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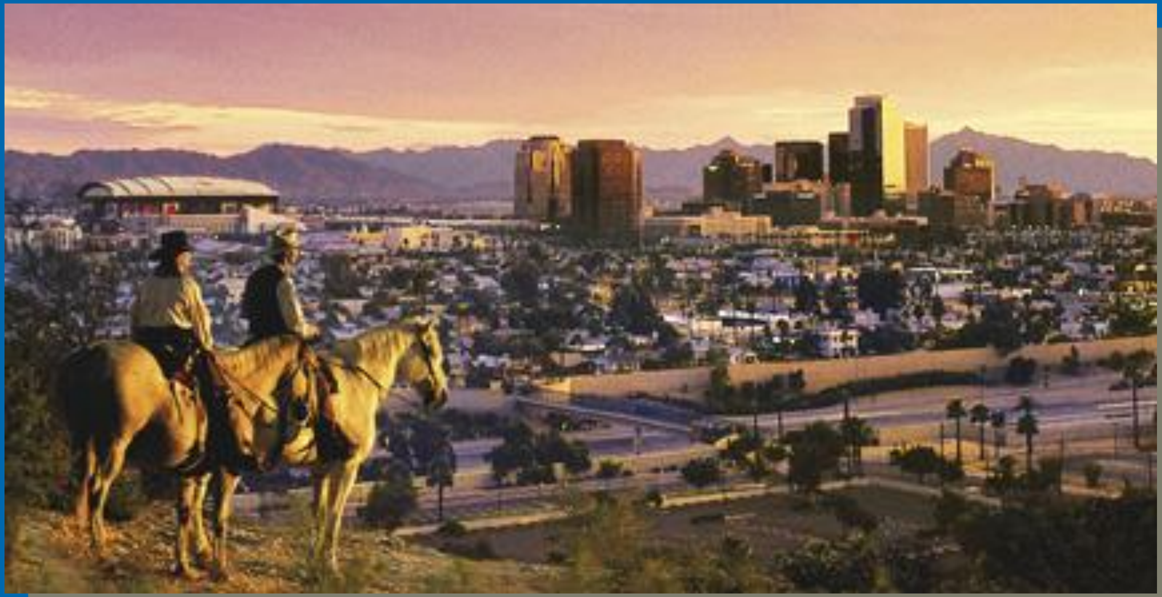

Seeking Adventure …. Advancing Knowledge

Roof Consultants Institute

Condensation Control Mechanisms in Exterior Wall Assemblies

By

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Roof Consultants Institute

KARIM ALLANA, P.E., RRC, RWC

- **EDUCATION:** B.S., Civil Engineering, Santa Clara University, 1983
- **REGISTRATION:** P.E., Civil Engineering, California, 1987
- P.E., Civil Engineering, Nevada, 2002

  P.E., Civil Engineering, Hawaii, 2005
- **CERTIFICATION:** Registered Roof Consultant (RRC), Roof Consultants Institute
- Registered Waterproofing Consultant (RWC), Roof Consultants Institute
- **OVERVIEW:**
  - Over 20 years experience providing technical standards in building envelope technology.
  - Expert Witness in Construction Defect Litigation
  - Principal consultant in design of building envelope, roofing and waterproofing systems, forensic investigations of building assemblies and failure analysis.
  - Expert in all aspects of building envelope technology.
  - Specialization in cement plaster, other siding types, roofing, wood, water intrusion damage, window assemblies, storefronts, below grade waterproofing, and complex assemblies.
  - Completed over 1300 projects: new construction, addition, rehabilitation, remodel and modernization projects for public and private sector clients.

OVERVIEW

- Address the effects of condensation related water damage leading to mold and indoor air quality
  - Principles of water phases, relative humidity, condensation, vapor retarders and vapor pressure
  - Examples of condensation caused by vapor transmission through interior and exterior walls, indoor showers, pools and spas
  - Calculations for vapor barrier design and water accumulation due to condensation over given time period.

BUILDING AREAS SUSCEPTIBLE TO CONDENSATION

- Compact roof assemblies, i.e., no attic – flat roofs or cathedral ceilings
- Exterior wall assemblies in cooling, heating and mixed climates
- Interior wall assemblies
- OSB sheathing materials are more susceptible to damage
- Hardboard siding manufacturers require vapor barrier

Relevant Terminology:

- WATER PHASES
- RELATIVE HUMIDITY
- CONDENSATION
- WATER VAPOR TRASMISSION
- PERMEANCE/PERMEABILITY
- VAPOR PRESSURE
- DIFFUSION

WATER PHASES

- Water can exist in three phases
  - Ice
  - Liquid, between 32 degrees (freezing) and 212 degrees F (boiling)
  - Gas phase (steam) from boiling, or gas phase (water vapor) from evaporation, when the temperature is below boiling point
- When cooled, water vapor will lose energy and return to liquid, i.e., it will *condense*

RELATIVE HUMIDITY

- The amount of water in its gaseous phase that can be contained within a given volume of air is a function of the air's temperature:
  - *Warm air holds more moisture than cold air!!*
- Relative humidity is expressed as a percentage: 100% humidity means that the air is saturated at that temperature

DIFFUSION/PERMEABILITY

- Diffusion is the transmission of water vapor through a material
- Some materials allow diffusion to occur more rapidly than others
- A material's ability to allow diffusion of water vapor is measured by "permeability" and "permeance"

PERMEANCE

- Permeance is based on given thickness of material.
  - Unit of measure = Perm
  - Is measured in perms per square meter
  - Rating under 0.5 = vapor barrier

PERMEABILITY

- Permeability is based on a given thickness range of material.
  - Unit of measure = Perm.inch
  - Example, Permeability of concrete = 3.2 perm.in
  - Permeance of 6” thick concrete slab = 3.2 perm.in/6” = .53 perm

Figure 5

Typical Water Vapor Permeance and Permeability Values[1,2]		
Material	Permeance (perm)	Permeability (perm•in)
Common roof membrane materials:		
Asphalt (hot applied, 2 lbs/100 ft²)	0.5	
Asphalt (hot applied, 3.5 lbs/100 ft²)	0.1	
Built-up membrane (hot applied)	0.0	
No. 15 asphalt felt	1.0	
No. 15 tarred felt	1.0	
Roll roofing (saturated and coated)	0.05	
Common insulation materials:		
Expanded polystyrene insulation		2.0 - 5.8
Extruded polystyrene insulation		1.2
Plastic and metal films and foils:		
Aluminum foil (1 mil)	0.0	
Kraft paper and asphalt laminated, reinforced	0.3	
Polyethylene sheet (4 mil)	0.08	
Polyethylene sheet (6 mil)	0.06	
Other common construction materials:		
Brick masonry (4 in. thick)	0.8	
Concrete (1:2:4 mix)		3.2
Concrete block (with cores, 8 in. thick)	2.4	
Gypsum wall board (plain, 3/8 in. thick)	50	
Hardboard (standard, 1/8 in. thick)	11	
Metal roof deck (not considering laps and joints)	0.0	
Plaster on metal lath	15	
Plaster on wood lath	11	
Plywood (Douglas fir, exterior glue, 1/4 in. thick)	0.7	
Plywood (Douglas fir, interior glue, 1/4 in. thick)	1.9	
Wood, sugar pine		0.4 - 5.4

CONDENSATION

- When air containing moisture cools, some of the moisture is released – it condenses into liquid water
- The temperature at which this occurs is the "dew point"
- Condensation occurs when humid air meets cold surfaces such as walls, chilled water lines, even insulation, above or near pools

Figure 4

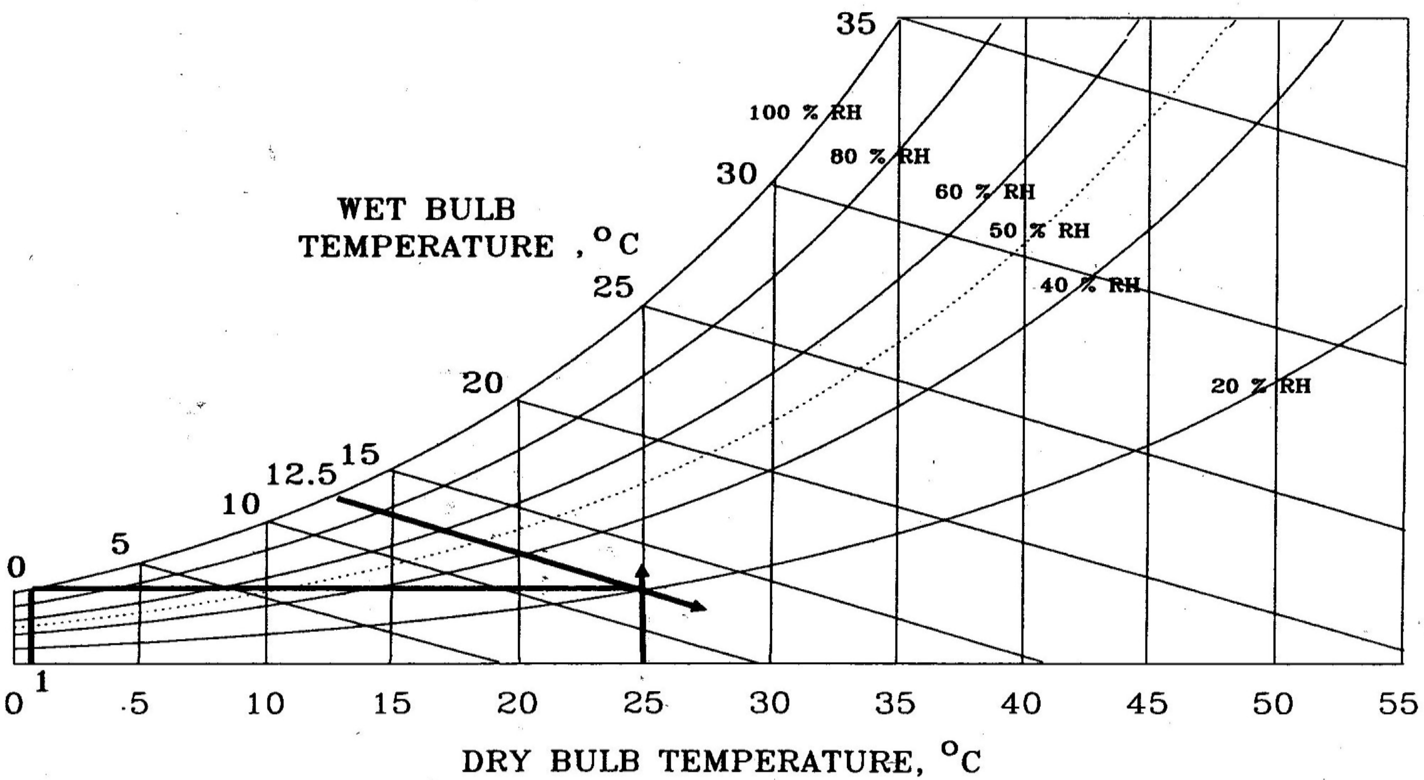


FIG. A4—Calculation of relative humidity and dew point temperature from psychrometric measurements.

Figure 3

The NRCA Roofing and Waterproofing Manual—Fifth Edition

APPENDIX 4: PSYCHROMETRIC TABLE

Dew-Point Temperature (°F)															
Relative Humidity	Design Dry Bulb (Interior) Temperature (°F)														
	32°F	35°F	40°F	45°F	50°F	55°F	60°F	65°F	70°F	75°F	80°F	85°F	90°F	95°F	100°F
100%	32	35	40	45	50	55	60	65	70	75	80	85	90	95	100
90%	30	33	37	42	47	52	57	62	67	72	77	82	87	92	97
80%	27	30	34	39	44	49	54	58	64	68	73	78	83	88	93
70%	24	27	31	36	40	45	50	55	60	64	69	74	79	84	88
60%	20	24	28	32	36	41	46	51	55	60	65	69	74	79	83
50%	16	20	24	28	33	36	41	46	50	55	60	64	69	73	78
40%	12	15	18	23	27	31	35	40	45	49	53	58	62	67	71
30%	8	10	14	16	21	25	29	33	37	42	46	50	54	59	62
20%	6	7	8	9	13	16	20	24	28	31	35	40	43	48	52
10%	4	4	5	5	6	8	9	10	13	17	20	24	27	30	34

Adapted from ASHRAE Psychrometric Chart, *1993 ASHRAE Fundamentals Handbook.*

WATER VAPOR PRESSURE

- Gases, including water vapor, exert pressure.
- The atmospheric pressure created by water vapor in the air.
- Water vapor will flow from the place of higher vapor pressure, to the place where the vapor pressure is lower
- Higher temperature = higher energy
- Pressure difference in building assemblies occurs in two typical conditions:
  - Cooling Climate, where exterior temperature and humidity is high
  - Warming Climate, where interior temperature and humidity is higher then exterior

Figure 1
Cooling Climate

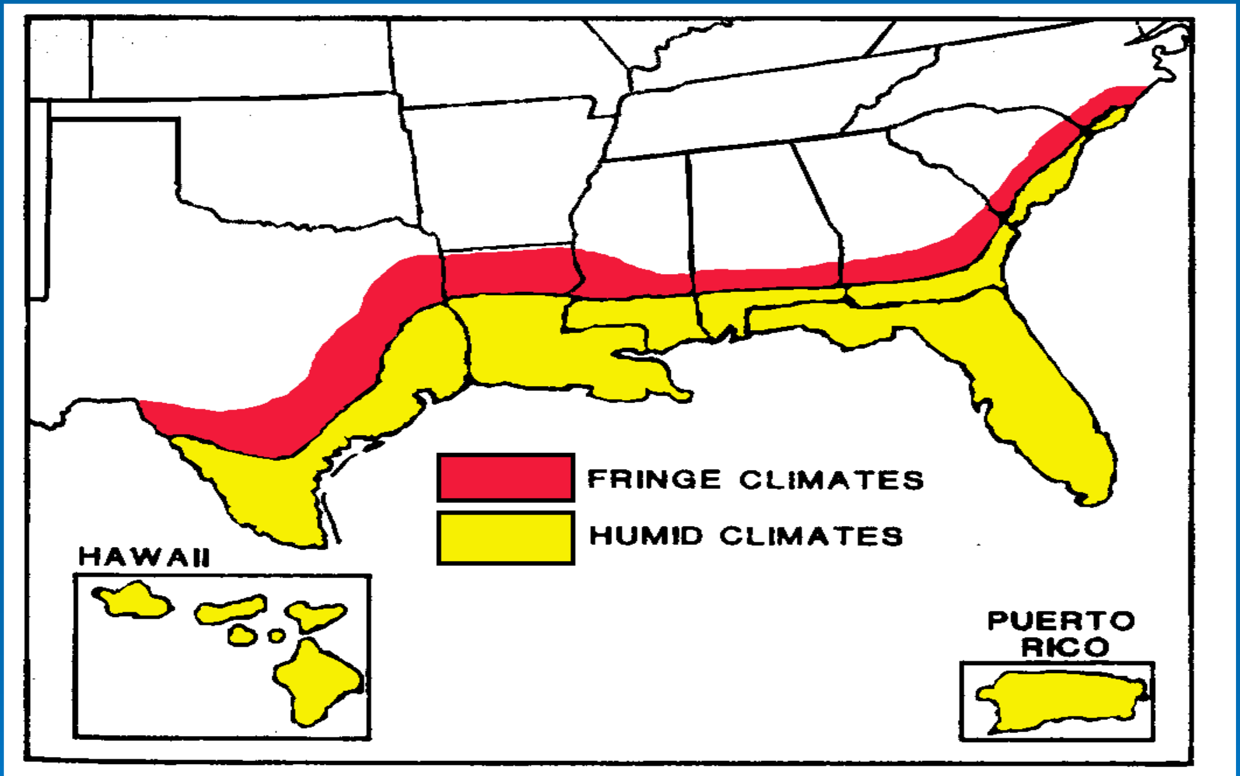


Figure 2
Warming Climate

Mean Average January Temperature

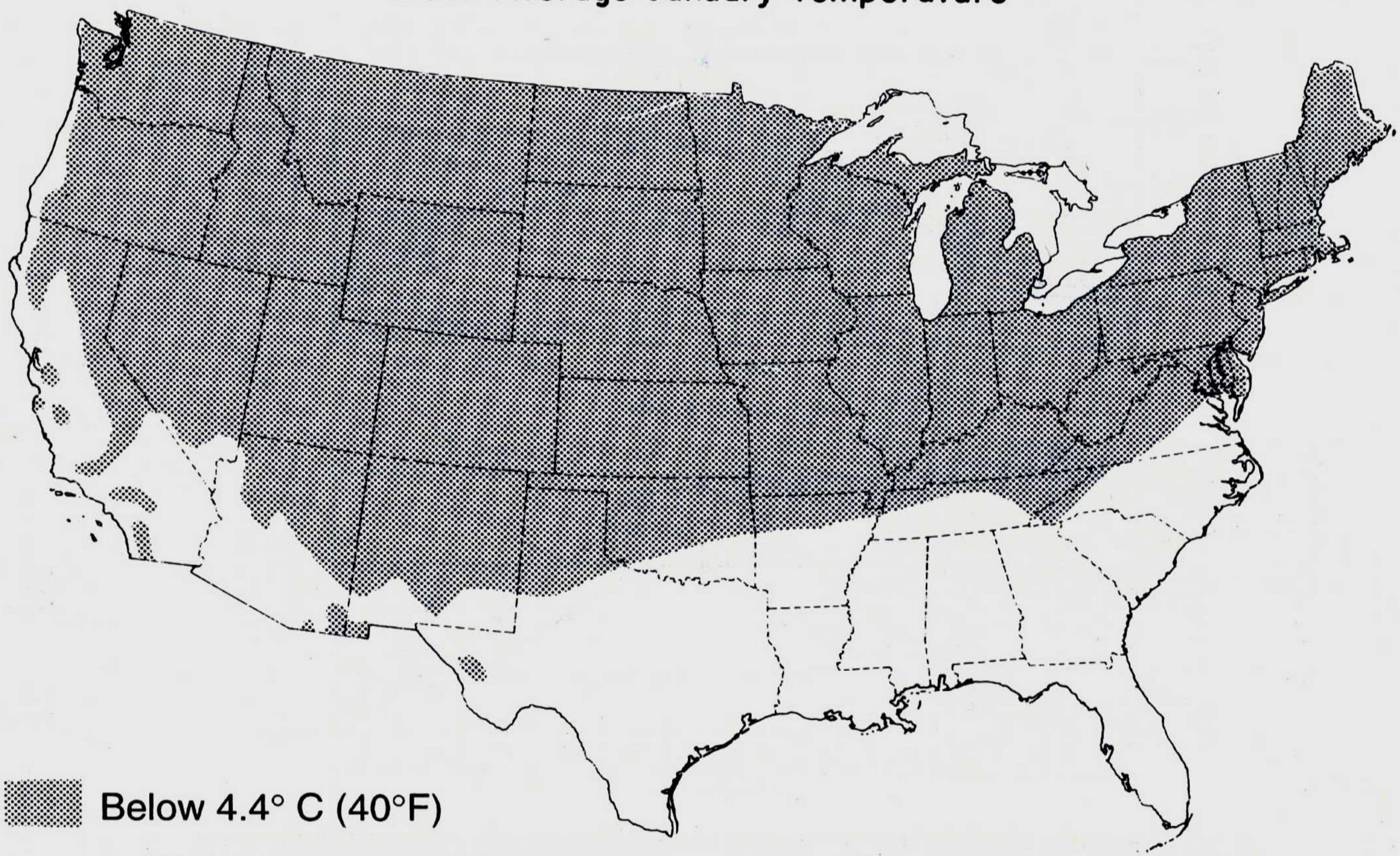


FIG. 10—Area of the United States that has a mean average January temperature below 4.4°C (40°F).

AREAS SUSCEPTIBLE TO CONDENSATION

- Exterior wall assemblies
- Interior wall assemblies
- Chilled water line insulation
- Indoor pools and spas

Case Study #1 (COOLING CLIMATE) EXAMPLE OF CONDENSATION IN HOTEL PARTY WALL

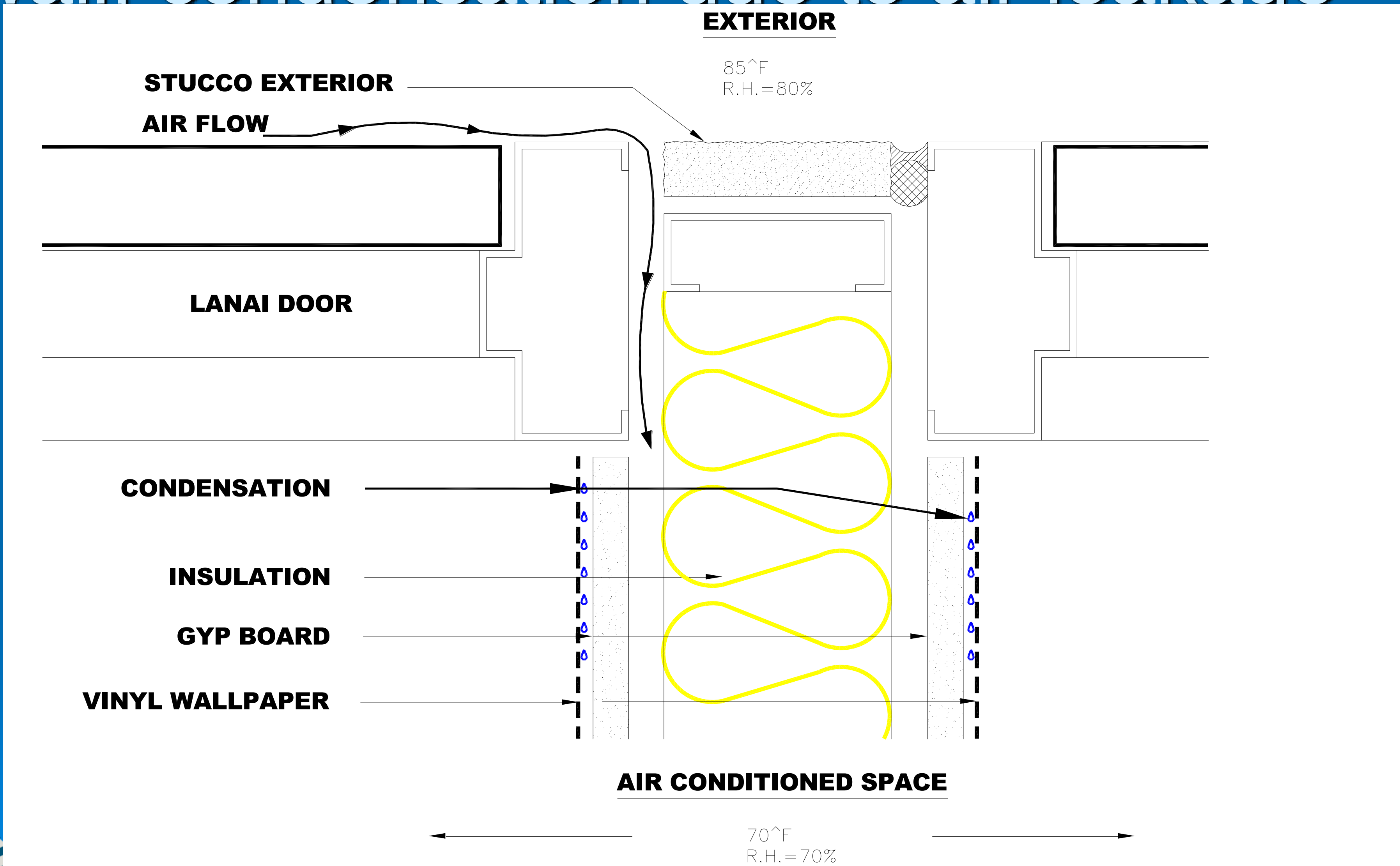
Case Study # 1

- Honolulu, Hawaii hotel
- Air leakage through failed sealant joint between lanai door and exterior wall
- Condensation between hotel party walls
- Calculate how much condensation (gallons) of water accumulates on the wall in 1 week time span.

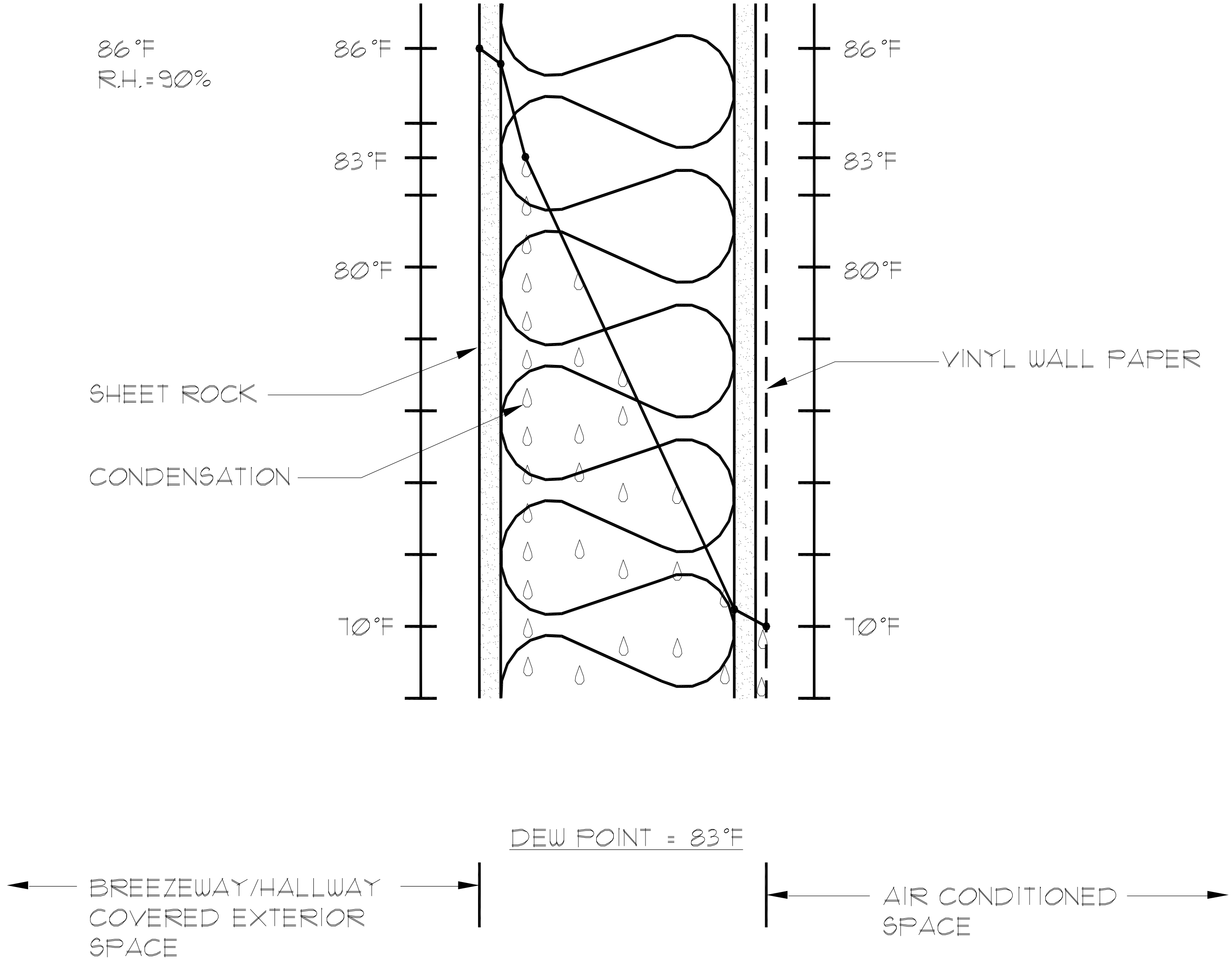
Condensation between hotel party walls

Moisture intrusion through air leakage at exterior side of party wall

Case Study # 1, Hawaii Hotel interior wall, condensation due to air leakage




Vinyl
wallpaper



WHERE CONDENSATION OCCURS

Case Study # 1: Moisture trapped in a shared wall cavity.

Gaps near an exterior door allow warm humid air to flow into a wall cavity in a Hawaii Hotel (see Figure 10). The affected wall area 10'x8'. Outside temperature and relative humidity are 85F and 80% respectively. The inside temperature and relative humidity are 70F and 70% respectively. Assume condensation forms at the back side of the low perm vinyl wallpaper coating. How much water can collect over a 1 week period?

Vapor Transmission Equation

$$VT = A \times T \times \Delta P \times \text{permeance}$$

VT = Water vapor transmission in grains (1lb=7000 grains)
A = Area (square feet)
T= Time (hours)
ΔP = Pressure difference (in. Hg)
Perms = Perm rating (grains/ft^2/hr/in. Hg)

Case Study # 1: Moisture trapped in a shared wall cavity.

Step 1: Area = 10'x8' = 80 ft^2

Step 2: Time = 1 week = 168 hrs

Step 3: Pressure difference – go to figure 9. At 85F, the saturated vapor pressure is 1.213 in.Hg. At 70F, the saturated vapor pressure is 0.7392 in.Hg. Multiply each of the saturated vapor pressures by their relative humidity. The pressure difference is $\Delta P = (1.213 \times 0.80) - (0.7392 \times 0.70) = 0.4523$ in.Hg

Figure 9 – Vapor Pressures for Saturated Air

°F	in Hg	°F	in Hg	°F	in Hg	°F	in Hg
-65	.0007	15	.0806	43	.2782	71	.7648
-60	.0010	16	.0847	44	.2891	72	.7912
-55	.0014	17	.0889	45	.3004	73	.8183
-50	.0020	18	.0933	46	.3120	74	.8462
-45	.0028	19	.0979	47	.3240	75	.8750
-40	.0039	20	.1028	48	.3364	76	.9046
-35	.0052	21	.1078	49	.3493	77	.9352
-30	.0070	22	.1131	50	.3626	78	.9666
-25	.0094	23	.1186	51	.3764	79	.9989
-20	.0126	24	.1243	52	.3906	80	1.032
-15	.0167	25	.1303	53	.4052	81	1.066
-10	.0220	26	.1366	54	.4203	82	1.102
-5	.0289	27	.1432	55	.4359	83	1.138
0	.0377	28	.1500	56	.4520	84	1.175
1	.0397	29	.1571	57	.4686	85	1.213
2	.0419	30	.1645	58	.4858	86	1.253
3	.0441	31	.1723	59	.5035	87	1.293
4	.0464	32	.1803	60	.5218	88	1.335
5	.0488	33	.1878	61	.5407	89	1.378
6	.0514	34	.1955	62	.5601	90	1.422
7	.0542	35	.2035	63	.5802	91	1.467
8	.0570	36	.2118	64	.6009	92	1.513
9	.0599	37	.2203	65	.6222	93	1.561
10	.0629	38	.2292	66	.6442	94	1.610
11	.0661	39	.2383	67	.6669	95	1.660
12	.0695	40	.2478	68	.6903	96	1.712
13	.0730	41	.2576	69	.7144	97	1.765
14	.0767	42	.2677	70	.7392	98	1.819

Case Study # 1: Moisture trapped in a shared wall cavity.

Step 4: Effective perm rating. The perm ratings for the materials are as shown in FIG 5:
Gypsum Board = 50

Step 5: Plug values into the vapor transmission equation:

$VT = 80\ ft^2 \times 168\ hr \times 0.4523\ in.Hg \times 50\ perm$
= 304,389 grains of water
= 43.5 pounds of water
= 5.24 gallons of water (in 1 week)

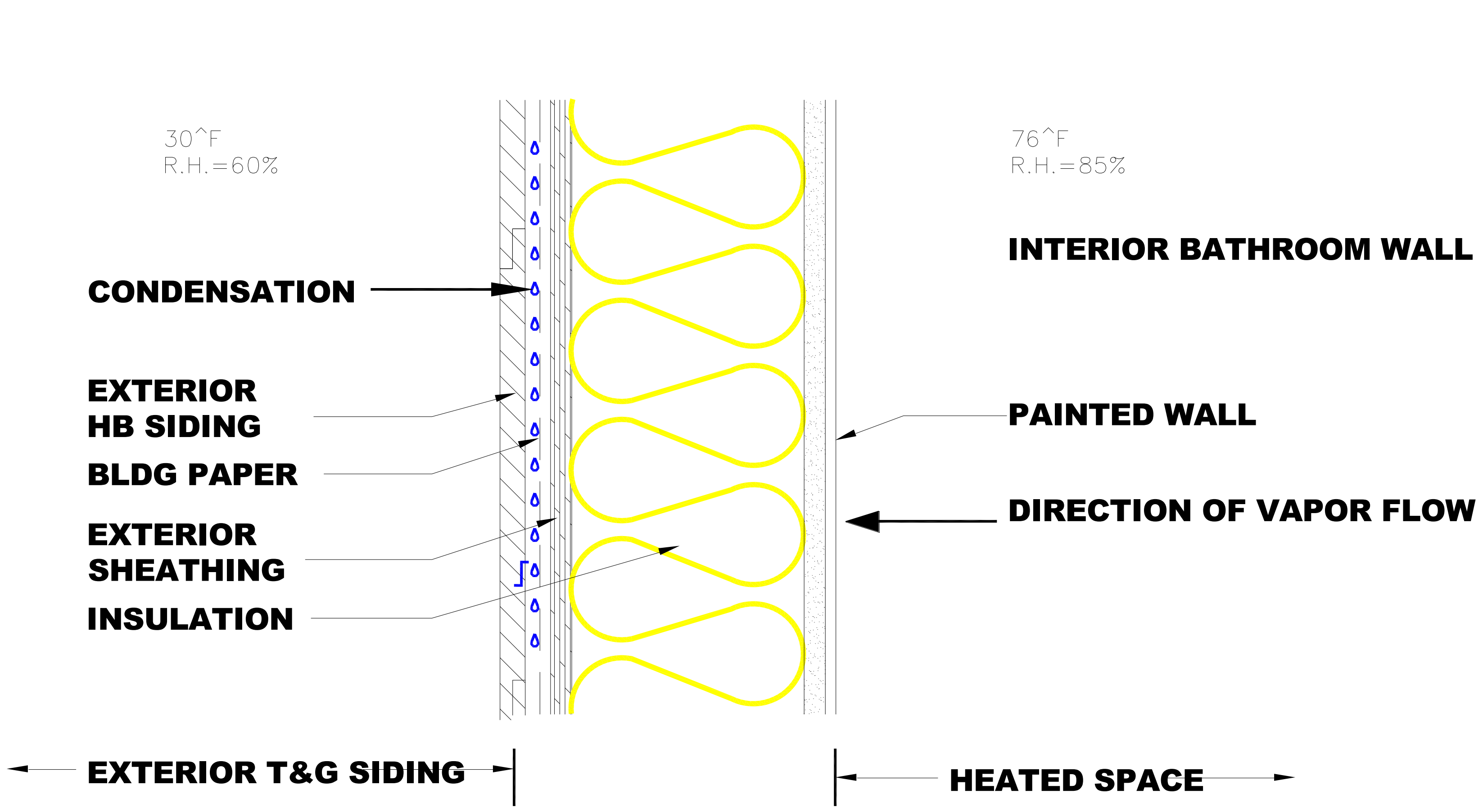
Case Study # 2: Moisture forming on exterior siding in California (Mixed Climate)

We observed water condensing behind exterior fiberboard siding on an apartment in central California (see Figure 12). The affected area is 30’x30’. Outside temperature and relative humidity are 30F and 60% respectively. The inside temperature and relative humidity are 76F and 85% (bathroom) respectively. Under these conditions, moisture will flow from inside to outside. How much moisture will reach the siding over a 72 hour period?

Case Study # 2, Warped Hardboard Siding due to Condensation

Case Study # 2, Condensation behind siding in Mixed Climate

CASE STUDY # 2 CONDENSATION ON EXTERIOR SIDING (Fig 12)



Vapor Transmission Equation

$$VT = A \times T \times \Delta P \times \text{permeance}$$

VT = Water vapor transmission in grains (1lb=7000 grains)
A = Area (square feet)
T= Time (hours)
ΔP = Pressure difference (in. Hg)
Perms = Perm rating (grains/ft^2/hr/in. Hg)

Case Study # 2: Moisture forming on exterior siding.

Step 1: Area = 100'x30' = 3000 ft^2
Step 2: Time = 72hrs
Step 3: Pressure difference – go to figure 9. At 76F, the saturated vapor pressure is 0.9046 in.Hg. At 30F, the saturated vapor pressure is 0.1645 in.Hg. Multiply each of the saturated vapor pressures by their relative humidity. The pressure difference is $\Delta P = (0.9046 \times 0.85) - (0.1645 \times 0.60) = 0.670$ in.Hg

Example: Moisture forming on exterior siding.

Step 4: Effective perm rating. The perm ratings for the materials excluding siding are as shown:

60 Minute Building Paper = 5

Plywood = 2

Insulation = 30

Painted Gypsum Board = 5

Determine the perm rating for the assembly behind the siding. Add the inverses of the individual perm ratings to obtain Z, the inverse effective perm rating:

$$Z = 1/5 + 1/30 + 1/2 + 1/5 = 0.933 \text{ perm}^{-1}$$

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Case Study # 2: Moisture forming on exterior siding.

Therefore, the assembly's effective perm rating is the inverse of Z:

Effective Perm Rating = 1/Z = 1.071 Perms

Step 5: Plug values into the vapor transmission equation:

VT= 3000 ft^2 x 72 hr x 0.670 in.Hg x 1.071 perm

= 154,995 grains of water

= 22 pounds of water

= 2.67 gallons of water (in 3 days)

Case Study # 3, Stucco Leak in wall. Study of slow diffusion

Few visible signs of distress

Relatively benign looking vinyl wall paper


Removal of a small area
displayed evidence of
some real problems

Case Study # 3, Slow diffusion due to vapor barrier on the inside face of wall

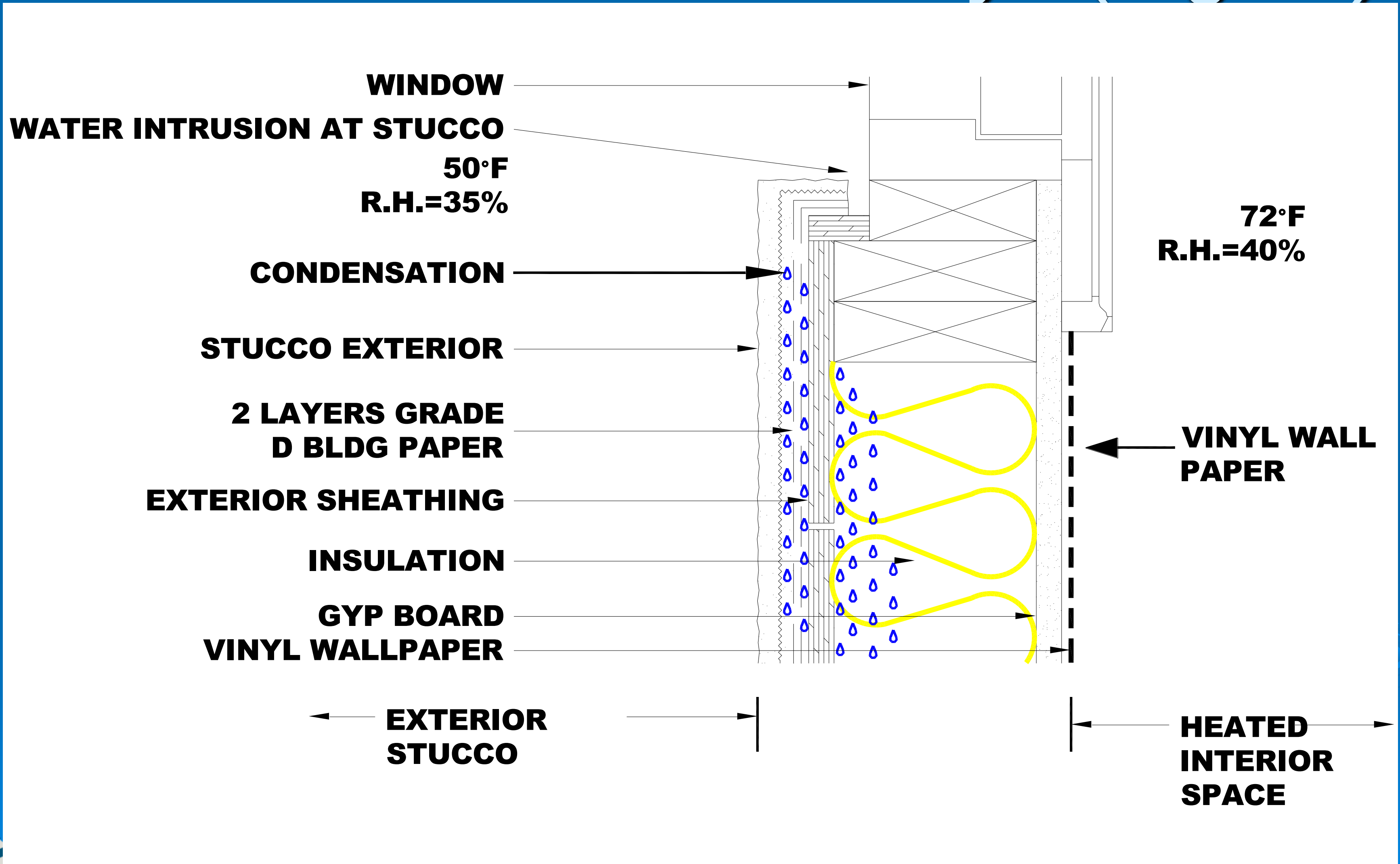
Mold and rot in the wall cavity

Case Study # 3, slow diffusion in wall can cause a lot of damage from leaks

Case Study # 3: Moisture trapped in different layers of a wall assembly, how long before it dries?.

During the rainy season, water collects in a wall due to a window leak in the locations shown (see Figure 13). The affected area is 100 ft^2. Outside temperature and relative humidity are 50F and 35% respectively. The inside temperature and relative humidity are 72F and 40% respectively. Under these conditions, moisture will flow from inside to outside. How much time will it take for the water to leave the assembly in each of the locations? Each location has 1 gallon of water intrusion.

Case Study # 3, Diffusion. How long does it take for water to dry? (Fig 13)



Example: Moisture trapped in a wall from a window leak.

Step 1: Area = 100 ft^2
Step 2: Pressure differences – go to figure 9. At 72F, the saturated vapor pressure is 0.7912 in.Hg. At 50F, the saturated vapor pressure is 0.3636 in.Hg. Multiply each of the saturated vapor pressures by their relative humidity. The pressure difference is $\Delta P = (0.7912 \times 0.40) - (0.3636 \times 0.35) = 0.1896$ in.Hg

Example: Moisture trapped in a wall from a window leak.

Step 3: Pressure distribution. The pressure at each material in the wall can be determined from the following formula:

$$\Delta P_{material} = (Z_{material}/Z_{wall}) \times \Delta P_{wall}$$

$\Delta P_{material}$ = Pressure drop at each material
$Z_{material}$ = Inverse permeance of each material
Z_{wall} = Effective inverse permeance of system
ΔP_{wall} = Total pressure change from step 2

Example: Moisture trapped in a wall from a window leak.

The permeance values for the materials in the wall are as follows:

Stucco over metal lath = 15

2 layers 60 min. building paper = 5 ea.

OSB sheathing = 2

Insulation = 30

Gypsum board = 50

Vinyl wallpaper = 1

These values each need to be reciprocated to obtain $Z_{material}$ for each material.

Example: Moisture trapped in a wall from a window leak.

The effective permeance, $Z_{wall,}$ is:

Z_{wall} = 1/15 + 1/5 +1/5 + 1/2 + 1/30 +1/50 + 1/1
= 2.02 $perm^{-1}$

Now we can determine the pressure drops at each material layer in the wall system using the formula for pressure differential provided earlier:

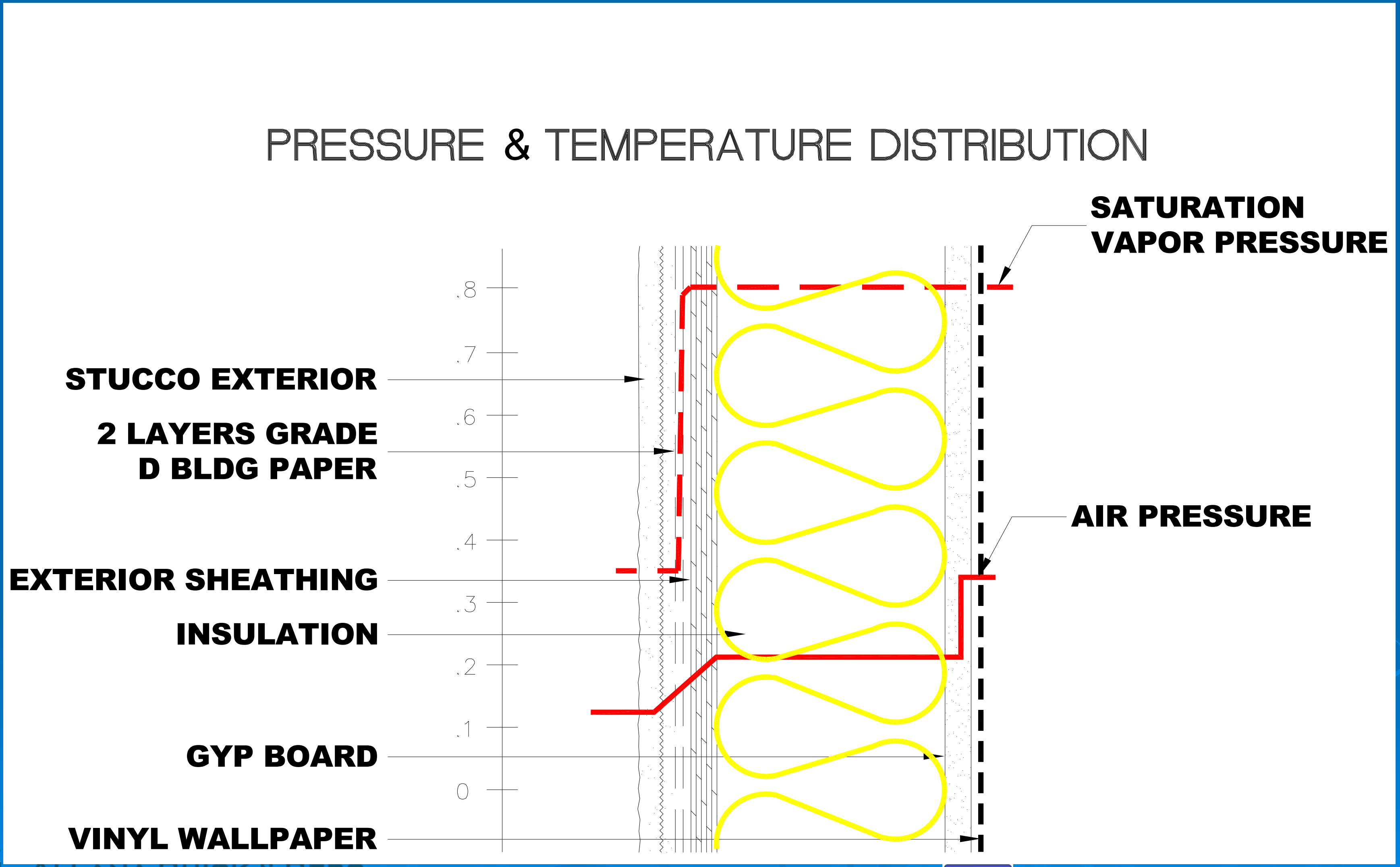
$$\Delta P_{material} = (Z_{material}/Z_{wall}) \times \Delta P_{wall}$$

Example: Moisture trapped in a wall from a window leak.

The pressure distribution in the wall is tabulated:

Material	Pressure Drop	ΔP
		0.3165
Wallpaper	0.09386	0.22264
Gypsum	0.001877	0.22076
Insulation	0.003129	0.21763
OSB	0.046931	0.17070
Paper	0.0187723	0.15193
Paper	0.0187723	0.13315
Stucco	0.006257	0.12690

Air and Saturation Pressure gradient: Figure 14



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Case Study # 3: Moisture trapped in different layers in the wall

Step 4: Determine the time required for diffusion at each location. Rearrange the Vapor Transmission Equation to isolate the time variable T:

$$VT = A \times T \times \Delta P \times \text{permeance}$$

$$T = VT / (A \times \Delta P \times \text{permeance})$$

Continue by applying the formula to each of the “wet” locations.

Case Study # 3: How long does it take for 0.1 Gallon of water to dry if trapped between paper & stucco?

Location 1- Moisture over the building paper: From the pressure distribution,

$$\Delta P = 0.13315 - 0.12690 = 0.0066 \text{ in. Hg}$$

The effective Z value only takes into account the stucco since moisture will be driven out from inside the building/wall assembly.

$Z = 1/15 \text{ perm}^{-1}$

Permeance = 15 perm

Case Study # 3: How long does it take for 0.1 Gallon of water to dry if trapped between paper & stucco?

Therefore, converting gallons into grains (1/10 gallon = 5809 grains):

T = 5,809 gr/(100ft2 x 0.0066 in.Hg x 15 perm)
= 587 hours
= 24 days

Case Study # 3: How long does it take for 0.1 Gallon of water to dry if trapped between OSB and paper?

Location 2- Over the OSB:

From the pressure distribution,

$$\Delta P = 0.17070 - 0.12690 = 0.0438 \text{ in. Hg}$$

Find the effective Z value:

$$Z = 1/15 + 1/5 + 1/5 = 0.4667 \text{ perm}^{-1}$$

$$\text{Permeance} = 1/Z = 2.143 \text{ perm}$$

Case Study # 3: How long does it take for 0.1 Gallon of water to dry if trapped between OSB and paper?

T = 5,809 gr/(100ft2 x 0.0438 in.Hg x 2.143 perm)
= 619 hours
= 26 days

Case Study # 3: How long does it take for 1 Gallon of water to dry if trapped between Insulation and OSB?

Location 3- Over the insulation:

From the pressure distribution,

$$\Delta P = 0.21763 - 0.12690 = 0.0907 \text{ in. Hg}$$

Find the effective Z value:

$$Z = 1/15 + 1/5 + 1/5 + 1/2 = 0.96667 \text{ perm}^{-1}$$

$$\text{Permeance} = 1/Z = 1.034 \text{ perm}$$

Case Study # 3: How long does it take for 1 Gallon of water to dry if trapped between Insulation and OSB?.

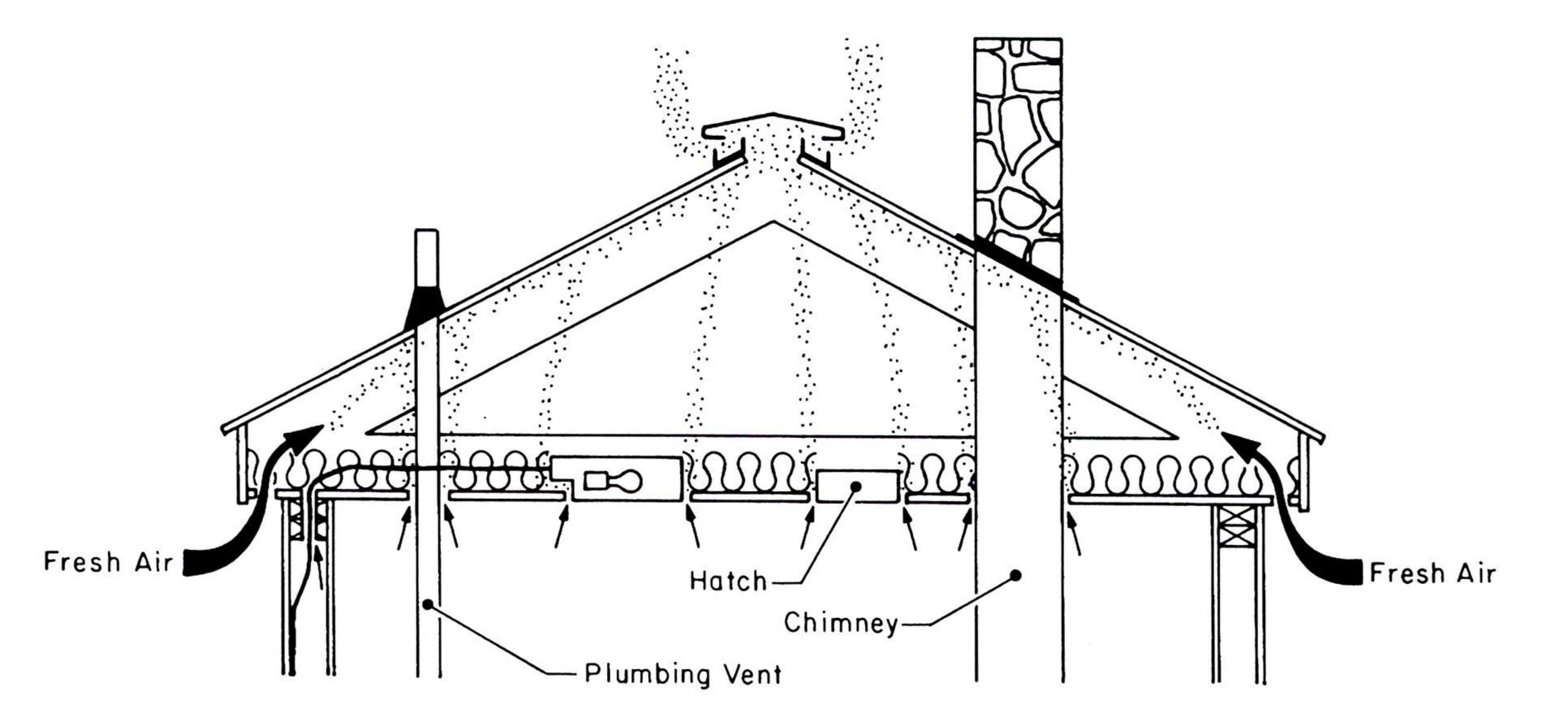
T = 58094 gr/(100ft2 x 0.0907 in.Hg x 1.034 perm)
= 6190 hours
= 264 days

The rate of diffusion did not change from location 2. This value didn't change much; the local pressure increased, however the perm rating at this point decreased. However, I increased the amount of water to 1 gallon to allow for insulation's ability to absorb water.

STUCCO LESSONS

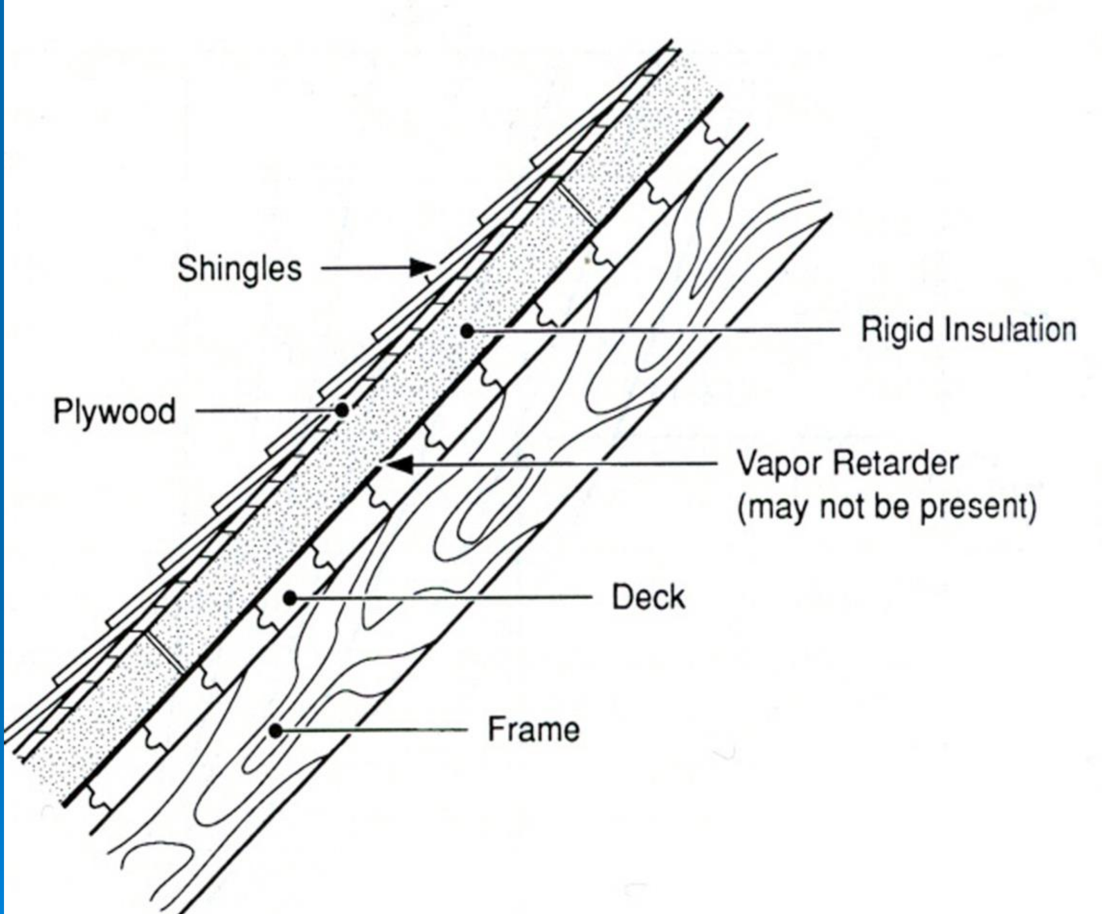
- Old stucco system with just Grade “D” building paper and no consideration for managing excess water does not work.
- Acceptable tolerance for incidental water intrusion needs to be greatly reduced.
- Design should consider building cement plaster more as a “barrier” system.
- Alternatively, provide a layer of “water management” system such as rain screen or pressure equalized behind the cement plaster finish.

Typical Roof Assembly with Attic Ventilation

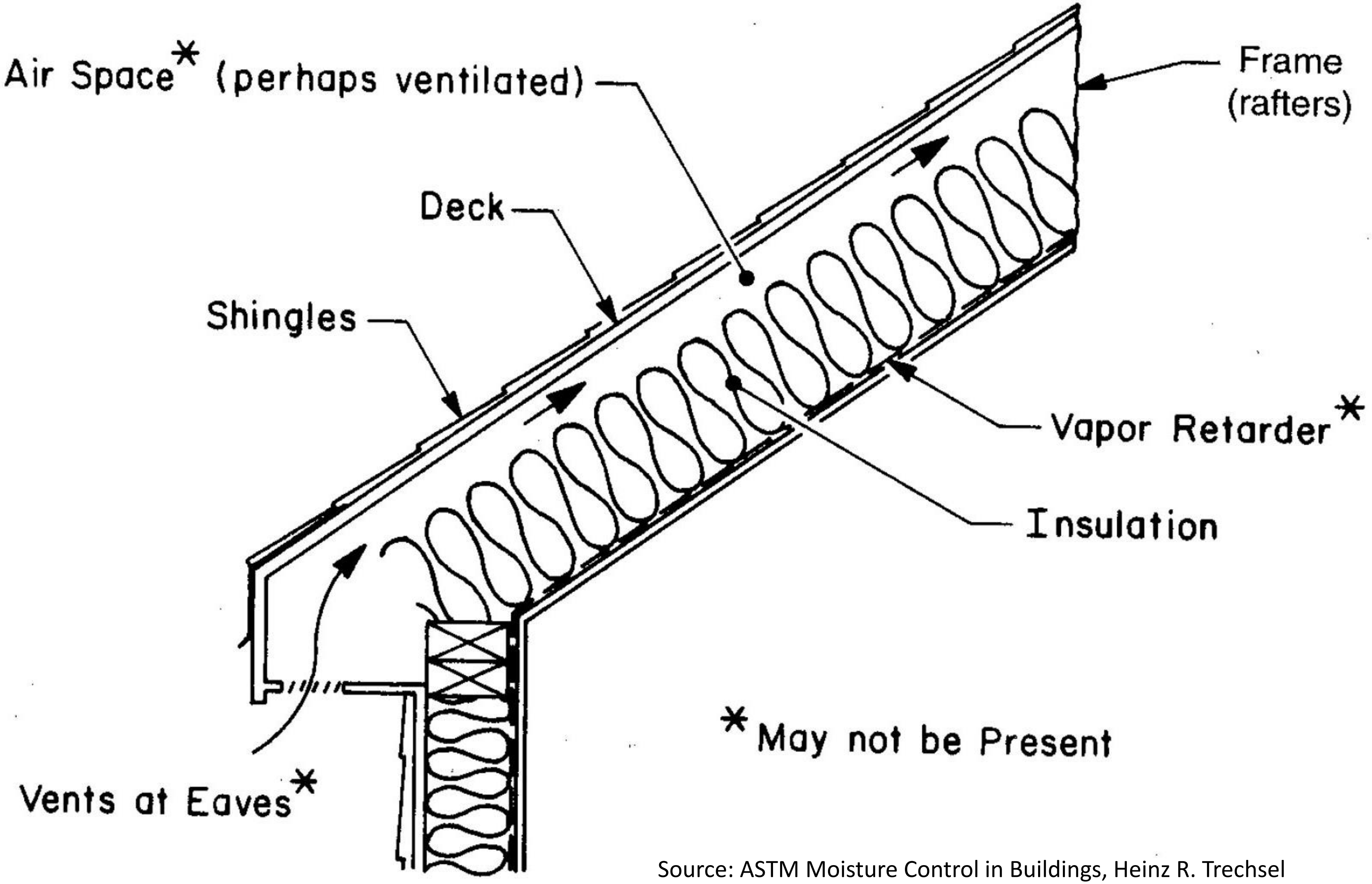


Source: ASTM Moisture Control in Buildings, Heinz R. Trechsel

Compact Roof Assembly with No Ventilation



Source: ASTM Moisture Control in Buildings, Heinz R. Trechsel



Source: ASTM Moisture Control in Buildings, Heinz R. Trechsel

Case Study # 4: San Jose, CA rooftop condensation problem.

Case Study # 4, Damage to roof Sheathing due to condensation

Compact Roof Assembly with no ventilation


Severe Damage to OSB Decking
Due to Condensation
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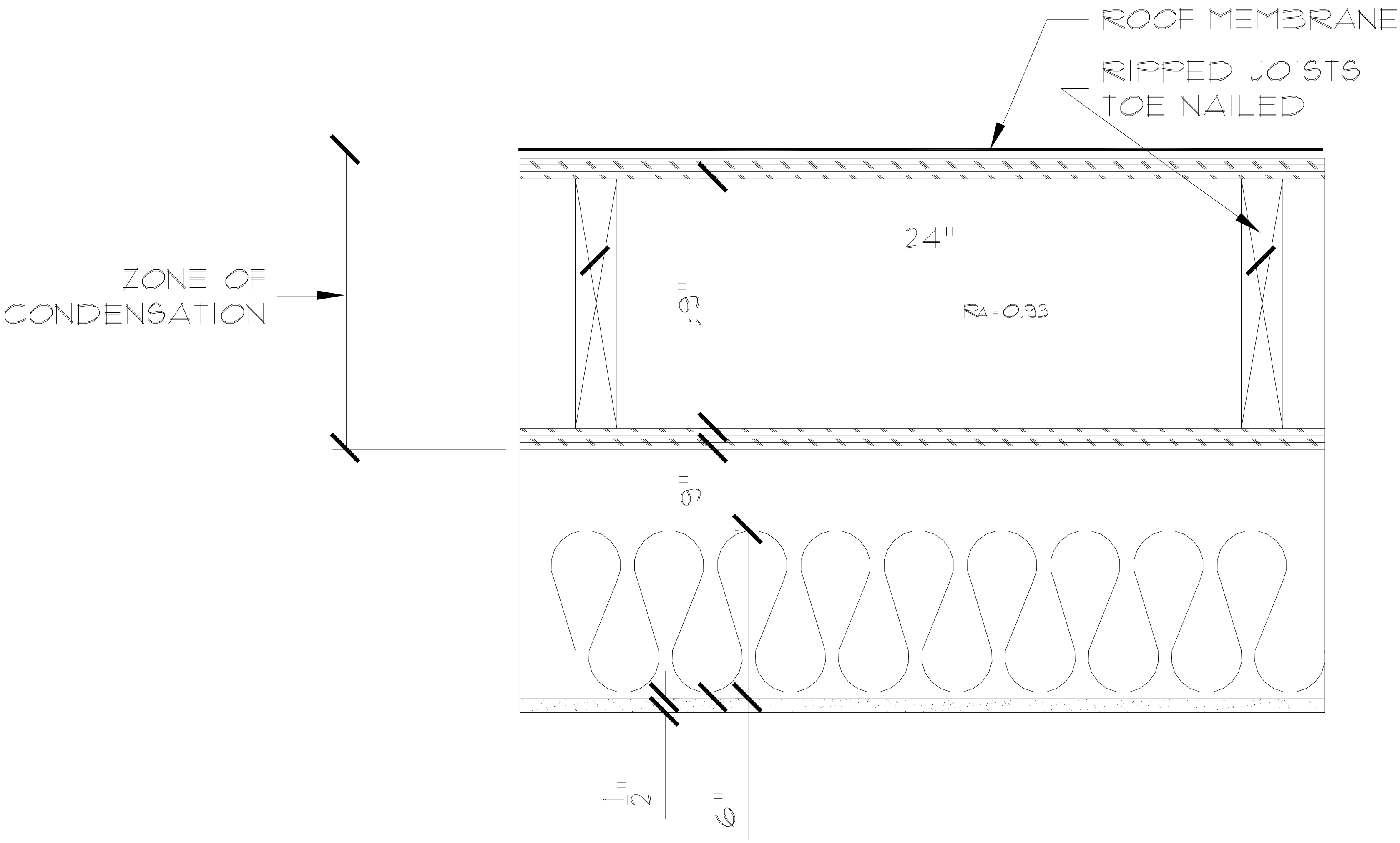
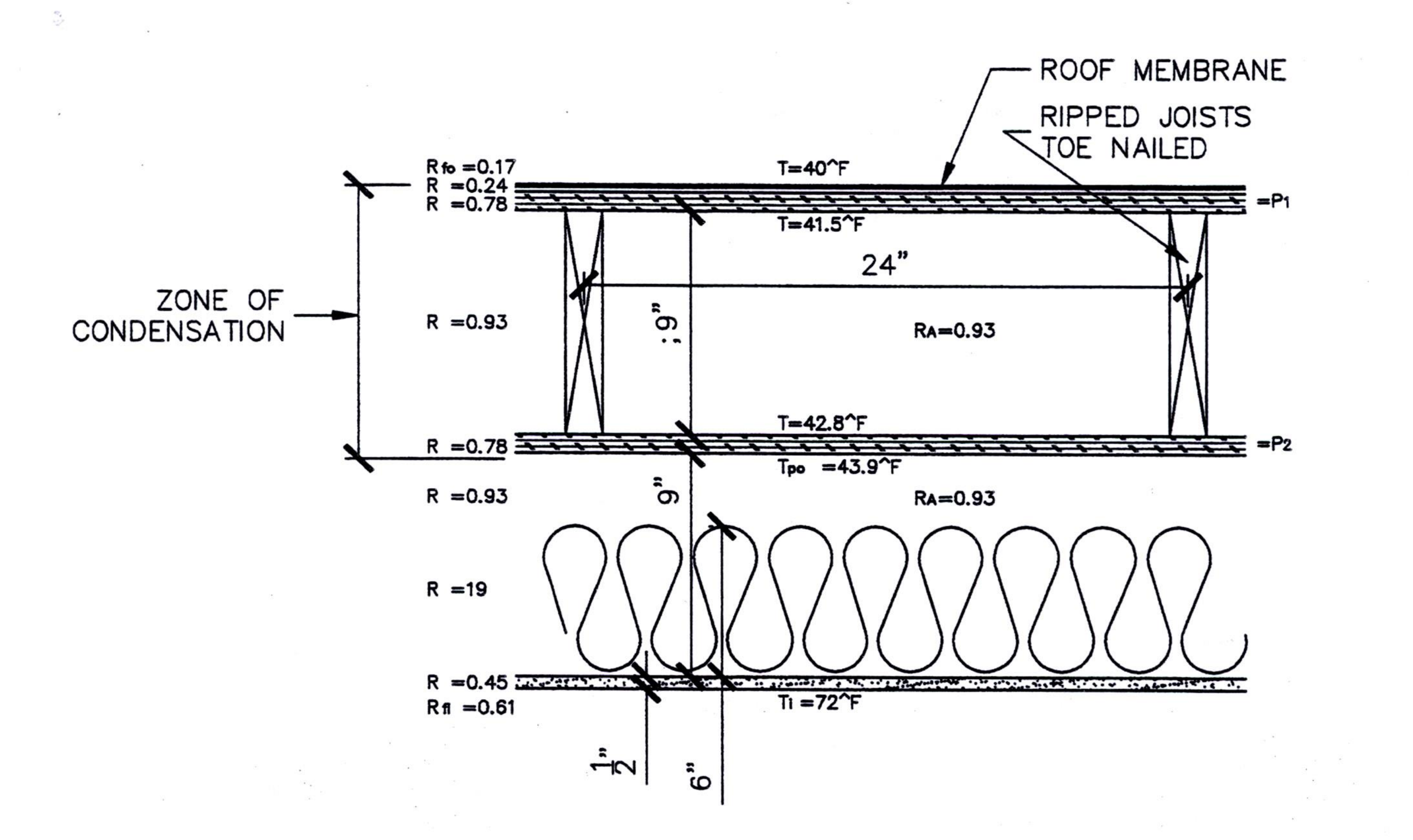
Case Study # 4: San Jose, CA rooftop condensation problem.

Assume that water condenses under a roof membrane (very low perm rating) during a cold week in San Jose, California (see Figure 11). The roof area is 100'x100'. Outside temperature and relative humidity are 40F and 35% respectively. The inside temperature and relative humidity are 72F and 40% respectively. Under these conditions, moisture will flow from inside to outside. How much water can collect under the roof membrane over a 48 hour period?

Figure 11


ROOF MEMBRANE
RIPPED JOISTS
TOE NAILED
24"
RA=0.93
ZONE OF
CONDENSATION

Case Study # 4, Where Condensation Occurs in Roof Assembly



Case Study # 4: San Jose, CA rooftop condensation; <u>How much Water condenses in 8 hours on a cold night?</u>

Step 1: Area = 100'x100' = 10,000 ft^2
Step 2: Time = 48hrs
Step 3: Pressure difference – go to figure 9.
At 72F, the saturated vapor pressure is 0.7392 in.Hg. At 40F, the saturated vapor pressure is 0.2478 in.Hg. Multiply each of the saturated vapor pressures by their relative humidity. The pressure difference is $\Delta P = (0.7392 \times 0.40) - (0.2478 \times 0.35) = 0.209$ in.Hg

Case Study # 4: How much Water condenses in 8 hours on a cold night?

Step 4: Effective perm rating. The perm ratings for the materials are as shown:
Plywood = 2
Insulation = 30
Gypsum Board = 40

Add the inverses of the perm ratings to obtain Z, the inverse effective perm rating:

$Z = 1/2 + 1/2 + 1/30 + 1/40 = 1.233 \text{ perm}^{-1}$

Case Study # 4: How much Water condenses in 48 hours?

Therefore, the assembly's effective perm rating is the inverse of Z:

Effective Perm Rating = 1/Z = 0.8108 Perms

Step 5: Plug values into the vapor transmission equation:

VT= 10,000 ft^2 x 48 hr x 0.209 in.Hg x 0.81 perm

= 81,320 grains of water

= 11.6 pounds of water

= 1.4 gallons of water

LESSONS LEARNT FROM CONDENSATION

- Construction methods have significantly changed. Buildings are built much more air tight.
- A lot of attention has been given to air barriers to control movement of moisture laden air.
- Air barriers also impede the “drying” out effect in walls. Diffusion is not enough to dry out walls.
- Construction labor is less skilled today

LESSONS LEARNT FROM CONDENSATION

- When designing wall assemblies, consider the following:
  - Be less reliant on building paper and "permeable" coatings.
  - Design walls to be more "barrier" assemblies or as rain screen assemblies.
  - Ventilate whenever possible.
  - Consider vapor retarders in all climates
  - Limit use of vinyl wall paper in exterior wall assemblies

Thank You

Questions?