonpolar wax you will need to use a nonpolar solvent, such as gasoline.

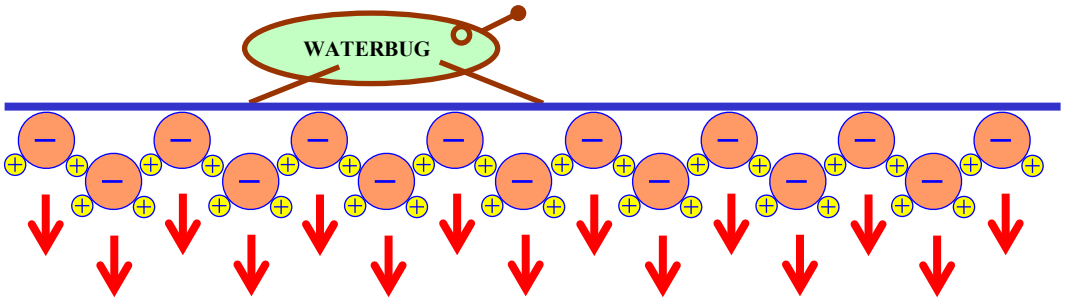
Interestingly, molecules known as ***surfactants*** (*surface active agents*) are polar on one end (and thus attractive to water) and nonpolar on the other end (and thus attractive to oil or grease). What happens when you add warm water and soap (a surfactant) to a sink filled with greasy pans? The soap molecules attach themselves to both the grease molecules and the water molecules, allowing you to rinse the entire mess down the drain.

➢ Part B – More Questions (with Some Partly Technical Answers)

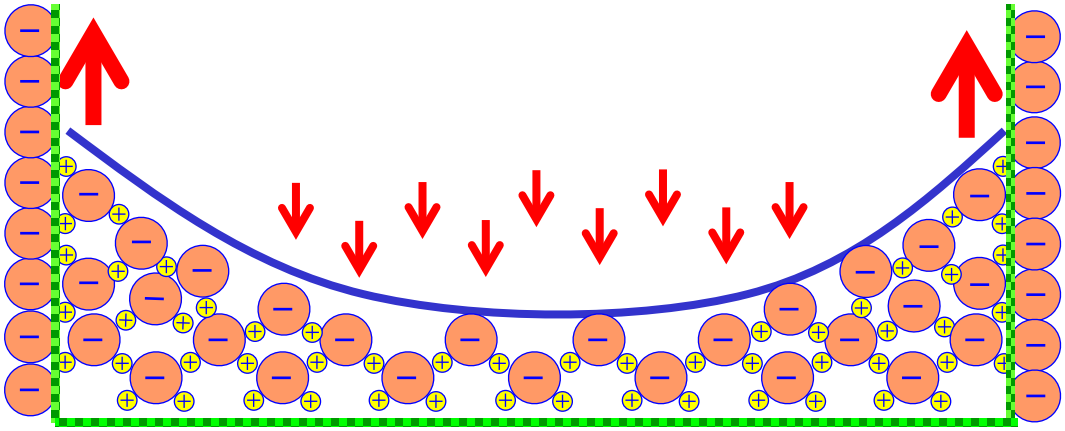
Armed with these seven fundamental concepts, construction professionals in the field are better prepared to consider various key questions:

a. What is 'surface tension' and 'capillary action'?

At the surface boundary of the liquid state a relatively taut 'skin' occurs as the combined attractive forces of hydrogen bonding produce an inward orientation of the outer molecules. It is this ***surface tension*** that allows water bugs to skitter across pond surfaces …



… and helps keeps water from climbing out of its container:



Liquid water in a partially filled glass will attempt to climb the walls of the container as the water molecules seek to form hydrogen bonds with available oxygen molecules at the glass surfaces.

What prevents these water molecules from climbing all the way to the top of the glass in their quest for more bonding is the mass of water molecules already stuck to them – ***air pressure*** (assisted by *gravity*) pushing on the surface 'skin' of the liquid provides a counteracting force resisting other molecules' efforts to ascend the walls.

These sticky (hydrogen-bonding) water molecules only can climb up to the point at which these opposing push-pull forces are in equilibrium.

In a typical glass of water the height of this ascent certainly would not be noticeable; however, let's envision a far narrower container, a glass 'capillary tube':

The narrower the diameter of a 'capillary tube', the higher these 'sticky' (hydrogen-bonding) water molecules can climb the glass walls.

The attractive forces driving the water molecules to climb these walls remain the same, but due to the far smaller surface areas of the liquid, the counteracting force from *air pressure*[4] is much diminished, thereby allowing the chain of hydrogen-bonded water molecules to climb even farther up the glass walls before reaching an equilibrium between the push-pull forces.

[4] Our atmosphere consists of a mix *(~ 78% nitrogen, ~ 20% oxygen, ~ 1% argon, ~ 0% to 4% water, and many others*) of gas molecules in continual kinetic motion. These speeding molecules repeatedly collide with other molecules and all adjacent surfaces. 'Air pressure' is the pushing effect of these molecules against any surface.

In summary, whenever groups of liquid water molecules are enclosed in very small spaces by materials that have available (unbonded) ends of oxygen molecules, the forces of hydrogen bonding may allow these water molecules to travel (via ***capillary action***) a significant distance 'uphill' before counteracting forces (such as *air pressure* and *gravity*) will prevent further upward movement.

In the building trades, failure by a designer or contractor to address this fundamental property of water can result in the localized 'wicking' shown in the photo below.

Backside of removed panel siding reveals the 'wicking' that can occur when a porous material is installed tight (with no 'capillary break') to a horizontal base flashing.

Importantly, note that strong counteracting forces, including gravity, typically will limit upward 'wicking' in plywood to about 6 to 10 inches (and ~ 20 inches for gypsum board) above the source of the water.

- Even though *live* trees can pump (via *transpiration* and *osmosis*) prodigious amounts of groundwater hundreds of feet upward, such gravity-defying moisture movement is not possible for *dead* trees, or sawn lumber, or engineered wood panels, or gypsum wallboard.

Similarly, consider a fundamental difference between OSB (oriented strandboard) and plywood panel sheathing: wax is a key component of the OSB manufacturing process.

- "*A small amount of wax (usually less than 1.5% by weight) is added in the OSB manufacturing process to improve the board's resistance to moisture and water absorption. Most OSB manufacturers use* ***slack wax****, which is obtained as a by-product of lube oil refining and has proven to be a cost-effective sizing agent for use in composite wood panels*."[5]

A rough rule of thumb is that a standard 4' x 8' panel of OSB or plywood weighs ~25 pounds per 1/4" of thickness. Thus, a typical 7/16" OSB sheathing panel can be expected to contain more than 1/2 pound of wax.

Clearly, the addition of this nonpolar waxy substance will affect the ***moisture exchange*** performance of the compressed wood strands that comprise the OSB panel.

Solely due to this moisture exchange performance issue, compared with plywood, OSB panels can be expected to better resist water infiltration (due to the absence of any hydrogen-bonding connections between the water and wax molecules) but also to suffer a decreased ability to dry out if these engineered panels ever become wet, for the very same reason.[6]

- There are, of course, multiple additional factors, including local climactic conditions, that would impact such moisture exchange performance differences between OSB and plywood panels.
- The potential for moisture-induced deterioration of poorly protected OSB is greater in humid San Francisco and Seattle than in dry Phoenix.
- Still, in all climates, these performance differences can become critical whenever unintended quantities of moisture are able, due to design or construction failures, to access the engineered wood sheathing.

[5] *Binders and Waxes in OSB*, Technical Bulletin 114, Structural Board Association, Toronto, 1996. (A copy of this bulletin is available upon request: info@avelar.net.)

[6] Important note: such resistance to moisture infiltration will be negated at cut panel ends of the OSB sheathing or at other areas (drilled holes, for example) at which the protective wax surface layer has been removed.

b. What is 'condensation' and 'evaporation'?

Evaporation simply is the transformation into vapor of a hydrogen-bonded water molecule that has gained sufficient kinetic energy to break its bond. Place a bowl of water out under the summer sun: the liquid water will ***evaporate*** as the water molecules are reenergized.

Condensation is the opposite. Reduced levels of available energy (from cooling temperatures) result in an increased amount of hydrogen bonding of the slowing water molecules ––– the de-energized vapor ***condenses*** into liquid.

- A great example is morning ***dew***: throughout the day, increased thermal energy causes (by evaporation) an increased number of vapor molecules in the air; however, the cooling temperatures at night eventually reach a level at which the de-energized vapor molecules must begin condensing onto the nearest cool surfaces, thereby producing dew. The temperature at which condensation begins is called the ***dew point temperature***.

Note in the photo below the distinct pattern of morning dew formation at a Seattle school building in winter months. The dew has formed only at the fiber-cement siding surfaces that are not being warmed by the conductance of interior heat through the underlying steel framing.

"Morning dew" forms only at areas of this fiber-cement siding not warmed by the underlying steel framing – which is being warmed by interior heat.

At normal temperature levels (in your living room, for example) such evaporation and condensation processes are occurring simultaneously – at the same time that some of the room's many water molecules no longer have sufficient energy to remain unbonded, other molecules are breaking their hydrogen bonds at the room's surrounds (such as the gypsum wallboard) to become ambient vapor.

The proportional balance between the processes of evaporation and condensation is determined by two factors: the amount of available ambient energy and the amount of available moisture.

Unless energy or moisture is added or subtracted from your room, its air and its porous "hygroscopic"[7] components will reach ***equilibrium moisture content*** levels at which a balanced rate of energy exchange is occurring during the continual transformations of ambient vapor to hydrogen-bonded moisture and vice versa.

- The moisture (energy) transfer processes at (and in) your gypsum wallboard jointly working to achieve *equilibrium moisture content* consist of vapor adsorption and liquid absorption.
- The driving force behind the constant ***energy exchange*** process necessary to achieve this moisture equilibrium is the ***Second Law of Thermodynamics***:

  …which requires, as a fundamental law of the universe, that when two pools of energy are connected the greater pool always will flow into the smaller pool until equilibrium is reached.[8]

What happens when you turn up the thermostat that controls your heating system?

The additional heat (thermal energy) added to the room unbalances the energy exchange equilibrium and results in increased evaporation from the surrounds (your gypsum wallboard will get dryer) until a new point of balanced energy transfer is reached between the continual processes of evaporation and condensation.

[7] Hygroscopic materials are those that, due to their *porosity*, are capable of continually exchanging moisture (via adsorption, absorption, and desorption) with surrounding air and other materials to maintain an equilibrium moisture content representing the current energy balance between continual processes of evaporation and condensation. Wood, gypsum board, masonry and stucco are hygroscopic construction materials; in contrast, steel, vinyl, and glass materials are not hygroscopic.

[8] https://en.wikipedia.org/wiki/Second_law_of_thermodynamics

Similarly, what happens when you frame an exposed wood structure during winter rains? The ongoing processes of energy exchange favor an evaporation/condensation balance that yields increased moisture levels within the wood framing. Conversely, after this structure has been 'closed in' and heated, a new evaporation/ condensation balance results in release of this moisture (as vapor) into the interior spaces, potentially promoting conditions of deterioration or mold growth at other areas of the building if adequate ventilation is not provided.

Note that a failure to provide sufficient energy (heat) to promote the evaporative drying of this wet wood framing inevitably will result in conditions of deterioration or mold growth. There are no alternative forces with sufficient power to break the strong hydrogen bonding that occurs between the water molecules and the wood molecules.

In other words, the building professional who believes that ***gravity*** will remove excess moisture held within typical framing and sheathing elements is courting disaster. Removal of such moisture requires the application of additional energy to break hydrogen bonds and to disturb the equilibrium of the energy exchange processes.

- *"Capillary and adsorbed moisture can only be dried by evaporation because it takes more energy to break the attractive forces than gravity can supply."*[9]

c. What is 'relative humidity'?

In the example above, the term ***relative humidity*** can be used to express the percentage of the available energy in your room that has been used to 'free' (via evaporation) sufficient water molecules from your wallboard (and your room's other hygroscopic materials) to reach energy exchange equilibrium between the continual processes of evaporation and condensation.

- A relative humidity (RH) of 50% means that half of the available energy surrounding you must be used to achieve the dynamic level of energy exchange equilibrium between the moisture in your room's surrounds and the ambient vapor molecules bouncing back and forth between its walls.

[9] J. F. Straube, *Moisture, Materials & Buildings*, HPAC Engineering magazine (April 2002), Cleveland, OH. (A copy of this article is available upon request: info@avelar.net.)

- Similarly, at 90% RH all but 10% of the available energy must be used to achieve the level of evaporation necessary to reach a dynamic equilibrium.
- At 100% RH, there no longer is sufficient available energy to maintain a moisture exchange balance between the water vapor in the room's air and the moisture contained within your room's surrounds; therefore, in a manner similar to the operation of a pressure relief valve, some of this excess ambient moisture must be dumped from the system.

  This relief is provided by the transformation (condensation) of some of this ambient vapor into free liquid water – in other words, highly localized 'rain' begins at the very-coolest surfaces (where dew point temperatures exist) at the walls within your room.

In summary, the term ***relative humidity*** can simply represent the percentage of available energy (heat) being used for the evaporation necessary to maintain a moisture exchange balance between your room's pool of ambient vapor and the adsorbed/absorbed moisture in your roof's wall/ceiling surrounds.

How does the RH level change if you turn up the thermostat? The total available energy has been increased by this added heat; therefore, the RH will be decreased (the *percentage* of available energy being used to maintain your room's ever-dynamic moisture exchange balance via evaporation will get smaller).

Conversely, turning down the thermostat means a greater *percentage* of this decreased supply of energy must be used to achieve equilibrium; therefore, the room's relative humidity will be increased.

In brief, increased energy from turning up the thermostat in your room results in:

- A decreased level of adsorbed and absorbed moisture in the walls as a new evaporation/condensation balance is achieved;
- A resulting increased amount of ambient water vapor within your room; and
- A decreased relative humidity.

Similarly, a decreased supply of heat (the thermostat has been turned down) results in:

- An increased level of adsorbed/absorbed moisture in walls and other hygroscopic materials as a new evaporation/condensation balance is achieved;
- A resulting decreased level of water vapor in the room's air; and
- An increased relative humidity.

As noted, relative humidity expresses the current operational efficiency of this ever-dynamic energy equilibrium process.

- At 50% RH, the system is running efficiently; the condensation/ evaporation balance is readily achieved and a significant surplus of energy remains available to handle increased demands that may occur.
- At 85% RH, the system is being pushed to its operational limits.

  What happens when you walk into a conditioned room with an 85% relative humidity?

  As you sense the room's 'muggy' atmosphere, you notice sweat accumulating on your body. Due to the diminished operational efficiency of the room's moisture exchange processes, timely evaporation of your body's perspiration no longer is possible.
- Conversely, what would you experience if the room had only 20% relative humidity?

  Your body's surface moisture would be so efficiently transformed into ambient vapor that your skin soon will become overly dry and 'chapped'.

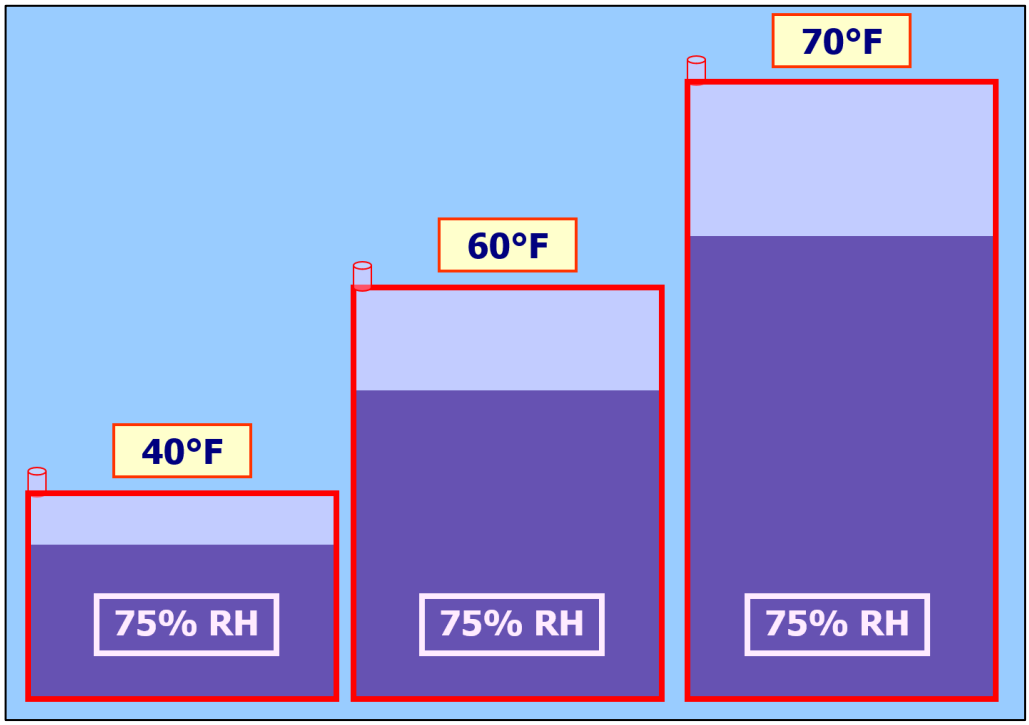
It is important to note that for our human interactions with this *evaporation/condensation* energy exchange process, relative humidity values generally have no clear meaning unless the corresponding temperature values (that is, the amount of available thermal energy) also can be determined.

In short, 85% RH has a far different meaning to a Chicago resident on a hot 'sticky' August day than it does to a Seattle resident on a cool drizzly March afternoon.

As an analogy, even though the gas gauges serving your car and my car might both read 3/4 full, it cannot be assumed that our vehicles' tanks hold the same amount of fuel. Depending upon the magnitude of their differing sizes, a tank that is 1/3 full may contain more gas than a tank that is 2/3 full.

Consider, for example, a Ford F-150 Super Crew pickup with a fuel capacity of 36 gallons and a Ford Focus coupe with a fuel capacity of 13½ gallons. When the coupe's fuel gauge indicates that the tank is 66% full, it contains only 9 gallons. When the F-150's gauge indicates that the tank is only 40% full, it still holds more fuel than the coupe. If both tanks are equally full (whether at 10%, 33%, 66% or 100%), the F-150 tank always will contain ~267% more gas than the coupe's tank.

Similarly, on a cool day in Seattle let's consider a heated apartment with an ambient temperature of 75º F and a nearby unheated unit with an ambient temperature of 47º F. Moisture science informs us that if these identically sized units have the same relative humidity levels then the heated apartment (the Ford F-150) will contain about 2.7 times as much ambient water vapor as the unheated unit (the Ford Focus).



In three identical apartments in Seattle (or San Francisco) with 75% RH levels, the heated (70° F) unit contains 3 times the amount of ambient water vapor that the unheated (40° F) unit. (Figuratively, the heated (70° F) identically-sized apartment has a 300% larger "tank" for holding ambient water vapor.)

However, even if the ambient relative humidity is the only known energy exchange value for your room, the hygroscopic performance of the room's porous inanimate elements can be estimated with fairly close precision. For all such hygroscopic materials, a particular relative humidity value will closely correspond (over time[10]) to a particular ***equilibrium moisture content*** value.

At the range of temperatures we typically encounter, this *equilibrium moisture content* property is not temperature-dependent: in other words, whether the temperature in your room is 40° F or 90° F, an ambient RH of 80% will result, over time, in approximately the same moisture content within a hygroscopic material in the room.

For example, a table published by the U.S. Forest Products Laboratory[11] provides the following moisture content values for wood in a state of energy equilibrium with its surrounding environment at 80% RH:

Temperature (F°)	Relative Humidity (%)	Moisture Content (%)
30	80	16.5
40	80	16.5
50	80	16.4
60	80	16.2
70	80	16.0
80	80	15.7
90	80	15.4

Compare these values with those encountered with wood that is in a state of energy equilibrium at 40% RH:

Temperature (F°)	Relative Humidity (%)	Moisture Content (%)
30	40	7.9
40	40	7.9
50	40	7.9
60	40	7.8
70	40	7.7
80	40	7.6
90	40	7.4

[10] RH values will change quickly due to increases/decreases in available moisture or energy; however, the resulting changes in moisture content within the surrounding hygroscopic materials will proceed far more slowly.

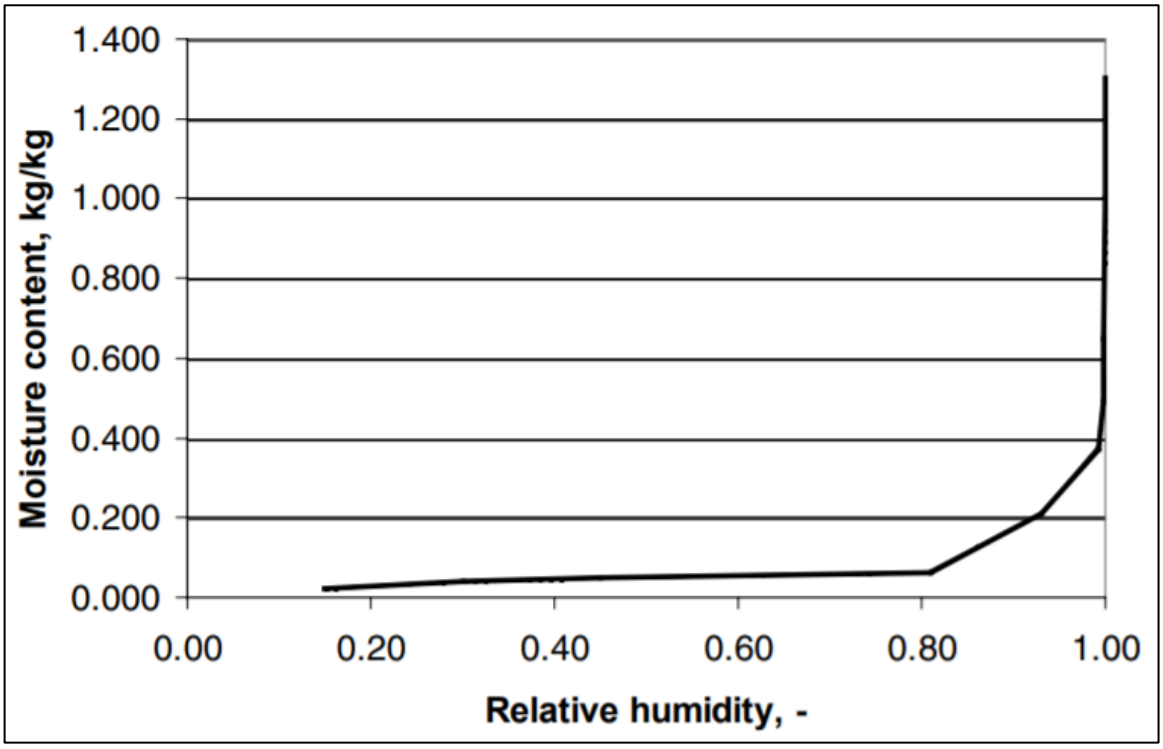
[11] https://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr190/chapter_04.pdf: *Wood Handbook – Wood as an Engineering Material, Chapter 4,* Forest Products Laboratory, U.S.D.A, Madison, WI.

Clearly, at a particular mean RH value, the moisture content of wood (or any other hygroscopic material) at a state of energy equilibrium is reasonably the same at all ambient temperatures.

- Forensic investigators should recognize that during humid winter months, bright and clean (and fully rain-protected) plywood panels still will have substantially higher moisture content levels than when measured during the less-humid summer months.

For each hygroscopic material, the relationship between relative humidity and moisture content can be expressed graphically with a ***sorption isotherm***.

A typical published *sorption isotherm* for plywood is provided in the figure below. Note that at about 80% RH (no matter the temperature) the moisture content of the plywood begins to increase exponentially. Due to the decreased supply of available energy to support water vaporization, the moisture exchange balance must be achieved by storing (first by *adsorption*, then followed by capillary *absorption*) exponentially more water molecules within the hygroscopic material.



"Sorption isotherm" for plywood, published by the Oak Ridge National Laboratory.[12]

[12] https://info.ornl.gov/sites/publications/Files/Pub57342.pdf: A.N. Karagiozis, *Building Enclosure Hygrothermal Performance Study – Phase 1*, Oak Ridge National Laboratory, ORNL/TM-2002-89.

Extended periods of ambient 80% RH are not uncommon in some parts of North America. As can be seen at the above *sorption isotherm*, the moisture content of a plywood panel (such as sheathing behind lap siding) exposed to this humidity level still remains acceptably low; however, even small amounts of added water vapor (perhaps due to rainwater leakage at a mislapped flashing) can serve to exponentially raise the overall moisture content of the plywood panel.

Very similar conditions will occur with all such porous (hygroscopic) construction materials, albeit each material will have a unique sorption isotherm[13] (and a distinct RH point at which its moisture content begins to increase exponentially).

It is clear that solely due to ambient relative humidity the designer and contractor working with hygroscopic construction materials must exercise greater care in a relatively high-humid environment, such as Seattle or Chicago, than in a less-humid climate, such as Albuquerque, because in high-humidity climates the construction materials have a diminished buffering ability to safely contain excess moisture until the next drying period.

d. What is a 'psychrometric chart'?

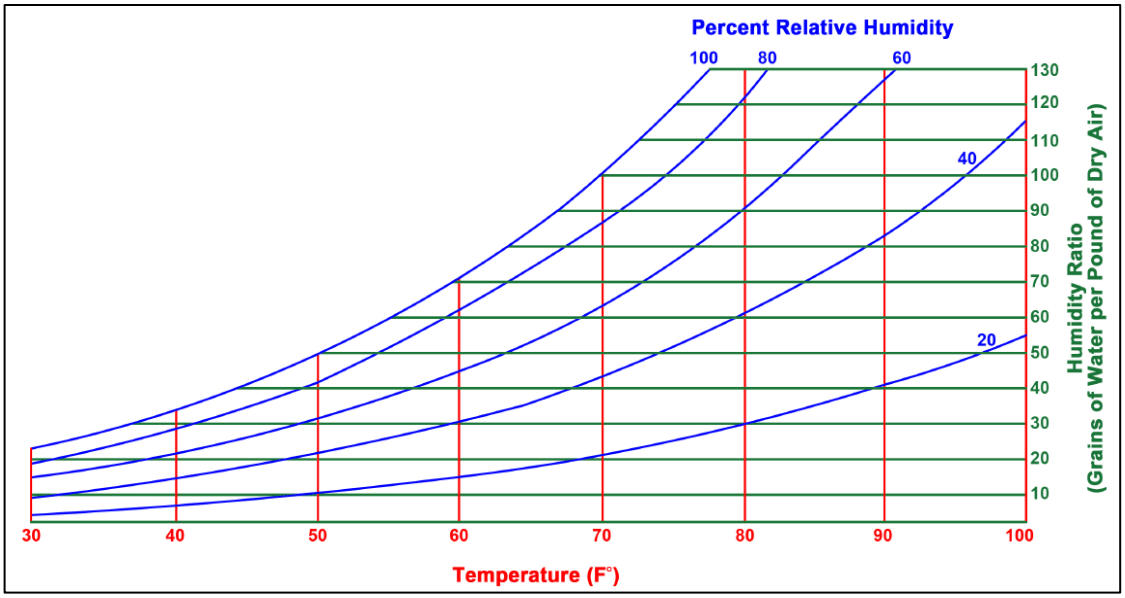
As reviewed, 'relative humidity' is (by definition) a nonlinear (relative) value defined by dynamic interactions between varying levels of energy and water molecules.

This thermodynamic nonlinear relationship between the amounts of available energy and ambient vapor often is described graphically with a ***psychrometric chart*** (*psychrometrics* is the science of air-water interaction).[14]

A simplified psychrometric chart is provided below:

[13] Note that for each material, its *sorption isotherm* can be considered to represent average values between its *adsorption isotherm* (which depicts the rate of increasing moisture content as relative humidity increases) and its *desorption isotherm* (which depicts the rate of decreasing MC as RH decreases). Under conditions of falling RH, the moisture content of most hygroscopic materials will be somewhat higher than for the same RH values when the relative humidity is rising. In simple terms, it is somewhat easier for water to enter a hygroscopic material than to exit this material. The lag effect between the MC values in the adsorption and desorption curves is termed *hysteresis*.

[14] Reference the *ASHRAE Fundamentals Handbook* published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, www.ashrae.org



Simplified "psychrometric chart". Example: the intersection of 70°F and 80% RH corresponds (at the Y-axis) to 88 grains of ambient water per pound of dry air.

- The horizontal x-axis in this chart quantifies the thermal energy available to power the evaporation/condensation processes.
- The vertical y-axis (***humidity ratio***) quantifies the total ambient vapor (*grains of water per pound of dry air*) associated with any particular interactive temperature/RH combination.
- Any x,y point on the graph identifies the corresponding relative humidity.
- The "dew point temperature" follows the 100% RH curve.

For example, at 70° F and 99 gpp (*grains of water vapor per pound of dry air*), 90% of the available energy must be used for the evaporation necessary to achieve energy exchange equilibrium. You can see that only a slight (~ 3° F) drop in temperature is sufficient to raise this RH value to 100% (the dew point), resulting in atmospheric condensation of sufficient free moisture to relieve the excess energy.

For us building professionals, a psychrometric chart can be a vital tool for analyzing moisture balance conditions and the associated potential for deterioration or mold growth.

For example, assume that metering devices within your room register 70° F and 50% RH – an energy exchange equilibrium (*humidity ratio*) representing ~54 grains of ambient water vapor per pound of dry air.

In addition, let's assume that your room has bookshelves installed at a poorly insulated exterior wall that (due to the winter storm raging outside) has a surface temperature of 55° F at the interior face of the poorly ventilated gypsum wallboard positioned directly behind this bookcase: *what is the relative humidity at this wallboard facer and why is blackish mold growing on it*?

Due to the leveling effects of the Second Law of Thermodynamics, the ambient moisture content of the room (54 grains of water vapor per pound of dry air) remains the same at all areas, even at this 'cold wall' behind the bookcase; therefore, per our psychrometric chart above, the ambient RH at the wallboard surface has increased to about 95%.

This higher RH equates to an increased equilibrium moisture content of the paper facer and the underlying gypsum wallboard. The wallboard and its paper facer have become wetter (due to adsorption, followed by absorption) behind the bookcase than anywhere else in the room.

Such additional moisture can be sufficient to promote the growth of many common mold species, particularly if the wet substrate (such as the pulp paper facers of standard gypsum wallboard panels) provides a 'ready-to-eat' meal (a metaphorical 'Big Mac') for some mold species.

Fortunately, after using your psychrometric chart to understand why mold is growing on the wall behind your bookcase, you also see that this condition can be remediated by: a) insulating the wall, and/or b) repositioning the bookcase or otherwise providing better ventilation to this colder 'dead air' space.[15]

e. If water molecules are so small, how do the permeable asphaltic building papers and 'housewrap' products prevent water entry?

All code-compliant building papers and housewraps must provide a minimum level of *permeance* (for vapor migrating from the interior) while simultaneously resisting liquid water leakage from the exterior. Asphalt-saturated building papers will provide an *absorptive* barrier to water infiltration (rated in minutes) and a buffering capacity for holding excess moisture until drying conditions return.

[15] These actions result in increased thermal energy at this air-to-wall transition and corresponding reductions in both the ambient RH and the moisture content of the wallboard.

The manufacturers of the various 'housewrap' products face a different situation where their polyolefin materials have no absorptive capability and easily could be manufactured as a true vapor barrier – thus, the critical question is how best to provide a degree of vapor permeability while retaining satisfactory resistance to liquid water penetration.

Some manufacturers address this issue with 'micro-perforations' (many tiny holes punched through the material); while others (such as Tyvek) manufacture a tight overlapping fibrous material *"engineered to create extremely small pores which readily allow moisture vapor to evaporate but are so small that liquid water has a very difficult time penetrating."*

- (Tyvek has published data indicating their product's tiny pores are far tinier than the tiny pores of their competitors' products).

Similar materials are used by Gore-Tex and its various competitors to manufacture weatherproof clothing that 'breathes' (allows *exfiltration* of the vapor molecules produced by our active bodies) while resisting *infiltration* of liquid water.

These materials generally work as designed because the hydrogen-bonded mass of water molecules that comprises a raindrop or other small cluster of liquid water is too large to fit through these tiny holes.

- The cohesive forces of liquid water are greater than the typical forces (air pressure, for example) trying to push individual pieces of the liquid body through the holes.
- In simple terms, the skin (surface tension) of the liquid mass is too tough to be broken by the forces attempting to push the bonded collection of molecules through the tiny holes.

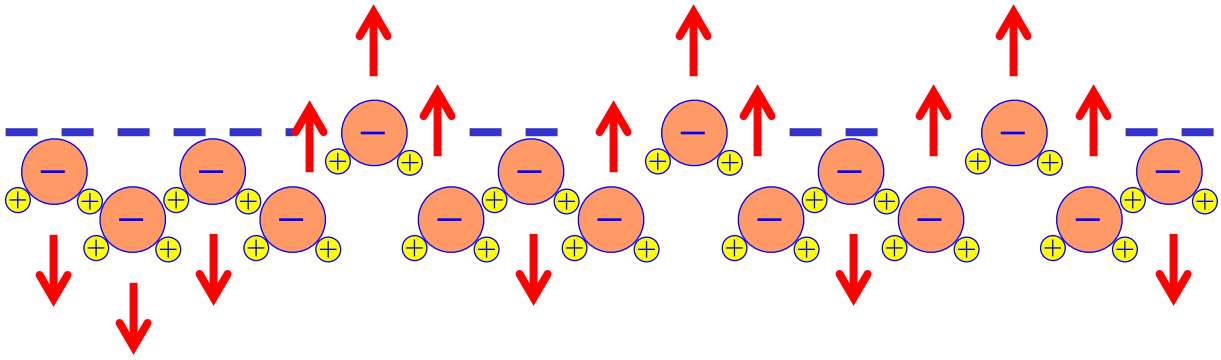
Be aware, though, that these same physical properties may also serve to trap any liquid water (perhaps caused by leakage or condensation) that may occur behind the micro-perforated wall wrap, roof membrane, or rain-gear material unless this trapped moisture mass can be heated sufficiently to produce vaporization.[16]

[16] Importantly, as also reviewed above, traditional non-perforated asphaltic building papers and felts can, to a limited degree, safely absorb such 'trapped' water, allowing it to later be dissipated to the building exterior.

f. Can soapy products safely be applied to housewraps, building papers, and breathable (such as Gore-Tex) clothing?

Soap is a powerful surfactant – the attractive power of the polar end of a soap molecule is sufficiently strong to rip apart the surface tension of liquid water, tearing individual molecules and smaller clusters loose from the condensed mass.

Now that the liquid's skin has been broken, individual water molecules may pass through the very tiny pore passages within these 'breathable' materials. This problematic condition can occur, for example, when lap siding is pressure-washed unless care is taken to protect the underlying housewrap from the soapy pressurized water.



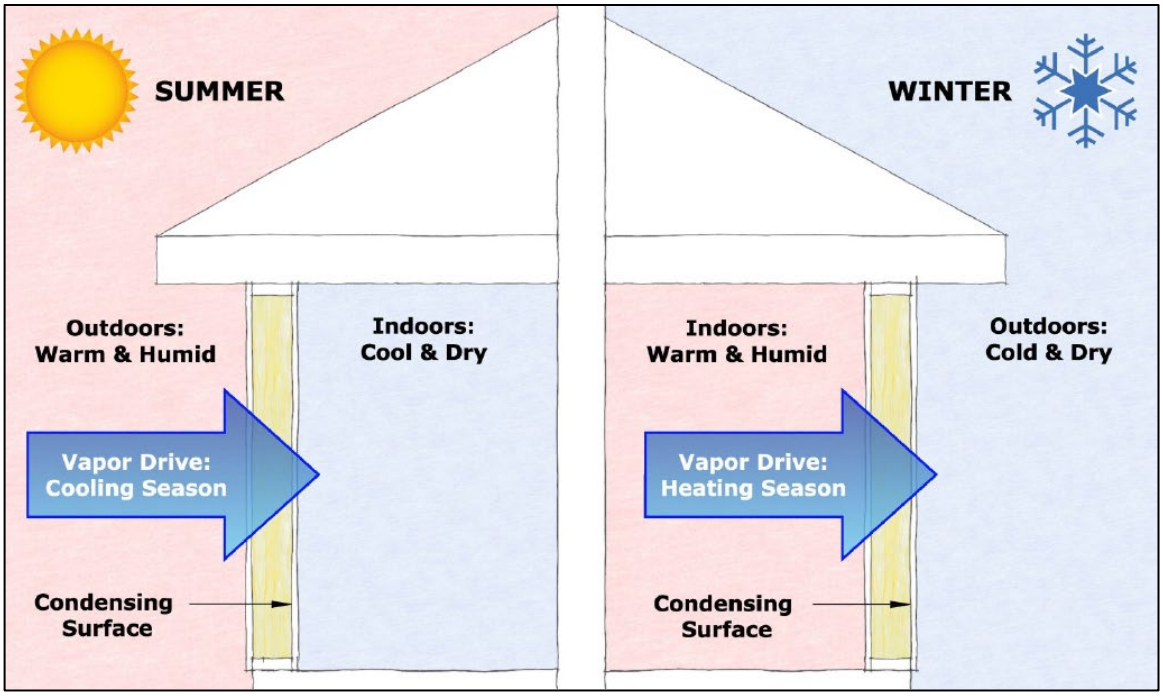
g. What is "vapor drive"?

As you read this paper, 'zillions' of zippy (heat-energized) water vapor molecules are bouncing off surrounding walls, furnishings, (and you). At the same time, both *inside* of your other rooms and *outside* of your building, 'zillions' of other zippy water vapor molecules are slamming into opposite sides of your building's walls.[17]

The collective ***vapor pressure*** imparted by these non-stop molecular collisions can be much stronger at one side of a wall (inside or outside) depending on which side has the most heat-energized water vapor. Clear-cut examples of such *vapor pressure differentials* include:

- In hot and highly humid Florida, there will be far stronger ***vapor drive*** occurring at the exterior faces of an air-conditioned house.
- During Colorado winters, there will be far stronger ***vapor drives*** occurring at the interior walls of heated homes.

[17] Moisture scientists report that the water vapor zipping around your room tends to travel in groups of 20 to 60 molecules.



Pressure differentials cause water vapor to "drive" from warmer/wetter toward colder/dryer zones.[18]

Remember: the Second Law of Thermodynamics tells us that whenever there is an accessible route, no matter how small, *warmer/wetter* forms of energy will always move toward lesser (*colder/dryer*) energy zones.

***Warmer/wetter* forms of energy will always move (drive) toward lesser (*colder/dryer*) energy zones.**

[18] https://www.iccsafe.org/wp-content/uploads/proclamations/TN06-Vapor-Retarders_pdf.pdf

While engineers can, of course, exactly calculate these *vapor pressure differentials*, we non-engineering building professionals typically do not have specific needs for such mathematical precision. Instead, it can be sufficient for our non-engineering purposes to understand that:

- *Vapor pressure* – similar to the *humidity ratio* (ambient moisture content) discussed above – can be calculated as a function of heat (*temperature*) and *relative humidity*.[19]

  Note: while there is no linear correlation between *vapor pressure* and *humidity ratio* values, when separate spaces are evaluated the area with the highest calculated *vapor pressure* also always will have the greater *humidity ratio* (ambient moisture content).

In short, when comparing different areas (such as interior and exterior sides of a wall), we non-engineering professionals simply need to know that higher *vapor pressures* always are correlated (no matter the RH and temperature readings) with greater concentrations of water vapor.

h. What are "vapor retarders"?

The term ***vapor retarder*** describes materials of varying classifications and types designed to impede (slow) such *diffusion* of vapor from such areas of high concentration to low.

Vapor retarder classifications are based upon a product's *permeance* – a lower **perm rating**[20] indicates that a material or assembly is less *permeable* (more resistant to the 'Second Law' process of more-to-less diffusion of water vapor) – and vice-versa.

- Class I retarders, with a perm rating of 0.1 perm or less, are deemed ***vapor impermeable*** (aka, ***vapor barrier***) – examples include sheet polyethylene and foil-faced insulated sheathing;
- Class II retarders (> 0.1 perm and < 1.0 perm) are deemed ***vapor semi-impermeable*** – examples include asphalt-backed kraft paper facing on fiber glass batt insulation, unfaced expanded polystyrene boards, and fiber-faced polyisocyanurate panels; and
- Class III retarders (> 1.0 perm and < 10 perms) are deemed ***vapor semi-permeable*** --- latex paint is a Class III retarder.

[19] While there is no direct linear correlation between "vapor pressure" values and the "humidity ratio" values, when separate areas are compared, the space with the highest measured vapor pressure also always will have the greatest humidity ratio reading (and vice-versa).

[20] The U.S. perm is defined as 1 grain of water vapor per hour, per square foot, per "inch of mercury" (pressure differential).

Class I (vapor impermeable) retarders are best suited for assemblies (walls/floors) where there are extreme differences in the magnitude of the competing vapor pressures.

Consider, for example, this concrete floor slab installed atop a wetland in California – the absence of a ***vapor barrier*** (sheet polyethylene) under this slab allowed a damaging upward vapor drive (diffusion due to massive pressure differentials – in accordance with the Second Law) through the concrete from the pooling groundwater below.

- This vapor then *condensed* at the bottom side of the vinyl-backed carpet tiles – the ensuing free water destroyed the tiles' adhesive and then saturated the carpeting as it migrated upward through the joints between each tile.

Damaging vapor drive through this concrete floor slab could have been prevented by installing a Class I vapor retarder (sheet polyethylene) under the slab, as originally specified by the project architect.

Similarly, at *very cold-in-winter* climate zones in Colorado (or the 'High Sierras' of California and 'High Cascades' of Washington and Oregon), *interior vs. exterior* wintertime pressure differentials can be massive – typically leading the designer to specify a Class I (or perhaps Class II) vapor retarder to blunt the force of these extreme vapor drives.

In contrast, Class III (vapor semi-permeable) retarders can work well for "moderate" climate zones, such as the San Francisco Bay Area, where *interior vs. exterior* pressure differentials are far smaller during winter months.

- In such climate zones, a Class II (vapor semi-impermeable) vapor retarder *might* provide too much resistance to the weak pressure drives --- thereby trapping within the wall assembly undue levels of moisture that instead should have been driven from the wall.

Importantly, all Class I, II, and III vapor retarders (if required by code or localized expertise) should be installed on the ***warm-in-winter*** side of an exterior wall's insulation, thus guarding against undue levels of vapor *diffusion* into these walls – followed by damaging *condensation* when this warm vapor is trapped (and cooled) at the ***cold-in-winter*** side of the wall.

➢ Part C – Summary Comments

Consider this following highly perceptive guidance: *"For a moisture-related problem to occur, it is necessary for at least four conditions to be satisfied:*

1. *A moisture source must be available.*
2. *There must be a route or means for the moisture to travel.*
3. *There must be some driving force to cause moisture movement.*
4. *The material(s) involved must be susceptible to moisture damage."*[21]

As reviewed throughout this paper, the ***driving forces*** that cause high-to-low moisture movement (such as gravity, heat, and air/vapor pressure differentials) represent fundamental manifestations of the Second Law of Thermodynamics.

Therefore, during a project's design and construction stages, the superior approach for long-term prevention of moisture damage is careful attention to controlling all:

1. potential ***sources*** of excess water (liquid and vapor), and
2. potential ***routes*** for unintended moisture intrusion that could reach ***materials that are susceptible to moisture damage***.

[21] J. F. Straube, *Moisture in Buildings*, ASHRAE Journal (January 2002), www.ashrae.org. (A copy of this article is available upon request: info@avelar.net.)

Further, the designer must strive to avoid ***vapor traps***. Safe discharge of excess moisture that might get caught within a wall assembly (perhaps due to leakage at a failed flashing) necessitates: i) a ***route*** for the moisture to escape from this potential trap, and ii) a ***driving force*** (typically heat and/or ventilation) to push the vaporized moisture along this route.

In summary, all forensic investigations of water-damaged buildings should include evaluations of potential ***sources***, ***routes***, and ***driving forces*** of this water damage in accordance with the perceptive guidance of renowned architect William B. Rose:

"*Most moisture problems can be diagnosed by looking at the condition and asking how much water it took to create that problem. Solving the problem amounts to asking where that amount of water could have come from and where it should go*."[22]

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RECOMMENDED READING LIST:

- ✓ All publications by Dr. John F. Straube: (https://uwaterloo.ca/scholar/jfstraub/home)
- ✓ All publications by Dr. Joseph Lstiburek: (https://www.buildingscience.com/users/joseph-lstiburek)
- ✓ A. N. Karagiozis, *Building Enclosure Hygrothermal Performance Study – Phase 1*, Oak Ridge National Laboratory, ORNL/TM-2002-89
- ✓ Donald P. Gatley, *Understanding Psychrometrics* (Third Edition) ASHRAE, Inc., Atlanta, GA 2013
- ✓ W. B. Rose, *Water in Buildings – An Architect's Guide to Moisture and Mold*, John Wiley & Sons, Inc., 2005

This AVELAR educational brief is general and introductory in nature and is neither intended nor authorized for any project-specific use by any attorney, construction professional or other participant in the building design or litigation fields.

[22] William B. Rose, *Water in Buildings – An Architect's Guide to Moisture and Mold*, John Wiley & Sons, Inc., 2005