Moisture Dome Tests

What Do They Measure?

by
Kenneth B. Bondy and Geoffrey D. Hichborn, Sr.

August 10, 2000

The moisture dome test was developed more than 40 years ago by the Rubber Manufacturer's Association as an aid in predicting if the surface of a concrete slab is dry enough to permit the successful installation of resilient flooring materials. The test has been used extensively for that purpose. In recent years, the test has also been used by consultants in construction defect litigation as a measure of concrete slab permeability and as a measure of vapor migration from below the slab into residential spaces above. The authors are of the opinion that the use of the moisture dome test for these new purposes is inappropriate. This is because no generally accepted standards exist, nor could they possibly exist, which relate the results of a moisture dome test to either concrete permeability or to acceptable levels of vapor entering an existing residential space.

In order to learn more about the physics of moisture dome tests and what they actually measure, the authors have performed a series of "tests on moisture dome tests" under controlled ambient environmental conditions. The goals of the testing program included the following:

- Determine if the test is reproducible. For any test to be scientifically reliable it must be reproducible. Tests run under identical conditions should yield substantially identical results.
- Determine the significant factors that influence the test results. Particularly, see how the test results are influenced within the typical range of ambient environmental conditions recommended by the test manufacturers and the two ASTM specifications that address the test protocol (F1869 and E1907).
- Determine and attempt to quantify the actual sources of water vapor measured by the test.

This paper presents the results of the tests and our conclusions about what they show.

THE MOISTURE DOME TEST

The moisture dome test kit consists of a rectangular clear plastic dome, a sealed container of calcium chloride crystals, and a gasket. The test kit is shown in Figures 1 and 2.

Figure 1

Figure 2

The dome has a flange with an adhesive gasket that attaches it to the concrete slab creating, hopefully, an airtight seal. Before the dome is sealed to the slab, a small container of calcium chloride crystals is weighed, opened, and placed inside the dome. The sealed dome, containing the calcium chloride crystals, is left in place for from a minimum of sixty hours to a maximum of seventy-two hours, whereupon it is opened and the crystals and container are weighed again. The increase in weight between the first and second weighing of the crystals represents water absorbed by the calcium chloride during the test. The weight of the water absorbed (in pounds) is divided by the area of slab covered by the dome (in square feet) and the duration of the test (in hours) to determine the vapor emission, expressed in typical test result units of pounds of water per one thousand square feet of slab surface per twenty-four hours. The opened container of calcium chloride crystals is shown in Figure 2.

TEST PROGRAM DESCRIPTION

The authors' tests were performed over a 16-month period starting in late 1998. They were run inside a typical wood-framed residential structure in an environment that could be effectively measured and controlled for humidity and temperature. All testing was done in a room with plan dimensions of 10 ft x 13 ft. A dedicated forced-air HVAC system served the room exclusively. Temperature in the room was controllable accurately in the range of 50°F to 95°F and relative humidity was controllable within the range of about 20% to 90%. Tests were performed on three surfaces:

1. The floor slab of the room, a nominal four-inch thick concrete slab cast in 1988 directly on dry sandy native soils in Southern California (soil moisture content = 2.7%). The 28-day concrete compressive design strength was 2,000 psi, consistent with a water-to-cement ratio of around 0.82 or lower[1].
2. A Plexiglas sheet set on a table in the room.
3. An 18-inch diameter, five-inch thick concrete core, in a dry condition and partially submerged in a tank of water. The 28-day design compressive strength of the core, removed from a Southern California residence, was 2,500 psi.

In 1990 a resilient tile floor was installed on the concrete slab. The tile flooring installation, under heavy continuous use as a darkroom floor, was fully successful for more than eight years with no blistering, discoloration, or dysfunction of any kind. Prior to the commencement of these tests the tile was removed and the slab surface cleaned by bead blasting.

Temperature and relative humidity in the room, and inside individual domes, were measured several times each day, at several locations in the room including in the soil below the slab, in the domes, and at various depths through the slab thickness. Temperature and relative humidity measurements were made with meters from Oregon Scientific, Model EM-913R. Weighing of calcium chloride crystals was done at the test site with a Tanita Digital Scale, Model 1479, accurate to 0.1g. Soil and concrete temperatures were measured with a digital probe thermometer (PROTEMP by Dunright & Vogel, Inc.). The entire program to date includes 93 individual dome tests and 5 open CaCl containers, from four different manufacturers, divided into six phases, each phase

[1] *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91) Reapproved 1997*, American Concrete Institute, 1997, Table 6.3.4(a), p. 211.1-9.

designed to provide information relating to particular aspects of the moisture dome test. Following is a description of each phase:

Phases 1 Through 3

Phases 1 through 3 were run between October 2 and 22, 1998. Each of these three series of tests consisted of sixteen domes arranged on the floor slab as shown in Figure 3. Phases 1 through 3 were specifically designed to study the following:

- Reproducibility.
- Edge effects.
- Effects of ambient environmental conditions.
- Sources of moisture measured.

Fourteen domes (identified in Figure 6 as locations #1 through #14) were clustered together in the shape shown in the foreground of Figure 3, and in a closer view in Figure 4.

Figure 3

Figure 4

Two additional domes (locations #15 and #16) were placed adjacent to the cluster but not touching it. They can be seen above the cluster in Figure 3. An open container of calcium chloride crystals, without a dome, was placed on the slab immediately adjacent to the cluster (Location #17). Temperature and relative humidity meters were placed inside selected domes in each phase. Figure 5 shows a dome with a meter inside. The open calcium chloride container can be seen in the upper right-hand corner of Figure 5. In each test phase, the domes were positioned at precisely the same physical location on the slab.

Figure 5

Additionally two tests were run with the dome attached to impermeable surfaces. The first was attached to a heavily varnished wood surface, the second to a Plexiglas sheet ½" thick.

Figure 6 shows a schematic diagram of the test layout indicating dimensions and identification numbers of the test locations.

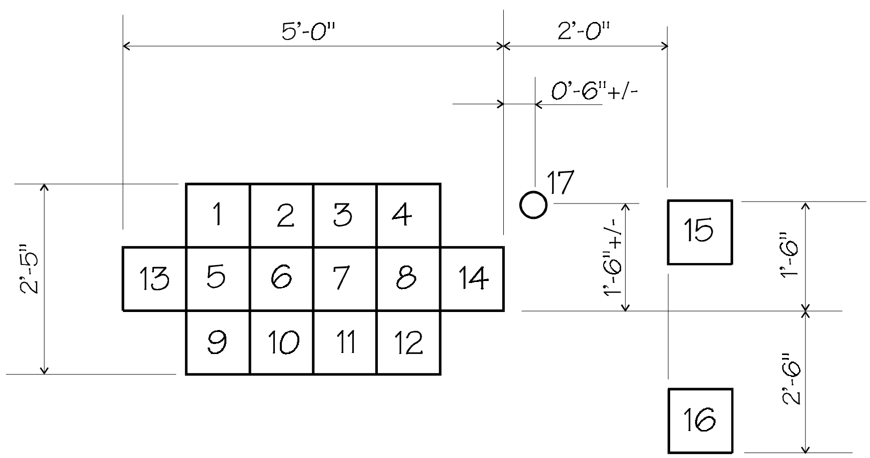

Figure 6

Phase 4

Test Phase 4 consisted of data from Phases 1-3 and 20 additional dome tests and 2 open containers, run on 8 separate times from December, 1998 through February, 2000. Phase 4 was designed to study the following:

- Relationship between test result and soil temperature.
- Reproducibility.
- Sources of moisture measured.

Phase 5

Test Phase 5 was run in August of 1999 and consisted of 8 dome tests run on an impermeable Plexiglas surface. Purposes of Phase 5 included:

- Determine the amount of water vapor measured by the test that is trapped in the air inside the dome.
- Study the reproducibility of the test with a known, constant moisture source.

The eight domes were sealed onto a 2-ft by 4-ft piece of ½” thick Plexiglas in a 4x2 arrangement shown in Figure 7:

Figure 7

Two of the eight domes were “blanks”, they contained only the CaCl container, and were used to study the amount of water vapor trapped in the air inside the dome. The remaining six domes had, in addition to the CaCl container, a small plastic dish containing approximately 30 grams of water initially, used as a constant moisture source. The results of these six “constant-source” domes were used to study the reproducibility of the test under virtually identical conditions of temperature, relative humidity, and vapor source.

Phase 6

Test Phase 6 was run from September of 1999 through February of 2000. To date it consists of 15 dome tests run on an 18-inch diameter concrete core, 5 to 5-1/2 inches thick, with the bottom 1 to 1-1/2 inches of the core submerged in water. The water level was marked on the side of the core and was maintained at that point throughout the test period. The purpose of this test was to observe the dome test results under the worst possible condition of moisture exposure at the bottom of the core, observe the extent of capillarity or “wicking” in the concrete, and to see how the test results varied with time under this extreme exposure condition. The test setup for Phase 6 is shown in Figure 8:

Figure 8

TEST RESULTS

Phases 1-3

Ambient environmental conditions for Phase 1-3 are shown in Table 1. "RH" is an abbreviation for relative humidity.

Test results for Phase 1 through 3 are shown in Table 2. Temperature and relative humidity readings shown in this table were based upon an average of values monitored during the test. Readings were made at roughly three to four-hour intervals during waking hours for the duration of the tests. In determining the soil vapor pressure it was assumed, as is customary, that the soil relative humidity is 100%.

Table 1: Environmental Conditions Phases 1-3

Phase	Room Temp (°F)	Room RH (%)	Soil/Conc. Temp (°F)	Room Vapor Pressure (P_{vR} psi)	Soil Vapor Pressure (P_{vS} psi)	ΔP_v (P_{vS} - P_{vR}) (psi)
1	59	61	72	0.18	0.40	0.22
2	59	42	72	0.15	0.40	0.25
3	79	40	72	0.21	0.40	0.19

Table 1

Table 2: Moisture Dome Test Results (lb/1000sq ft/24hrs)

Location #	Phase		
	1	2	3
1	15.2	13.3	14.9
2	14.3	12.4	13.8
3	17.5[4]	14.8	17.1
4	11.8	11.2	12.6
5	11.5	9.5	10.2
6	15.9[4]	10.7[4]	11.7
7	14.8[4]	12.0[4]	13.9
8	12.5	9.7	10.2

9	11.0	9.0	10.9
10	11.0	9.3	10.9
11	12.2 (59/91/0.23)[1]	10.9	12.2
12	12.7	9.5	11.1
13	10.4	8.7	7.6 B
14	13.5	5.8 B (59/93/0.23)	8.0 B (79/78/0.39)
15	10.8 (59/98/0.24)	7.2 (59/94/0.23)	9.0 C (79/67/0.33)
16	8.4 B[5]	10.2 C	10.2 C
17 (open)	12.8	6.4	9.9
Average[2]	12.7	10.3	11.5
Range[3]	8.4-17.5	5.8-14.8	7.6-17.1

Table 2

Notes:

1. The temperature (°F), relative humidity (%), and vapor pressure (psi) inside this dome.
2. The average of the dome test results (excluding the open container).
3. The lowest result and the highest result of the dome tests (excluding the open container).
4. Visible condensation on the inside top surface of the dome.
5. The letters B and C indicate that that particular dome test kit was supplied by Manufacturer B or C. Absence of a B or C indicates that the dome test kit was supplied by Manufacturer A.

The blank attached to the varnished wood surface (room temperature 73ºF and relative humidity 60%) had a test result of 1.0 lb/1000sf/24hrs. The test run on Plexiglas had a test result of 0.5 lb/1000sf/24hrs. Room temperature and relative humidity were 59ºF and 61% respectively. This latter dome was instrumented, and the inside air temperature and relative humidity were 55ºF and 12% respectively.

Phase 4

Test results for Phase 4 are shown in Table 3. In the "ID #" column of Table 3, the manufacturer of the test kit (A, C, or D) is shown in parentheses. The relationship between the soil temperature and the test result is shown graphically in Figure 9. Each point on the graph is the average of the tests made concurrently at each different time. For example, the tests completed on December 1, 1999, included three domes, identified as 5a, 5b, and 5c, all supplied by manufacturer A. The average of the three tests was (6.7+7.3+5.2)/3=6.4#/24hr/1000sf, and the soil temperature during the test was 64.7ºF. This point, 6.4# at 64.7ºF is plotted in Figure 9.

Tests 1c and 3e were open CaCl containers placed outside the adjacent domes. Dome 3b was placed directly over a ½" diameter hole drilled completely through the slab. "Location" refers to the numbered locations shown in Figure 6.

Table 3: Effect of Soil/Concrete Temperature

Cluster ID #	Date	Location	Room		Dome		Soil/ Conc Temp (ºF)	Test Result
			Temp (ºF)	RH	Temp (ºF)	RH		
1a (C)	12/29/98	14	63	27			62.0	4.4
1b (C)	12/29/98	15	63	27			62.0	3.0
1c (C)	12/29/98	17 (open)	63	27			62.0	6.6

2a (C)	7/8/99	14	68	67	68	64	65.4	7.8
2b (C)	7/8/99	15	68	67	68	71	65.4	4.5
3a (D)	7/25/99	13	69	50	70	68	67.1	7.2
3b (D)	7/25/99	15 (hole)	69	50	68	64	67.1	6.1
3d (D)	7/25/99	3	69	50	68	81	67.1	7.7
3e (D)	7/25/99	17 (open)	69	50			67.1	11.9
4a (A)	10/10/99	3	70	46	70	65	68.2	8.5
5a (A)	12/1/99	2					64.7	6.7
5b (A)	12/1/99	3					64.7	7.3
5c (A)	12/1/99	4					64.7	5.2
6a (A)	1/15/00	2	65	40	64	66	63.2	5.2
6b (A)	1/15/00	3	65	40			63.2	6.8
6c (A)	1/15/00	4	65	40	64	55	63.2	4.7
7a (A)	2/8/00	2	63	58	63	69	62.7	5.4
7b (A)	2/8/00	3	63	58			62.7	7.8
7c (A)	2/8/00	4	63	58	63	63	62.7	4.7
8a (A)	2/21/00	2	60	55			60.2	6.3
8b (A)	2/21/00	3	60	55	60	70	60.2	5.9
8c (A)	2/21/00	4	60	55			60.2	5.0

Table 3

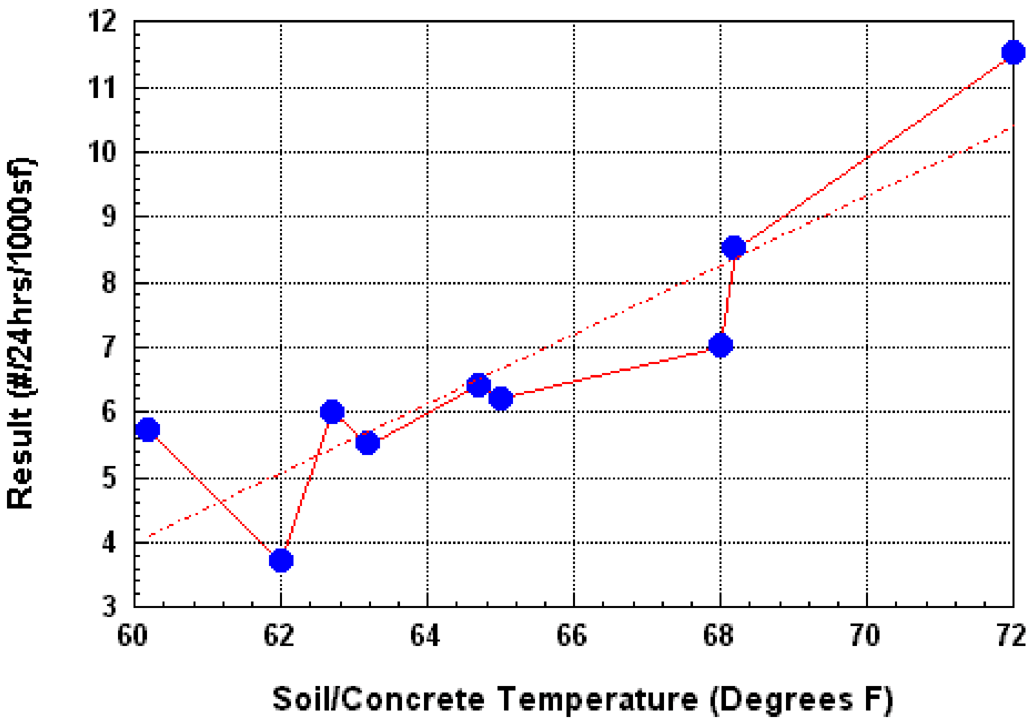

Figure 9

Phase 5

The results of the Phase 5 tests are shown in Table 4. The temperature and relative humidity outside the domes during this Phase were 73ºF and 54% respectively. The relative humidity inside the instrumented blank dome #6 reduced from 65% to 9% over the duration of the test, with an average reading of 23%. Relative humidities inside the domes with water dishes increased substantially over that outside the domes.

Table 4: Tests on Plexiglas

Dome ID #	Water Loss in Dish (g)	Water Gain in CaCl (g)	Inside Dome		Test Result (#/24hr/1000sf)
			Temp (ºF)	RH (%)	
1 (A)	5.0	4.8	72	67	8.5
2 (A)	5.0	4.9			8.6
3 (A)	6.0	5.9			9.0
4 (A)	5.4	5.2			7.9
5 (A)	Blank	0.3			0.5
6 (A)	Blank	0.5	72	23	0.8
7 (D)	7.0	6.7	72	72	10.2
8 (D)	6.4	6.2			9.4

Table 4

The test results for blanks can be predicted with reasonable accuracy by mathematical calculations considering temperatures and relative humidities inside the dome.

Phase 6

The results of the Phase 6 testing on a core partially submerged in water are shown graphically in Figure 10. The test at zero days was made on the core in a "dry" state, prior to submerging in water. The dashed line is the trend of the results calculated using a "moving average" method.

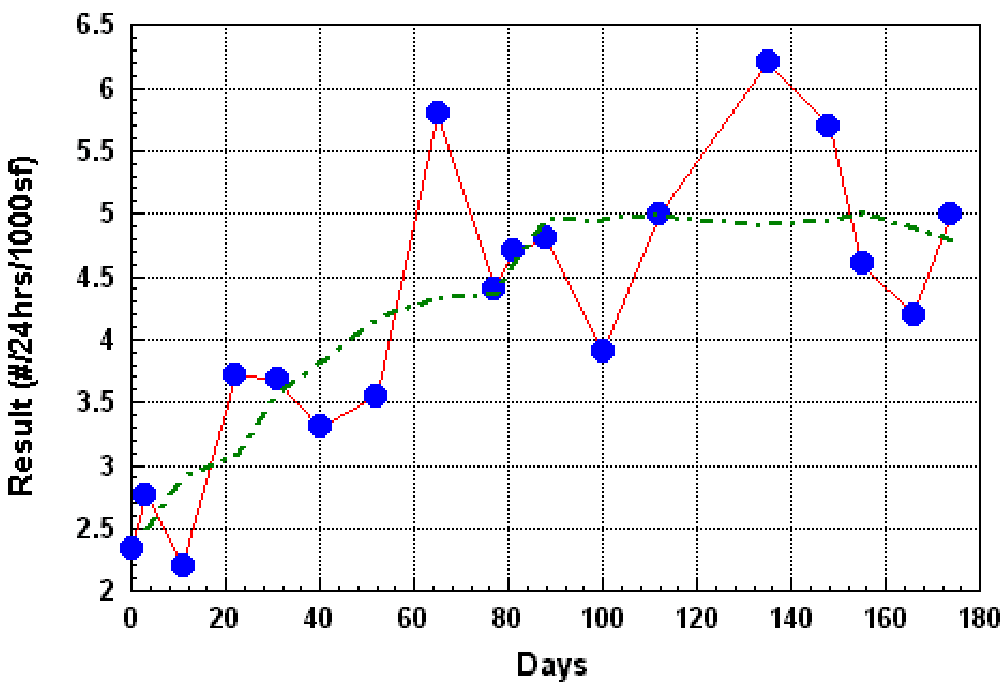

Figure 10

After about 4 days of immersion a wetted zone on the side of the core was visible extending irregularly approximately 1/4 to 1/2 inch above the waterline. A small amount of efflorescence was noticed at the top of the wetted zone after two weeks of immersion. The appearance of this wetted zone, including the efflorescence, remained constant for the entire duration of the test.

DISCUSSION OF RESULTS

Reproducibility

The moisture dome test is not reproducible. To compare the differences between tests run under identical conditions, a percentage variation is defined as follows:

$$\text{Percent Variation} = \left[\frac{\mathit{Highest}}{\mathit{Lowest}} - 1\right] x100$$

In Phase 1 through 3 the test results varied (between the highest and lowest values) by more than 100% within the same phase (108% in Phase 1, 155% in Phase 2, 125% in Phase 3). These large percent variations occurred between domes that were in identical environmental conditions and were no more than a few feet distant from one another. ***Adjacent*** domes commonly had test results that varied by more than 40%, some over 90% (see #3 and #4 in Phase 1 [48%], #1 and #13 in Phase 2 [46%], #4 and #14 in Phase 2 [93%], #4 and #14 in Phase 3 [58%], and #1 and #13 in Phase 3 [96%]).

Phase 1-3 test results also seemed to be a function of the test kit manufacturer. One Manufacturer B consistently had results less than half of the other two manufacturers under identical conditions. In each of these three phases the test kits with the highest and lowest values came from different manufacturers. The highest result in all 3 phases was from Manufacturer A. The lowest result in all three phases was from Manufacturer B. If we examine the test results in Phases 1-3 by manufacturer, the ranges and variances are as follows in Table 5 (a single number in the Range column indicates that only one dome from that manufacturer was used in that phase. A dash appearing in the Range column indicates that no domes from that manufacturer were used in that phase):

Table 5: Percent Variation by Manufacturer

	Manufacturer A		Manufacturer B		Manufacturer C	
Phase	Range	Variation (%)	Range	Variation (%)	Range	Variation (%)
1	10.4-17.5	68%	8.4	---	---	---
2	8.7-14.8	70%	5.8	---	10.2	---
3	10.2-17.1	67%	7.6-8.0	6%	9.0-10.2	13%

Table 5

The percent variation between domes from the same manufacturer was substantially less than that between all manufacturers combined, however domes from Manufacturer A still showed a percent variation of approximately 70% in each phase.

In Phase 4 tests a single manufacturer was used for each “cluster” of tests performed at different times and soil temperatures. In each cluster, the domes were immediately adjacent to one another. Ranges and percent variations for each cluster of tests are as follows in Table 6:

Table 6: Percent Variation Within Clusters

Cluster ID #	Range	Variation	Manufacturer
1	3.0-4.4	47%	C
2	4.5-7.2	60%	C
3	6.1-7.7	26%	D
4	8.5	---	A
5	5.2-7.3	40%	A
6	4.7-6.8	45%	A
7	4.7-7.8	66%	A

Table 6

The percent variation in test results from Phase 5 would be expected to be the least of all tests, since the tests were run at the same time, under identical environmental conditions, and with a constant water source. This was true, however the range of results from Phase 5 was still significant, 7.9 to 10.2, a variation of 28%. Two manufacturers were represented in Phase 5, A and D. Kits from Manufacturer A had a range from 7.9 to 9.0, a variation of 14%. Kits from Manufacturer D had a range from 9.4 to 10.2, a variation of 8%. It is interesting to note that in each phase, or in any series of tests run at the same time under identical conditions with kits from different manufacturers, the highest and lowest test results always came from different manufacturers.

The authors feel that a primary reason for the non-reproducibility of the moisture dome test is the lack of uniformity in the particle size (the “grind”) of the calcium chloride crystals. In running these fifty-seven tests we observed a significant percent variation in the grind of the crystals, not only between the four test kit manufacturers we used, but also between kits from the same manufacturer. The crystals would vary from coarse and clumpy to very fine, almost powdery. The wide difference in particle size and resultant difference in surface area for the same weight of crystals, in our opinion, substantially explains the large percent variations in test results run under identical conditions. We are surprised that neither of the ASTM specifications dealing with this test (F1869 and E1907) requires standardized particle size distributions, since this appears to be a major factor affecting the results of the test.

Another significant factor affecting the reproducibility of the test, or lack thereof, is the fact that pretest activities and slab condition may influence the test results. Floor preparation procedures such as removal of vinyl and adhesives and bead blasting or wire-brushing may leave a non-uniform surface. As the amount of surface abrasion increases, the surface roughness increases, leading to a greater surface area and more sites for vapor to exit. This either changes the floor so that it is no longer representative of its original condition, invalidating the results outright, or increases the test variability so greatly that they become meaningless. Moisture applied, cleaners used, cleaning methods, and floor cleanliness may all influence the test results by changing the floor’s initial conditions or material properties. The period between floor preparation and the testing may not be sufficient to restore equilibrium or remove its effects, contributing to lack of reproducibility in test results. We feel that the bead-blasting of the floor, despite being consistent with ASTM protocols, was the primary reason for the high test values in Phases 1 through 3.

Effect of Ambient Environmental Conditions
The test protocol supplied by the kit manufacturers, and the ASTM specifications themselves, recommend that the test be run within a range of temperatures between 65°F and 85°F, and a range of relative humidities between 40% and 60%. We found that the test results are clearly influenced by the ambient conditions of room temperature and humidity, and will vary by up to 30% within the recommended range of temperatures and humidities.

For example, maintaining the room temperature at 59°F and reducing the relative humidity from 61% to 42% reduced the average of 16 dome test results by 23% (comparing Phase 1 and 2). In these two phases, the lowest test results reduced by 31% and the highest test results reduced by 15%. Maintaining the relative humidity at about 40% but increasing the temperature from 59°F to 79°F (Phase 2 and Phase 3) increased the average test result by 12%, where the highest results increased by 16% and the lowest results increased by 31%. It appears reasonable from the results of these tests to expect a percent variation in moisture dome test results of up to 30% within the range of recommended ambient environmental test conditions.

Contrary to commonly published treatises on vapor emission testing, we did not find a consistent relationship between test results and differential vapor pressures. Referring to Table 1, the largest differential vapor pressure between room and soil existed in Phase 2 (0.25 psi). This would suggest, if vapor pressure differentials were influencing the dome test results, that the highest test values should have been measured in Phase 2. In fact, Phase 2 had the ***lowest*** average test value (10.3 lb) and the lowest single value measured in any dome in Phases 1-3 (5.8 lb). Similarly, the vapor pressure differentials between Phase 1 (0.22 psi) and Phase 2 (0.25 psi) would suggest higher test results in Phase 2 than Phase 1. The reverse was found, Phase 2 had average test results 19% less than Phase 1. The vapor pressure differentials in Phase 2 (0.25 psi) and Phase 3 (0.19 psi) would suggest lower test values in Phase 3 than in Phase 2. The reverse was actually found, Phase 3 had average test values 10% higher than in Phase 3.

Similar inconsistencies can be found by examining vapor pressure differentials and test results for individual instrumented domes. For example, in Phase 2 Dome #14 had a differential vapor pressure between the air inside the dome and the soil of 0.4-0.23=0.17 psi. In Phase 3 the differential vapor pressure at the same dome was 0.4-0.39=0.01, or essentially zero. However the test result for Dome #14 actually increased by 38% between Phase 2 and 3 (5.8 lb to 8.0 lb). At Dome #15 the differential vapor pressure between dome and soil was essentially the same in Phases 1 and 2 (0.24 and 0.23 psi respectively.) Yet the test results for Dome 15 varied by 50% between Phases 1 and 2, 10.8 lb in Phase 1 and 7.2 lb in Phase 2.

This suggests that a) differential vapor pressures are not the primary driving force influencing the test, and/or b) the test does not primarily measure vapor transmitted through the slab. We believe that ***both*** of these conclusions are true and correct.

The most significant single factor affecting the results of a moisture dome test appears to be the soil/concrete temperature. This can be seen by comparing the results of Phase 2 and Cluster #1 from Phase 4. The room temperatures in these two phases are very close. The relative humidity in Phase 2 is 42% and 27% in Phase 2, however the test results for the open calcium chloride containers in the two phases are similar, 6.4 lb/1000sf/24hrs vs. 6.6 lb/1000sf/24hrs. This suggests that ambient environmental moisture conditions between the two phases were not substantially different. However the soil temperature in Phase 4 was ten degrees lower than in Phase 2 (reflecting the general decrease in daily temperatures between October and December in Southern California). This, in our opinion, was the primary reason for the substantial 64% reduction in the average of test results between Phase 2 and Phase 4. This strongly suggests that, in general, moisture dome test results will tend to be significantly higher in the summer, and lower in the winter.

Our tests were performed over soil/concrete interfaces with a temperature range between 62 and 72ºF. We found the relationship between dome test result and soil/concrete temperature to be approximately linear within that range. The relationship is shown in Figure 9.

Sources of Water Vapor Measured in a Moisture Dome Test

Four unique sources of water vapor measured in the moisture dome test can be logically identified. They are shown in Figure 11, identified numerically and shown graphically as Sources 1 through 4.

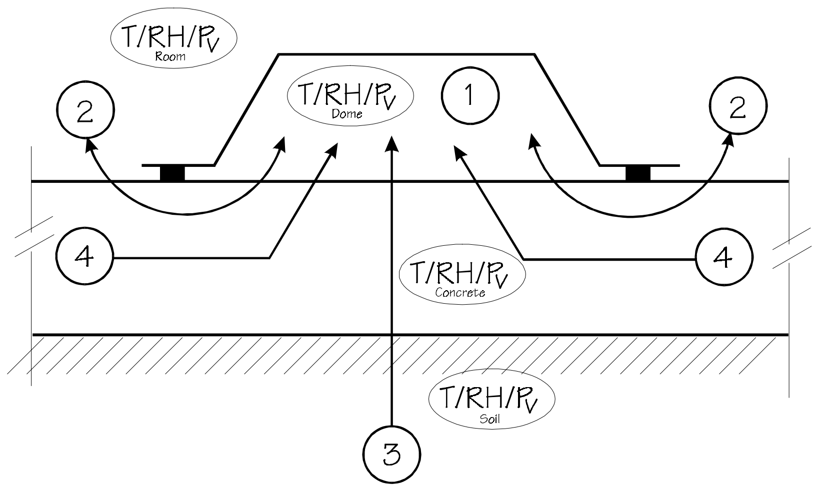

Figure 11

Also shown schematically in Figure 11 are the four unique environmental conditions of temperature (T), relative humidity (RH), and vapor pressure (P_v) which exist in the room (the air surrounding the dome), inside the dome itself, in the concrete below the dome, and in the soil.

Source 1 is the water vapor contained by air trapped inside the dome when the test is first sealed to the slab. Depending on the temperature and relative humidity our tests and calculations show that this moisture will contribute 0.5 to 1.0 lb/1000sf/24hrs to the results of the dome test.

Source 2 is water vapor which is initially either in the room air or the dome air, and is driven either in or out of the dome during the test due to differentials in environmental conditions which develop between the room and the dome during the test. This vapor travels under the gasket; either directly under an imperfect seal or through the topmost pores of the concrete.

We attempted to isolate and identify Source 2 in our tests using the cluster arrangement of domes in Phase 1 through 3. The fourteen domes in the cluster had varying numbers of “free edges” under which Source 2 vapor could pass. For example, Domes #13 and 14 had three free edges, Domes #1, 4, 9, and 12 had two free edges, Domes #2, 3, 10, and 11 had one free edge, and Domes #5-8 had no free edges. Additionally, Domes #15 and 16 had four free edges. If Source 2 was a significant contributor to the results of the dome test, that would be reflected, we reasoned, in some logical relationship between the results of the dome tests and the number of free edges.

Based upon the temperature and humidity measurements we made it appears in all cases that the vapor pressures inside the domes were higher than the vapor pressures in the room air surrounding the domes. Thus if vapor pressure is the primary driving force for Source 2, vapor should have been forced from the dome out into the room. Using that hypothesis, the incremental effect of Source 2 vapor would have resulted in test results that were inversely proportional to the number of free edges. Considering Source 2 vapor only, Domes #15 and 16 should have had the lowest results, Domes #13 and 14 the next lowest results, and so on to the highest results in Domes #5-8. A review of the test results in Figure 8 shows that this relationship cannot be consistently demonstrated.

We conclude from all of the above that, while the Source 2 mechanism undoubtedly exists, within the range of temperatures and humidities normally encountered in these tests it results in a relatively small flow of water vapor either into or out of the dome and cannot be isolated from Source 4, which is discussed below.

Source 3 is water vapor that originates in the soil below the slab, and passes through the slab into the dome, commonly thought to be driven through the slab by a differential vapor pressure between the soil below and the dome above. Many consultants and interested parties opine that this is the primary, indeed the ***only***, source of water vapor measured by the dome test. We find this opinion to be incorrect. Fortunately, this source has in fact been quantified by published work on vapor transmission through concrete slabs done by Brewer[2] at the Portland Cement Association in 1965. Brewer found that very little water vapor passes through mature concrete slabs, even those with high water/cement ratios. Mature slabs, for our purposes, are concrete slabs where the excess construction water, added at the time the concrete was batched, has substantially evaporated.

Brewer found that most of the construction water which is ever going to evaporate from residential concrete slabs evaporates in about one year. Brewer established the upper bound for Source 3 vapor transmission through concrete slabs by directly exposing slabs of varying water/cement ratios to water vapor, i.e., he placed an inexhaustible water surface directly below the slab. He ran parallel tests which isolated the effects of

---

[2] Brewer, H.W., *Moisture Migration – Concrete Slab-on-Ground Construction*, Journal of the PCA Research Development Laboratories, Portland Cement Association, May, 1965

drying (evaporation of excess construction water). Brewer found that the maximum amount of water vapor which can pass ***through*** a four-inch thick concrete slab with a water/cement ratio of 1.0, directly exposed to a water surface immediately below the slab, was 2.05 lb/1000sf/24hrs[3]. That value establishes a definitive upper bound for Source 3 vapor, since the water/cement ratio in our test slab was less than 1.0 and the sandy soils below the slab were extremely dry. The actual amount of Source 3 vapor measured in our tests was impossible to isolate, but we know it is less than 2.05 lb/1000sf/24hrs. Moisture dome test values higher than 2.05 lb/1000sf/24hrs are measuring vapor which did not pass through the slab. Considering the actual conditions above and below our test slab, it is likely that the actual amount of Source 3 vapor measured in our tests was less than 1 lb/1000sf/24hrs. We feel this is a representative value for Source 3 moisture for most residential slabs.

It is our opinion that the *maximum* amount of water vapor in our test results contributed from Sources 1 and 3 is about 3 lb/1000sf/24hrs, 1 lb from Source 1 and less than 2 lb from Source 3. The fact that all but one of our test results on the slab-on-ground exceeded 3 lb/1000sf/24hrs, and some were as high as 17.5 lb/1000sf/24hrs, strongly suggests that ***Source 4,*** with some contribution from Source 2, is the primary source of vapor measured in the dome test on a mature slab. We believe this is true, not only for our tests, but for moisture dome tests in general.

Source 4 vapor resides in the concrete pores and entrapped voids which originally held the batch water. Some of the batch water may still be present, some went to hydrate the cement, some has evaporated since placement, and some was replaced by water from the environment, either by cleaning or by absorbing humidity from the air and humidity and/or liquid from the soil in contact with it. After sufficient time, the amount of water leaving the system equals the amount entering it from all sources and equilibrium is established. The moisture dome test is therefore dependent upon the relative moisture abundance in the slab and the relative ease with which the moisture resident at equilibrium can depart.

Mature residential concrete slabs contain a large and ready supply of Source 4 moisture. The authors have investigated many samples of mature concrete cores removed from residential slabs, and have found that they typically contain about 4% water by weight. One square foot of four-in thick slab weighs fifty lb, therefore the weight of water in this square foot of slab is 0.04x50=2 lb. The moisture dome covers approximately seventy square inches of slab surface, therefore the weight of water stored in the pores of a mature concrete slab which lies directly under the dome is 2x70/144=0.97 lb, or 441 grams. For a seventy-two hour dome test, this weight of water would produce a moisture dome test result of 667 lb/1000sf/24hrs. Just the top one-quarter inch of slab under the dome contains enough water to produce a dome test result of 42 lb/1000sf/24hrs. Obviously, Source 4 moisture is readily available in virtually all residential concrete slabs.

[3] In Series 2 and 3 (Table 5, p.15), for a slab with a *w/cm* ratio of 1.0, exposed directly to water vapor, Brewer found after 365 days a ***total*** emission of 3.77 lb/1000sf/24hrs. In a slab with a *w/cm* ratio of 1.0 after 365 days the "drying only" emission was 1.72 lb/1000sf/24hrs. The vapor passing ***through*** the slab is the difference between these two values, 3.77-1.72=2.05 lb/1000sf/24hrs.

In our opinion, Source 4 vapor is drawn into the dome test *by the test itself*, and is in fact the largest contributor to most moisture dome test results. Indeed, we feel it is likely that virtually *all* of the vapor measured in a mature slab moisture dome test in excess of 3 lb/1000sf/24hrs is Source 4 vapor. A number of factors support this hypothesis:

- In every case the temperature measured inside the domes was substantially the same as the temperature in the room. The relative humidity inside the domes on the slab, however, ***increased*** dramatically above that in the room. The relative humidity inside the domes approached and in some cases reached 100% (condensation was visible on the inside top surface of some domes in Phase 1 and 2).

- The relative humidity inside the dome attached to Plexiglas ***decreased*** dramatically below that in the room and approached zero. Thus when no Source 4 moisture is available, the calcium chloride crystals are able to substantially remove all of the water vapor from the air inside the dome. On the concrete slab, however, the ready availability of Source 4 moisture, and the ambient environmental conditions created by the dome, draws more vapor into the dome than can be absorbed by the crystals. This explains why the relative humidity inside the dome on concrete increases substantially, in some cases to 100%, while the relative humidity inside the dome on Plexiglas decreases substantially and approaches zero.

- In Phase 2 fifteen domes (all but one) had higher test results than the open container on the slab immediately adjacent to the domes. In Phase 3 13 domes (all but three) had higher test result values than the open container. In Phase 1 38% of the domes (six of sixteen) had higher test values than the open calcium chloride container. The calcium chloride crystals inside the domes were thus consistently absorbing more water vapor than the crystals outside the domes. That strongly suggests that the test itself is drawing moisture into the dome at a much greater rate than that which is available to the uncovered calcium chloride crystals outside the dome.

Moisture Dome Test Results and Concrete Permeability

Classic permeability testing assumes a known flowpath with a defined, usually constant-shaped and sized area of flow. The flowpath for vapor into a moisture dome, on the other hand, is completely indeterminate in size, shape, and section. Also, the nature of the path is complex, changing significantly according to the average slab thickness and local variations in slab thickness. Further, the concept of permeability assumes an isotropic material, while the finished slab surface, and the concrete material itself, contradicts this assumption. Clearly the moisture dome test cannot be related in any way to a determination of permeability simply due to its classic definition alone.

If we examine the sources of moisture measured in the test, we arrive at the same conclusion. Source 1 vapor does not pass through the concrete therefore it cannot be related to any concrete property. Source 2 vapor, while it originates in the air above the concrete, may pass through a portion of the concrete under the gasket and therefore could possibly be related to the permeability of the concrete. The same can be said of

Source 4 vapor. It does originate in the concrete and therefore could be related to concrete permeability. It is logical to assume that Source 2 and 4 vapor would increase as the permeability of the concrete increases. But since the flow of Source 2 and 4 vapor in a dome test is ***caused*** by the test itself, we find there is no practical significance in attempting to relate these sources to concrete permeability. Source 2 is already in the air above the slab, and only passes through the concrete in its travel into or out of the dome during the test itself. Source 4 moisture will remain in the pores of the concrete indefinitely, in equilibrium with the room and soil environment, until it is drawn out by the test itself. Thus concrete of ***any*** permeability would be equally functional in mitigating Source 2 and 4 vapor transmission until a major change in ambient environmental conditions occurs, like the dome test itself. Source 2 and 4 moisture has no practical effect, then, on the transmission of vapor into an existing residence, therefore we find it meaningless to attempt to relate those sources to concrete properties.

The only vapor source which can be related to concrete permeability, and which has practical significance (i.e., is not activated by the test itself) is Source 3. The relationship between Source 3 vapor and concrete permeability, expressed in terms of water to cement ratio (*w/cm*), has already been established by Brewer under carefully controlled methods. An upper bound for this source of vapor has been found for virtually all residential concrete at about 2 lb/1000sf/24hrs. This upper bound was determined for concrete with a very high *w/cm* ratio of 1.0 and directly exposed to an underlying water surface, either or both highly unlikely in typical residential construction. Source 3 moisture thus contributes a relatively small and insignificant amount to the results of most moisture dome tests.

Finally, the difference in vapor transmission through high permeability concrete and low permeability concrete is simply too small to be reliably identified by the moisture dome test. Brewer in his tests showed that the difference in vapor transmission between high permeability concrete (*w/cm*=1.0) and low permeability concrete (*w/cm*=0.4) is only 1.37 lb/1000sf/24hrs[4]. Because of the inherent variability of the dome test, and the fact that the majority of water vapor measured in the test does not transmit through the slab, the difference between low permeability concrete and high permeability concrete will not be apparent in most dome test results. The influence on dome test results of test variability is greater than, and will generally mask, the influence of concrete permeability.

For example, with a 30% variability (fairly modest, since we found percent variances greater than 100%), a dome test result of 5 lb represents a range of possible values between 4.25 lb and 5.75 lb. This range of variability (1.5 lb) is greater than the measured difference in vapor transmission of 1.37 lb between concretes with water/cement ratios of 0.4 and 1.0. Clearly the differences in slab vapor transmission between high and low permeability concretes cannot be identified by moisture dome tests. A dome test run on low permeability concrete could actually have a higher test

[4] In Series 2 and 3 (from Footnote 2, Table 5, p. 15), for a slab with *w/cm*=1.0 exposed directly to water vapor, Brewer found after 365 days a total emission of 3.77lb/1000sf/24hrs and a "drying only" emission of 1.72 lb/1000sf/24hrs, for a net vapor transmission of 3.77-1.72=2.05 lb/1000sf/24hrs. For a slab with *w/cm*=0.4 the total emission after 365 days was 1.37 lb/1000sf/24hrs, the "drying only" emission was 0.69 lb/1000sf/24hrs, and the net vapor transmission was 1.37-0.69=0.68 lb/1000sf/24hrs. The difference in vapor transmission between concrete with *w/cm*=1.0 and *w/cm*=0.4 is therefore 2.05-0.68=1.37 lb/1000sf/24hrs.

result than one run on high permeability concrete, particularly if the two dome tests come from different manufacturers.

Lack of reproducibility alone would preclude the use of the test for this purpose, but all of the above further supports the authors' opinion that the results of moisture dome tests cannot be related to ***any*** concrete property, including permeability.

Moisture Dome Test Results and Vapor Transmission Into Residential Space

To the best of our knowledge, there are no generally accepted, published, quantitative standards for acceptable levels of vapor transmission, from any source and by any path, into existing residential spaces. It follows that there are no published standards for relating the results of moisture dome tests to acceptable levels of vapor transmission through concrete slabs into such spaces. The evaluation of vapor transmission through concrete slabs into existing residential spaces becomes, therefore, highly subjective.

As stated above, Source 3 moisture is the only moisture which actually is transmitted through the slab into the room, and which is not activated by the test itself. Therefore it is the only source of moisture in a dome test result which could have any practical significance in evaluating vapor transmission into existing residences. Source 1 and 2 moisture is already in the room, and Source 4 will remain indefinitely in the concrete unless activated by a major change in ambient environmental conditions, like the dome test itself. Since the upper limit for Source 3 moisture is 2 lb/1000sf/24hrs, it becomes important to evaluate the significance of that amount of vapor entering into an average-sized residential space in a twenty-four hour period. One qualitative way to do that is to relate that upper limit of vapor transmission to the amount of water which can be removed by the type of air conditioning unit often found in residential construction.
If we assume a production home with a footprint area of 1,600 square feet, the maximum amount of Source 3 vapor which can be transmitted ***in a twenty-four hour period*** is 1.6x2=3.2 lb. This home, in Southern California, is likely to have a three-ton air conditioning unit installed (one "ton"=12,000 BTU/hr). Based upon data provided by air conditioning equipment manufacturers, we determined, for typical residential conditions, that a three-ton unit can remove 1.8 gallons (15 lb) of water per hour. This figure can be substantiated rather accurately by mathematical calculations. The ***maximum*** amount of vapor transmission possible through the 1,600 square foot slab ***in a twenty-four hour period*** can therefore be removed by running the air conditioner for about thirteen minutes. In our opinion this amount of vapor transmission is negligible, and cannot possibly have any deleterious effects on the occupants or contents of the residence.

It is our opinion that the results of a moisture dome test cannot be related to acceptable levels of vapor transmission through concrete slabs into residential spaces. First, no such standards of acceptability exist, and second, the test not only lacks reproducibility but measures primarily moisture which is not transmitted through the slab. We further feel that the actual amount of vapor transmitted through the slab is negligible, even at the maximum possible rate of 2 lb/1000sf/24hrs. Residential slabs are normally less permeable than the one used to establish that upper limit of vapor transmission (they have lower water/cement ratios), they normally are not directly exposed to an inexhaustible supply of water immediately below the slab, and they typically have not only a visqueen vapor retarder but several inches of sand separating them from the native soil below.

Additional Questions Raised About the Moisture Dome Test

Our investigation of moisture dome tests has raised some additional questions about their reliability, even for their original purpose of installing resilient flooring. First, there seems to be considerable doubt about their ability to predict the success or failure of flooring installations, even among flooring specialists. Our Phase 1 through 3 test results averaged 11.5 lb/1000sf/24hrs with a high value of 17.5 lb/1000sf/24hrs. Most flooring manufacturers and flooring specialists recommend a maximum test result of 3 lb/1000sf/24hrs for the installation of resilient tile. Our test results, almost four times higher than this on average and ranging up to almost six times higher, would suggest that a successful resilient tile could not be installed on this slab. Yet a highly successful resilient tile floor ***was*** in fact installed on this slab and it functioned normally for more than eight years of heavy usage prior to being removed for our test program. We are aware of similar inconsistencies between the results of moisture dome tests and the success or failure of flooring material installation. We believe that the lack of reproducibility of the test, the fact that test results will vary by more than 100% under identical conditions, may largely explain the apparent inability of the test to serve even its originally intended sole purpose.

Second, it is our opinion that the rate of vapor absorption into the crystals is non-linear. The rate appears to be much higher in the initial part of the test than in the final part. At some point, left to continually absorb vapor, the crystals will fully liquefy, and at that point their rate of absorption becomes zero. We have observed that the results of a sixty-hour test can be substantially different from that of a seventy-two hour test, both run under identical conditions, yet both time periods are acceptable according to the test protocol, and therefore presumably should yield the same test result. In our test program, we had the opportunity to monitor and determine the test results for the open calcium chloride containers at any time during the test. We did this at various time periods by simply weighing the crystals, noting the test time, and calculating the test result at that time. We found that the test results varied wildly as a function of the test duration, even during the acceptable "window" of sixty to seventy-two hours. In some instances the test result for the open containers calculated at sixty hours was higher than the test result at seventy-two hours, in some cases it was lower. This would suggest that to attempt to standardize the test results, among many other things, the time window should be substantially tightened, probably to within just a few hours. We also feel that the total test period should be much longer. We doubt that an equilibrium condition can be achieved in only seventy-two hours.

Finally, we found that the water vapor contained in the air trapped originally in the dome can contribute a significant amount (up to 1 lb/1000sf/24hrs) to the test result. That amount of water vapor is a function of the volume of the dome. Yet to our knowledge no published protocol for the test, including the two ASTM specifications, provide any criteria, tolerances, or limitations of any kind on the ***maximum*** volume of the dome.

SUMMARY

- The moisture dome test is not reproducible. Test results have been shown to vary by more than 100% under identical test conditions. A primary reason for the non-reproducibility of the test is the lack of a standard for the particle size distribution of the calcium chloride crystals.

- The primary source of water vapor measured in a moisture dome test on a mature slab, and virtually all of the vapor measured beyond 3 lb/1000sf/24hrs, is from water which was in equilibrium in the pores of the concrete and is activated by the test itself.

- The ***maximum*** amount of water vapor which can be transmitted through a typical residential concrete slab, from the soil below up into the room above, is 2 lb/1000sf/24hrs. That amount of water vapor, emitted in a twenty-four hour period, can be removed by a three-ton air conditioning unit in an average sized production home in thirteen minutes.

- Moisture dome tests will vary by up to 30% within the range of temperatures and relative humidities recommended by ASTM specifications. The most influential variable affecting the results of the test is the soil/concrete temperature. Differential vapor pressures do not seem to be related in any consistent way to test results.

- Moisture dome test results cannot be related to any concrete property, including permeability. No standards exist which relate the results of the moisture dome test to concrete properties, and most of the water measured in the test is activated by the test itself, or influenced greatly by ambient environmental conditions having nothing to do with concrete properties.

- Moisture dome test results cannot be used as a measure of acceptable levels of vapor transmission into an existing residential space. No such standards of acceptability exist, and most of the moisture measured in the test is not transmitted through the slab.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to Mr. David Baxter for his extensive contributions in executing the test program, calculations, and research described in this article.