Arnold Schwarzenegger
Governor

ENERGY PERFORMANCE OF UNDERFLOOR AIR DISTRIBUTION SYSTEMS

Part II: Laboratory Layouts and Normaliation of Room Air Stratification Profiles

APPENDIX B

Prepared For:
California Energy Commission
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ENERGY PERFORMANCE OF UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEMS PART II: ROOM AIR STRATIFICATION FULL SCALE TESTING

LABORATORY LAYOUTS

The laboratory layouts are ordered in the sequence as they are discussed in the body of the report. Figure 1 shows the legend for the laboratory layouts.

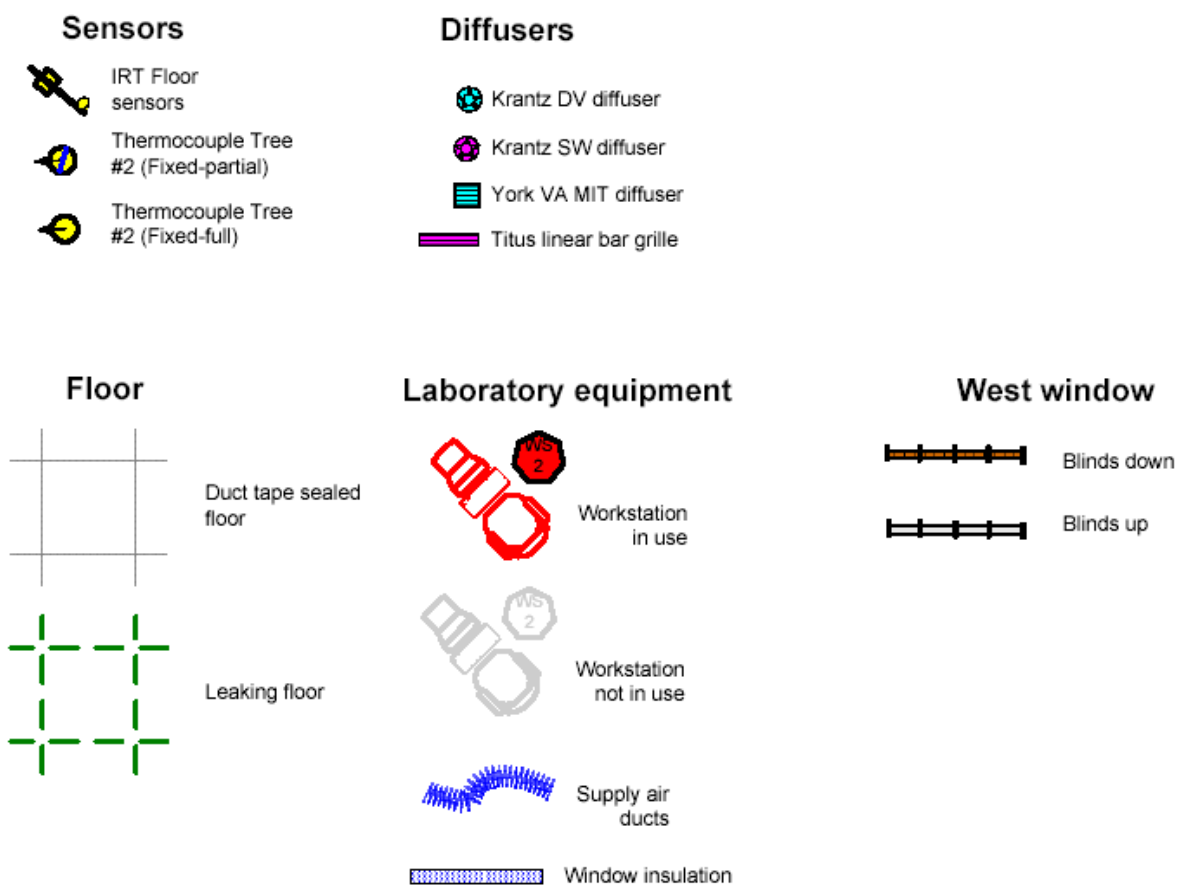

Figure 1: Legend for Laboratory Layout

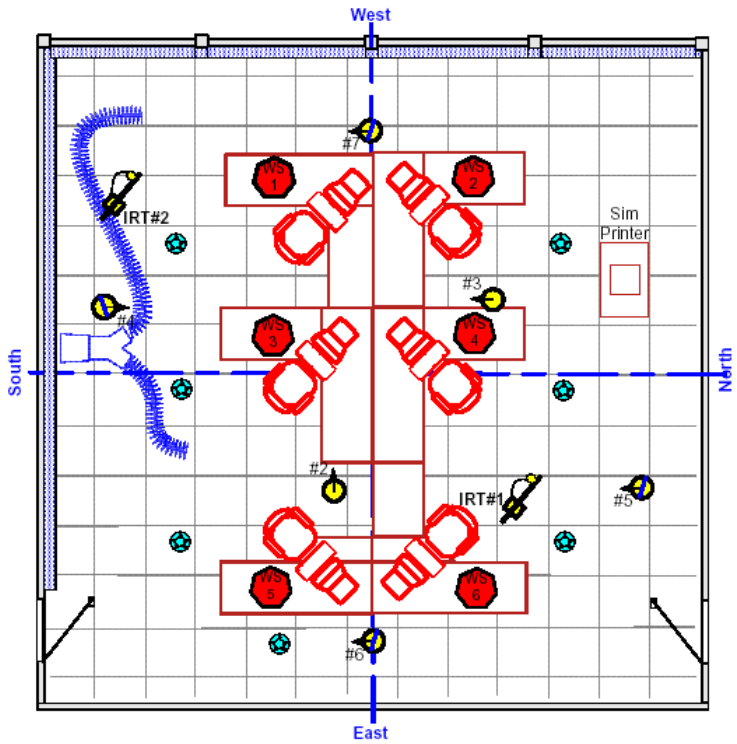

Figure 2: Test INT 6-1, 22.2°C (72°F), 6 WS, 7 DV

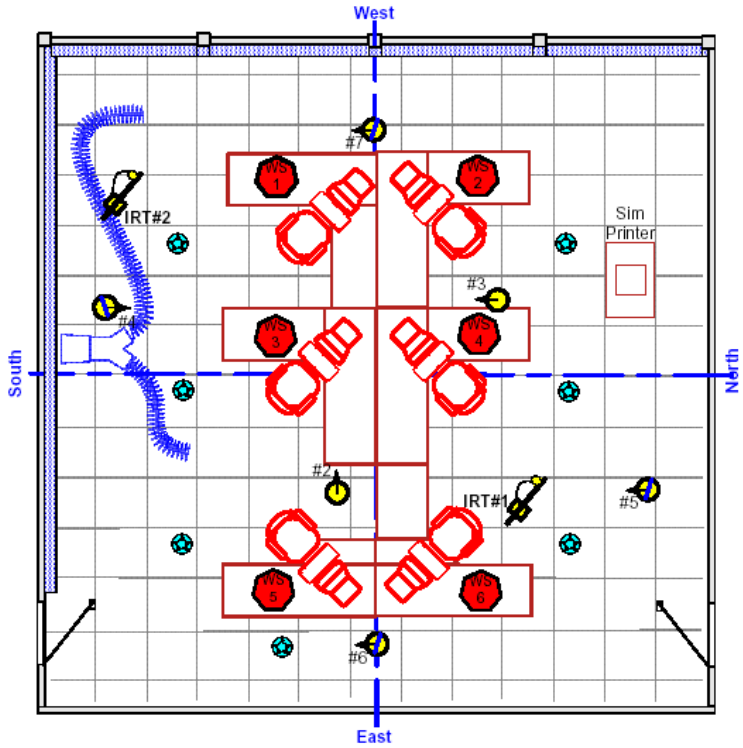

Figure 3: Test INT 6-2, 24.4°C (76°F), 6 WS, 7 DV

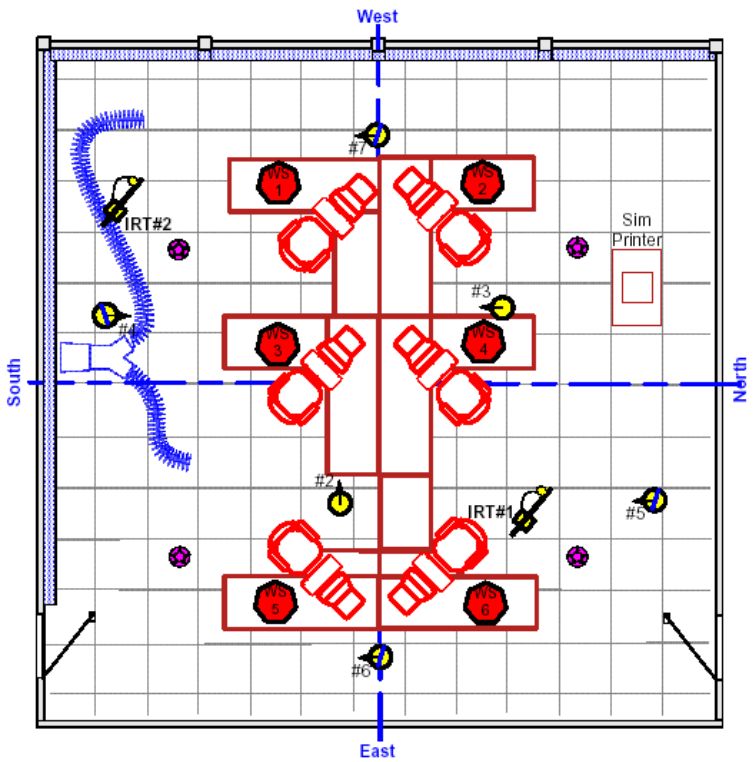

Figure 4: Test INT 6-6, 24.4°C (76°F), 6 WS, 4 SW

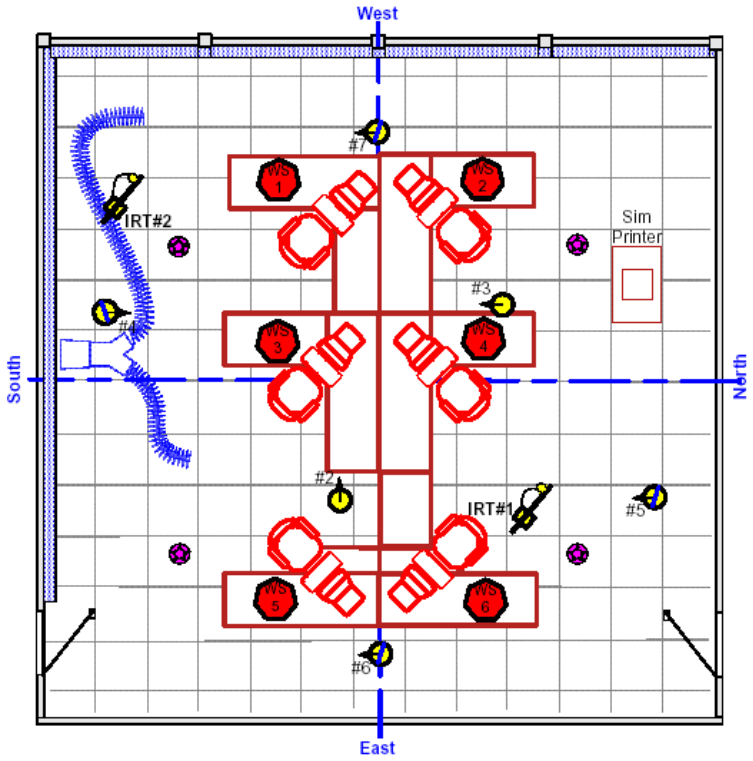

Figure 5: Test INT 6-7, 24.4°C (76°F), 6 WS, 4 SW

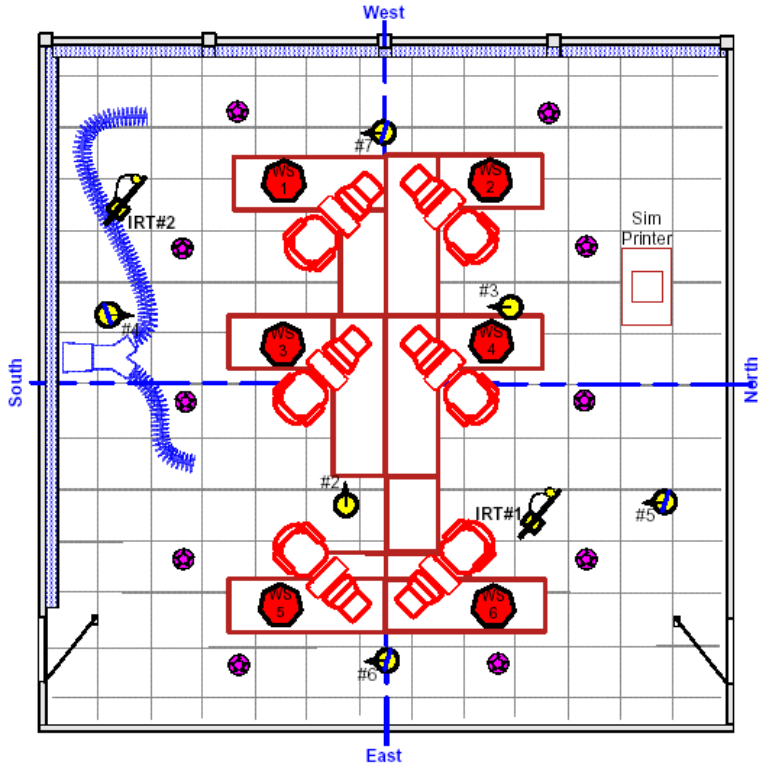

Figure 6: Test INT 6-8, 22.2°C (72°F), 6 WS, 10 SW

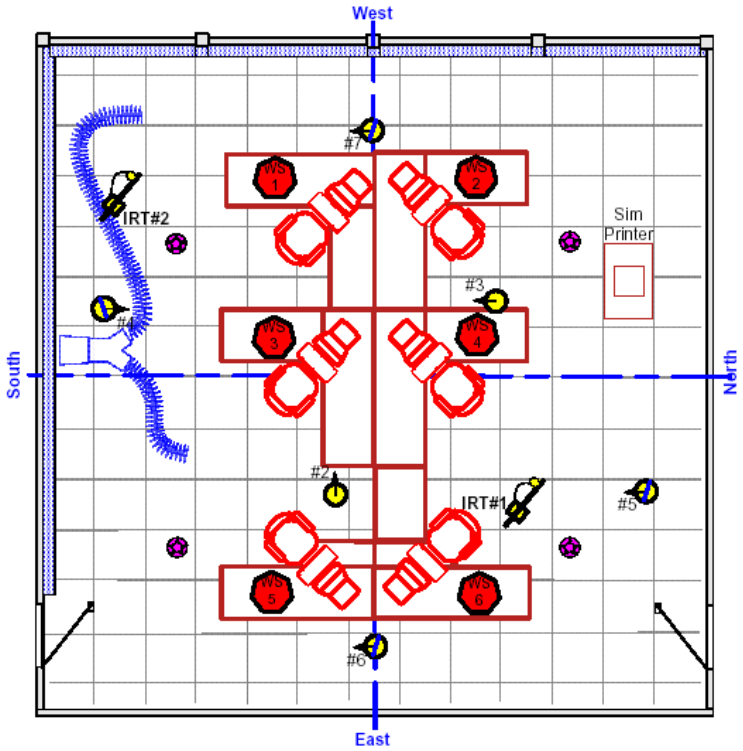

Figure 7: Test INT 6-11, 22.2°C (72°F), 6 WS, 4 SW

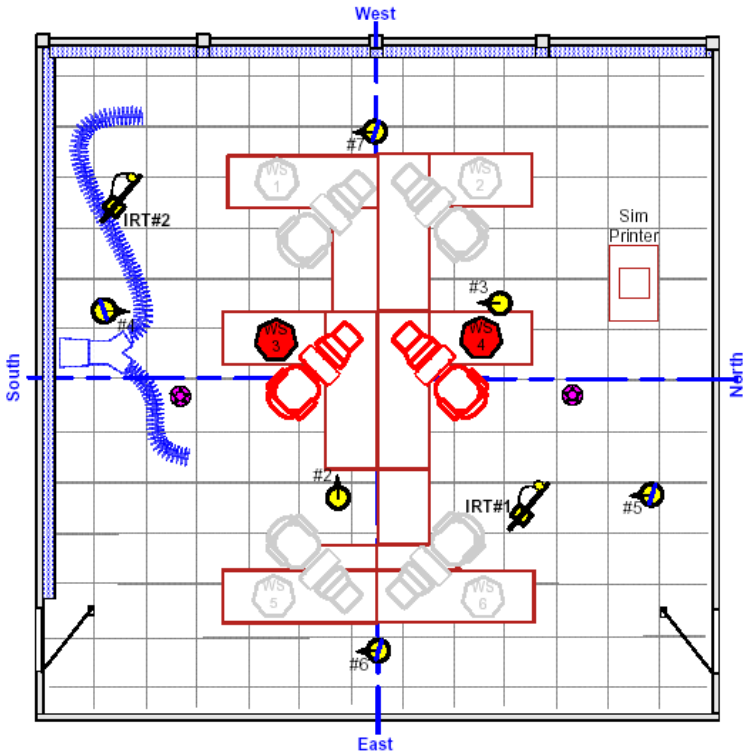

Figure 8: Test INT 6-4, 24.4°C (76°F), 2 WS, 2 SW

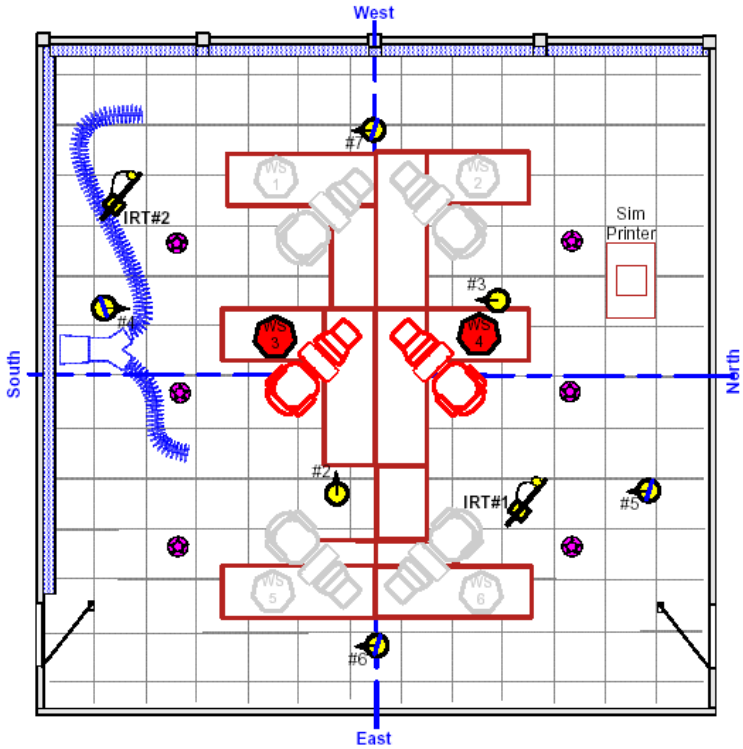

Figure 9: Test INT 6-9, 22.2°C (72°F), 2 WS, 6 SW

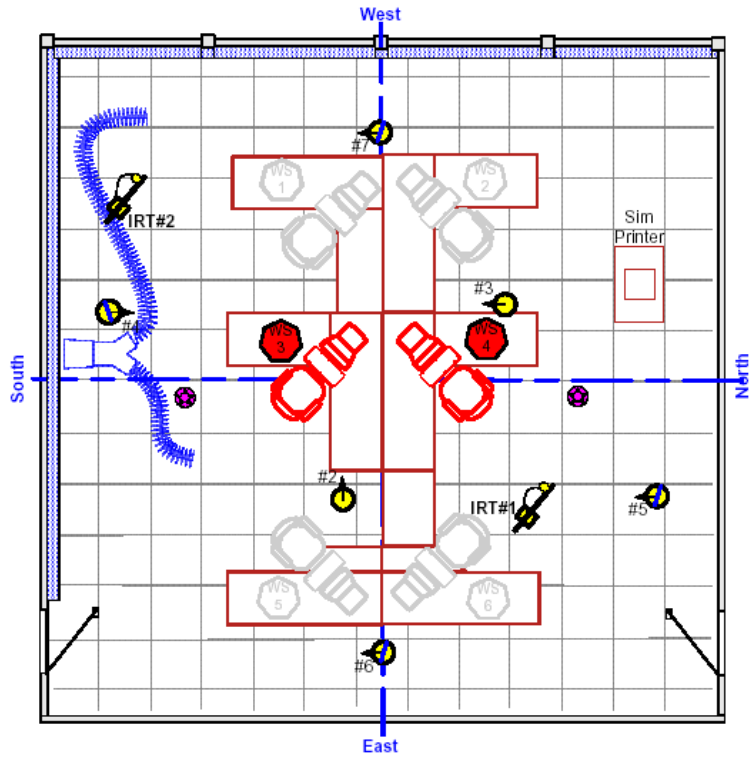

Figure 10: Test INT 6-10, 22.2°C (72°F), 2 WS, 2 SW

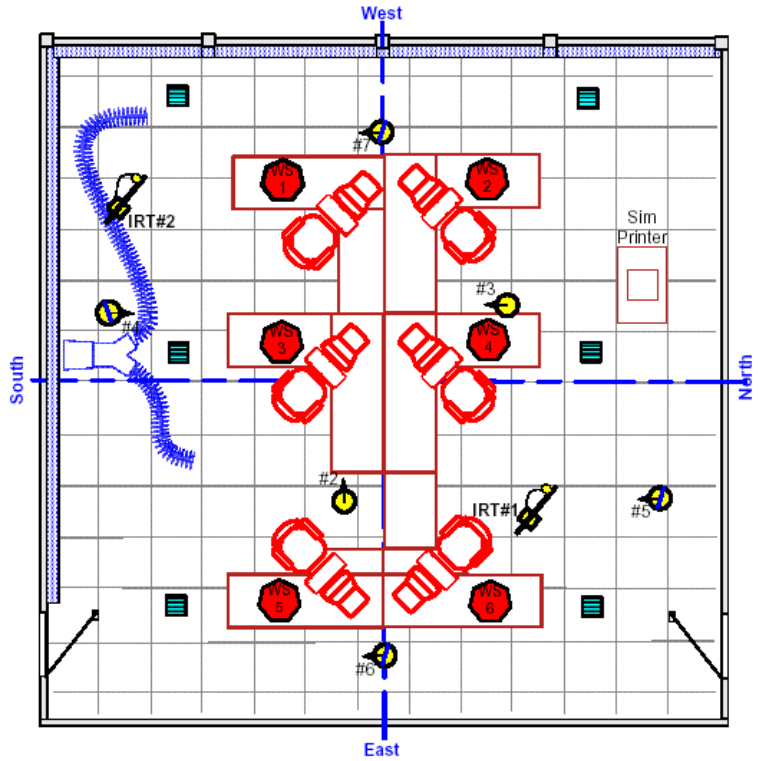

Figure 11: Test INT 6-13, 22.2°C (72°F), 6 WS, 6 VA

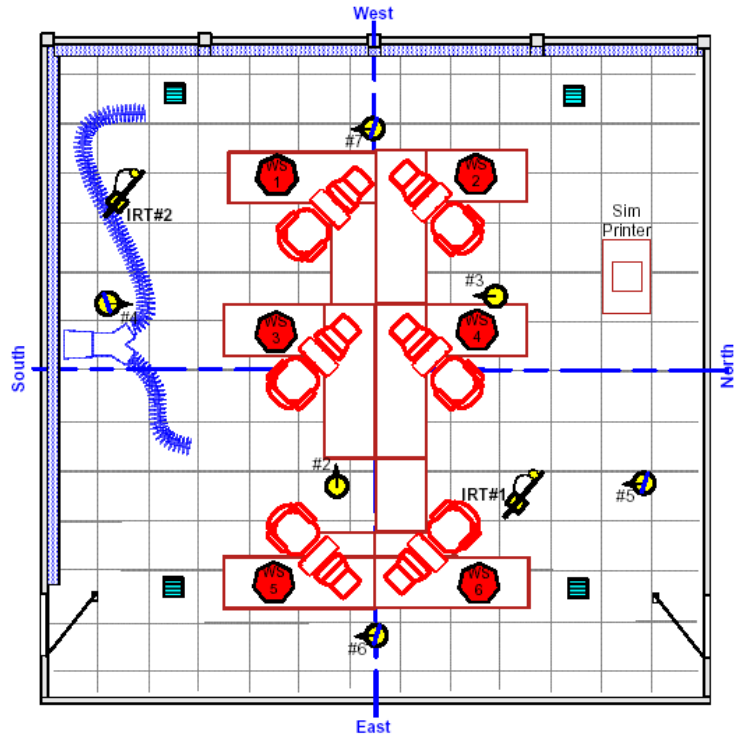

Figure 12: Test INT 6-14, 22.2°C (72°F), 6 WS, 4 VA

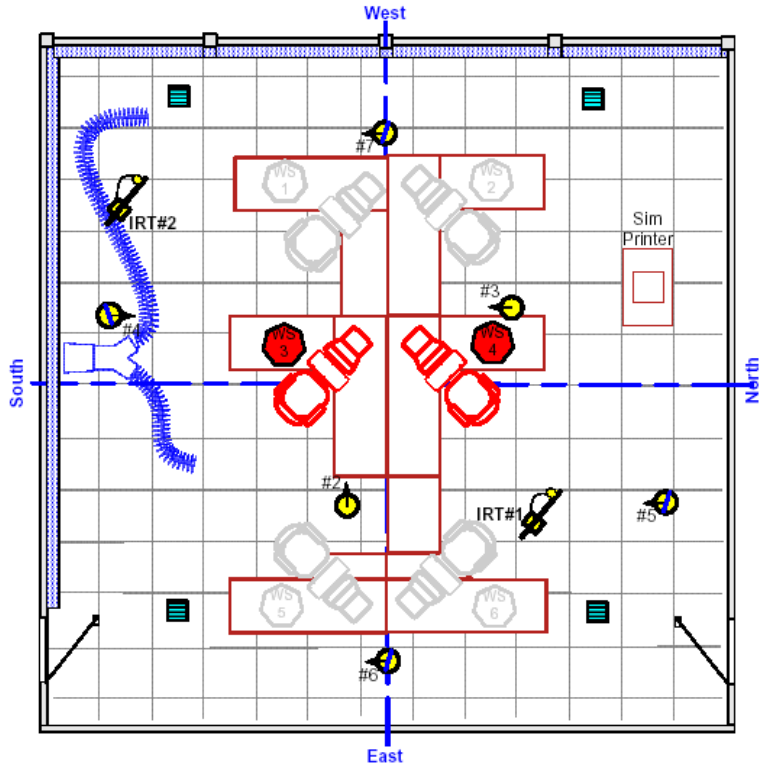

Figure 13: Test INT 6-15, 22.2°C (72°F), 2 WS, 4 VA

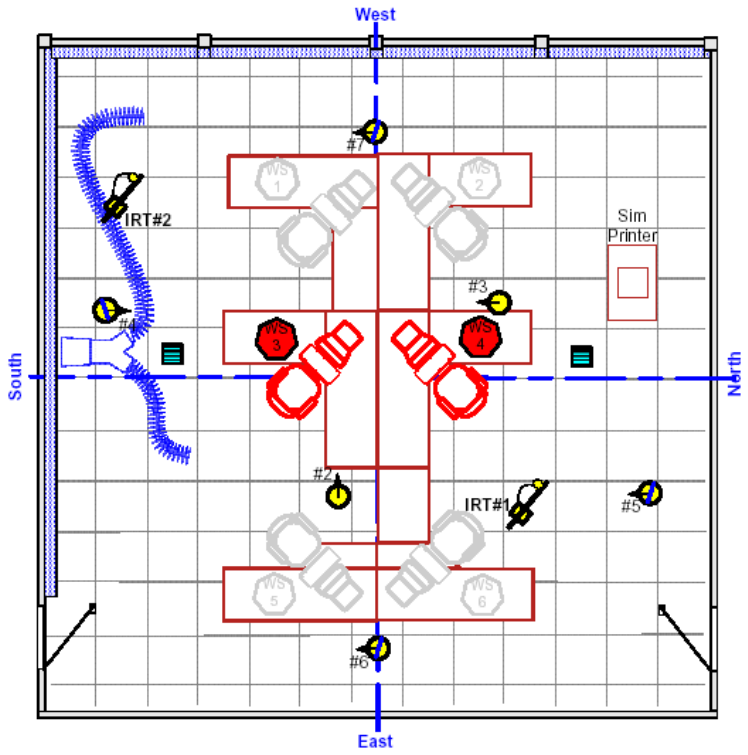

Figure 14: Test INT 6-16, 22.2°C (72°F), 2 WS, 2 VA

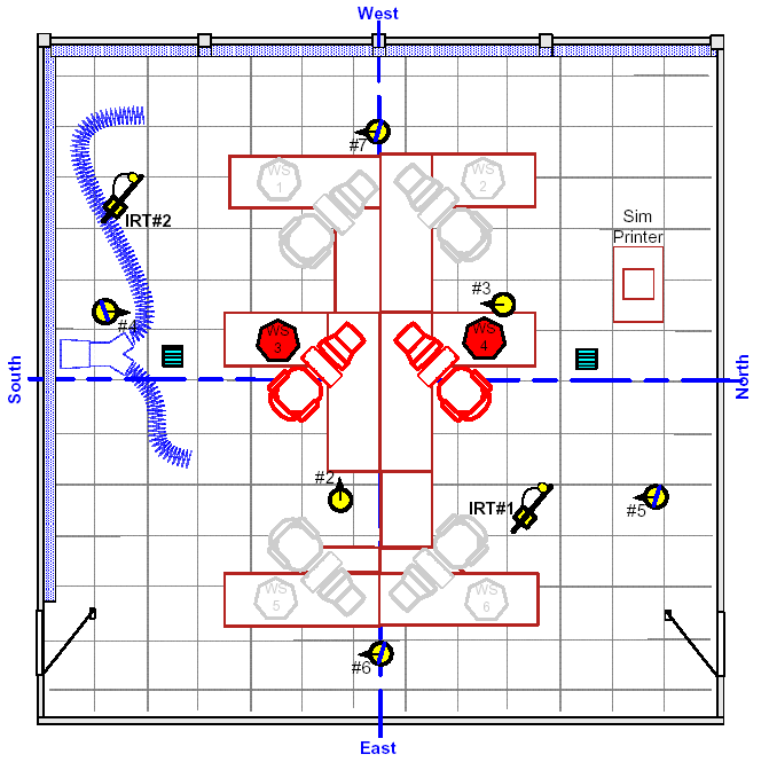

Figure 15: Test INT 6-17, 24.4°C (76°F), 2 WS, 2 VA

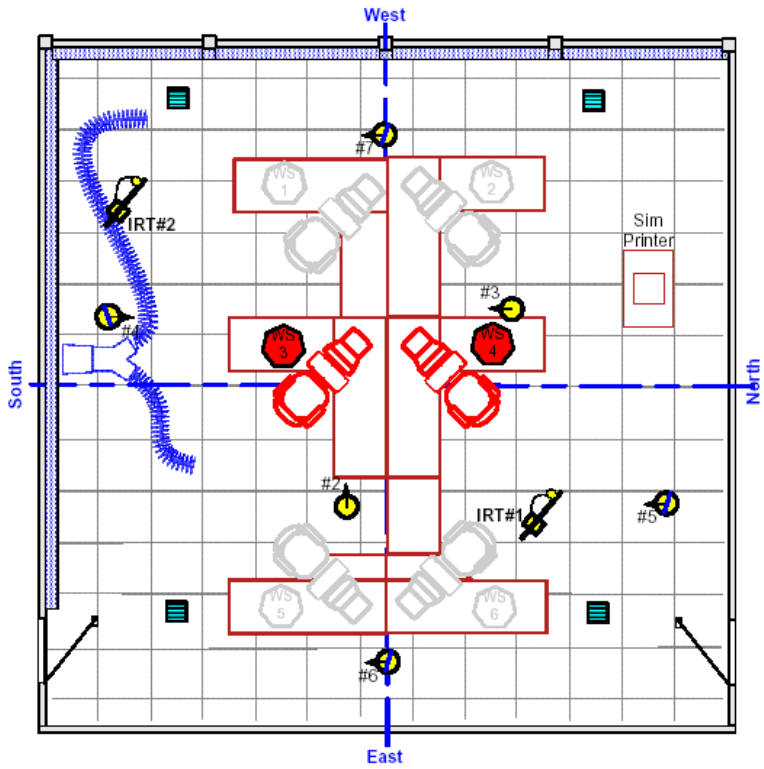

Figure 16: Test INT 6-18, 24.4°C (76°F), 2 WS, 4 VA

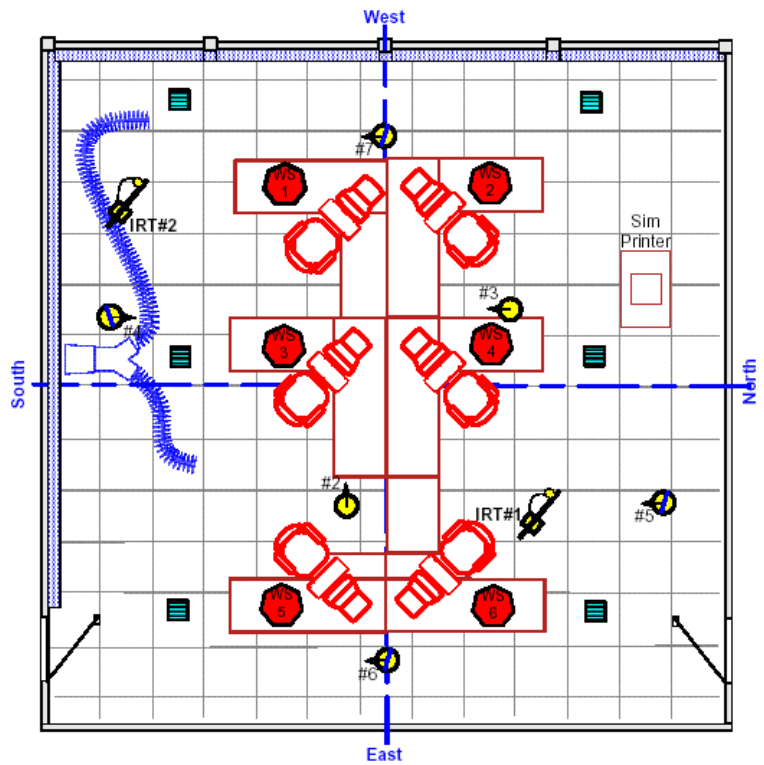

Figure 17: Test INT 6-19, 24.4°C (76°F), 6 WS, 6 VA

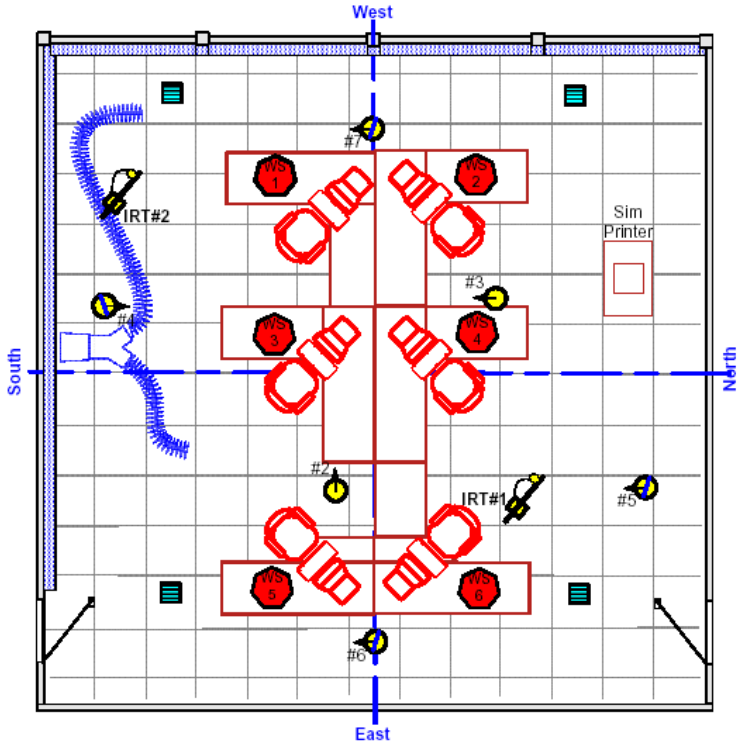

Figure 18: Test INT 6-20, 24.4°C (76°F), 6 WS, 4 VA

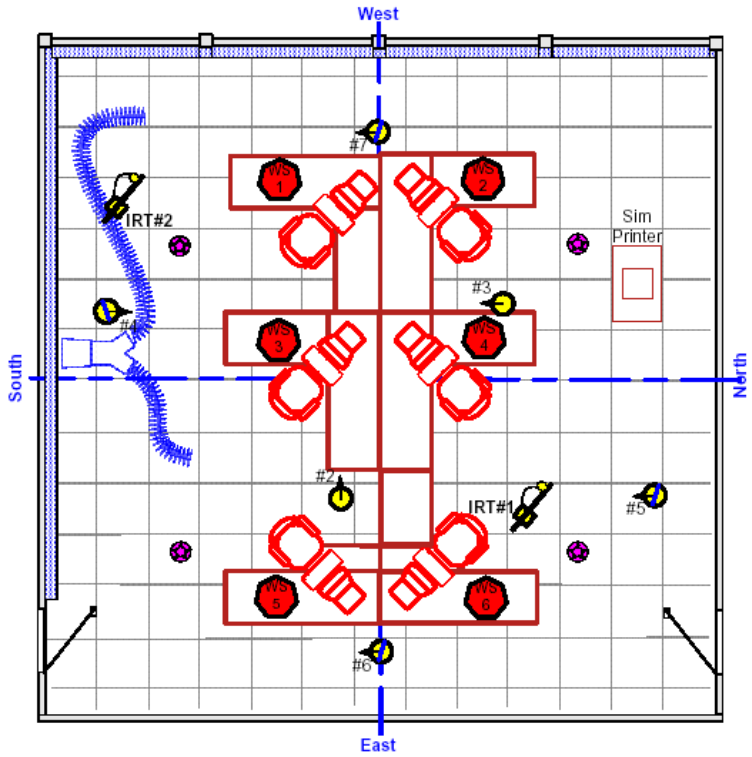

Figure 19: Test INT 8-7, 23.3°C (74°F), 6 WS, 4 SW

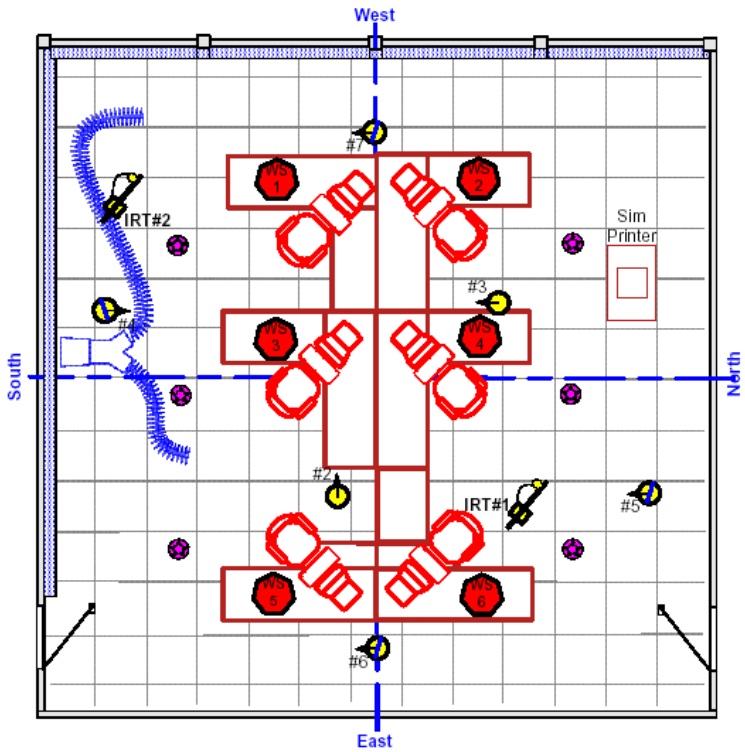

Figure 20: Test INT 8-2, 23.3°C (74°F), 6 WS, 6 SW

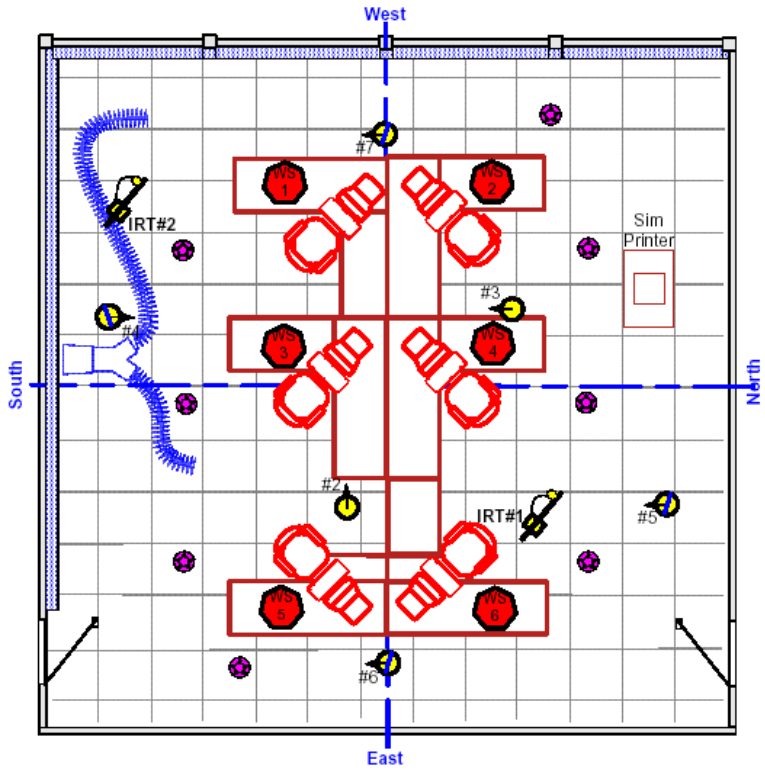

Figure 21: Test INT 8-3, 23.3°C (74°F), 6 WS, 8 SW

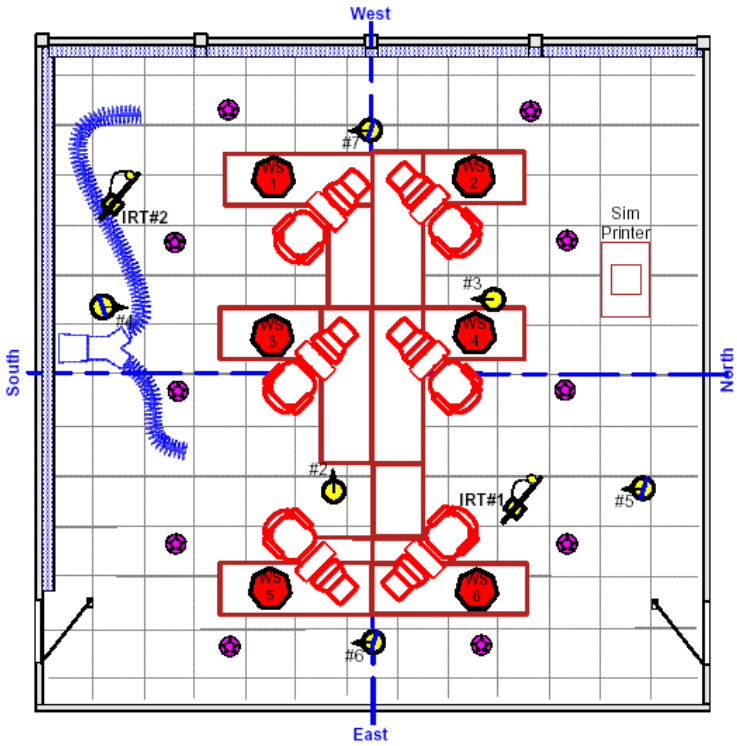

Figure 22: Test INT 8-4, 23.3°C (74°F), 6 WS, 10 SW

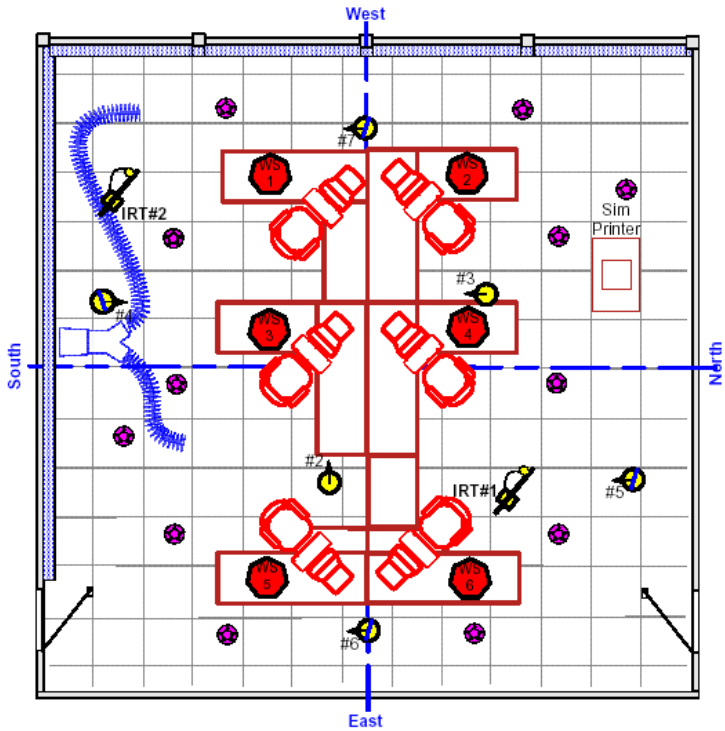

Figure 23: Test INT 8-5, 23.3°C (74°F), 6 WS, 12 SW

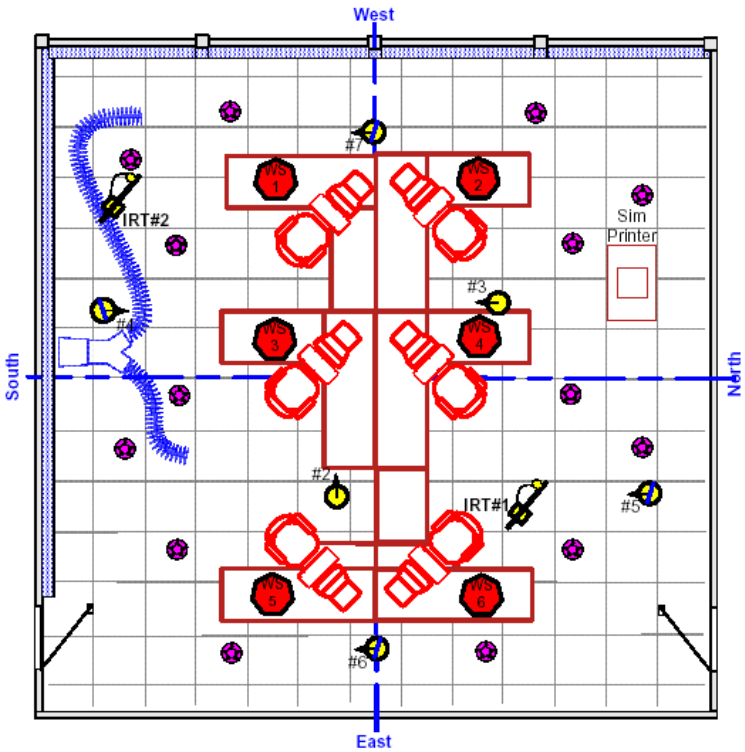

Figure 24: Test INT 8-6, 23.3°C (74°F), 6 WS, 14 SW

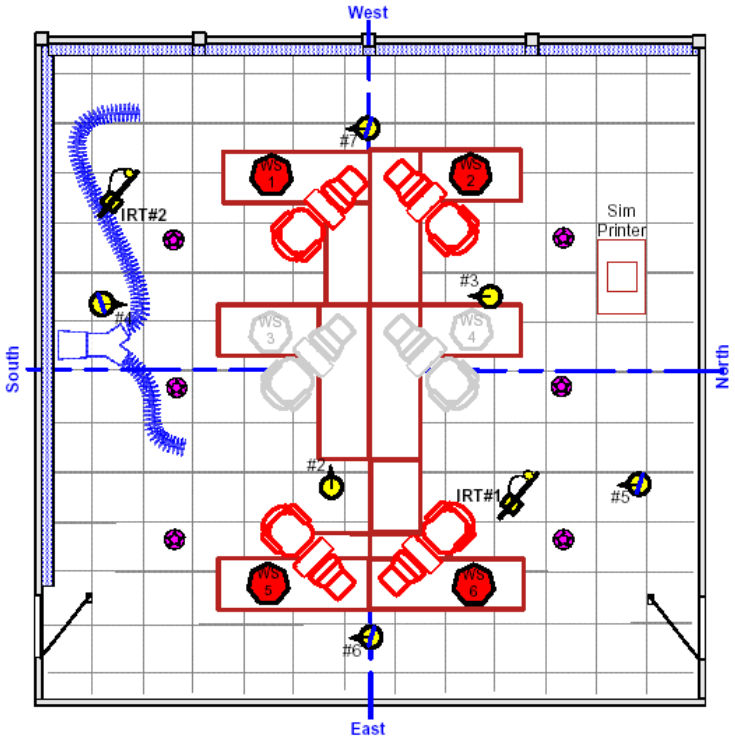

Figure 25: Test INT 8-8, 23.3°C (74°F), 4 WS, 6 SW

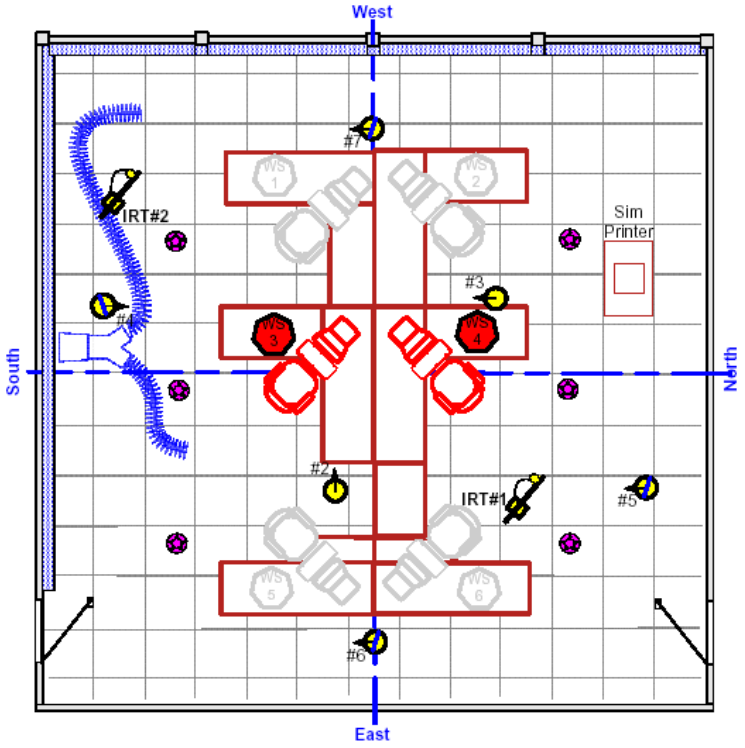

Figure 26: Test INT 8-9, 23.3°C (74°F), 2 WS, 6 SW

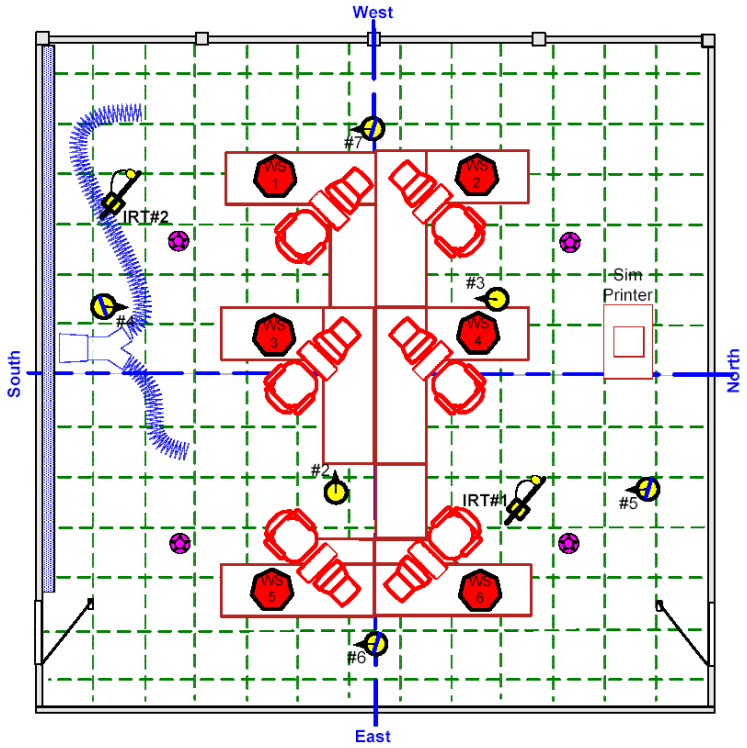

Figure 27: Test INT 8-15, 23.3°C (74°F), 4 WS, 4 SW

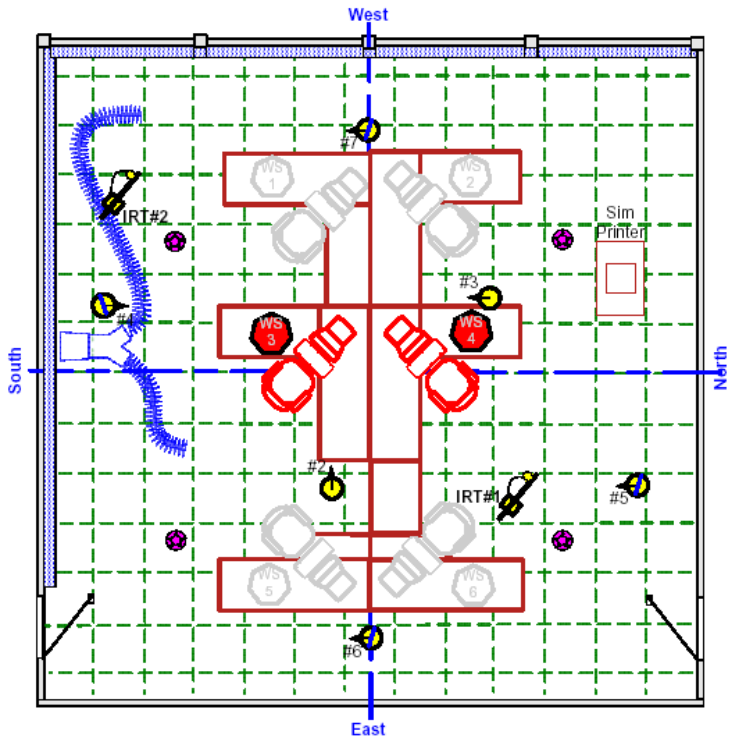

Figure 28: Test INT 8-16, 23.3°C (74°F), 2 WS, 4 SW

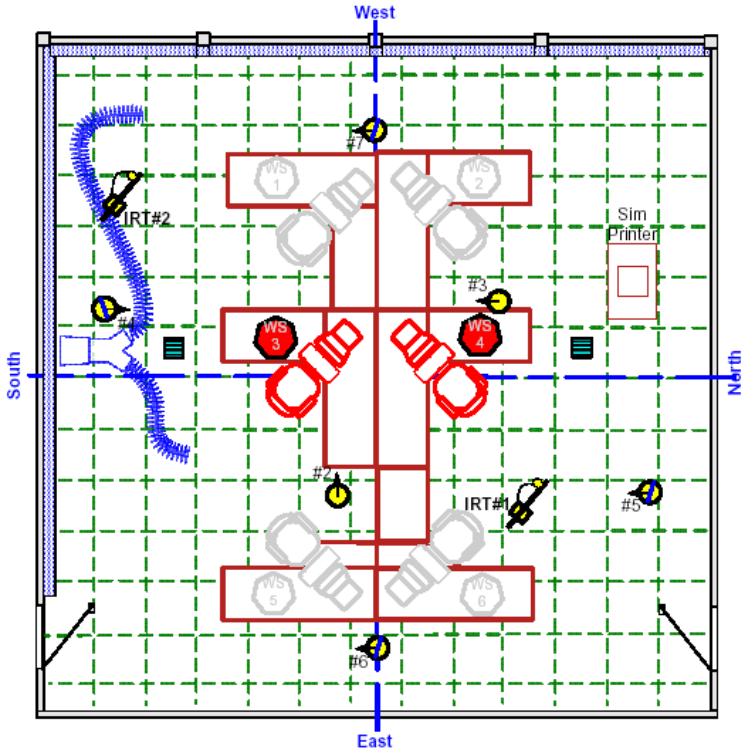

Figure 29: Test INT 8-17, 23.3°C (74°F), 2 WS, 2 VA

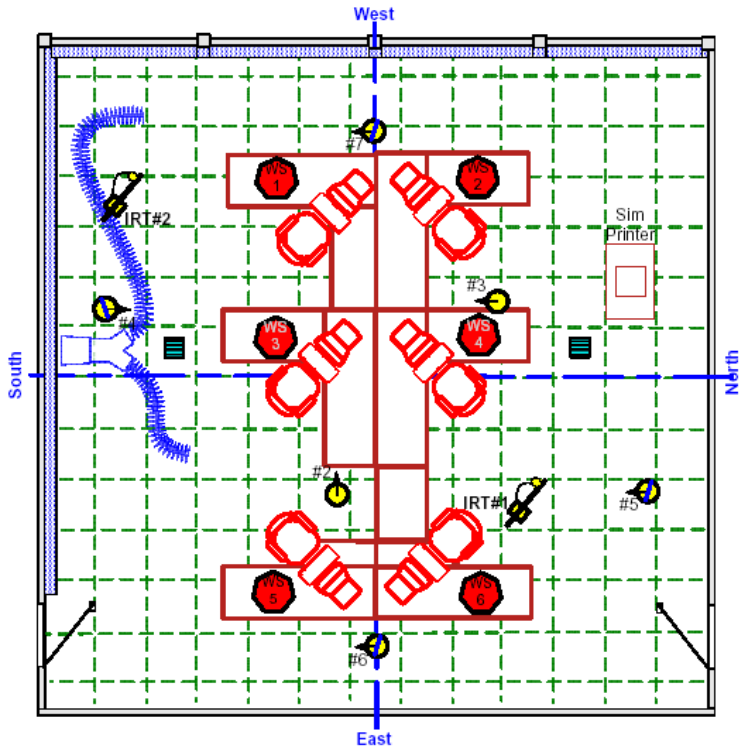

Figure 30: Test INT 8-18, 23.3°C (74°F), 6 WS, 2 VA

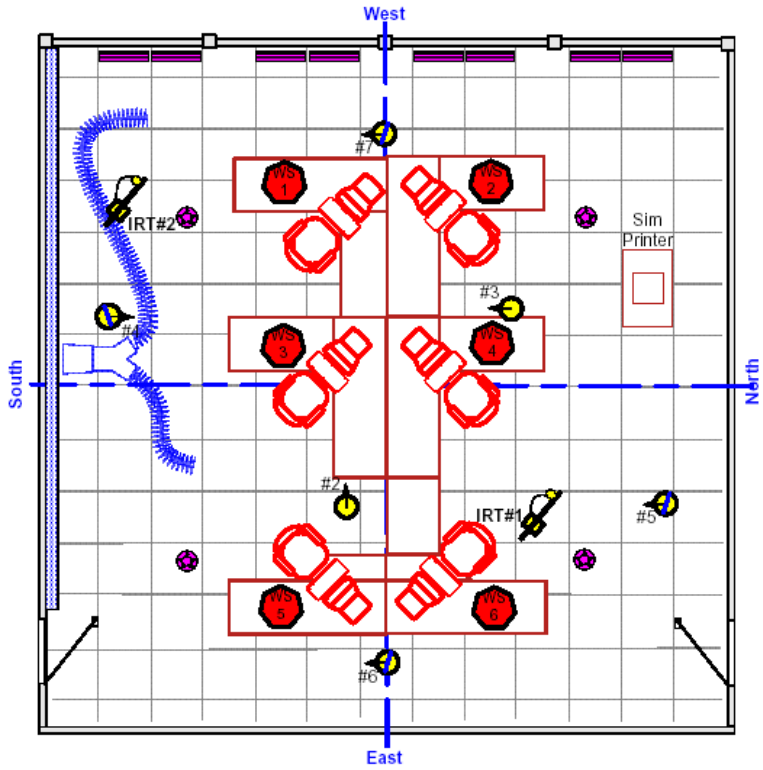

Figure 31: Test PER 8-19, 24.4°C (76°F), 6 WS, 4 SW, 8 LI, vanes at 53°, 2 solar

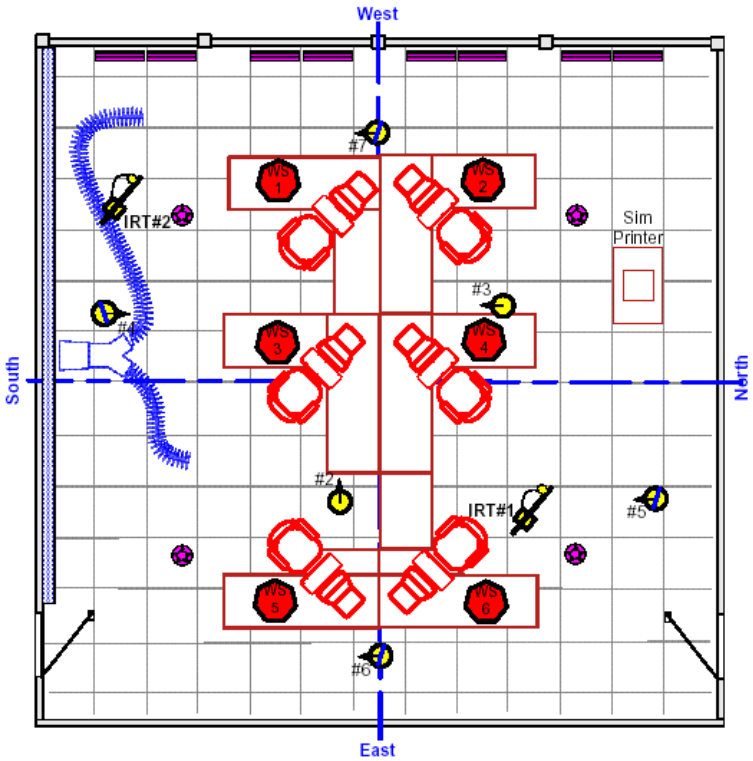

Figure 32: Test PER 8-21, 24.4°C (76°F), 6 WS, 4 SW, 8 LI, vanes at 90°, 2 solar

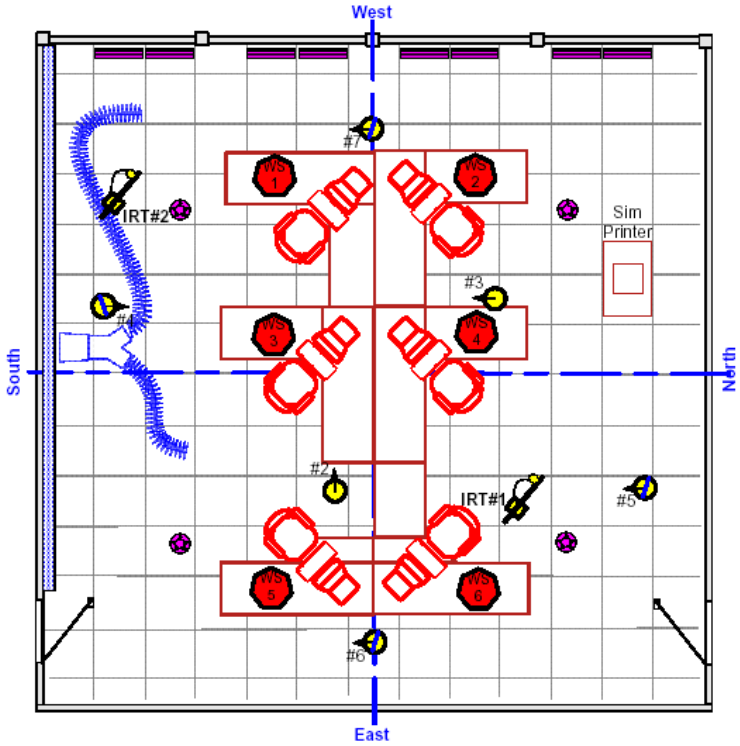

Figure 33: Test PER 8-20, 24.4°C (76°F), 6 WS, 4 SW, 8 LI, vanes at 90°, 1 solar

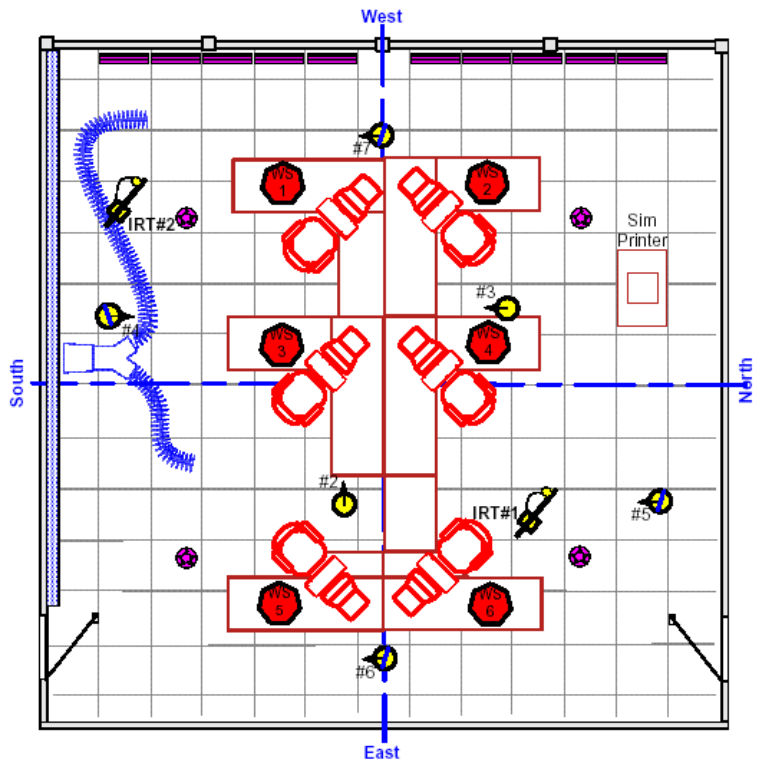

Figure 34: Test PER 8-22, 24.4°C (76°F), 6 WS, 4 SW, 10 LI, vanes at 53°, 2 solar

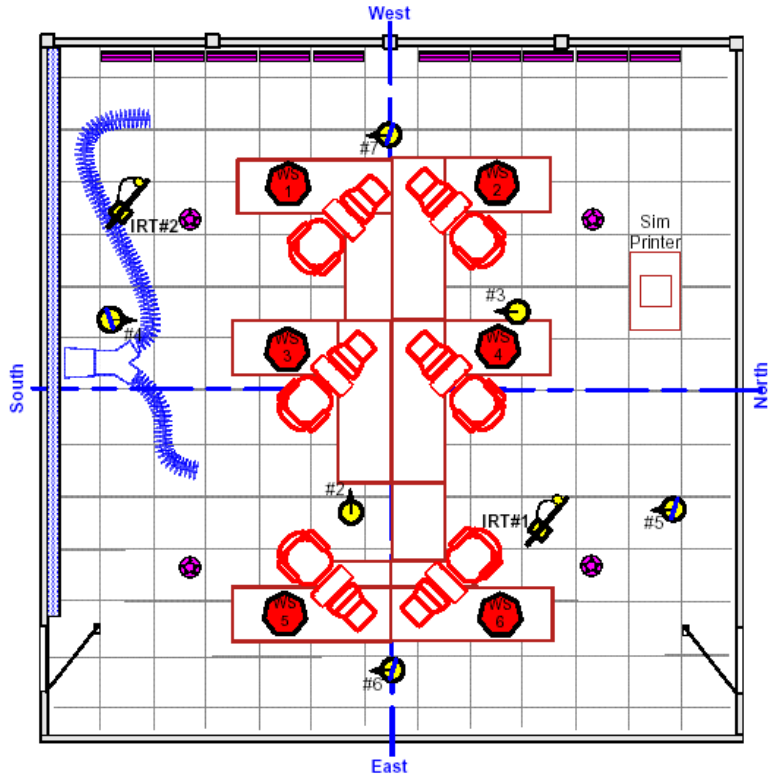

Figure 35: Test PER 8-23, 24.4°C (76°F), 6 WS, 4 SW, 10 LI, vanes at 90°, 1 solar

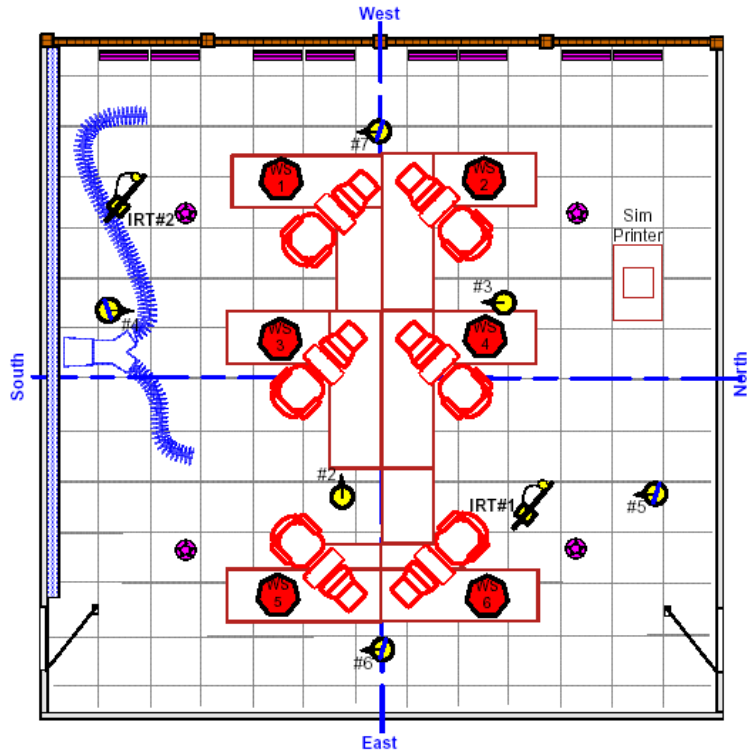

Figure 36: Test PER 8-18, 24.4°C (76°F), 6 WS, 4 SW, 8 LI, vanes at 90°, 2 solar

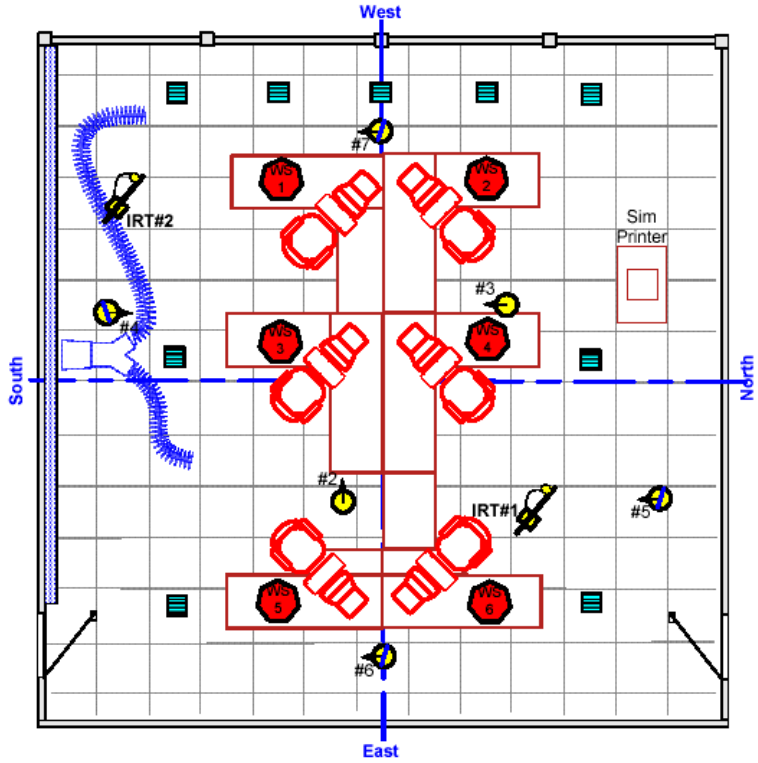

Figure 37: Test PER 8-2, 24.4°C (76°F), 6 WS, 9 VA, 2 solar

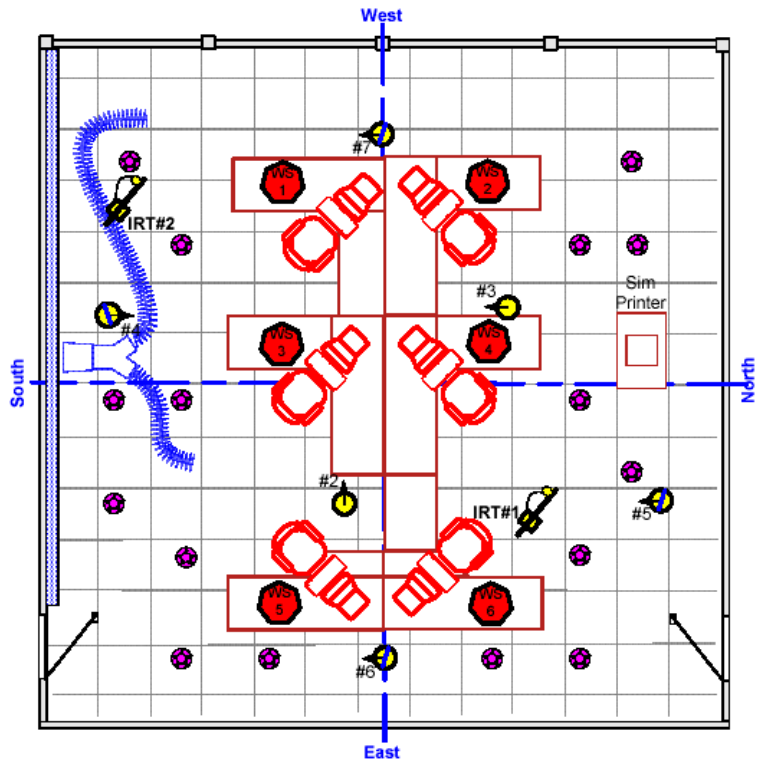

Figure 38: Test PER 8-11, 24.4°C (76°F), 6 WS, 16 SW, 2 solar

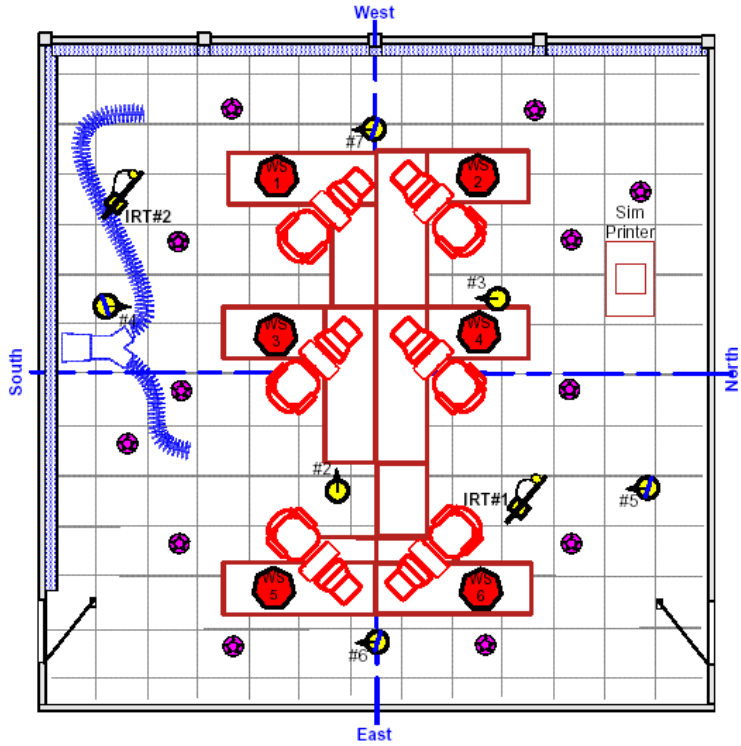

Figure 39: Test INT 8-12, 24.4°C (76°F), 6 WS, 12 SW

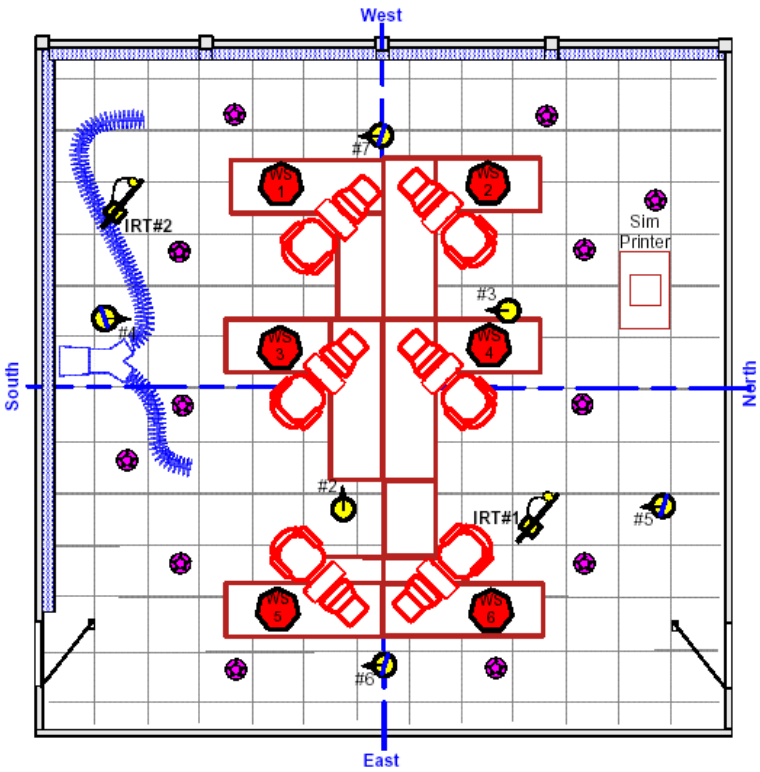

Figure 40:Test INT 8-14, 24.4°C (76°F), 6 WS, 12 SW, low emissivity ceiling

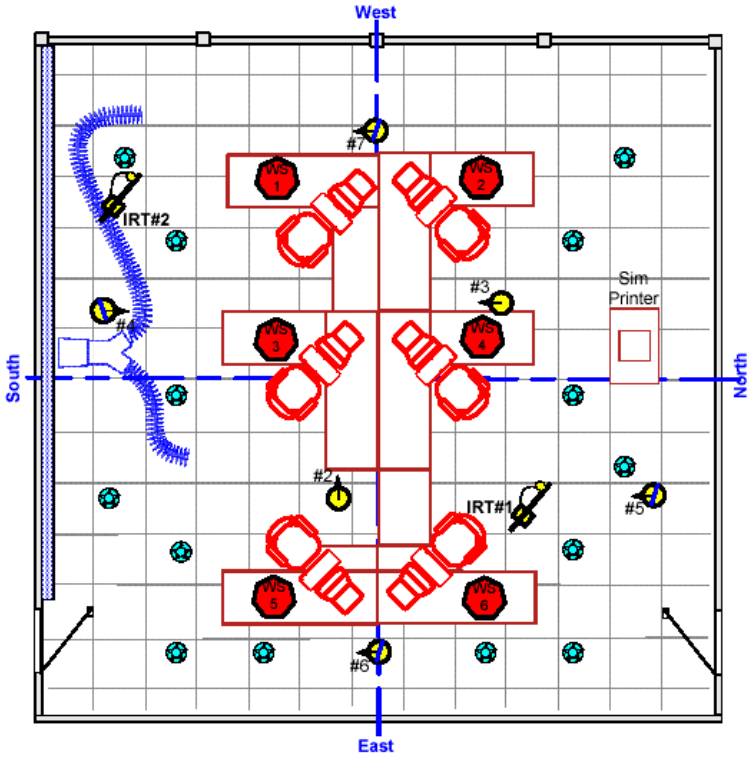

Figure 41: Test PER 8-14, 24.4°C (76°F), 6 WS, 14 DV, 2 solar

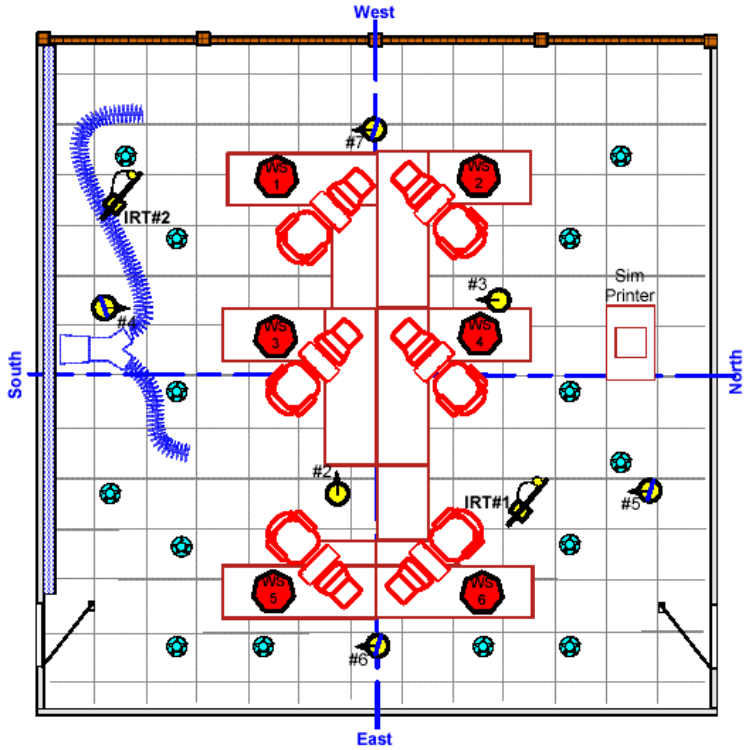

Figure 42: Test PER 8-15, 24.4°C (76°F), 6 WS, 14 DV, 2 solar, low emissivity ceiling

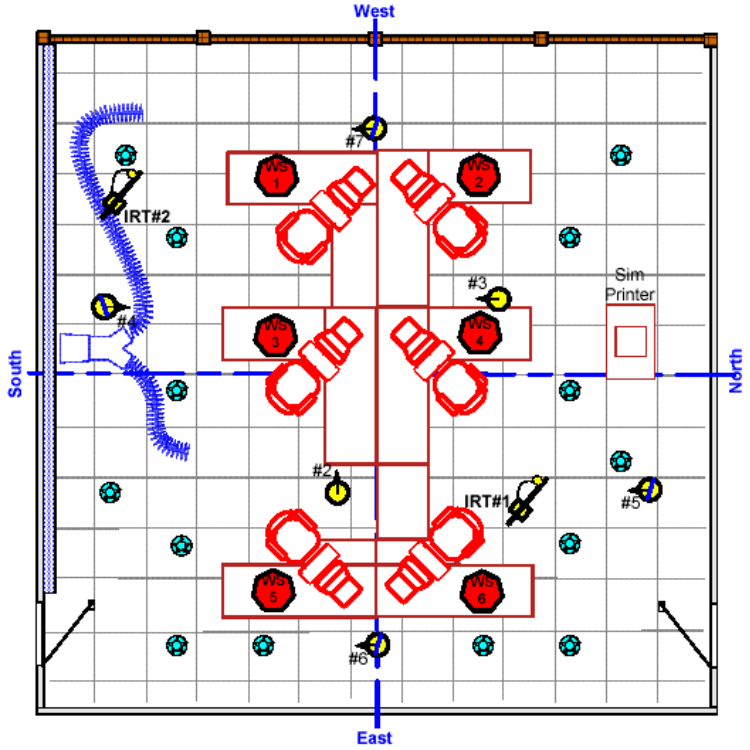

Figure 43: Test PER 8-16, 24.4°C (76°F), 6 WS, 14 DV, 2 solar

ENERGY PERFORMANCE OF UNDERFLOOR AIR DISTRIBUTION (UFAD) SYSTEMS PART II: ROOM AIR STRATIFICATION FULL SCALE TESTING

NORMALIZATION OF ROOM AIR STRATFICATION (RAS) PROFILES

When temperature plots from different tests are compared to one another it is difficult to identify performance differences due to variations in supply air temperature and room control point that occur during testing. Analysis is facilitated when these variations in driving parameters can be factored out so the differences due to design and operating parameters can be made more apparent. By a process we call "Normalization" we can make comparisons of RAS temperature profiles on an equivalent basis by adjusting the profile to a common supply air temperature and room control point. It should be noted that this process has not been fully rationalized in terms of theory, and most likely introduces some amount of error when the profiles are transformed. However, since in most cases the differences in operating parameters are relatively small, these errors are minimized.

B.1 RAS PROFILE CHARTS

To facilitate our analyses we plot the vertical temperature gradient in the room as shown by Figure B-1 . The curve is the RAS profile.

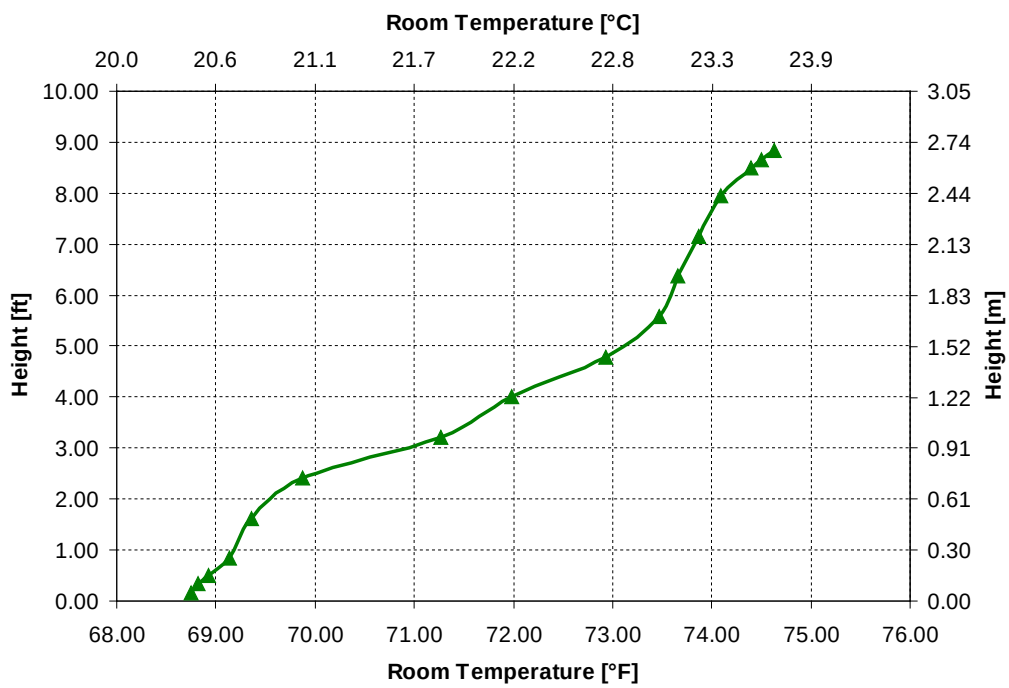

Figure B-1: Example plot for a room air stratification profile

The x-axis represents the time and spatially averaged temperature at a given height based on the thermocouple trees chosen in the Matlab HeaderMaker GUI. The y-axis represents the height, with a room height of about 2.7 meters (9 feet).

B.2 NORMALIZATION OF RAS PROFILES

The normalization method involves two calculation steps. First, we normalize the measured supply air temperatures (SAT) (i.e., diffuser SAT of airflow entering the room) are normalized to an identical, virtual supply air temperature, usually 18.3°C (65°F). We attempted to control each test to this SAT. In the second step we shift the measured temperature profile from the actual room control point to the specified set point. To verify the accuracy of this procedure, we compared normalized RAS profiles to measured RAS profiles with the same SAT and room set point.

B.2.1 NORMALIZING FOR SUPPLY AIR TEMPERATURE

The phi-curve (see Figure B-2) represents the ratio of the temperature difference between the room temperature at a given height and the supply air temperature divided by the temperature difference between the top of the room and the supply air temperature and has been defined in equation B.2-1

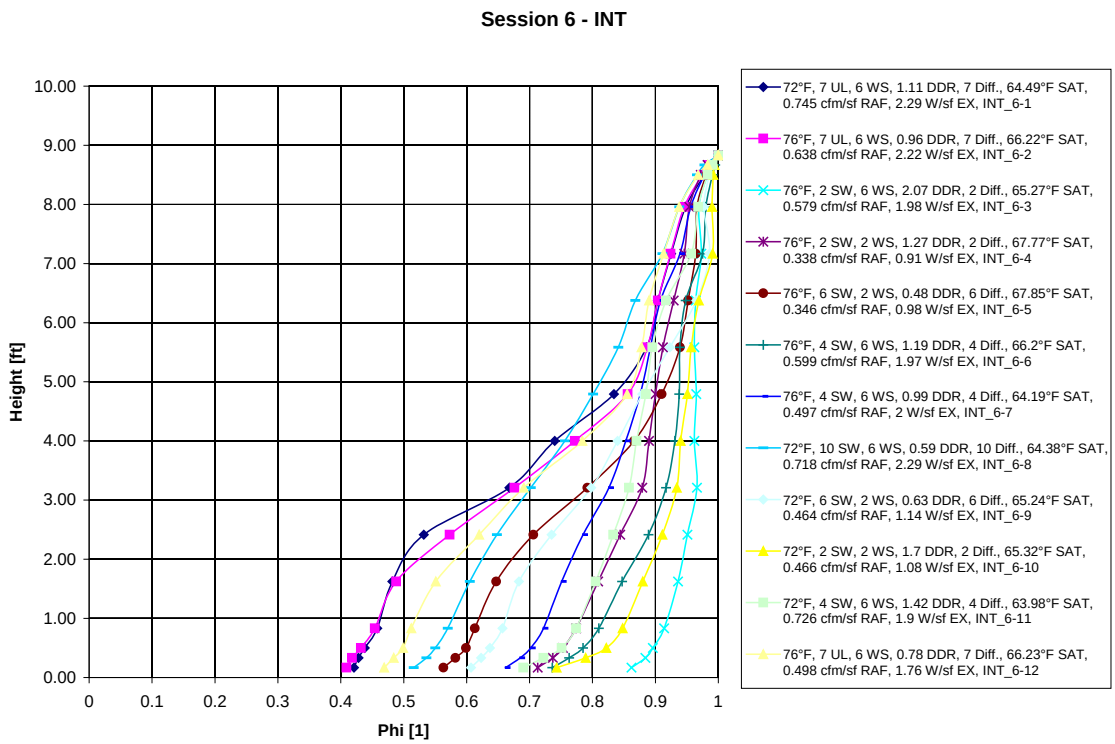

Figure B-2: Typical Phi curves showing Session 6 swirl diffusers

$$\Phi_i = \frac{T_i - T_{SAT}}{T_{top} - T_{SAT}} = const. \qquad B.2\text{-}1$$

Assuming that the phi-curve remains constant from one condition to the next, we can derive a new temperature difference ΔT_{room} between the top of the room and the supply air temperature by re-arranging equation B.2-1.

And if we assume that the temperature at the control point, $T_{4'}$ (at 4 ft for these tests) also does not deviate:

$$\Phi_{4'} = \frac{T_{4'} - T_{SAT}}{T_{top} - T_{SAT}} = const.$$

$$T_{4'} = \Phi_{4'} \cdot \left(T_{top} - T_{SAT}\right) + T_{SAT} = \Phi_{4'} \cdot \Delta T + T_{SAT}$$

$$\Delta T = \frac{T_{4'} - T_{SAT}}{\Phi_{4'}} \qquad (B.2\text{-}2)$$

$*\,T_{4'}$ = Temperature at the height of the thermostat (4 feet) for normalized supply air temperature

In Table B.2-1 we show the updated temperature difference between room top and supply air temperature. The data from this test will also be used to identify changes for the next calculation steps.

Table B.2-1: Determining ΔT_{room} of INT 6-1

Item	INT 6-1
Phi at 4' [1]	0.74
T at 4' [°C]	22.2
ΔT [°C], before	5.63
ΔT [°C], after	5.25

Test INT 6-1 has a measured temperature difference of 5.63°C (10.13°F). The change in supply air temperature from 18.04°C (64.48°F) to 18.3°C (65°F) decreases the temperature difference to 5.25°C (9.45°F).

To calculate the new temperatures at any height with the new ΔT due to the adjusted SAT, we can re-arrange equation (B.2-2):

$$T_i = \Delta T \cdot \Phi_i + T_{SAT} \qquad (B.2\text{-}3)$$

When we substitute the updated ΔT into equation (B.2-3) the temperatures at each height for the adjusted SAT are revealed. Table B.2-2 shows these results for test INT 6-1 and compares it to the measured data.

Table B.2-2: Comparison of temperatures for normalization in SAT

Tree Height		INT 6-1 measured		INT 6-1 norm. for SAT	
[m]	[ft]	[°C]	[°F]	[°C]	[°F]
2.69	8.83	23.68	74.62	23.57	74.43
2.64	8.67	23.61	74.49	23.51	74.31
2.59	8.50	23.55	74.39	23.46	74.22
2.43	7.96	23.38	74.09	23.30	73.94
2.18	7.17	23.26	73.86	23.18	73.73
1.94	6.38	23.14	73.65	23.07	73.53
1.70	5.58	23.04	73.47	22.98	73.36
1.46	4.79	22.74	72.93	22.70	72.87
1.22	4.00	22.21	71.98	22.21	71.98
0.98	3.21	21.81	71.26	21.83	71.30
0.74	2.42	21.04	69.87	21.12	70.02

0.50	1.63	20.76	69.36	20.86	69.55
0.25	0.83	20.63	69.13	20.73	69.32
0.15	0.50	20.51	68.92	20.63	69.13
0.10	0.33	20.46	68.82	20.58	69.04
0.05	0.17	20.42	68.75	20.54	68.97

Since the measured supply air temperature for INT 6-1 is not much different than 18.3°C (65°F), the difference in the newly calculated temperatures are not large; the difference at the top of the profile is about 0.11°C (0.2°F). As the offset increases, temperature differences between measured and calculated values will increase as well, causing the slope of the profile to either increase or decrease, depending on the supply air temperature (higher SAT than 18.3°C (65°F) will increase the slope, lower SAT will decrease it).

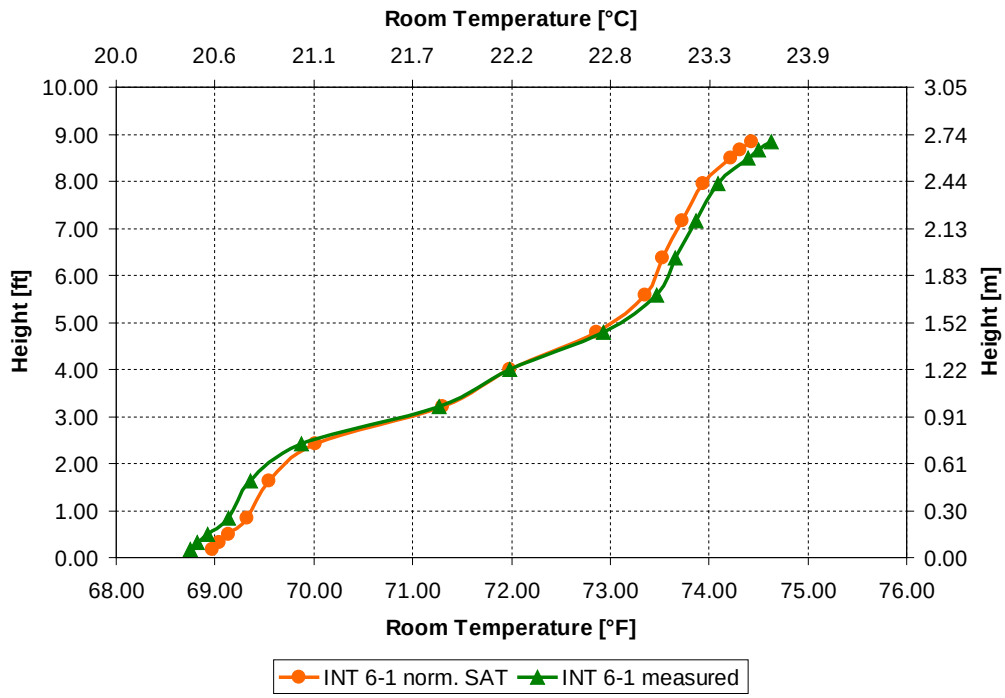

Figure B-3: Comparison of measured data and its SAT normalized temperature profile

Figure B-3 shows the difference in the temperature profiles. Due to the lower SAT of 18.3°C (65°F) for the measured data, the slope of the normalized temperature profile decreases in comparison to the original measured one. It is our hypothesis that this represents a real difference; if the test was conducted at these exact values of SAT and setpoint the profile would look like the normalized one. (See Normalization errors below)

If we assume that the extraction rate stays constant, the change in temperature difference between the air entering and leaving the room leads to a change in airflow as well (equation (B.2-4)). [1]

$$\dot{Q} = \dot{m}_{measured} \cdot c \cdot \Delta T_{measured} = const.$$
$$\dot{Q} = \dot{m}_{SAT\ norm.} \cdot c \cdot \Delta T_{SAT\ norm.}$$

[1] This is not strictly true for large changes in operating point (for the same internal gains) since greater return temperatures will result in more radiant exchange with the floor, thus lowering the extraction rate.

$$\dot{m}_{SAT\ norm.} = \frac{\Delta T_{SAT\ notm} \cdot c}{\dot{Q}} \qquad (B.2\text{-}4)$$

Since the temperature difference for this example test decreases, the airflow has to increase assuming that the room extraction rate remains constant.

Table B.2-3 demonstrates the change in airflow due to the normalization in supply air temperature. The airflow for this matter increases about 7% in comparison to the measured one.

Table B.2-3: Airflow differences due to normalization in SAT

Measured airflow	0.23 m³/s	503.6 cfm
SAT normalized airflow	0.26 m³/s	540.1 cfm

B.2.2 Normalizing for Room Set Point

The offset between setpoint and actual value makes it necessary, for the sake of comparison, to shift temperature profiles to either the cooler or warmer side.

ΔT_{room} was defined to be the temperature difference between the top of the room and the supply air temperature. If as before we assume constant Phi curves, then equation (B.2-5) can be developed through substituting in equation (B.2-2), normalizing the temperature profiles to a given setpoint at a specific height. We normalized all tests to the thermostat height of 1.22m (4ft).

$$T'_{top} - T'_{SAT} = \Delta T$$

$$\Delta T = \frac{T'_4 - T'_{SAT}}{\Phi_4}$$

$$\Phi_i = \frac{T''_i - T'_{SAT}}{T'_{top} - T'_{SAT}} = const.$$

$$T''_i = \Phi_i \cdot \left(T'_{top} - T'_{SAT}\right) + T'_{SAT}$$

$$T''_i = \Phi_i \cdot \left(\frac{T'_4 - T'_{SAT}}{\Phi_4}\right) + T'_{SAT} \qquad (B.2\text{-}5)$$

The apostrophes in the equations above indicate the step in the normalization procedure. One apostrophe refers to results from the supply air temperature normalization and two apostrophes refer to results from the room setpoint normalization.

Substituting the Phi values for each height into equation (B.2-5), we can find the temperatures for the normalized setpoint. Table B.2-4 and Figure B-4 show these results and the differences to the measured data for test INT 6-1. The setpoint in this case is 22.2°C (72°F).

Table B.2-4: Comparison of temperature normalized in SAT and setpoint

Tree Height		INT 6-1 measured		INT 6-1 norm. for SAT and setpoint	
[m]	[ft]	[°C]	[°F]	[°C]	[°F]
2.69	8.83	23.68	74.62	23.59	74.46
2.64	8.67	23.61	74.49	23.52	74.34
2.59	8.50	23.55	74.39	23.47	74.25
2.43	7.96	23.38	74.09	23.32	73.97
2.18	7.17	23.26	73.86	23.19	73.75
1.94	6.38	23.14	73.65	23.08	73.55
1.70	5.58	23.04	73.47	22.99	73.38
1.46	4.79	22.74	72.93	22.72	72.89
1.22	4.00	22.21	71.98	22.22	72.00
0.98	3.21	21.81	71.26	21.84	71.32
0.74	2.42	21.04	69.87	21.13	70.03
0.50	1.63	20.76	69.36	20.87	69.56
0.25	0.83	20.63	69.13	20.74	69.33
0.15	0.50	20.51	68.92	20.64	69.14
0.10	0.33	20.46	68.82	20.58	69.05
0.05	0.17	20.42	68.75	20.55	68.98

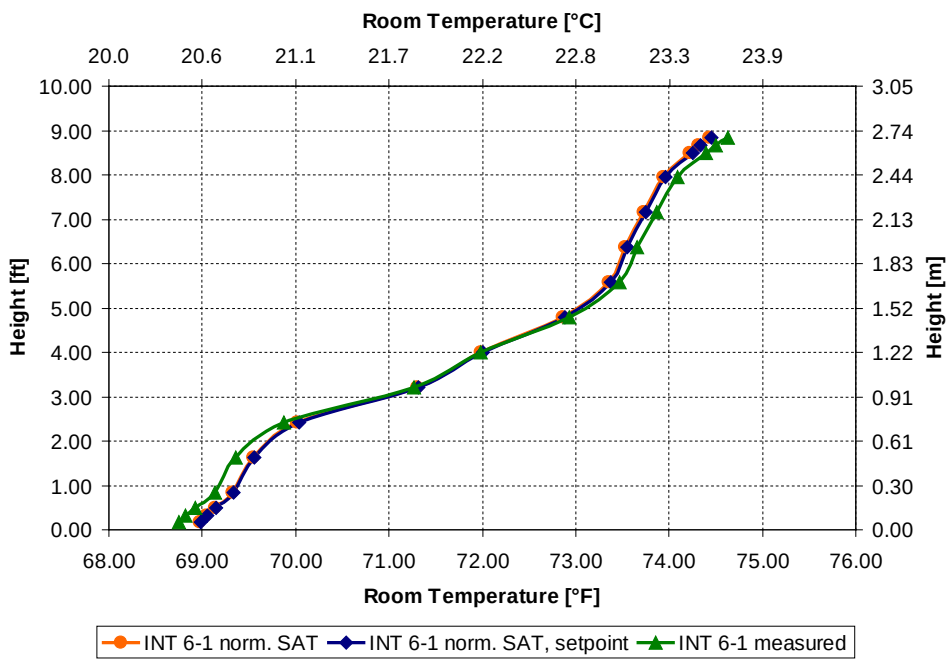

Figure B-4: Comparison of measured data and its SAT and setpoint normalized temperature profile

The chart above shows that there is little difference between the two normalized temperature profiles. This is due to the fact that the measured temperature at the control height was almost at the desired value of 22.2°C (72°F). For tests with larger offsets, the difference between the two normalized profiles will be more significant.

Also the airflow rate changes according to equation (B.2-4). The results are shown in Table B.2-5.

Table B.2-5: Comparison of airflow rates

Measured airflow	0.24 m³/s	503 cfm
SAT normalized airflow	0.25 m³/s	540 cfm
SAT and setpoint normalized airflow	0.26 m³/s	557 cfm

B.3 VERIFICATION OF NORMALIZATION PROCEDURE

To verify the accuracy of this procedure, we compared actual and normalized profiles for a variety of conditions. These examples represent a worst case evaluation because we are comparing over large control point temperature differences (e.g., set point from 72°F or 74°F or 76°F). Normally, we apply the procedure to a given test where the control point temperatures differences are very small compared to these. We also note that we only apply this method to tests where throw characteristics are similar between the two (see below for more detailed discussion). When we normalize a given test to standardized parameters, we avoid this issue.

B.3.1 HD SWIRL DIFFUSER COMPARISON

In this study we compared tests INT 6-1 and INT 6-2. These tests differ in the room setpoint, where INT 6-1 has its setpoint at 22.2°C (74°F) and INT 6-2 at 24.4°C (76°F).We conducted this evaluation by changing the setpoint of INT 6-1 in the normalization procedure to the setpoint of INT 6-2 and by matching the supply air temperatures:

Normalization parameters:	[°C]	[°F]
New SAT for INT 6-1 (measured for INT_6-2)	19	66.2
Measured SAT for INT_6-1	18.05	64.49
New setpoint for INT 6-1 (measured for INT_6-2)	23.9	75
Measured temperature at setpoint height	22.21	71.98

The results are presented in Figure B-5, the offsets between measured and normalized temperatures are shown in Table A.2-1.

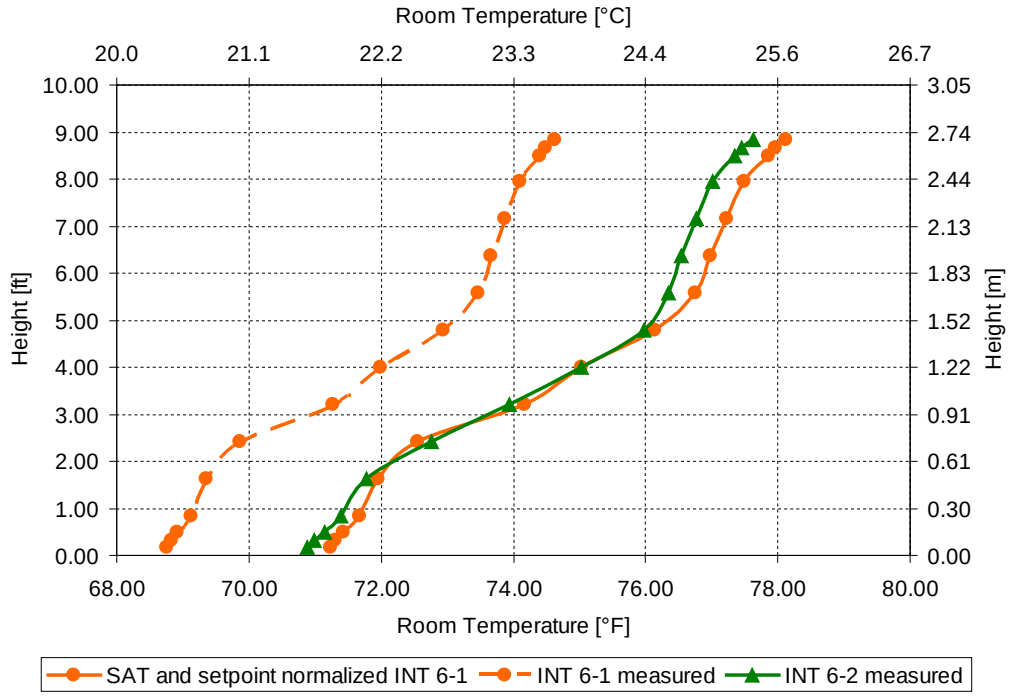

Figure B-5: Verification of normalization for DV diffusers

Table B.3-1: Error in normalization for HD diffusers

Tree Height		Normalization Error (Difference)	
[m]	[ft]	[°C]	[°F]
2.69	8.83	0.33	0.59
2.64	8.67	0.34	0.61
2.59	8.50	0.34	0.61
2.43	7.96	0.36	0.65
2.18	7.17	0.43	0.77
1.94	6.38	0.35	0.63
1.70	5.58	0.15	0.27
1.46	4.79	0.02	0.04
1.22	4.00	0.00	0.00
0.98	3.21	0.11	0.20
0.74	2.42	0.15	0.27
0.50	1.63	0.12	0.22
0.25	0.83	0.13	0.23
0.15	0.50	0.08	0.14
0.10	0.33	0.07	0.13
0.05	0.17	0.07	0.13

The results show that the method in this case is reasonably accurate. Although there is more error in the upper part of the profile in Figure B-5 , we believe the errors in the lower part are acceptable for the purpose of comparing tests of different design and operating conditions, especially since the temperatures in the occupied zone are more important for our analyses. In addition, these errors are most likely less than the measurement errors for a given profile (See forthcoming Appendix on measurement uncertainty).

B.3.2 Swirl Diffuser Comparison for Low Throw

To evaluate the generality of the normalization method, we compared two Krantz swirl diffusers with low throw to one another. We normalized INT 6-9 to the same supply air temperature and setpoint measured in test INT 6-5. The input values for INT 6-9 (same as measured values for INT_6-5) are shown below:

Normalization parameters:	[°C]	[°F]
New SAT for INT 6-9 (measured for INT_6-5)	19.9	67.9
Measured SAT for INT_6-9	18.5	65.24
New setpoint for INT 6-9 (measured for INT_6-5)	24.4	75.9
Measured temperature at setpoint height, INT_6-9	22.2	71.88

Results are shown in Figure B-6 and Table B.3-1.

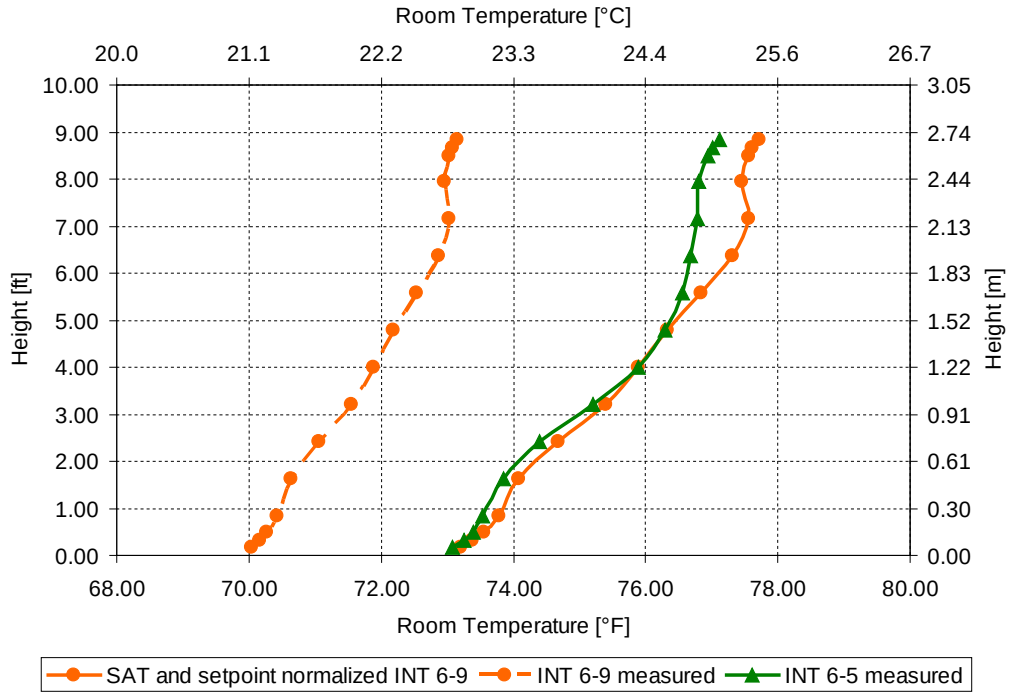

Figure B-6: Verification of normalization for swirl diffusers with low throw

Table B.3-2: Normalization errors for swirls with low throw

Height		Normalization Error (Difference)	
[m]	[ft]	[°C]	[°F]
2.69	8.83	0.33	0.59
2.64	8.67	0.34	0.61
2.59	8.50	0.34	0.61
2.43	7.96	0.36	0.65
2.18	7.17	0.43	0.77
1.94	6.38	0.35	0.63
1.70	5.58	0.15	0.27
1.46	4.79	0.02	0.04
1.22	4.00	0.00	0.00
0.98	3.21	0.11	0.20
0.74	2.42	0.15	0.27
0.50	1.63	0.12	0.22
0.25	0.83	0.13	0.23
0.15	0.50	0.08	0.14
0.10	0.33	0.07	0.13
0.05	0.17	0.07	0.13

Table B.3-2 shows that the maximum error is about 0.4°C (0.7°F), which occurs at the height of about 2.1m (7ft). However, in the lower zone the errors are less than 0.2°C.

B.3.3 SWIRL DIFFUSER COMPARISON FOR HIGH THROW

In this case, we used tests INT 6-11 and INT 6-6 to compare to each other. Both of these tests were carried out using swirl diffusers. INT 6-11 is calculated with the input parameters that were measured for INT 6-6:

Normalization parameters:	[°C]	[°F]
New SAT for INT 6-11 (measured for INT_6-6)	19.0	66.2
Measured SAT for INT_6-11	17.76	63.98
New setpoint for INT 6-11 (measured for INT_6-6)	24.5	76
Measured temperature at setpoint height, INT_6-11	22.21	71.98

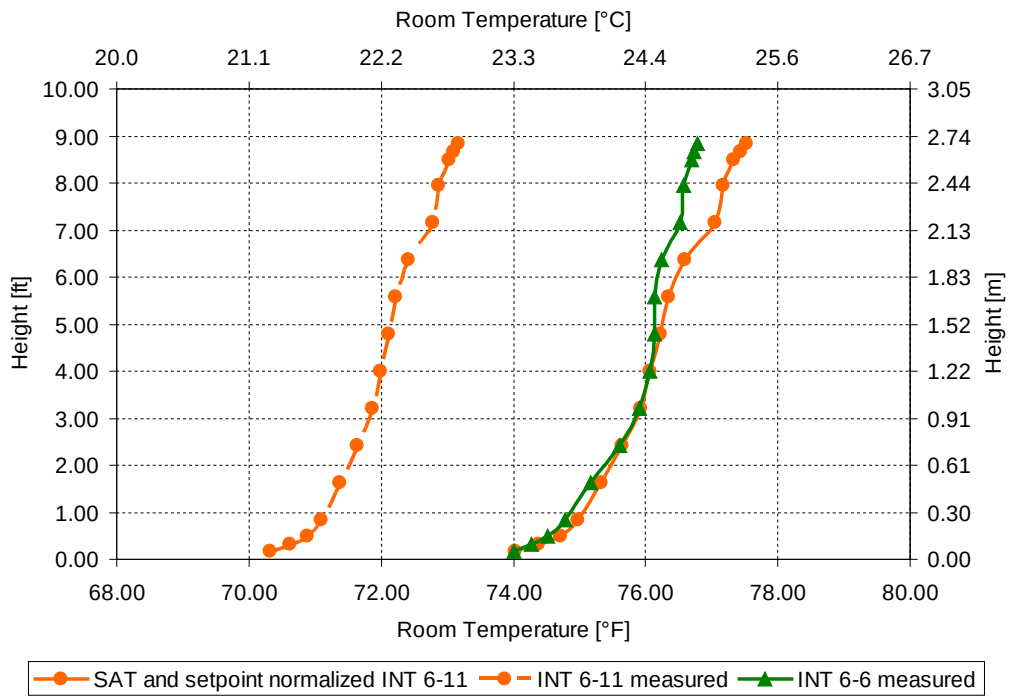

Figure B-7: Proof of normalization for swirl diffusers with high throw

Table A.2-3: Normalization error for swirls with high throw

Height		**Normalization Error (Difference)**	
[m]	[ft]	[°C]	[°F]
2.69	8.83	0.41	0.74
2.64	8.67	0.39	0.70
2.59	8.50	0.36	0.65
2.43	7.96	0.33	0.59
2.18	7.17	0.29	0.52
1.94	6.38	0.2	0.36
1.70	5.58	0.11	0.20
1.46	4.79	0.06	0.11

1.22	4.00	0	0.00
0.98	3.21	0.01	0.02
0.74	2.42	0.02	0.04
0.50	1.63	0.09	0.16
0.25	0.83	0.11	0.20
0.15	0.50	0.11	0.20
0.10	0.33	0.06	0.11
0.05	0.17	0.01	0.02

Again, the normalization procedure with errors of less than 2% is considered acceptable. The differences near the ceiling are a little bit higher than in the case of the DV diffusers, but tolerable.

B.3.4 Comparison Of Two Tests With Different Throw Characteristics (Unequal DDR)

All of the above comparisons used tests with a similar diffuser design ratio (DDR). DDR is defined to be the ratio of the measured flow per diffuser to its design flow (equation (B.3-1)) and is a characteristic of throw, i.e. the throw height.

$$DDR = \frac{\dot{m}_{measured}}{\dot{m}_{design}} \qquad (B.3\text{-}1)$$

Here we compare INT 6-7 with DDR = 0.99 to INT 6-8 with DDR = 0.59.

INT 6-8 is normalized to the conditions for INT_6-7:

Normalization parameters:	[°C]	[°F]
New SAT for INT 6-8 (measured for INT_6-7)	17.9	64.2
Measured SAT for INT_6-8	17.98	64.37
New setpoint for INT 6-8 (measured for INT_6-7)	24.2	75.5
Measured temperature at setpoint height, INT_6-8	22.52	72.55

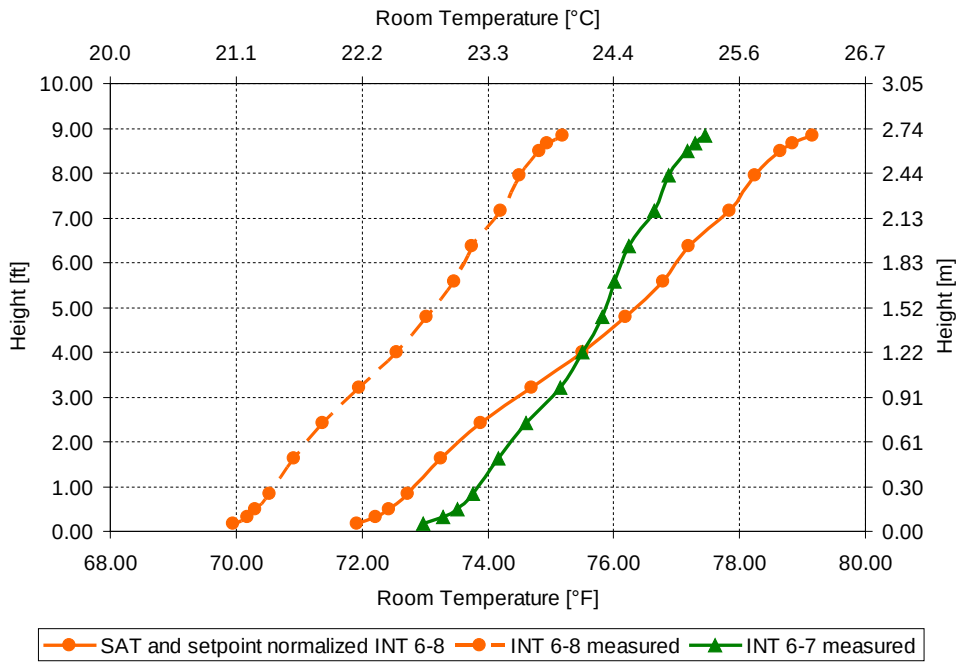

Figure B-8: Comparison of normalization for swirl diffusers with different DDR

Table B.3-4: Normalization error for swirls with different DDR values

Height		Normalization Error (Difference)	
[m]	[ft]	[°C]	[°F]
2.69	8.83	0.95	1.71
2.64	8.67	0.86	1.55
2.59	8.50	0.82	1.48
2.43	7.96	0.76	1.37
2.18	7.17	0.66	1.19
1.94	6.38	0.53	0.95
1.70	5.58	0.42	0.76
1.46	4.79	0.20	0.36
1.22	4.00	0.00	0.00
0.98	3.21	-0.25	-0.45
0.74	2.42	-0.40	-0.72
0.50	1.63	-0.51	-0.92
0.25	0.83	-0.58	-1.04
0.15	0.50	-0.60	-1.08
0.10	0.33	-0.59	-1.06
0.05	0.17	-0.59	-1.06

Obviously, a comparison between tests with different airflow and therefore DDR (for the same diffuser type) is not feasible as demonstrated in Figure B-9 and Table A.2-1. The offsets are too large and there is no obvious way to normalize two tests of this type. This leads to the following conclusion:

Normalization is only useful when throw characteristics are similar, i.e., DDR remains constant!

Since the amount of airflow either increases or decreases during the normalization procedure due to new ΔT_{room}, the DDR would change as well. In order to keep the DDR constant, the only thing that can be changed is the number of diffusers. For this particular reason, whenever normalized temperature profiles are presented, a legend will include a fictitious amount of diffusers (e.g. 4.7) allowing the DDR to remain constant.