Permeance of Steel Roof Decks and Effect on Hygrothermal Performance of Roofing Systems

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ABSTRACT

The majority of commercial roofs consist of corrugated steel roof decks, with or without concrete fill. Steel decks used with concrete fill typically contain perforations along the ribs (flutes) to allow drying of the concrete, termed "vented decks." Steel roof decks without concrete fill are typically "unvented," but still have seams that are only tack welded or mechanically fastened together. Decks without concrete fill have additional penetrations due to fasteners used to attach insulation and roofing membrane layers. Despite being an integral part on the majority of all commercial roofs, surprisingly little research has been performed to study the air and vapor permeance of steel roof deck construction. Designers are forced to estimate the effect on the air and vapor permeance of steel roof decks that results from unsealed laps and fastener penetrations, as well as intentional vents (perforations). The quantification of these effects is needed for use as inputs into hygrothermal models.

This paper presents the results of a series of laboratory experiments designed to quantify the air and vapor permeance of several steel deck constructions, including vented and non-vented decks and including the effect on permeance when the metal deck is filled with concrete. This paper provides values for designers to use in hygrothermal models for both design and investigation of roof systems containing metal deck.

INTRODUCTION

Description of Typical Steel Roof Deck Construction

The majority of commercial roofs consist of corrugated steel roof decks, with or without concrete fill. Steel decks used with concrete fill typically contain perforations along the ribs (flutes) to allow drying of the concrete, termed "vented decks." Steel roof decks without concrete fill are typically "unvented," but still have seams that are only tack welded or mechanically fastened together. Decks without concrete fill have additional penetrations due to fasteners used to attach insulation and roofing membrane layers. Virtually all roof decks have various penetrations including HVAC ducts, drains, pipe and conduit penetrations, roof hatches, skylights, smoke vents, etc. These penetrations also create gaps that affect the permeability of the in-situ deck.

In the United States, most roof decks are 1.5 in. deep and are characterized as Type A, narrow rib; Type F, intermediate rib; or Type B, wide rib decks. Standard decks have a six-inch spacing of the ribs, and the variation from one type to another is in the geometry of the ribs as shown in Figure 1. Typical deck units are 24 in., 30 in., or 36 in. wide and generally come in lengths up to about 42 ft. In constructing the roof deck, the deck units are lapped at the end joints and generally have nested side laps. Although the field of the steel deck is impermeable, the side and end laps contain gaps that permit water vapor and air to pass through the deck; consequently, the vapor permeability of the deck needs to be evaluated as it relates to the performance of the overall in-situ roof deck system. Side laps are generally welded or mechanically fastened using sheet-metal screws, button punches, or by crimping (Figure 2). The ends of the

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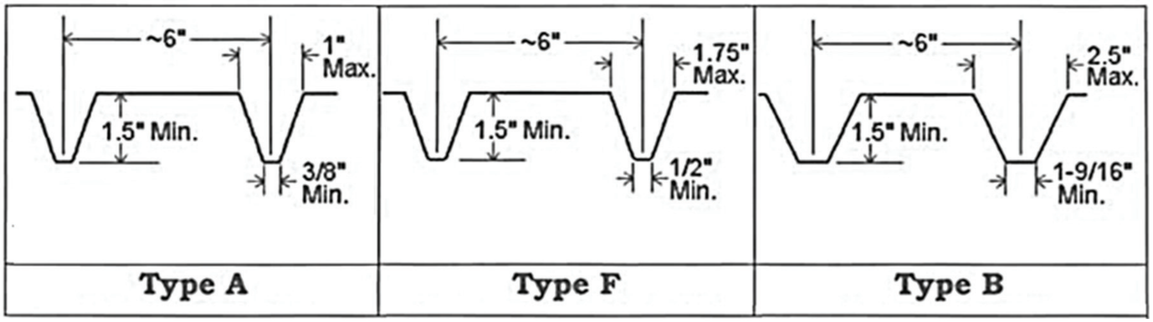


Figure 1 *Common types of steel roof deck used in the United States.*

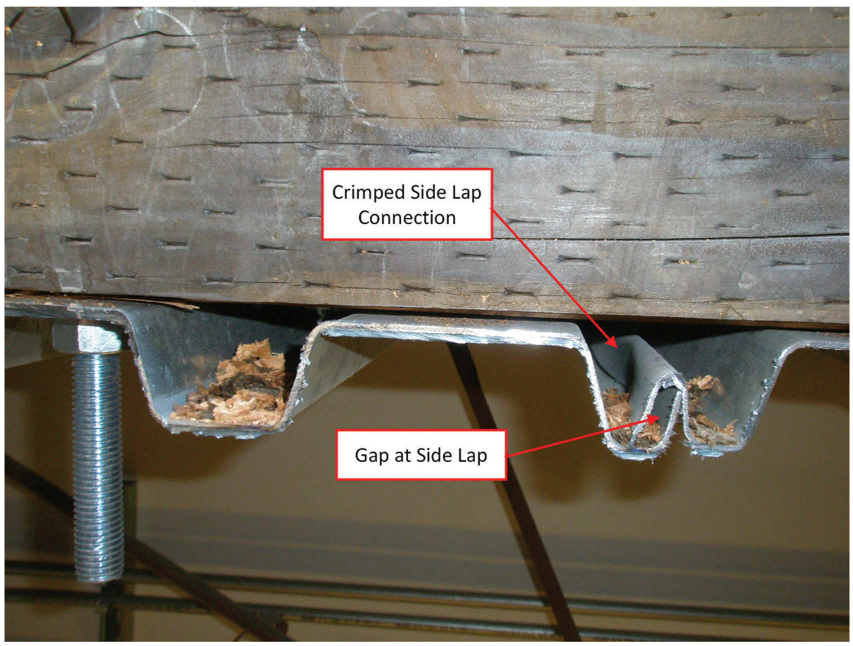


Figure 2 *Common types of steel roof deck used in the United States.*

deck units are generally overlapped and welded or mechanically fastened using self-drilling, self-tapping fasteners or pneumatically driven fasteners. Mechanical fasteners are mis-driven sometimes and removed, leaving holes, and sometimes welding leaves burn holes. These methods of joining the deck units often leave substantial gaps and openings (Figure 3).

In addition to the gaps at the deck unit laps, large gaps or holes in the deck often occur at the deck penetrations. Figures 4 and 5 show some typical penetrations that occur in steel roof decks. At drains, skylights, and perimeter walls, there are gaps equal to the cross sectional area of several ribs. In addition, there are often additional gaps at locations where there is a change in slope of the roof deck or where there is a change in direction of the roof deck (Figure 6).

Overview of Typical Roofing Systems Installed over Steel Deck

Figure 7 shows the typical commercial roofing systems that are installed without a vapor retarder over steel deck either with or without concrete fill. The typical systems consist of a roofing membrane over a gypsum or perlite based cover board, over multiple layers of insulation. When a vapor retarder is specified, it is typically installed over the concrete or over the steel deck (for non-concrete decks), often with a gypsum based cover board under the vapor retarder to provide support and fire protection to the assembly.

When the decks are filled with concrete, the insulation, cover board, and roofing membrane layers are typically adhered with adhesive or asphalt. For steel decks without concrete fill, the layers are typically mechanically fastened,

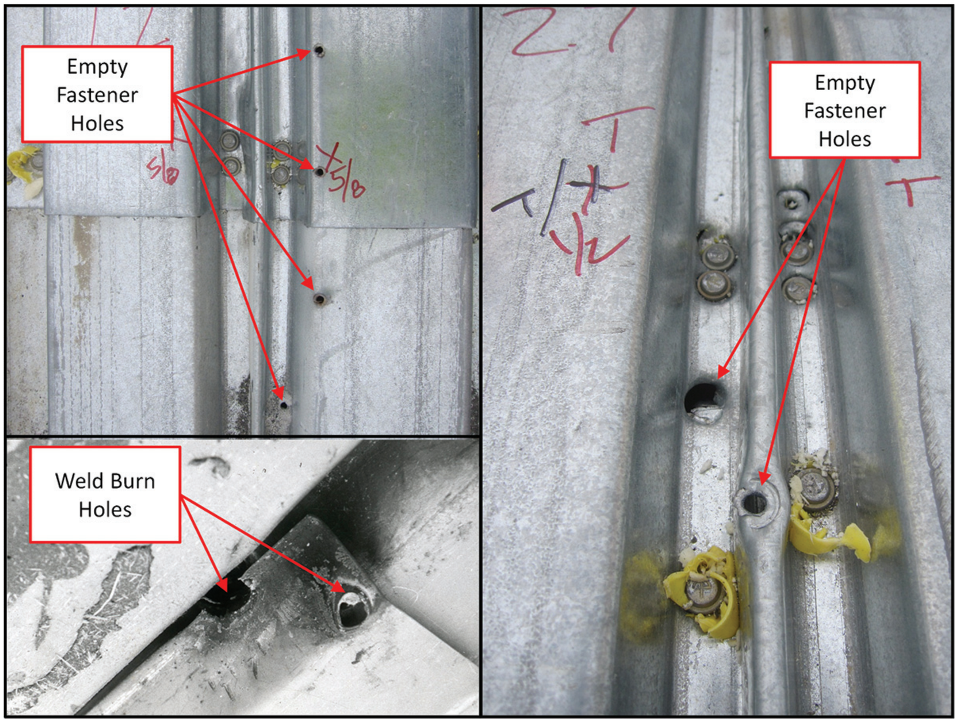


Figure 3 *Typical gaps and holes in steel deck side and end laps.*

Figure 4 *Typical penetrations in a steel roof deck including a skylight hatch, roof drains, and perimeter terminations.*

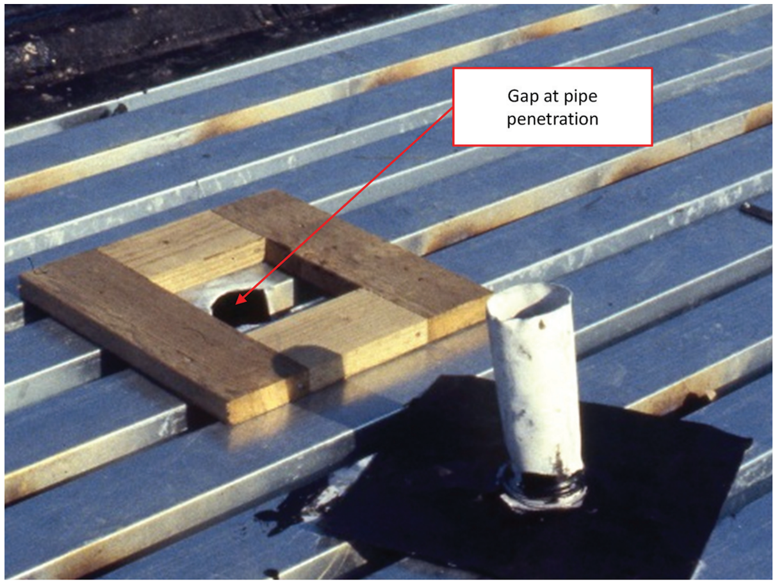


Figure 5 *Large gap around pipe penetrations.*

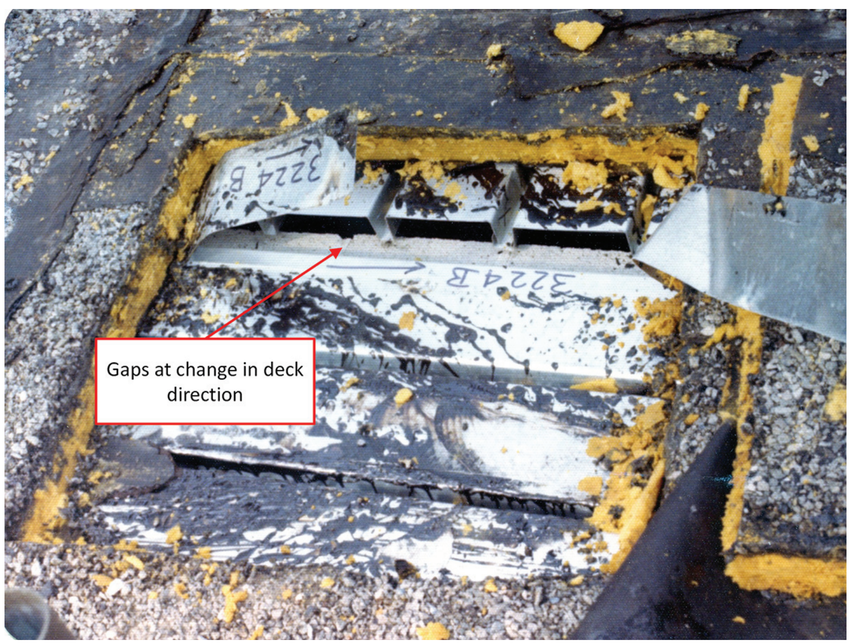
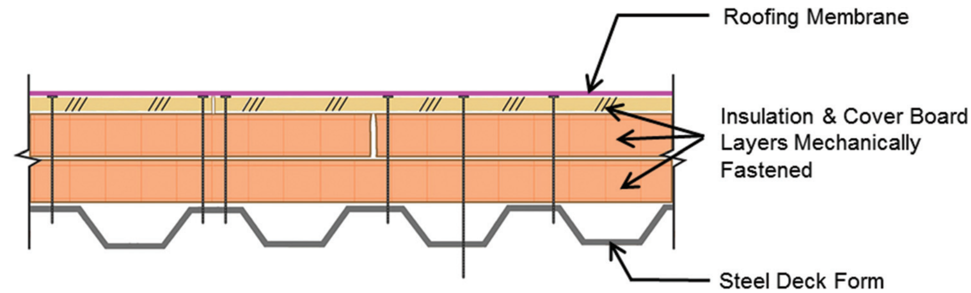


Figure 6 *Large gap at change in steel deck orientation*

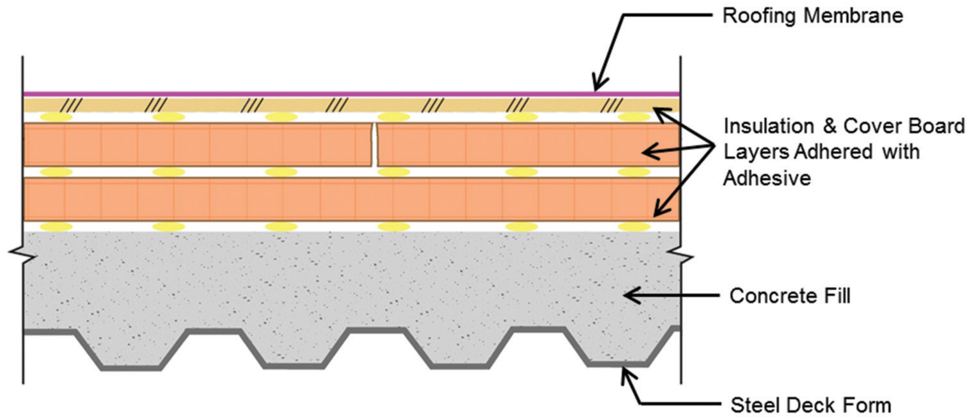
except for the roofing membrane which can either be mechanically fastened or fully adhered to the cover board.

Overview of Previous Research

Despite being an integral part on the majority of all commercial roofs, surprisingly little research has been performed to study the air and vapor permeance of steel roof deck construction. Seiffert (1970) performed ASTM E-96 test of aluminum foil that showed that the effective permeance of the foil increased by a factor of 4,000 when perforated with holes representing as little as 0.22% of the surface area of the foil. In a research study that included perforated metal foil radiant barriers, Wilkes (1991), compared theoretical calculations using a parallel path analogy with unpublished experimental results from colleagues to estimate the effect of holes on a low permeance vapor retarder to be described by the following equation:



(a)



(b)

Figure 7 *Typical roof assemblies over steel deck: (a) mechanically fastened with no concrete fill and; (b) adhered over concrete filled deck.*

$$P = 56,200 \times \left(\frac{A_{holes}}{A_{totals}}\right) \tag{1}$$

Later in this paper we compare both Wilkes's estimate and Seiffert's test results to our test results.

Other than Wilkes and Seiffert's papers, the only other information available on the effect of holes in vapor retarders is anecdotal evidence or differing opinions on whether a small percentage area holes can significantly increase the permeance of a vapor retarder. The Steel Deck Institute (2008), for example, has issued a technical bulletin claiming that the 0.5% to 1.5% area of holes available on "vented" (perforated) steel deck has an insignificant effect on the permeance of the deck in terms of the drying (to the interior) of concrete that is cast in the metal deck.

Most building scientist and building enclosure designers agree that if there is airflow through the holes, then the effective permeance of the steel deck, or vapor retarder membrane, is significantly increased to the point where it can be ignored, due to the ability of the airflow through small gaps to both bypass the low permeance surface and to transport significant amounts of water vapor compared to diffusion.

Example Theoretical Calculations of Effective Permeance for Steel Roof Deck

Since diffusion of water vapor is analogous to conduction of heat, one can consider the diffusion of water vapor across a steel deck with holes (or other vapor retarder membrane with holes) to be similar to parallel path heat transfer that results from thermal bridging of a steel stud (or other highly conductive element) across an insulated cavity. The electrical circuit analogy often used in heat transfer calculations is shown in Figure 8.

Similar to heat flow, the vapor flow will take the path of least resistance. Since the vapor resistance of the steel without holes is close to infinity, the path through the steel goes to zero. The resulting prediction is that it takes only a small percentage area of holes to increase the effective permeance of the steel significantly. This effect is similar to a thermal bridge that can cause a much larger amount of heat loss than its area would suggest (more heat will flow along the path of least resistance). This effect is also how certain housewrap materials achieve a higher permeance by perforating a non-permeable material with micro-sized holes.

The parallel path analogy also shows that the resulting predicted effective permeance is highly dependent on the permeance of the hole. In Table 1 we show the effective permeance calculated with and without concrete fill to demonstrate that the predicted effective permeance using this parallel path analogy assuming concrete fills the holes can be more than 100 times lower than if only air is assumed to fill the holes. Furthermore, in practice, concrete fill will also block airflow that would further decrease the effective permeance of the steel deck.

Others have performed a similar calculation to determine the effect that airflow through the holes has on the effective permeance of a low permeance material and concluded that it only takes a small amount of airflow to significantly increase the effective permeance of the material (Straube and Burnett 1995).

In addition to the steel deck layer, a typical roofing system will have multiple other layers, such as insulation, cover board, and a low permeance roofing membrane (Figure 7). For analyzing thermal bridging, ASHRAE (2009) provides two methods based on the parallel path analogy. These two methods are termed the "parallel path" and "isothermal planes" methods. In Figure 9 we illustrate these two paths in terms of vapor diffusion resistance for a typical steel deck roofing system without concrete fill. According to ASHRAE, the parallel path method tends to under-predict the amount of thermal resistance, while the isothermal planes method tends to over-predict the amount of thermal resistance. In terms of flow of water vapor, these two methods provide significantly different predictions,

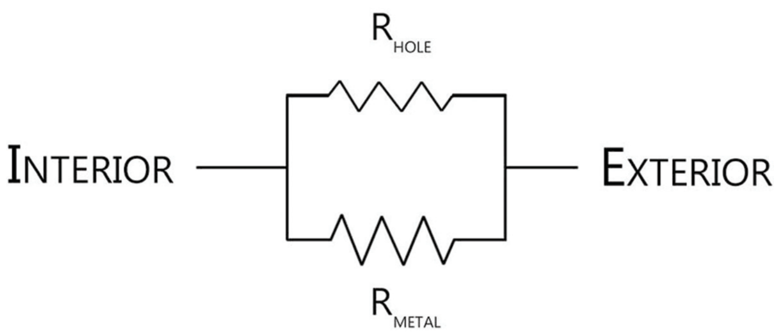


Figure 8 *Example of a parallel path analogy for vapor diffusion through a steel deck with holes.*

Table 1. Parallel Path Effective Permeance Calculation for 18 Gauge Steel Deck with Holes with and without Concrete Fill

% Area of Holes	No Concrete (assume holes in deck are filled with 18 gauge thick air layer) [Perm]	Deck Filled with 3 Different Types of Concrete (assume holes in deck are filled with 18 gauge thick layer of concrete) [Perm]		
		1.4 Perm-In. Concrete	0.716 Perm-In. Concrete	0.519 Perm-In. Concrete
0.00%	0.0	0.00	0.00	0.00
0.04%	1.0	0.01	0.01	0.00
0.06%	1.5	0.02	0.01	0.01
0.22%	5.8	0.06	0.03	0.02
0.46%	12	0.13	0.06	0.05
0.50%	13	0.14	0.07	0.05
1.0%	26	0.27	0.14	0.10
1.5%	40	0.41	0.21	0.15
2%	53	0.54	0.28	0.20
5%	132	1.4	0.69	0.50
10%	264	2.7	1.4	1.0

particularly for cases where there is another low permeance material in the flow path, as is the typical case with most roofing membranes. Table 2 shows how different predictions from these two methods can be. In general, in the isothermal planes method, it only takes a small percentage of holes to make the steel deck ineffective as a vapor retarder.

Later in this report we compare our experimental results to the predictions of these two methods and discuss how our results indicate that the isothermal planes method appears to be the more accurate analogy.

Given the above uncertainties in actual performance of the steel deck, designers are forced to estimate the effect on the air and vapor permeance of steel roof decks that results from unsealed laps and fastener penetrations, as well as intentional vents (perforations). The quantification of these effects is needed for use as inputs into hygrothermal models.

Objective

The objective of this work is to determine realistic ranges of values that can be used for the equivalent vapor permeance of steel roof decks with and without concrete fill.

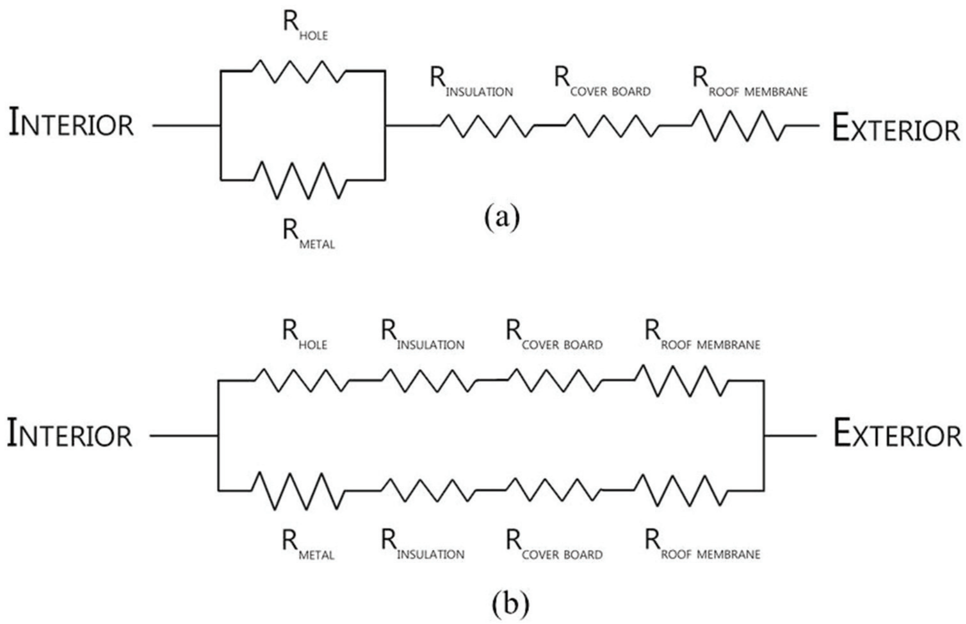


Figure 9 *(a) Isothermal planes method analogy and (b) parallel path method analogy.*

Table 2. Comparison of Predictions on Effective Permeance of Steel Deck in a Roof System for Parallel Path and Isothermal Planes Methods Shown in Figure 9

% Area of Holes	Predicted Effective Permeance of Steel Deck Layer with Holes when Installed in a Roof System [Perm, IP Units]	
	Parallel Path Method	Isothermal Planes Method
0%	0	0
0.05%	0.00012	1.32
0.1%	0.00015	2.64
0.5%	0.00033	13.2
1%	0.00056	26.4
5%	0.00249	132
10%	0.00515	264

Scope

We conducted research and laboratory testing to quantify the permeability for several deck configurations. In order to keep the specimen size as given in ASTM E 96, we utilized flat sheet metal rather than corrugated steel deck. In some regards, the use of flat sheet-metal work creates a condition with lower permeability than would be achieved with a corrugated deck due to the tighter nesting of the laps. In order to study the effect of the varying gaps and holes that can occur in actual construction (Figures 2 and 3), we tested specimens with varying number of fasteners, fastener holes, and varying width of gaps at the laps.

The size of the specimens relative to the potential paths of moisture migration through the specimen is different than occurs in standard construction. Consequently, in order to determine useful permeability for actual construction, we had to determine the equivalent vapor flow per feature of the deck such as per fastener, per hole, and per length of lap. We then calculated the permeability of in-situ decks given typical insulation fastening patterns and deck panel sizes.

In this paper we focus primarily on the effect of holes in steel deck given diffusion only (no induced airflow) for the following reasons. First, it is well documented that a small amount of airflow can transport an order of magnitude more moisture than vapor diffusion, thereby bypassing the vapor resistance of the material. Second, a paper by Kan and Piñon (2005) showed that the concept of equivalent permeance is of limited use in predicting the in-situ performance of walls due to airflow. Therefore, where there is air leakage through a steel deck roof system, the potential hygrothermal effects on the roof system are more than just making the vapor resistance of the steel deck negligible.

LABORATORY TESTING

Experimental Setup

We measured the water vapor permeance using the wet cup method in accordance with ASTM E 96 *Standard Test Methods for Water Vapor Transmission of Materials*. We conducted 17 separate tests; the configuration of the specimens for each is described in Table 3. Specimen 1 had a flat sheet of 18 gauge sheet-metal set into a specimen pan with the perimeter sealed in the same fashion as used for the remaining specimens. This specimen was used to confirm the specimen preparation was appropriate, and the test confirmed that this condition resulted in zero perms.

We selected the remaining specimen configurations described in Table 3 to simulate actual field conditions such as mechanical fasteners used to attach insulation and/or membranes to steel decks, varying thickness of the gap within the side and end laps (e.g., Figure 2), and holes left from fasteners installed incorrectly and removed and/or reroofing situations or from weld burn holes (e.g., Figure 3). In addition, we also tested configurations with a vapor permeable air barrier over the sheet metal specimen to get a sense of the

Table 3. Description of Test Specimens

Specimen Number	Condition
1	Sealed steel deck
2	2 insulation fasteners
3	1 screw hole from insulation fastener, fastener removed
4	Lap, 2 sheet metal screws
5	Lap, 2 sheet metal screws, covered with Air Barrier
6	12 screw holes from insulation fasteners, fasteners removed
7	25 screw holes from insulation fasteners, fasteners removed
8	25 screw holes from insulation fasteners, fasteners removed, covered with Air Barrier
9	2 screw holes from insulation fasteners, fasteners removed
10	3 screw holes from insulation fasteners, fasteners removed
11	3 screw holes from insulation fasteners, fasteners removed, covered with Air Barrier
12	Lap, 2 sheet metal screws 1/32 in. gap
13	Lap, 2 sheet metal screws 1/16 in. gap
14	Lap, 2 sheet metal screws 1/8 in. gap
15	Lap, two sheet metal screws 1/32 in. gap, covered with Air Barrier
16	Lap, two sheet metal screws 1/16 in. gap, covered with Air Barrier
17	Lap, two sheet metal screws 1/8 in. gap, covered with Air Barrier

permeance where the steel deck may be filled with concrete (no airflow). Examples of the test specimens are shown in Figures 10 and 11.

RESULTS

General

To relate these experimental test results to behavior in actual steel deck construction, it is necessary to calculate the effective permeability for a representative steel deck area in an actual construction based on the test values. The ratio of the lap length to the area of the deck in the test specimens is different than that ratio is in actual construction. We chose to use the area of a single deck unit as a representative steel deck area for our calculations. We use deck panels of 20, 30, and 40 ft. (6.1, 9.1, and 12.2 m) in length and 36 in. (0.91 m) wide. We used the calculations described below to compute the permeability in the actual construction based on the results obtained in our tests.

A perm is defined as

$$1 \text{ perm} = 1 \text{ grain/h per ft}^2 \text{ per in. Hg}$$
$$(57.2 \times 10^{-12} \text{ kg/s per m}^2 \text{ per Pa})$$

To calculate the permeability for actual construction from the tests results, we must calculate the number of grains/h per in. Hg that pass through a representative area of the actual steel

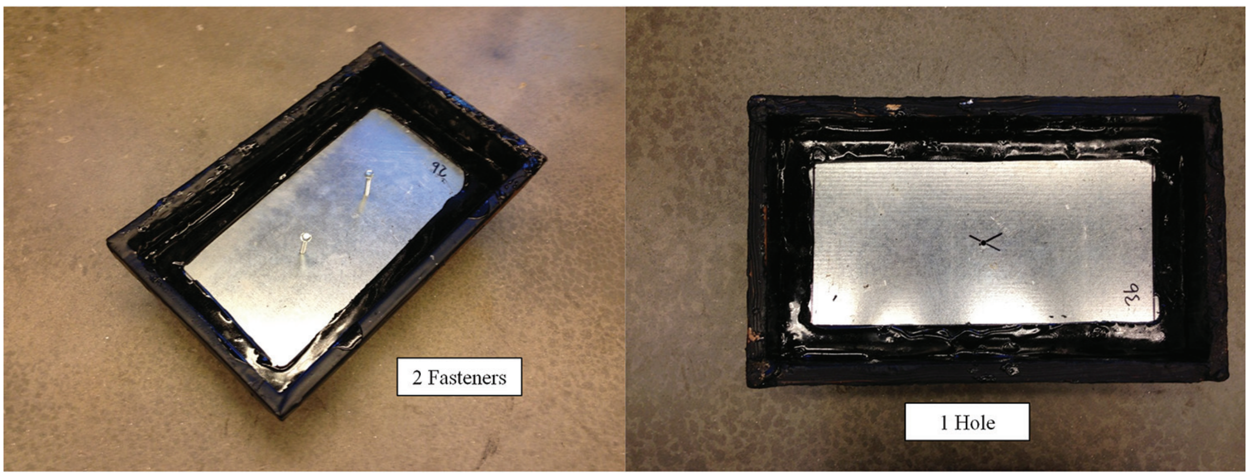


Figure 10 *Example of two test specimens.*

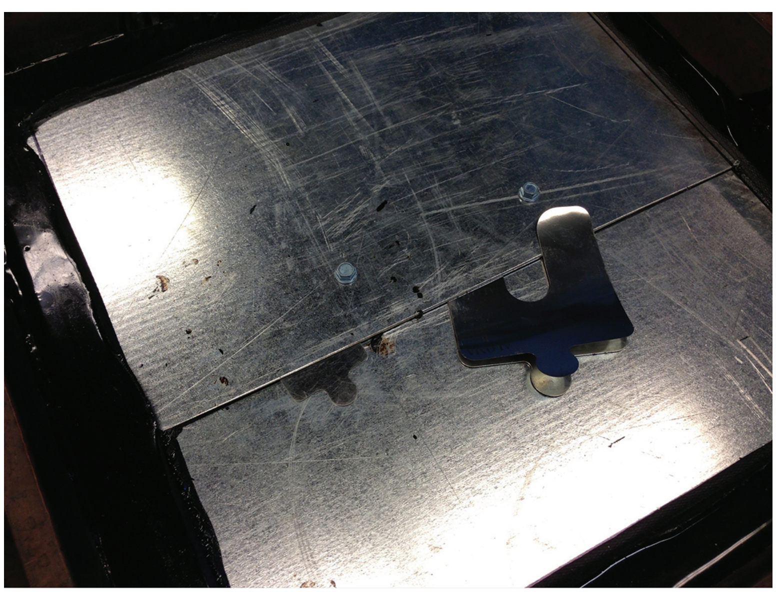


Figure 11 *Example of a test specimen with a lap joint and feeler gauge to measure lap gap.*

deck construction and then divide by that representative area to obtain grains/h per ft^2 per in. Hg to obtain perms.

We recognize that the permeability for the 12 in. × 12 in. test specimens is the number of grains/h per in. Hg for the 1 ft^2 specimen which is the number of grains passing through the gap at the lap since the steel deck itself is impervious.

We perform the following calculation:

Let w = width of deck unit

ℓ = length of deck unit

g_ℓ = number of grains that pass through a unit length of lap

Then for the actual steel deck construction:

$$\text{Perms}_{lap} = (w+\ell)g_\ell \div w\ell \tag{2}$$

The calculations for the permeability for fasteners only and for empty fastener holes only are accomplished in a similar fashion. We recognize that the specimen size for these tests was 0.5 ft^2.

For fasteners let

n_f = number of fasteners in the test specimen

n_{fa} = number of fasteners in the actual construction

g_f = number of grains that pass through a fastener location = $\text{Perm}_{\text{specimen}} \times 0.5 / n_f$,

Then,

$$\text{Perm}_{\text{fasteners}} = n_{fa} g_f \div w\ell \tag{3}$$

For empty fastener holes let

n_h = number of fastener holes in the test specimen

n_{ha} = number of fastener holes in the actual construction

g_h = number of grains that pass through a fastener hole location = $\text{Perm}_{\text{specimen}} \times 0.5/n_h$

Then,

$$\text{Perm}_{\text{holes}} = n_{ha} g_h \div \text{w}\ell \tag{4}$$

The permeability for a steel deck including the effects of the laps, fasteners, and empty screw holes can be expressed as:

$$\text{Perm} = [(\text{w}+\ell)\text{g}_\ell + n_{fa} g_f + n_{ha} g_h] \div \text{w}\ell \tag{5}$$

Calculated Results

Table 4 shows the results of the laboratory tests. The columns under the light grey headings define the specimen sizes and configurations as well as the permeability determined from the tests under ASTM E-96. The shaded columns show values determined from the calculations we made to convert the permeability values from our tests to the values for the units contained in the right most column.

Table 5 shows the permeability of in-situ deck taking into account the permeability resulting from the laps only. In this Table, the data from Table 4 are utilized to calculate the data in Table 4 consistent with Equation 2.

Table 6 shows the permeability of in-situ deck taking into account only the permeability resulting from fasteners only. In this table, the data from Table 4 are utilized to calculate the data in Table 6 consistent with Equation 3.

Table 7 shows the permeability of in-situ deck taking into account only the permeability resulting from empty fastener holes. The data from Table 4 are utilized to calculate the data in Table 7 consistent with Equation 4.

Table 8 shows the permeability of in-situ deck taking into account the permeability resulting from the gaps at laps, the presence of screw fasteners, and the presence of empty fastener holes. The data from Table 4 are utilized to calculate the data in Table 8 consistent with Equation 5.

Graphs of Results of Calculation

Figure 12 is a plot of our calculated results showing the effect on permeability resulting from varying the dimension of the gap at the deck laps for deck panels that are 20, 30, and 40 feet long.

Figure 13 shows the permeability of a deck with holes where the area of the holes is expressed as a percentage of the deck area. On Figure 13 we also compare the predictions from the parallel path method and test results from the previous research discussed in the introduction section of this paper.

DISCUSSION

Area of Gaps and Holes and the Effect on Permeability

It is well known that un-perforated steel deck is impervious, and our tests on Specimen 1 confirm that this is true. In real construction, decks without perforations are nonexistent. Since deck units come in finite sizes smaller than a typical roof area, end laps and side laps affect the permeability. Our study confirms that larger gaps at laps create higher permeability than tighter laps. In addition, decks are attached to the substructure with welds or mechanical fasteners which penetrate the deck and often leave holes in the deck as shown in Figure 3. These holes add to the deck gaps and increase permeability. The majority of the lap length for a steel deck is the side laps, which often have gaps that are wider than the gaps at end laps. Generally, end laps are fastened to the substrate at 12 or 6 in. on center, while side laps are fastened at wider intervals such as 18 or 24 in. Consequently, the gaps at side laps are generally greater than at end laps.

Laboratory tests show that fasteners penetrating the steel deck to attach insulation or membranes have a relatively small effect on the permeability of steel deck. Even when as many as 16 screws per 4 × 4 insulation board are used, the screw density is one screw per square foot, which raises the permeability of the deck to approximately 0.02 perms. On the other hand, the tests showed that empty screw holes (fastener removed) have a greater effect on permeability. One empty screw hole per sq ft (0.093 m^2) raises the permeability of the deck to approximately 0.246 perms which is in the order of 12 times as much as the case when screws are present. Furthermore, the tests show that when the percentage of the deck area that has holes is relatively small, the permeability is raised significantly to the point where a hole area of approxi-

Table 4. Laboratory Test Results

Laboratory Specimen Dimensions and Test Results						Calculated Values	
Specimen Number	**Specimen Description**	**Lap Length [in]**	**Lap Gap [in]**	**Air Barrier Present (Y/N)**	**ASTM E-96 Permeability [Perms - IP Units] (Perms - SI Units)**	**Calculated Permeability**	**Calculated Units**
1	Solid deck	NA	NA	N	0 (0)	0.00	perms
2	2 fasteners	NA	NA	N	0.08 (4.58E-12)	0.02 1.06E-15	g_f = grains H_2O/h per in. Hg per fastener g_f = kg/s per Pa per fastener
3	1 screw hole	NA	NA	N	0.34 (1.95E-11)	0.17 9.02E-15	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
4	2 holes	NA	NA	N	1.18 (6.77E-11)	0.30 1.57E-14	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
5	3 holes	NA	NA	N	1.80 (1.03E-10)	0.30 1.59E-14	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
6	12 holes	NA	NA	N	6.33 (3.62E-10)	0.26 1.40E-14	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
7	25 holes	NA	NA	N	10.31 (5.90E-10)	0.21 1.09E-14	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
8	3 holes, Air Barrier	NA	NA	Y	0.42 (2.40E-11)	0.07 3.70E-15	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
9	25 holes, Air Barrier	NA	NA	Y	6.36 (3.64E-10)	0.13 6.75E-15	g_h = grains H_2O/h per in. Hg per hole g_h = kg/s per Pa per hole
10	Lap: 0.013 in. Gap	12	0.013	N	0.71 (4.06E-11)	0.71 1.24E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
11	Lap: 1/32 in. Gap	12	1/32	N	1.15 (6.59E-11)	1.38 2.41E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
12	Lap: 1/16 in. Gap	12	1/16	N	1.70 (9.74E-11)	2.04 3.57E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
13	Lap: 1/8 in. Gap	12	1/8	N	5.05 (2.89E-10)	6.06 1.06E-12	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
14	Lap: 0.013 in. Gap, Air Barrier	12	0.013	Y	0.49 (2.80E-11)	0.49 8.55E-14	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
15	Lap: 1/32 in. Gap, Air Barrier	12	1/32	Y	2.76 (1.58E-10)	3.31 5.79E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
16	Lap: 1/16 in. Gap, Air Barrier	12	1/16	Y	0.85 (4.83E-11)	1.01 1.77E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap
17	Lap: 1/8 in. Gap, Air Barrier	12	1/8	Y	1.48 (8.44E-11)	1.77 3.09E-13	g_l = grains H_2O/h per in. Hg per ft of lap g_l = kg/s per Pa per m of lap

Table 5. Permeability of In-situ Deck Panels for Laps Only

Lap Gap [in]	Panel Length [ft]	Panel Width [ft]	Length of Lap per Panel [ft]	Calculated Permeability per ft (m) of Lap (g_l)		Grains per Panel	Kilograms per Panel	Permeability of Assembly for Lap Only ($Perm_{lap}$)	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)
0.013	20	3	24.1	0.71	1.24E-13	17.11	9.10E-11	0.285	1.63E-11
0.013	30	3	34.1	0.71	1.24E-13	24.21	1.29E-10	0.269	1.54E-11
0.013	40	3	44.1	0.71	1.24E-13	31.31	1.67E-10	0.261	1.49E-11
1/32	20	3	24.1	1.38	2.41E-13	33.29	1.77E-10	0.555	3.18E-11
1/32	30	3	34.1	1.38	2.41E-13	47.10	2.51E-10	0.523	3.00E-11
1/32	40	3	44.1	1.38	2.41E-13	60.91	3.24E-10	0.508	2.91E-11
1/16	20	3	24.1	2.04	3.57E-13	49.25	2.62E-10	0.821	4.70E-11
1/16	30	3	34.1	2.04	3.57E-13	69.69	3.71E-10	0.774	4.44E-11
1/16	40	3	44.1	2.04	3.57E-13	90.12	4.80E-10	0.751	4.30E-11
1/8	20	3	24.1	6.06	1.06E-12	146.13	7.78E-10	2.436	1.40E-10
1/8	30	3	34.1	6.06	1.06E-12	206.77	1.10E-09	2.297	1.32E-10
1/8	40	3	44.1	6.06	1.06E-12	267.40	1.42E-09	2.228	1.28E-10

(d) Length of lap per panel includes an additional 1.1 ft (0.10 m) of lap to account for the added length along the profile of the corrugations compared to the steel deck coverage width at an end lap (refer to Figure 1 for typical dimensions of corrugations)
(e) IP units: g_l = Perms × Area ÷ Length = Grains H_2O/h per in. Hg per ft of Lap
(f) SI units: g_l = Perms × Area ÷ Length = kg/s per Pa per m of Lap
(g) IP units: Grains per panel = (Grains H_2O/h per in. Hg per ft of Lap) × (Length of Lap per panel)
(h) SI units: kg per panel = (kg/s per Pa per m of Lap)*(Length of Lap per panel)
(i) IP units: $Perm_{lap}$ = Grains per panel / (Panel Area) = Perms (grains H_2O/h per ft^2 per in. Hg)
(j) SI units: $Perm_{lap}$ = kg per panel / (Panel Area) = Perms (kg/s per m^2 per Pa)

Table 6. Permeability of In-situ Deck Panels for Fasteners Only

Number of Fasteners per 4 × 4 ft Insulation Board	Number of Fasteners per ft^2	Fasteners per 30 × 3 ft Deck Panel	Calculated Permeability per Fastener (g_f)		Grains per Panel	Kilograms per Panel	Permeability of Assembly for Fasteners Only ($Perm_{fasteners}$)	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
4	0.25	22.5	0.020	1.06E-15	0.45	2.39E-14	0.005	2.86E-15
5	0.3125	28.1	0.020	1.06E-15	0.56	2.98E-14	0.006	3.57E-15
6	0.375	33.8	0.020	1.06E-15	0.68	3.58E-14	0.008	4.28E-15
8	0.5	45.0	0.020	1.06E-15	0.90	4.77E-14	0.010	5.71E-15
9	0.5625	50.6	0.020	1.06E-15	1.01	5.37E-14	0.011	6.42E-15
11	0.6875	61.9	0.020	1.06E-15	1.24	6.56E-14	0.014	7.85E-15
12	0.75	67.5	0.020	1.06E-15	1.35	7.16E-14	0.015	8.57E-15
14	0.875	78.8	0.020	1.06E-15	1.58	8.36E-14	0.018	9.99E-15
16	1	90.0	0.020	1.06E-15	1.80	9.55E-14	0.020	1.14E-14

(d) IP units: g_f = Grains H_2O/h per in. Hg per fastener
(e) SI units: g_f = kg/s per Pa per fastener
(f) IP units: Grains per panel = (Grains H_2O/h per in. Hg per fastener)*(Number of Fasteners/30 ft Panel)
(g) SI units: kg per panel = (kg/s per Pa per fastener)*(Number of Fasteners/9.14 m Panel)
(h) IP units: $Perm_{fasteners}$ = Grains per panel/(Panel Area) = Perms (grains H_2O/h per ft^2 per in. Hg)
(i) SI units: $Perm_{fasteners}$ = kg per panel/(Panel Area) = Perms (kg/s per m^2 per Pa)

Table 7. Permeability of In-situ Deck Panels for Empty Fastener Holes Only

Number of Holes per 4 × 4 ft Insulation Board	Number of Holes per ft^2	Holes per 30 × 3 ft Deck Panel	Calculated Permeability per Hole (g_h)		Grains per Panel	Kilogram per Panel	Permeability of Assembly for Holes Only ($Perm_{holes}$)	
(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)
4	0.25	22.5	0.297	8.92E-13	6.65	3.48E-11	0.074	4.17E-12
5	0.3125	28.1	0.293	8.81E-13	8.19	4.24E-11	0.091	5.07E-12
6	0.375	33.8	0.288	8.71E-13	9.68	4.94E-11	0.108	5.91E-12
8	0.5	45.0	0.280	8.50E-13	12.53	6.22E-11	0.139	7.44E-12
9	0.5625	50.6	0.277	8.40E-13	13.88	6.78E-11	0.154	8.11E-12
11	0.6875	61.9	0.267	8.19E-13	16.44	7.78E-11	0.183	9.30E-12
12	0.75	67.5	0.264	8.09E-13	17.65	8.20E-11	0.196	9.81E-12
14	0.875	78.8	0.255	7.88E-13	19.92	8.92E-11	0.221	1.07E-11
16	1	90.0	0.246	7.68E-13	22.00	9.44E-11	0.244	1.13E-11

(d) IP units: g_h = Grains H_2O/h per in. Hg per hole
(e) SI units: g_h = kg/s per Pa per hole
(f) IP units: Grains per panel = (Grains H_2O/h per in. Hg per hole) × (Holes/30 ft Panel)
(g) SI units: kg per panel = (kg/s per Pa per hole) × (Number of holes/9.14 m Panel)
(h) IP units: $Perm_{holes}$ = Grains per panel/(Panel Area) = Perms in IP units (grains H_2O/h per ft^2 per in. Hg)
(i) SI units: $Perm_{holes}$ = kg per panel/(Panel Area) = Perms in SI units (kg/s per m^2 per Pa)

Table 8. Effective Permeance of In-situ Deck Panels for Laps, Fasteners and Fastener Holes

Lap Gap in.	Permeance of Assembly for Lap Only (Perms)		Permeance of Assembly for Laps + 8 Fasteners per Insulation Board (Perms)		Permeance of Assembly for Laps + 8 Fasteners & 8 Holes per Insulation Board (Perms)	
(a)	(b)	(c)	(b)	(c)	(b)	(c)
0.013	0.27	1.54E-11	0.28	1.60E-11	0.42	2.40E-11
1/32	0.52	2.99E-11	0.53	3.05E-11	0.67	3.85E-11
1/16	0.77	4.43E-11	0.78	4.49E-11	0.92	5.29E-11
1/8	2.30	1.31E-10	2.31	1.32E-10	2.45	1.40E-10

(b) IP units: Perms (grains H_2O/h per ft^2 per in. Hg)
(c) SI units: Perms (kg/s per m^2 per Pa)

mately 0.02% of the total deck area raises the permeability above one perm, rendering the steel deck ineffective as a vapor retarder.

The presence of an air barrier reduces the permeability associated with laps and screw holes to a value that is approximately 1/2 the permeance when the air barrier is not present. In our tests we did not induce an air pressure difference across the sample, therefore, we expect an air barrier in an in-situ deck to have a much greater effect, since as we discussed in the introduction, it is well documented in the literature that even a small amount of airflow through small holes can transport significantly more moisture than diffusion alone. However, the tests with the air barrier demonstrate that the large increase in permeance due to the holes is not all due to air exchange through the holes. Our data with air barrier included also suggests that when concrete fill is used on the steel deck, the effect of laps and holes is diminished; however, decks that are made for concrete placement generally have many holes (perforations) that are present to allow the concrete to dry out from below.

Deck Penetrations and the Effect on Permeability

Figure 13 shows that holes that represent a very small percentage of the deck area can increase the permeance of the steel deck system significantly. From a practical standpoint, this means the deck cannot function as a vapor retarder. The holes studied in our tests are quite small, but in actual construction, deck penetrations and terminations

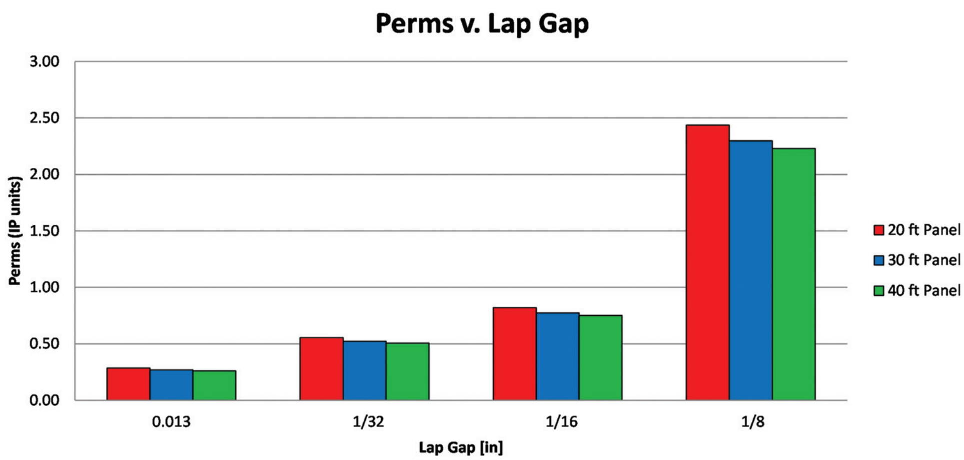


Figure 12 *Effect of gap dimension on deck permeance.*

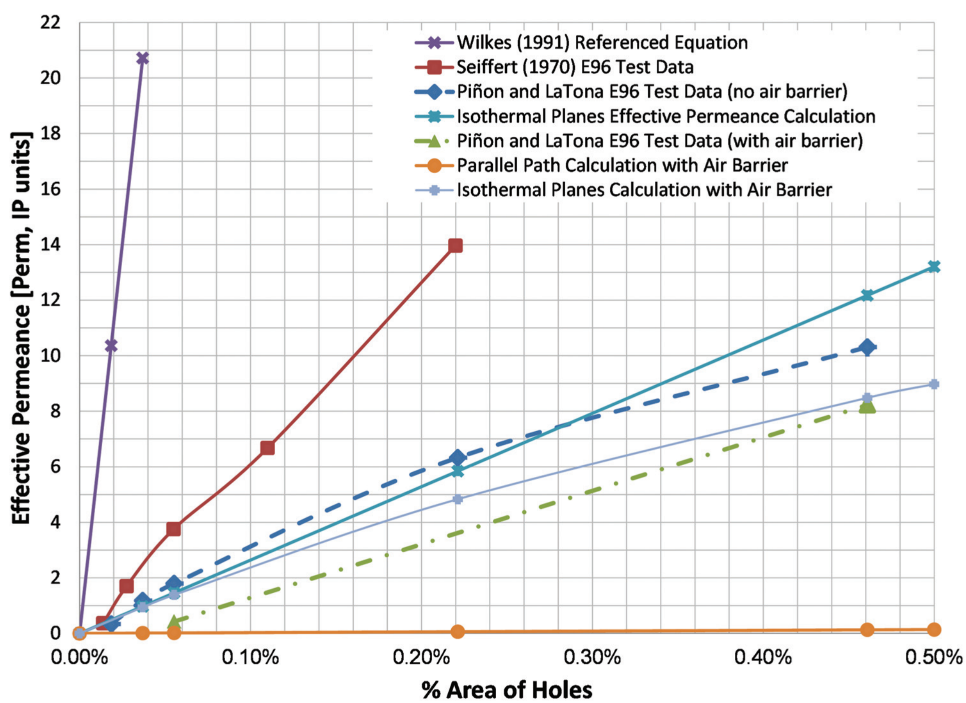


Figure 13 *Effect of percentage area of holes on deck permeance.*

can lead to a much larger percentage of holes in the deck area (Figures 4 and 5).

Figure 13 also shows how our data compares to the previous test data discussed in the introduction and that an estimate using a simple isothermal planes analogy (refer to Figure 8) matches our data relatively closely for area of holes less than 0.30%. At greater hole areas the simple isothermal planes analogy appears to over-predict the effective permeance. However, note the predicted and measured effective permeance of the deck with 0.30% area of holes is already about 8 perms, meaning that the steel deck already is too permeable to function as a vapor retarder.

How these Data Are Used in Hygrothermal Models

Our results reinforce the previous published data that it takes only a small percentage of holes to render a vapor retarder ineffective. However, there is still a question as to whether the effect of the holes would diminish as you add more layers to the exterior side of the steel deck as occurs in a roofing system and as predicted by the parallel path method calculation results shown in Table 2 and graphically shown in Figure 9. Our results with the air barrier membrane (one additional layer to the exterior of the steel) suggests that the effective permeance of a steel deck with holes in a roof system is more similar to that predicted by the isothermal planes method, meaning that a small percentage of holes will still render the steel deck ineffective as a vapor retarder.

Furthermore, we have performed extensive hygrothermal modeling that indicates that once the effective permeance of the steel deck is raised above 1 perm, it is ineffective as a vapor retarder for roofing systems where the roofing membranes are typically between 0.2 and 0.05 perms or even lower for multi-ply asphalt applied built-up roofing systems.

Based on these results and analysis, for steel decks without concrete fill, we conclude that the steel deck can be safely ignored in hygrothermal models in terms of both its diffusion or airflow resistance. If the hygrothermal analysis shows a vapor retarder and/or interior air barrier is needed, then the designer needs to specify a vapor retarder/air barrier system and not rely on the steel deck for this purpose.

For steel decks with concrete fill, the situation is not as clear cut. Table 1 shows that even a thin layer of concrete filling the holes in the steel deck can reduce the effect of the holes significantly. For concrete, the amount of permeance added by the holes would also be limited in practice by the rate of moisture redistribution with the adjacent areas of concrete that is not over a hole. However, the estimates shown Table 1 show that a steel deck "vented" with 1.5% area of perforations, can potentially increase its effective permeance from impermeable to 0.40 perms. These results are likely conservative since they assume the holes are completely filled with concrete. However, they provide a starting point for designers.

We have run hygrothermal models to show that an increase in the permeance of the steel deck from impermeable to 0.40 perms can assist the drying of the concrete to the interior. However, for most concrete roof decks in most climates there is still a significant drive of moisture from the concrete into the roofing system with or without a steel deck. Also, the concrete itself has a good amount of resistance to diffusion, the typical thicknesses used to fill steel roof decks results in a permeance of between 0.1 to 0.4 perms.

Therefore, our contention is that for concrete filled steel decks, the amount of moisture in the concrete is of more hygrothermal significance than knowing the exact effective permeance of the steel deck assembly. Until more experimental information is available on the benefit vented decks might provide to drying of concrete, we recommend that designers use an effective permeance for the steel deck assembly between 0.05 and 1.0 perms depending on the percentage of venting.

CONCLUSIONS

We conclude the following from our experimental results and analysis:

- The vapor resistance of a steel roof deck without concrete fill can be ignored in terms of its effect on the diffusion or airflow across a typical roofing system. The amount of gaps, holes, and unsealed seams render it ineffective as a vapor retarder.
- For concrete filled steel decks, we estimate the effective permeance to be between 0.05 and 1 perms depending on the area of venting (perforations) and other gaps and holes.
- In general, it only takes a small percentage area of holes (less than 0.1%) to render a vapor retarder ineffective, however, more research is needed if this same finding holds true for roof and wall systems that include multiple layers of building materials on the exterior side of the steel deck or vapor retarder.

RECOMMENDATIONS

We recommend that additional research and testing be performed on both wall and roof systems consisting of multiple layers on the exterior side of a vapor retarder to find out the relationship between percent area of holes and the effective permeance of the vapor retarder. If the finding that only a small percentage area of holes renders the vapor retarder ineffective, then that has significant implications on how we design, specify, and install vapor and air retarder membranes..

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