


Air Leakage Test Report
EPA Region 8 Headquarters, Denver, CO

Fred Bauman, Tom Webster, and Darryl Dickerhoff

Center for the Built Environment (CBE)
University of California, Berkeley

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

On May 16-18, CBE researchers, in collaboration with EIG, Opus NW Management/GPT, and EPA, conducted air leakage testing of the pressurized underfloor supply plenum on the 7th floor of the EPA Region 8 Headquarters Building in Denver, CO. Key findings are summarized below in Table 1 and Table 2.

As shown in Table 1, the measured air leakage from the 7th floor indicates that the construction of the supply plenum was done to very high standards. Construction quality leakage (Category 1) contributes about 0.01 cfm/ft^2, and floor leakage to the room (Category 2) makes up the large majority of total leakage, even though it is also low at 0.16 cfm/ft^2 for a total leakage of 0.17 cfm/ft^2. In the fourth column, we show the leakage rates as a percentage of our estimated floor design airflow of 42,907 cfm at 0.05 iwc.

The results shown in Table 1 are based on CBE's new multi-path air leakage testing method. We have successfully demonstrated the potential of the multi-path method to provide greater detail about the air leakage through all major pathways from the underfloor plenum on the 7th floor. These included leakage to the following adjacent areas; (1) room (except for leakage at perimeter sill grilles), (2) room through cracks at perimeter window sill, (3) 6th floor, and (4) outside. The multi-path method gives a more realistic and accurate measure of each of the two air leakage types (Category 1: construction quality leakage, and Category 2: floor leakage to room). Leakage results are expressed as a function of pressure difference, allowing the determination of leakage under peak design conditions. Although we are continuing to research and develop this method, based on the results of this test, we recommend that the multi-path method be considered as part of revised leakage testing protocols.

Table 1: Summary of Air Leakage Test Results, 7th Floor, EPA Region 8 Headquarters based on multi-path method (Assumptions: 7th floor area = 29,892 ft^2, design plenum pressure = 0.05 iwc, design airflow = 1.43 cfm/ft^2;

	Leakage at design conditions		
Description	**Leakage Flow (cfm)**	**cfm/ft^2**	**% of Design**
Category 1 leakage	440	0.01	1
Category 2 leakage	4,720	0.16	11
Total leakage	5,160	0.17	12

Our review of the GSA test procedure indicated that there were two additional components of air leakage that would be added to the actual total, if the GSA protocol was followed without modification. Table 2 lists these two components: (1) leakage through manually closed diffusers, and (2) leakage due to incomplete sealing of perimeter grilles. As discussed in greater detail in the report, both of these "false leakages" represent airflow that resulted from the test methodology (e.g., incomplete sealing of leakage pathways), not from the actual construction or normal operation of the plenum. If both of these components were included in the total air leakage measurement, the result would have been 2.4 times the true air leakage amount. Also shown in this table are percentages of leakage flow based on the design airflow for the floor.

Table 2: Leakage including "False leakage" Sources, 7th Floor, EPA Building (Assumptions: 7th floor area = 29,892 ft^2, plenum pressure = 0.05 iwc, design airflow = 1.43 cfm/ft^2)

	Leakage at design conditions		
Description	**Leakage Flow (cfm)**	**cfm/ft^2**	**% of Design**
Total leakage (from Tab. 1)	5,160	0.17	12.1
False leakage from manually closed swirl diffusers	3,170	0.11	7.4
False leakage from incompletely sealed perimeter diffusers	4,220	0.14	9.9
Total including both false leakages	12,550	0.42	29.4

We recommend that the GSA procedure be modified to account for these findings with greater clarification on procedures to avoid potential errors.

INTRODUCTION

On May 16-18, 2008, CBE researchers working in collaboration with key personnel from Engineered Interiors Group (EIG), Opus NW Management/GPT, and the Environmental Protection Agency (EPA), conducted air leakage tests in the EPA Region 8 Headquarters Building in Denver, CO. There were two primary objectives for this testing:

1. Determine the characteristic air flow leakage rate from the underfloor air distribution system on the 7th floor, and
2. Using alternative testing methods assess the overall accuracy and effectiveness of the GSA leak testing protocol.

We begin this report with a description of the EPA building, a background description of the basic leakage types, discussion of airflow measurement methods, and a description of the GSA protocol. This is followed with a section that documents the results of all testing accomplished and includes discussions of these results and their implications for the GSA protocol. In the Appendices, we provide a detailed documentation of the test and calibration procedures and reprint the GSA Protocol.

DESCRIPTION OF EPA REGION 8 HEADQUARTERS BUILDING

The construction of the new EPA Region 8 Headquarters building was a collaborative effort between EPA, the U.S. General Services Administration, Opus Northwest, LLC, and Zimmer Gunsul Frasca Partnership and was designed to be a high-performance, environmentally responsible, and secure working space. The building received a LEED Gold certification in 2007. The 9-story, 418,300 gsf building (Figure 1) was completed and occupied in December 2006. It includes rentable office space, ground-level retail, and underground parking. The area breakdown is shown in Table 3. Unlike other GSA projects we have studied, the EPA headquarters building is privately owned and leased to EPA, with approximately 800 EPA employees and contractors occupying the office space. As indicated by Table 3, the first three floors of the building are served by an overhead (OH) air distribution system, while floors 4-9 are conditioned by an underfloor air distribution (UFAD) system. The building design incorporates a

Figure 1: EPA Region 8 Headquarters, Denver, CO

"double-L" floor plan wrapped around a central 9-story atrium space, allowing views to either the outside or central atrium from most locations of the predominantly open plan office space.

Figure 2 shows a schematic plan view diagram of the 6th floor (nearly identical to the 7th floor). The 7th floor has 29,892 ft^2 of conditioned floor area.[1] The diagram shows the atrium centrally located on the north half of the floorplate. Also shown are the two HVAC supply shafts, each serving four air highways that deliver and direct supply air into various regions of the open plenum. These shafts and air highways are shown in yellow on either side of the larger central return air shaft (shown in yellow). There are eight pressure sensors (small green circles) located in the large open underfloor plenum, each controlling the volume of air delivered by one of the eight supply air highways, as indicated, to maintain the desired plenum pressure setpoint.

Figure 2 also displays the design of the perimeter cooling and heating system. On the 7th floor, this consists of 21 underfloor fan-coil units, which are ducted to a series of linear grilles located in the window sills of the building. Each fan unit serves approximately 6-10 diffusers, depending on exposure and layout. The variable-speed underfloor fan boxes draw air directly from the plenum and use variable-air-volume (VAV) control to maintain the nearby perimeter thermostat at setpoint. During heating mode, a reheat coil provides warm air to the space.

[1] The net floor area is approximately equal to the gross floor area minus the atrium, shafts, etc.; in the remainder of the report, we assume the conditioned area is represented by the net area.

Table 3: EPA building floor area breakdown

Floor	Purpose	Gross area	Net area[1]
basement	Parking	106,400	102,330
1	First floor, (OH) (retail, lobby, services)	39,996	36,774
2-3	Offices, OH	77,891	64,015
4	Offices, UFAD	36,133	31,723
5	Offices, UFAD	32,867	29,053
6	Offices, UFAD	33,282	29,464
7	Offices, UFAD	33,282	29,892
8	Offices, UFAD	33,282	29,377
9	Offices, UFAD	20,303	17,691
	Total UFAD	189,149	**167,200**
	Total EPA	267,040	231,215
	Total building	413,436	370,319

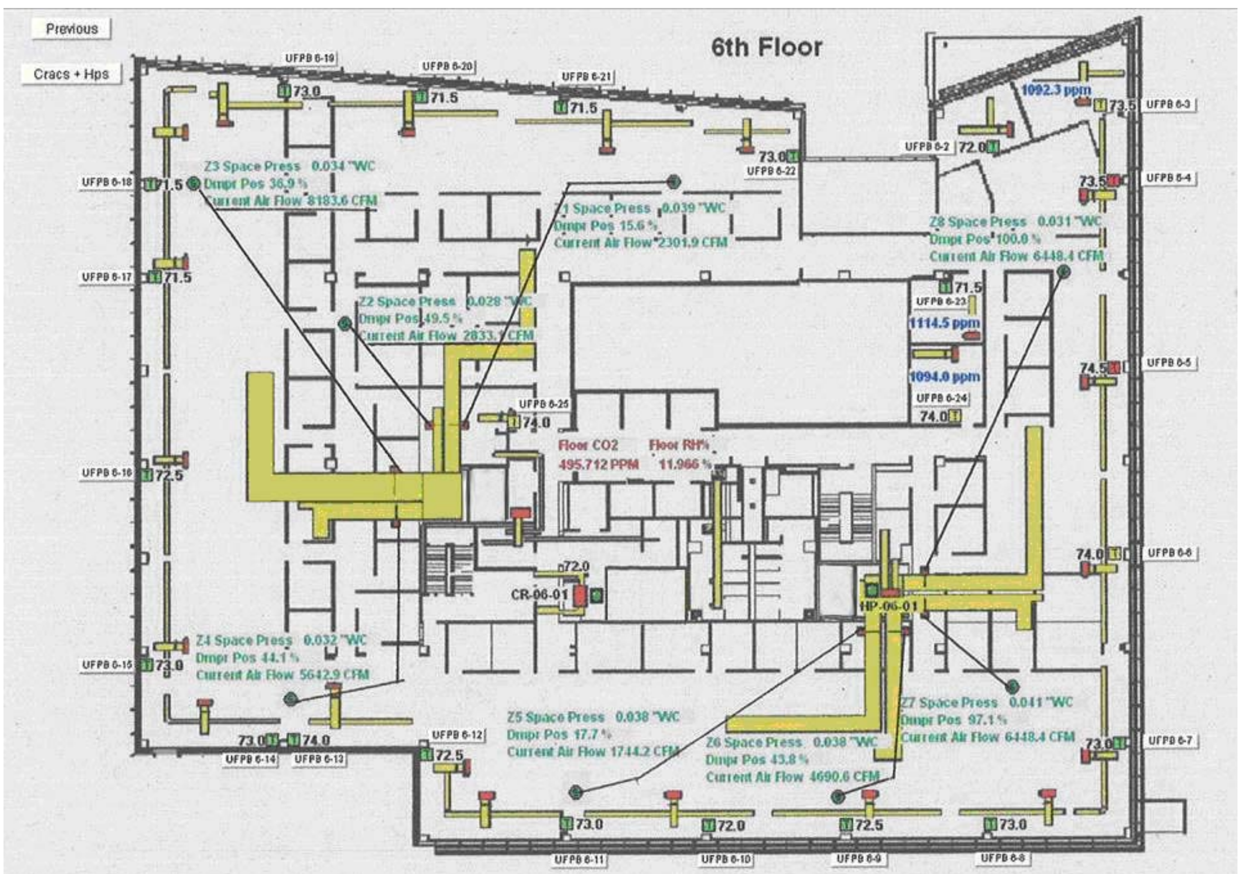

Figure 2: Schematic 6th floor plan taken from building automation system screenshot

BACKGROUND

LEAKAGE CLASSES

Air leakage from pressurized underfloor air supply plenums is one of the most important issues facing the UFAD industry. Evidence from completed projects indicates that uncontrolled air leakage from a plenum can impair system performance. In some documented cases, the amount of leakage has been substantial (greater than 50% of design airflow). To date, plenum air leakage has been divided into two primary types, as defined below:

1. **Category 1 – Construction quality leakage (**Figure 3): The most detrimental to system performance is leakage out of the plenum walls and joints that result in air passing through wall cavities, columns, and other short-circuiting pathways to the return plenum above, directly to the outside the building, or back to the return of the floor below via fire stops or other floor penetrations. These leaks represent air loss that is detrimental to the operation of the system, causing an increase in fan power, and possibly an increase in cooling load.
2. **Category 2 – Floor leakage** (Figure 4)**:** Leakage from the plenum through the raised floor into the occupied space is a class of leakage that has varying consequences depending on a number of factors. In general, this leakage is not necessarily detrimental to the operation of the system, and in fact, under certain circumstances may actually help the performance. However, if the leakage rate is large, or if it occurs at the wrong place (i.e., near an occupant) it may cause comfort problems. These leaks occur through floor panel gaps, electrical outlets and other floor openings, and joints at the edges of the floor and around columns.

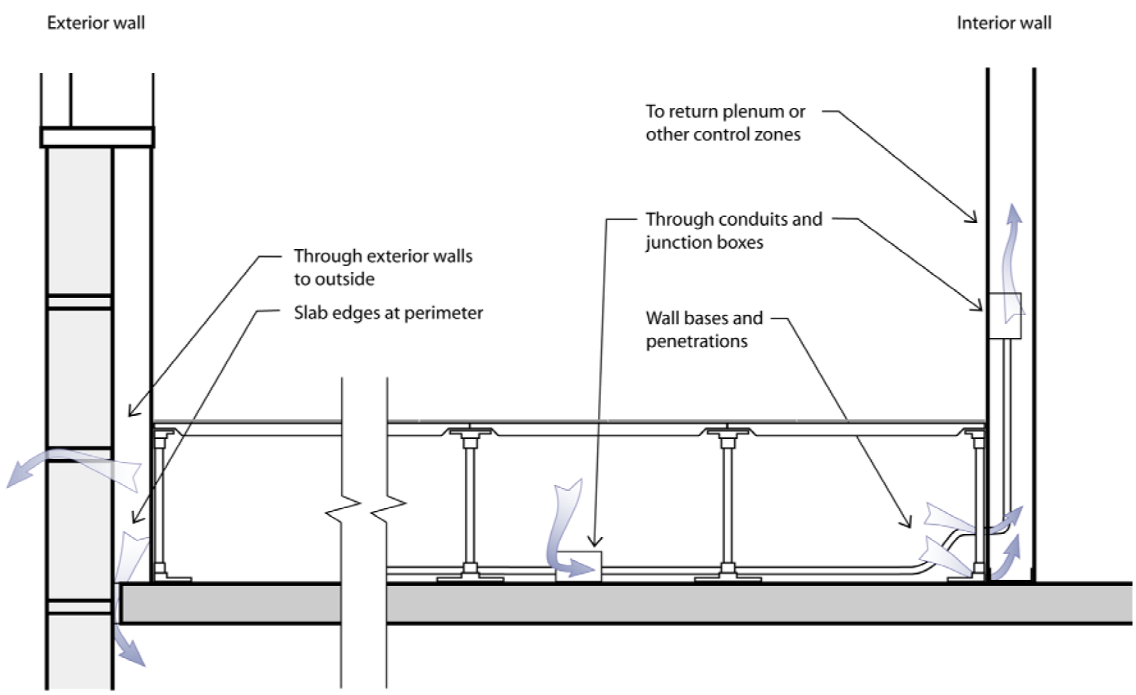

Figure 3: Category 1, or construction-quality, leakage

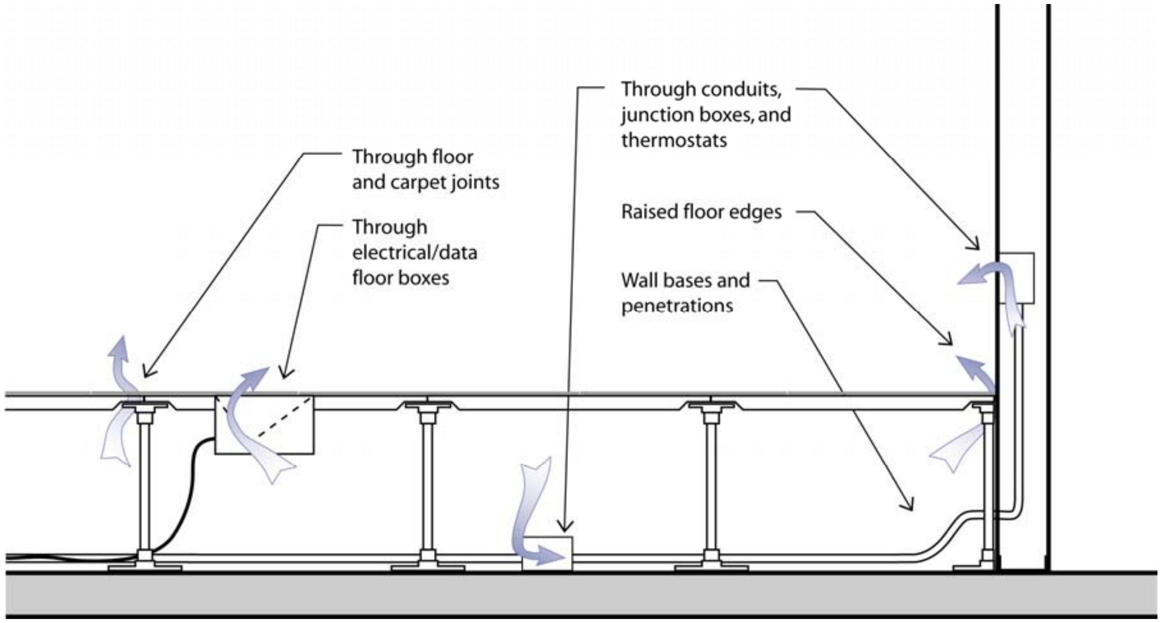

Figure 4: Category 2, or floor, leakage

LEAKAGE TESTING PROTOCOLS

While practitioners have used a variety of means to evaluate leakage in UFAD systems, there has been very little systematic research on this topic. Although the GSA protocol has been the most widely used method for this testing, based on our review and analysis described below, we believe it can be improved upon. Furthermore, it should be recognized that the overall goal of these methods is to establish a standardized leakage rating that best represents leakage under normal operating conditions. This is no easy task because of differences in design (e.g., some systems operate at constant pressure while others use variable pressure) and due to the dynamic nature of these systems during operation; this makes it more difficult to find one test condition that represents an average operating condition. Finally, it should be noted, that nobody has yet determined what the actual impact of the various types of leakage are on comfort or energy use. Until this has been established, we will not know what rates are acceptable.

GSA LEAKAGE TESTING PROTOCOL

To date in the building industry, the most frequently used air leakage testing protocol has been the one introduced a few years ago by the U.S. General Services Administration (GSA) as part of their effort to assemble a set of design guidelines for UFAD systems in GSA projects. [NIBS 2008] A copy of the GSA air leakage test method is included in Appendix C for reference purposes. As described above, one of our primary objectives of this testing was to conduct tests using the GSA protocol, and, using alternative test methods, to assess the accuracy and effectiveness of the GSA method. To our knowledge, the GSA air leakage testing protocol has not previously undergone a peer-review. In our description and presentation of the test methods and results below, we include a discussion of our evaluation of the GSA protocol along with any recommended changes or new methods.

CBE METHODS

As part of our work in developing commissioning guidelines for UFAD systems [CEC 2008] we are conducting research on leakage testing methods. To date we have reviewed a number of reports using various techniques and we will continue this effort in our ongoing studies. For the EPA project we have introduced a new method (that we call the multi-path method) that we believe represents a potential improvement over other methods. This method is in its formative stages and cannot be considered a final protocol at this point. However, we believe it overcomes a number of deficiencies in other methods we have evaluated and correctly represents Category 1 and 2 leakage rates. The leakage rates that we present for the EPA building are based on this method.

AIRFLOW MEASUREMENT

Air leakage testing in UFAD systems requires that the airflow, to the plenum zone being tested be delivered and accurately measured over the range of desired airflow rates typical of variable-volume operation. There are two primary methods of air delivery that have been used in practice:

1. *Building's air handling unit (AHU).* The installed airflow sensors for the building management system (BMS) (if they exist) must be calibrated (e.g., using a hot wire, pitot tube traverse, or calibrated fan, or by other alternative methods) to be able to record accurately the airflow entering the plenum zone being tested. When the AHU serves multiple zones, the airflow entering the plenum zone of interest must be isolated so the individual zone airflows can be measured accurately. This approach has the advantage of testing the plenum in the same way that airflow is normally delivered but can be challenging when the zone airflows are small, and the AHU flow sensors do not lend them selves to calibration easily.
2. *Contractor-provided blower panel assembly.* A separate fan unit (or multiple fans) is installed to blow air into the plenum being tested through one or more removed or specially fitted floor panels. This requires that all plenum inlets from the AHU be found and tightly sealed. This approach has the advantage that the quantity of air being delivered into the plenum zone of interest can be more easily controlled and accurately recorded with the (typically high quality) sensors that are part of the blower panel assembly.

In the case of the EPA building, each floor served by the UFAD system is configured to have a single open plenum across the entire floorplate (7th floor area = 29,892 ft^2). Due to the large size of this single plenum zone and resulting high range of required airflow for air leakage testing, it was decided to use the building's two AHUs that deliver air down each of the two supply shafts. As described further below, this required calibration of the 8 air highway flow measurement stations serving the 7th floor supply plenum.

AIR LEAKAGE TESTING: RESULTS AND DISCUSSION

To aid the reader in the following discussion, we have numbered the different tests and have labeled the ones conducted according to the GSA protocol **[*GSA*].** All other tests were developed for the specific objectives stated in the purpose statement.

TEST 1: DYNAMIC AIRFLOW TEST [*GSA*]

Purpose: As stated in the GSA document, the purpose of the dynamic airflow test is to verify that the capacity of the AHU will be sufficient to maintain the design airflow rate at the design static pressure of the plenum.

Discussion: As a general rule, it is a good idea to conduct a test like this prior to a major effort to perform comprehensive air leakage testing over several days (typically on a weekend, when the building is unoccupied). Potentially, a well conceived test like this could help identify with a minimal amount of effort any major problems (e.g., excessive leakage rates, or undersized AHU) that may impact the feasibility of and methods for detailed air leakage testing. If the test shows a clear mismatch between design airflows and plenum pressures, then additional diagnostic work is recommended to find and seal major leaks and/or confirm that the AHU is properly sized.

Design airflow: The GSA protocol does not clearly define several key issues related to this type of test. For example, the procedure requires the delivery of the design airflow, but does not specify what design airflow is intended. Although it refers to that shown on the Mechanical Schedule, it is not clear what design airflow is to be used; i.e., the central AHU or *building block load airflow;* a floor under test *floor block load* airflow, or the floor or zone *peak airflow.* It seems to imply that peak airflow should be used since it specifies that the testing be conducted at plenum design pressure; this makes sense because it is making a comparison on an apples-to-apples basis. However, if this is the case, it is unlikely that the AHU would be able to supply the *sum of all peak* airflows for the entire building since it is normally sized for block load conditions. Specifying that one floor be tested under peak conditions may be more appropriate but then it is more difficult to evaluate the results in terms of AHU performance. However, we believe it is more appropriate to determine leakage for typical operating conditions, not for peak conditions that only occur a fraction of the time. Further clarification of exactly what "design airflow" means, how to conduct this test, and how to evaluate the results, would help standardize this test. If the intent is to evaluate that adequate plenum pressures can be maintained (i.e., zones are not starved for air), a review of BMS trend logs may be more practical.

Diffuser positions in relation to design condition: The GSA method states that the dynamic test should be conducted with all floor diffusers and grilles within the AHU zone set at their original or "as is" positions (meaning full open, closed, or partially open). It is not clear how this original diffuser configuration matches up with the desired "design airflow." Also, no guidance is given regarding what to do with the perimeter grilles. Often, these grilles are served via ductwork by underfloor fan coil units and have no dampers to close or adjust. Again, further clarification is needed in the GSA protocol.

Steady state pressure measurements: Furthermore, the GSA method also specifies how steady state conditions are to be verified prior to recording air leakage measurements.

> *"Obtain static pressure measurements in the floor plenum at five minute intervals in each 1000 ft^2 of floor space within the zone being tested. Steady-state should be defined by at least six contiguous sets of readings of plenum static pressures that do not vary by more than +/- 0.005 in. wg. (1.2 Pa at each measurement location)."*

This procedure is impractical, and in fact unnecessary. In a normally operating UFAD system, measured pressures in the underfloor plenum will naturally propagate quite rapidly (within seconds). It is not necessary to wait five minutes between each separate pressure reading. A recommended procedure would be to collect the six (or even larger) consecutive readings with a short scan rate of something like 15 seconds, allowing each measurement to be completed within 1-2 minutes.

Moreover, in practical terms, the most likely source of longer term instability (non-steady-state conditions) will be due to the operation of the HVAC system under automatic control. It is therefore highly recommended that the controls be switched to manual mode for these air leakage tests. The first time this is done, it may be necessary to observe system performance over a longer period of time (e.g., 15 minute) to confirm that the system is under control and is operating in a steady condition (e.g., not in startup mode). But, once the manual control is working, the subsequent test conditions can be dialed-in and tested fairly quickly.

Number of pressure sensors: It is also not necessary to measure plenum pressure in each 1,000 ft^2 of floor space within the zone being tested. Since static pressures in open plenums are generally quite uniform (unless major obstacles or flow resistance are present), it is only needed to measure the pressure at enough locations to verify that no major variations are occurring. A good rule of thumb is at least one measurement per 5,000 ft^2 of floor space. A requirement of one sensor for each 1,000 ft^2 of floor space would have resulted in using 29 pressure sensors in the EPA building on the 7th floor.

EPA Test Results: In the case of the EPA building, which had been in operation for 1½ years before the air leakage test, we felt it was impractical to conduct a dynamic airflow test due to the many inconsistencies described above. However, based on the discussion above we derived our approach to analyzing leakage performance as follows: The design engineer for the HVAC systems of the EPA building stated that the UFAD system design airflow is 1.43 cfm/ft^2 which yields a design volume for the AHUs of 240,000 cfm. Allocating this to the 7th floor yields 42,907 cfm design airflow. Assuming the design pressure for the 240 swirl diffusers is 0.05 iwc and each of the 21 fan coil units has capacity of 1200 cfm, the floor *sum of peaks* airflow would be about 42,600 cfm, very close to the AHU design volume. Therefore, it appears that the system was designed on a sum of peaks basis, which suggests that we should determine the leakage at these conditions, i.e., at 0.05 iwc plenum pressure. However, these systems only operate at peak load conditions a small portion of the time so leakage at these conditions does not represent typical operating condition leakage. (And as stated before, this depends on the system design as well as its control and on actual operating loads.) Inspection of some operating data from the BMS shows that the average operating pressure for the plenum is about 0.035-0.040 iwc. We estimate that leakage under these conditions would be reduced about 15%, however, if we are consistent in our method we should compare this new leakage to the average operating airflow which should yield the same percentage leakage as shown for the design condition.

TEST 2: SEALED DIFFUSER TEST [*GSA*]

Purpose: The intention of this test procedure is to seal all openings that connect the underfloor supply plenum with the room (i.e., Category 2 leakage), leaving only Category 1 leakage.

Discussion: While the goal of separating Category 1 and Category 2 leakage is desirable, in practice Category 2 leakage pathways are not all easily sealed (i.e., it is not just limited to diffusers and PVD outlets). It is impractical to tape all gaps between floor panels on a large floor plate, such as the EPA building, and in addition, leakage into the room around the edges of the space (where the raised floor meets walls) is potentially the largest source for Category 2 leakage. The description of the GSA protocol for this test states that:

> *"…the floor panel and edge joints, the supply air diffusers and the cable floor (pvd) connectors should be tightly sealed…"*

This approach is also listed as being applicable to mockups of the pressurized plenum. If the mockup is not too large, then this may be more practical, but only if the carpet tiles have not yet been installed. The GSA protocol also states that

> *"…the purpose is to measure the air leakage rate at two specific static pressures in the plenum that are representative of design and operating conditions (i.e., 0.07 and 0.10 iwc (17.7 and 25 Pa))."*

Once the test configuration is set up, it is quite easy to vary the plenum pressures and airflows, and there is no reason to limit the number of individual steady state tests to two. In fact, during most of our tests, we conducted between 5-10 separate tests, allowing the development of a characteristic airflow vs. pressure equation for each leakage pathway being tested. It is also not necessary to test all the way up to 0.10 iwc, as once the leakage equation has been determined, it can be extrapolated to other pressures.

As described in our test procedures above, we sealed all floor diffusers (primarily swirl), perimeter linear grilles on the window sills, and some of the PVD floor outlets. We did not attempt to seal any gaps between floor panels or along the room edges where the floor panels meet walls. During these leakage tests, we monitored the pressure difference between the underfloor plenum and the room, as well as the 6th floor return plenum and the outside of the building, accounting for all major air leakage pathways from the underfloor plenum. This same multi-zone pressurization analysis will be used in Test 3 described below.

EPA Test Results: Table 4 summarizes airflow rates for all 7th floor plenum air leakage tests (Tests 2-6) that we conducted for the EPA building. For each major air leakage test configuration, we developed an airflow correlation of the form:

$$Q = k\,\Delta P^{n} \qquad (1)$$

Where:

Q is the leakage airflow rate (cfm)

ΔP is the pressure across the leakage pathway (iwc, or Pa]

k and n are regression coefficients (0.5<=n<=1)

Table 4 indicates that at a plenum static pressure of 0.05 iwc (in relation to the room), the sealed diffuser test resulted in an air leakage rate of 9,380 cfm, or 0.31 **c**fm/ft^2. If our attempts were successful to eliminate all airflow pathways entering the room through diffusers under normal operating conditions, this leakage amount would represent the total of Category 1 and 2 leakage as tested with all diffusers (interior and perimeter) sealed. However, due to the incomplete sealing of the perimeter system at the window sills, we discovered that this total measured airflow included an additional component of airflow that resulted from our test methodology, not the actual leakage characteristics of the plenum. See the Test 3 on multi-path leakage for an explanation of the breakdown of this rate.

Table 4: Airflow Measurement Results for 7th Floor (29,892 ft^2) of EPA Building
Results shown for plenum design pressure of 0.05 iwc, and design volume of 1.43 cfm/ft^2

Description	Airflow (cfm)	cfm/ft^2	% of Design	Comments
Design airflow, floor peak	42,600	1.43	100.0	From designer
Test 2: Sealed diffusers	9,380	0.31	22	All diffusers taped (Cat 1 + 2 leakage plus "false perimeter leakage")
Test 3: Multi-path tests To room To 6th floor To outside Through per. sill cracks	 4,720[2] 143 299 4,220	 0.161 0.005 0.010 0.141	 11.2 0.30 0.69 9.8	All diffusers taped (Sum of multi-path tests = Test 2)
Test 4: Manually closed diffusers	12,550	0.42	29	Perimeter diffusers taped; swirl diffusers closed but not taped; (Cat 1 + 2 leakage plus "false perimeter and swirl leakage")
Test 5: Fully open swirls	22,240	0.74	52	Perimeter diffusers taped (Test 2 plus 12,860 cfm open swirl airflow)
Test 6: Fully open swirls and perimeter diffusers	24,360	0.81	57	All tape removed; perimeter fan boxes off (Test 2 plus 14,980 cfm open swirl and perimeter airflow)

[2] It should be noted that to more accurately represent operating condition leakage, the closed diffuser leakage (based on an audit of number of diffusers that are closed in the "as is" configuration) should be added to the Category 2 value. To estimate this magnitude will require further research on closed diffuser leakage rates and the details of how diffusers are closed off; (e.g., we found a number of them that were closed with plastic bags, paper, carpet pieces, and trash cans).

In column 4, for reference purposes, we show percentage of design values based on the design airflow of 1.43 cfm/ft^2.

TEST 3: MULTI-PATH LEAKAGE TEST

Purpose: This is a new test method that we developed to measure leakage independently from GSA procedures. The purpose of this test is to simultaneously characterize airflow rates through all major leakage pathways from the underfloor plenum, including to the room (Category 2 leakage), to the adjacent 6th floor, and to outside the building.

Discussion: This approach uses a more realistic model of leakage from the underfloor plenum by measuring and determining the air leakage correlation for each major leakage pathway. Rather than limiting our attention and measurements to only the pressure difference between the plenum and room (leaving other pathways poorly determined), this measurement technique provides greater detail by modeling the total leakage from the underfloor plenum as the sum of several right hand terms from Equation (1) each representing the leakage through a major pathway. In the case of our tests in the EPA building, we used the following equation:

$$Q = k_1 * \Delta P_1^{\,n1} + k_2\ \Delta P_2^{\,n2} + k_3\ \Delta P_3^{\,n3} + k_4\ \Delta P_4^{\,n4} \qquad (2)$$

Where:

$k_i\ \Delta P_i^{ni}$ is the leakage contribution from each of the following four pathways:

i = 1, room through all openings except near perimeter grilles (see below)

i = 2, 6th floor

i = 3, outside

i = 4, room through cracks at perimeter sill grilles

For Equation (2) to be used successfully, the pressure differences governing the various pathways must be independently changed and sufficient data points taken to yield a good regression. Although it would be desirable to be able to hold one pressure (for example, the plenum/room pressure difference) constant, it is not necessary to do this as long as enough data points are collected. It is also quite difficult to do this in practice using a building's control system. In the EPA building, we manually adjusted the supply fan speed, return fan speed and 6th and 7th floor supply damper positions in different combinations to allow a range of differential pressures to be obtained for each leakage pathway. In the case of the outside, natural fluctuations in wind speed and direction provided the necessary pressure variations. Note that we added the 4th term in Equation (2) after discovering that there was significant leakage through cracks along the edges of the window sills even when the grilles themselves were sealed with tape. In this case the pressure driving flow through the leak is the same as to the room and the value of its flow exponent, n4, is forced to be equal to the exponent found in separate leakage tests of the perimeter fan/duct/diffuser system.

The advantage of the multi-path leakage test is that by developing a unique correlation for the leakage from the plenum to all openings, it can accurately predict true Category 2 leakage as a function of pressure difference. This can be accomplished without the difficulty of finding and sealing all such openings, a limitation of the GSA protocol.

EPA Test Results: Table 4 summarizes the test results for Test 3 for each of the four contributing air leakage pathways for the 7th-floor plenum at a pressure of 0.05 iwc. Note that as these measurements were made with the same "sealed diffuser" configuration as the first test, the sum of these four leakage components equals the total airflow of 9380 cfm obtained in the "sealed diffuser" Test 2 (@ 0.05 iwc). Several significant observations can be made:

- Leakage to the 6th floor and to the outside (equal to Category 1 leakage) is extremely small at 442 cfm and is just over 1% of the design airflow rate of 1.43 cfm/ft^2 (see Table 1).
- Nearly half of the total leakage is through cracks along the edges of the window sill. This leakage was created when we taped over the perimeter linear grilles, thereby diverting the air out through the unsealed cracks on both edges of the window sills. Since the intent of taping over the grilles was to prevent any airflow from entering the room, this leakage can be considered as a “false leakage” resulting from our inability to seal the perimeter diffusers completely. In normal operation the pressure at this leak site is determined by the operation of the perimeter fans and is not well coupled to the underfloor plenum pressure and in fact may be minimal compared to the opening of the perimeter diffuser itself. As discussed further below, it should be subtracted from the measured leakage to obtain the true Category 2 leakage to the room.
- Leakage to the room (except for the perimeter crack leakage described above) represents the true Category 2 leakage and was measured to be 0.16 cfm/ft^2, or 11.2% of the design airflow of 1.43 cfm/ft^2, as listed in Table 1.

Figure 5 is a chart that shows the regression curves that resulted from the multi-path analysis. The various curves show total measured leakage as a function of plenum/room pressure difference for different combinations of pressure differences along the other two air leakage pathways: to the 6th floor and to the outside. These results demonstrate that you can obtain a different measurement result for total leakage depending on the pressure differences that exist along all leakage pathways at the time of the measurement, not the plenum/room pressure difference alone.

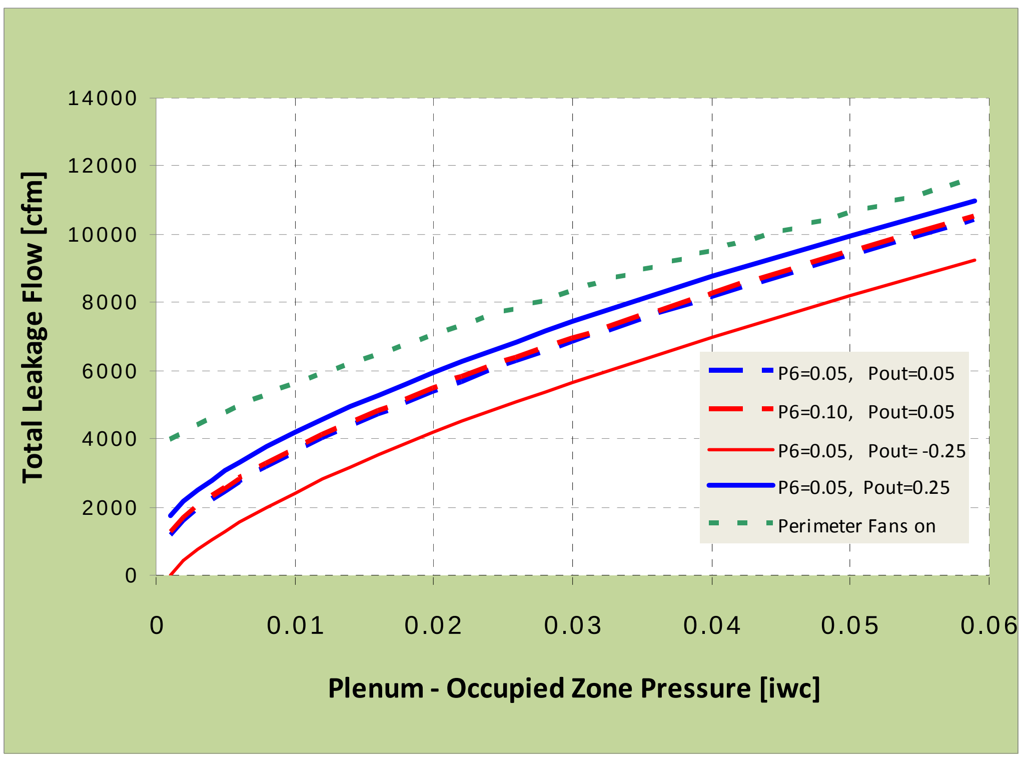

Figure 5: Leakage flow rates for selected pressure differences per leak path where P6 = pressure difference to 6th floor, and Pout = pressure difference to outside

TEST 4: MANUALLY CLOSED DIFFUSER TEST [*GSA*]

Purpose: The purpose of this test is to measure the total (Category 1 and Category 2) leakage from the underfloor plenum.

Discussion: In the GSA protocol (see Appendix A) the method of "closing" all diffusers is described as follows:

> *"All floor diffusers and grilles, whether automatically or manually controlled, should be adjusted to their fully closed design positions."*

While all swirl diffusers and common VAV diffusers have dampers that can be manually set to their closed position, this description does not address perimeter systems consisting of underfloor fan-coil units ducted to perimeter linear bar grilles. If nothing is done to seal this airflow pathway, even with the fan unit off, their will be considerable airflow when a positive pressure is maintained in the underfloor plenum. How to seal perimeter systems of the type installed in the EPA building (or any other configuration not covered) should be clearly described in any recommended air leakage test protocol. We interpreted the intent of this test is to close off any airflow through the perimeter system and therefore we taped all perimeter grilles.

It is well known that manually closed swirl diffusers, as well as other common VAV diffusers with dampers, do not close off completely. By including this additional airflow amount in the total leakage measurement, the GSA protocol is adding a "false leakage" to the result. In practice, there would never be a situation where all diffusers were closed while maintaining a design pressure in the plenum. We recommend that the component of leakage associated with the manually closed diffusers be subtracted from the total to provide a more accurate measurement of air leakage, and in particular the Category 2 leakage.

EPA Test Results: Table 4 lists the result for the manually closed diffuser Test 4 as 12,550 cfm @ 0.05 iwc. The significance of this is that if we used the GSA method for measuring the total of Category 1 plus 2 we would have inadvertently included an additional 3,170 cfm (12,550-9,380 cfm) of "false leakage" airflow (0.11 cfm/ft^2) to the total. When combined with the false leakage from the improperly sealed perimeter diffusers, we estimate that the total measured Category 1 plus 2 leakage (12, 550 cfm) is 2.4 times the true total air leakage (5,160 cfm), as shown in Tables 1 and 2. To explore ways to account for this extra leakage we measured the leakage from an individual swirl diffuser in the manually closed position; we report these results below in the Single Swirl Diffuser section.

TEST 5: FULLY OPEN SWIRL DIFFUSER TEST

Purpose: The purpose of this test was to determine the feasibility of measuring total leakage from the plenum without taping the diffusers.

Discussion: The idea behind this test is to measure the total airflow including swirl diffusers in their fully open position. Then the airflow through each open diffuser is estimated by either using manufacturer's performance data, or (in our case) direct measurement using a powered flow hood (see Figure 9). By counting or otherwise estimating the number of swirl diffusers in the plenum zone being measured, the total flow through the fully open diffusers can be calculated by multiplying the number of diffusers times the flow per diffuser.

EPA Test Results: Table 4 lists the result for the fully open swirl diffuser Test 5 as 22,240 cfm @ 0.05 iwc. In the case of the 7th floor of the EPA building, we counted approximately 240 swirl diffusers. This means that 12,860 cfm of total airflow (22,240– 9,380) is being delivered through the open swirl diffusers at 0.05 iwc. The manufacturer lists 72.6 cfm as the expected airflow through an open diffuser at this pressure. From our single diffuser measurements (described below in the Single Swirl Diffuser section) we computed an average airflow of 69.1 cfm per diffuser. Applying these two diffuser flows to the 240 diffusers on the 7th floor results in estimated airflows through the open diffusers of 17,424 and 16,594 cfm, respectively, a difference of 5%. However, during our inspection and measurement of several swirl diffusers, we determined that the damper of the swirl diffusers (consisting of concentric slotted baskets below the floor grille) were not consistently fully open, even when the floor grille had been rotated to its "fully open" position. This was due to problems with the rotating mechanism, and in some cases, the installed stops within the diffuser basket had been broken. Also, we are not sure that every diffuser was open during this test since some were sealed with paper or plastic by the occupants to control noise or airflow. Therefore, we do not know the exact number of open diffusers or the proportion of diffusers that were in this "partially fully open" condition so we cannot rely on the average of 69.1 cfm to be an accurate representation of the entire floor plate. While the 5% difference shown above indicates that this method has promise we believe that more research is warranted before we can recommend this method.

TEST 6: FULLY OPEN SWIRL AND PERIMETER DIFFUSER TEST

Purpose: The purpose of this test was to determine the difference in airflow between the previous test (with perimeter grilles taped) and this test (with tape removed from the perimeter grilles) to check the magnitude of perimeter diffuser "false leakage" if the perimeter diffusers had not been sealed in a GSA closed diffuser test.

Discussion: Because the GSA-protocol does not specifically address sealing the perimeter system, this flow might, in some cases, be reported as leakage and distort the leakage results.

EPA Test Results: Table 4 lists the result for the fully open swirl and perimeter diffuser Test 6 as 24,360 cfm @ 0.05 iwc. It would appear that not sealing the perimeter diffusers (but sealing the window sills) would only have resulted in 2,120 cfm of "false leakage". However when the diffusers were untapped the pressure at the window sill leakage site dropped dramatically leading to considerable uncertainty under actual operating conditions; further research is warranted to understand these types of leakage better. This result suggests that the sill leakage when the diffuser is sealed is roughly equivalent to the airflow from the unsealed diffusers driven by underfloor pressure. It is unlikely that this configuration of sealing would be done during normal leakage testing but serves as an example of the difficulties of determining leakage by successive sealing of parallel leakage paths.

TEST 7: PERIMETER FAN BOX/DIFFUSER TEST

Purpose: The purpose of this test was to characterize the air leakage associated with 2-3 perimeter systems, consisting of an underfloor fan-coil unit with connecting ductwork to an array of 5-10 perimeter linear grilles located in the window sills.

Discussion: No guidance is specifically given in the GSA protocol on how to deal with perimeter diffusers. As discussed earlier, the GSA method requires that all diffusers be *manually adjusted* to their closed position, even though most linear bar grilles (commonly used in perimeter zones) have no such adjustment. More guidance is needed as it relates to perimeter system testing. Furthermore, the EPA building has a unique perimeter system configuration that requires extra testing and analysis to be understood. Instead of installing the perimeter linear grilles on the floor, they are installed in the window sills, creating a situation where there is an increased chance for leakage from the ducts connecting the fan boxes and perimeter grilles, especially as they pass through the wall cavity below the windows. Because of this added complexity, we conducted separate air leakage tests on three fan boxes and their associated sill grilles. We used the results from these three units to extrapolate our air leakage results to the entire perimeter of the 7th floor.

During the course of these tests, we discovered that the perimeter window sills had a unique design in which the grille openings were actually cut directly into the sill plate (see Figure 13). The sill plate formed a cap on the top of the perimeter wall below the window, but did not form a solid seal over the duct built into the wall serving the grilles. The result was that when we applied tape over the sill grilles, significant airflow was still able to leak into the room through these gaps or cracks along the edges of the sill plate. In our testing we discovered this extra leakage and were able to account for it in our analysis. Our testing method included additional measurements when we completely taped and sealed all cracks along the window sills of three of the 21 perimeter fan units. Since this extra leakage was created only when we unsuccessfully taped the perimeter grilles shut during the sealed diffuser test, we recommend that it be subtracted from the total leakage measurement to obtain the true leakage from the plenum.

EPA Test Results: There were two configurations of window sill flow: one where file cabinets partially blocked the flow path and one where the window sill cap overhung the wall. In the former case we measured a leakage rate of 0.37 cfm/inch of perimeter at 0.05 iwc and for the latter 0.80 cfm/inch. Applying this to the total perimeter yields an estimated leakage of 4,420 cfm. We obtained virtually the same leakage with the multi-path pressurization test method at 4,220 cfm (see Test 3). This close agreement of the two methods is an indication of the potential of the multi-path pressurization test method.

TEST 8: SINGLE SWIRL DIFFUSER TEST

Purpose: The purpose of this test was to measure the airflow from a single swirl floor diffuser over the range of manually closed to fully open.

Discussion: As mentioned earlier, during our testing and inspection of the swirl diffusers, we discovered substantial range of variability in the actual position of the diffuser damper (e.g., not quite closed, or not quite fully open) when adjusted by rotating the diffuser face. This inconsistency makes it difficult to accurately extrapolate single diffuser data over a larger floor plate area.

EPA Test Results:

Fully open diffusers: We measured the fully open flow at 0.05 iwc from three floor diffusers and obtained rates of 55, 75 and 77 cfm, respectively with an average of 69.1 cfm. As noted above, these varied due to differences in how the diffuser damper operated. In some cases they could not open 100% and in other cases the "fully open" adjustment actually went past the optimal spot and started closing them again. The manufacturer's value of 72.6 cfm might be achieved if the damper could actually be set to maximize the air flow.

Fully closed diffuser: Our measurement of air leakage from one manually closed swirl diffuser was lower than the lowest flow that our device was capable of measuring, 32 cfm. The actual leakage flow was probably significantly lower. Assuming a worst case of 32 cfm, when multiplied by the number of swirl diffusers on the 7th floor (~240), the closed diffuser leakage would be estimated to be 7680 cfm, which is much higher than the 3,170 cfm we measured during the manually closed diffuser test. Further research needs to be done to improve the measurement capability of low flows. We used the lower value (3,170 cfm) for the closed diffuser leakage that would be attributed to Category 2 leakage in the GSA protocol. This airflow, if added to the Category 2 leakage, can lead to measured leakage rates that are higher than would be obtained during normal operation of the UFAD system.

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NIBS. 2008. "PBS Standard for Raised Floor Systems With and Without Underfloor Air Distribution: Supplement to PBS P-100: Facilities Standard for the Public Building Service." February 2008. Draft, National Institute for Building Sciences, Washington, D.C. Developed for U. S. General Services Administration

APPENDIX A: AIR LEAKAGE TESTING PROCEDURES

Air leakage testing on the 7th floor was scheduled for the weekend of May 16-18, 2008, coinciding with times when the building was largely unoccupied. Work began on Friday, May 16, after 5 pm and continued until 8 pm on Sunday evening. An overview of the test procedures are presented below.

FRIDAY, MAY 16, 2008

1. We focused our efforts on Friday evening making preparations that did not involve operating the building's HVAC system. The following tasks were completed on Friday.
2. Establish command center in conference room on 7th floor.
3. Review building design drawings, BMS trend log capabilities, and UFAD system control sequences.
4. Install pressure sensing tubing from command center to eight underfloor plenum pressure measurement locations on the 7th floor to allow multi-point monitoring of plenum pressure distribution during subsequent air leakage tests (see Figure 6 and Figure 7. These eight locations were selected to match the eight installed plenum pressure sensors shown in Figure 2. Also run tubing to the 6th floor (all floor were open (i.e., no return plenum) with "cloud" acoustical ceilings) and to the outside to allow monitoring of pressures in adjacent spaces to 7th floor underfloor plenum.
5. Seal all floor diffusers (swirl) and perimeter linear grilles (located on window sills) using specially sized wide tape ("carpet mask" and "duct mask"). See Figure 8. Some floor cable (PVD) outlets were also sealed, although the building had very few since electrified modular furniture was used throughout the largely open plan office.

Figure 6: Installation of tubing for plenum pressure measurement

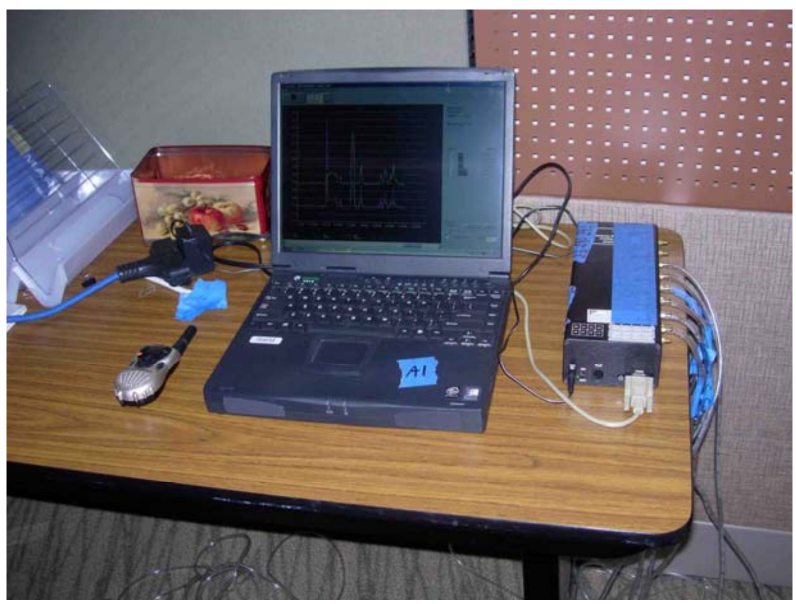

Figure 7: Plenum pressure measurement base station

Figure 8: Applying wide "carpet mask" tape over swirl diffuser

SATURDAY, MAY 17, 2008

On Saturday morning, we began formal testing with the operation of the central AHU. We conducted air leakage testing for a series of plenum configurations following different test methods (some GSA, and some alternatives) as described below. We used recorded airflow readings from the 8 underfloor flow stations as a basis for determining leakage rates.

1. Conduct sealed diffuser test. This test is included in the GSA protocol. Approximately 5-7 steady state measurements were taken, each for a different plenum pressure covering the range of about 0.02 – 0.10 iwc. For each separate test condition, we recorded total airflow delivered to the 7th floor, and pressure difference between the 7th floor conditioned space and each of the following: 7th floor underfloor plenum (in eight locations), 6th floor, and outside the building.
2. Conduct multi-zone pressurization leakage test. With all diffusers sealed as in the first test above, this new test method simultaneously investigated air leakage through all major pathways from the underfloor plenum, including not only leakage to the room, but also leakage to the adjacent 6th floor and to the outside. We adjusted the supply airflow rate, as well as the return damper opening and fan speed on both the 6th and 7th floors in different combinations to allow 5-7 separate steady state measurements to be recorded over a range of differential pressures for each leakage pathway (similar to test #1 above).
3. Conduct closed swirl diffuser test. This test is included in the GSA protocol. We removed the tape on all swirl diffusers, marked the original diffuser damper position, and then manually set all swirl diffusers to their closed position. The perimeter grilles remained in their sealed position. Five separate steady state measurements were taken.

4. Conduct fully open swirl diffuser test. This test is not included in the GSA protocol. This test is not included in the GSA protocol. We manually set all swirl diffusers to their fully open position. The perimeter grilles remained in their sealed configuration. Four separate steady state measurements were taken.
5. Conduct fully open swirl and perimeter diffuser test. We removed the tape from the perimeter grilles so that all diffuser (both swirl and perimeter) were unsealed and fully open. Three separate steady state measurements were taken.

SUNDAY, MAY 18, 2008

On Sunday, we focused our efforts on testing various components and subsystems to support our analysis of air leakage in the building. We calibrated the eight flow measurement stations on the 7th floor, characterized air leakage from three selected perimeter systems (consisting of a perimeter underfloor fan-coil unit, ductwork, and perimeter linear grilles), and measured airflow from individual swirl diffusers.

1. Conduct calibration of eight flow measurement stations serving the underfloor plenum on the 7th floor. The primary measurement equipment was a variable flow control and measurement device called a Duct Blaster® made by The Energy Conservatory (Figure 9). This was done within each of the two access plenums located between the two supply shafts and their respective four supply air highways (refer to Figure 2). We fabricated a custom manifold (Figure 10) that allowed two side-by-side Duct Blasters to be attached and sealed over the entrance to each air highway (see Figure 11). By controlling the airflow through one or both Duct Blasters simultaneously, we were able to collect at least ten separate airflow measurements over the range of approximately 400 – 1,600 cfm, depending on the size of the control damper and air highway. This allowed us to develop a best-fit calibration correlation for each flow measurement station. See appendix B for details of the calibration results. We applied these correlations to all collected airflow measurements during our analysis of the air leakage test results from Saturday.
2. Conduct air leakage tests of three separate underfloor fan coil units along with their associated ductwork serving between 5-10 perimeter linear diffusers. A Duct Blaster was connected to the inlet side of the underfloor fan coil unit (Figure 12), allowing 5-7 separate readings of airflow vs. pressure over the range of about 0.02 to 0.1 iwc and/or 100 – 600 cam. After taping the linear grilles (Figure 13), we determined that significant additional leakage occurred from the cracks on both the front and back edges of the window sill. To characterize this leakage in greater detail we conducted testing for three different taping configurations on the perimeter sill grilles: (1) sealed grilles only, (2) sealed grilles and cracks, including around cabinets that blocked access to the front crack (Figure 14), and (3) open grilles and cracks (no tape). Note that this sill leakage is not a true leak but an artifact of the testing protocol; therefore it was not included as Category 2 leakage in the final total.
3. Conduct airflow measurements of 2-3 swirl floor diffusers. These tests were intended to characterize the airflow through the diffuser for two manually adjusted damper positions: (1) fully open and (2) fully closed. A powered flow hood was used to measure these small flows. A powered flow hood uses a calibrated fan, in this case a Duct Blaster, to measure the flow and to overcome the flow resistance of the relatively small flow sensor necessary for accurate determination of low flows. Flows as small as 10 cfm can accurately be made using a Duct Blaster (see section 13.3 of the Duct Blaster manual).
4. Remove and discard all tape, return all swirl diffusers to original damper positions, pack up all equipment, and clean command center area.

Figure 9: Duct Blaster shown being used as a powered flow hood to measure flow through swirl floor diffuser

Figure 10: *Duct Blaster manifold*

Figure 11: Two Duct Blasters with manifold being installed at entrance to one supply air highway

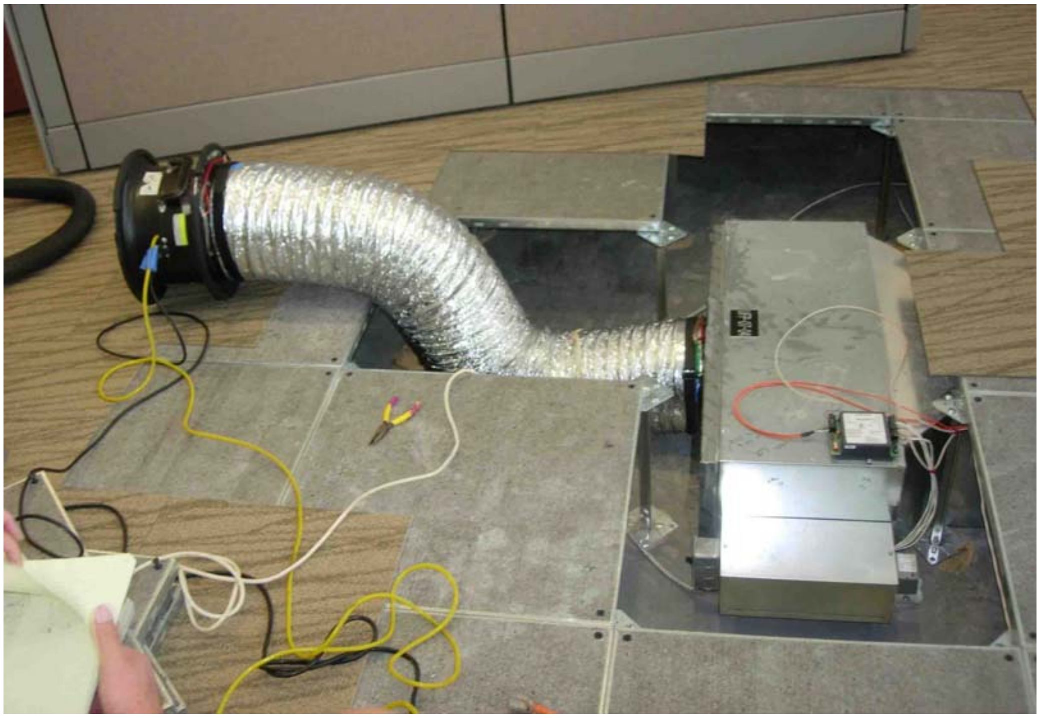

Figure 12: Duct Blaster connected to inlet of fan-coil unit for perimeter system testing

Figure 13: Sealed perimeter linear grilles

Figure 14: Taping cracks and cabinets at perimeter

APPENDIX B: CALIBRATION OF FLOW MEASUREMENT STATIONS

Purpose: The purpose of this test was to calibrate the eight airflow measurement stations serving the 7th floor to verify (and correct, if necessary) the accuracy of all air leakage measurements made using these sensors.

Discussion: Calibration of the primary measurement devices is of critical importance to a successful air leakage test. In the case of the EPA building, since we used the installed airflow measurement stations, we developed a procedure using two Duct Blasters with variable volume control and high quality pressure measurement instrumentation (Energy Conservatory Model DG700) to calibrate each air highway flow sensor in a separate test (see Figures 9 and 10). The accuracy of the Duct Blasters is 3% but the signal from the airflow station was very noisy and we estimate the overall uncertainty of the calibration to be about 6%. For any given building, it will be very important to assess the best way to control and measure the airflow into the plenum for leakage testing purposes. Depending on the size of the plenum being tested (in our case, we tested the entire 7th floor) and the HVAC configuration (e.g., how easy is it to calibrate the installed flow sensors, etc.), the best solution will vary. Careful consideration is needed.

EPA Test Results: Calibration of the eight flow stations was performed to account for zero and span drift of the buildings flow grid pressure sensor, as well as possible inaccuracies in the calibration supplied by the manufacturer of the flow grid.

Because the flow vs. pressure relationship has a square root form the correction factor is not a linear correction. The correction can be formulated as:

$$Q = \sqrt{a * T^2 \pm b^2}$$

Where:

Q is the correct flow [cfm]
T is the Trend Value flow [cfm]
a is a regression coefficient (a^2 is a span correction)
b is the sensor offset (found by regression or the value reported when there is no flow)

Note that the sign in front of the sensor offset ("b") term is determined by the offset bias, i.e. a "+" indicates that the trend value shows no flow when there actually is flow. "b^2" is used rather than just "b" because "b" can be easily determined from the trend values when there is no flow.

Figure B1 shows the calibration data for flow grid #5, and Table B1 has the values determined for each flow grid.

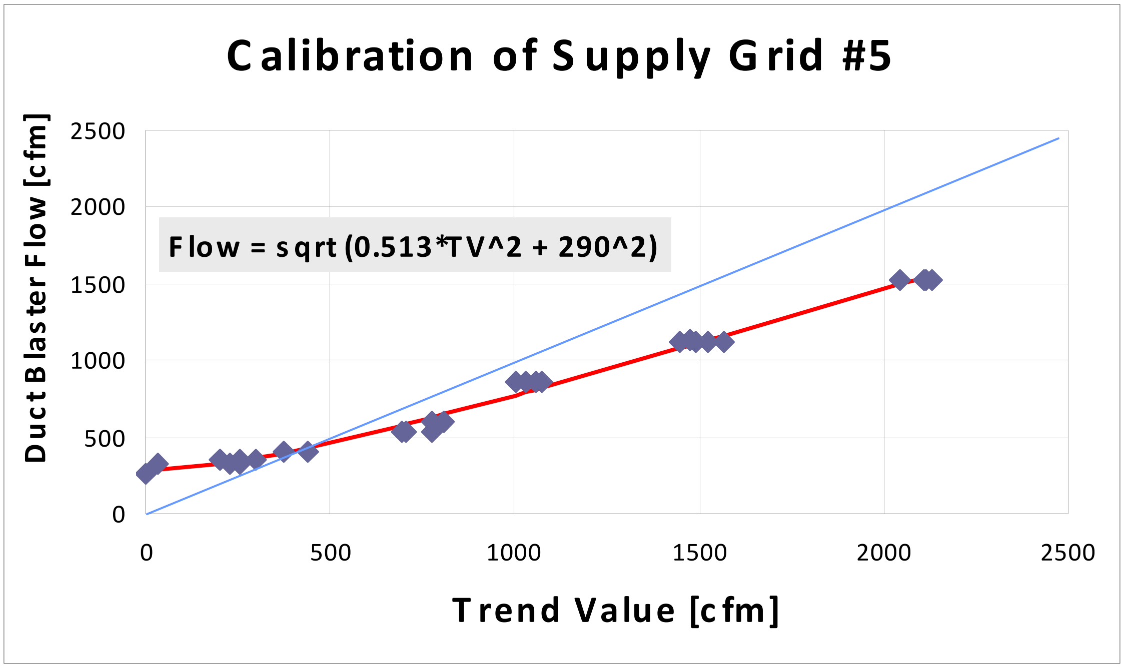

Figure B1: Example calibration data for flow station 5.

Table B1: Calibration values for the eight flow stations

Flow Station	1	2	3	4	5	6	7	8
a (≈span)	0.817	0.600	0.597	0.880	0.513	0.774	0.628	0.668
b (offset)	358	200	-684	403	290	61	-160	545

APPENDIX C: GSA AIR LEAKAGE TEST PROTOCOL

Note: We include below two GSA-specified step-by-step procedures.

1. *The first one describes the dynamic airflow test to be applied prior to initial occupancy, but after all significant construction is completed. This method does not attempt to separately measure the Category 1 and Category 2 leakage rates, most likely due to the fact that it is extremely difficult to seal all Category 2 leakage pathways after construction is completed.*
2. *The second one describes a more detailed static pressure test to be applied to a mockup earlier in the construction process. It includes procedures that attempt to separately measure the Category 1 and Category 2 leakage rates.*

Test Procedures for Air Leakage in Pressurized Plenum Prior to Initial Occupancy

The lessons learned from successfully completing the test procedures should be disseminated to all the trades involved in the construction of the plenums as supplemental information. The lessons learned should also be distributed to all inspection and approval authorities on the project.

After successful completion of Step 11 in the above, all, pressurized plenums in the building should be tested by the following procedures.

1. The testing should be performed after the concrete surfaces of the plenum have been sealed, and all mechanical and electrical devices, equipment, cables, racks, diffusers, power connectors and voice/data connectors have been installed, but prior to installation of furniture, fixtures, equipment and finishes that may be vulnerable to damage from testing procedures.
2. The permanent air-handling system should have been installed, inspected and successfully tested.
3. The static pressure sensing component of the BAS should have been installed and calibrated before the test. One independent, calibrated static pressure gauge per UFAD zone should be installed adjacent to each permanent sensor (1000 square feet).
4. Prior to conducting the static pressure tests on the UFAD zones for air leakage, a *dynamic airflow test* should be conducted. The purpose of the dynamic airflow test to verify that the capacity of the AHU will maintain the design airflow rate at the design static pressure of the plenum (e.g., 0.07 in. w.g. (17.5 Pa)) shown on the AHU and Diffuser/Grille Mechanical Schedules of the Project Drawings:
   a. This test should be conducted with all floor diffusers and grilles within the AHU zone in the positions as adjusted by the TAB contractor.
   b. Adjust the AHU to provide the design airflow rate shown on the Mechanical Schedule.
   c. Obtain static pressure measurements in the floor plenum at five minute intervals in each 1000 ft^2 of floor space within the zone being tested. Steady-state should be defined by at least six contiguous sets of readings of plenum static pressures that do not vary by more than +/- 0.005 in. wg. (1.2 Pa) *at each* measurement location.

d. When steady-state is achieved, measure the supply air from the AHU to the pressurized plenum. This measurement should be obtained either by recording the calibrated output from the installed flow-monitoring device, or by a standardized pitot-tube traverse method.
e. Compare the measured supply airflow rate and the maintained plenum mean value and range of static pressure with the conditions shown on the AHU and Diffuser/Grille Mechanical Schedules.
    1. If the design value of the supply airflow rate for the AHU zone is within 10% of the value shown in the AHU Mechanical Schedule, and the maintained mean value of the plenum static pressure measurements for the zone (see 4c, above) is within 10% of the value shown in the Diffuser/Grille Mechanical Schedule, proceed to Step 5;
    2. Otherwise, procedures should be taken to re-inspect, determine sources or causes of the discrepancies, repair or correct, and retest - repeating this process until compliance with these criteria is achieved.

Test Procedures for Air Leakage in Mockup of Pressurized Plenum

The mockup of the pressurized plenum should be tested under static pressure prior to the construction of any of the permanent building pressurized plenum systems by the following procedure. The purpose of this static pressure test to determine the air leakage rate from the plenum at two specific static pressures in the plenum that are representative of design and operating conditions (i.e., 0.07 and 0.10 in. w.g. (17.7 and 25 Pa)). The 11 steps for this Procedure are as follows:

1. A calibrated test fan or fans should be provided which should have the capability of supplying various airflow quantities from shutoff to 120% of the design airflow quantity required for the zone being tested and should be driven by a variable speed controller.
2. The test fan(s) should be installed together with a calibrated airflow test station. The discharge duct of the test fan(s) should be connected to the plenum through an opening by removing a floor panel and using an adhesive seal to secure a pressure tight connection.
3. A calibrated static pressure sensor-controller should be inserted into the plenum to control the speed of the test fan(s).
4. All floor diffusers and grilles, whether automatically or manually controlled, should be adjusted to their fully closed design positions.
5. The test fan(s) should be operated to hold the test static pressure in the plenum at 0.07 and 0.10 in. wg. (17.5 and 25 Pa).
6. The test fan(s) should be operated for a sufficient time to establish a steady-state static pressure within the zone being tested. Measurements should be taken at five minute intervals in each 1000 ft^2 of floor space within the zone being tested. Steady-state should be defined by at least six contiguous sets of readings of plenum static pressures that do not vary by more than +/- 0.005 in. wg. (1.2 Pa) for all measurement locations.
7. After steady-state has been established, the measured static pressure (in. wg. or Pa) and airflow rate (CFM or l/s) should be recorded for six consecutive times at uniform intervals of

approximately 10 minutes. The average value of these airflow rates should be considered the sum of the Category 1 and Category 2 leakage and called the ∑ leakage.

8. With the test fan(s) off, the floor panel and edge joints, the supply air diffusers and the cable floor connectors should be tightly sealed by taping, blanking off and other means, and steps 5 - 7 should be repeated. The resultant average value of the airflow rates should represent the Category 1 leakage.
9. Subtracting the Category 1 leakage rate from the ∑ leakage rate should represent the Category 2 leakage rate.
10. The leakage rates in steps 8 and 9 should be compared to the allowable rates from the table below. If the rates are found to exceed the table values in either category, procedures should be taken to re-inspect, determine sources or causes of the leakage, repair or correct, and retest - repeating this process until the rates are within the table.
11. The systemic corrections that are required for the mockup to bring it into compliance with the test limits should be incorporated into the construction process and procedures for the remaining pressurized plenums in the building.

Mock up Table. Maximum allowable pressurized plenum air leakage rates in mock-up and building floor plenums, when measured at design operating static pressure.

Test	∑ Air Leakage (CATEGORY 1 + CATEGORY 2)	Category 1
Mock-up	0.1 cfm/ft^2 floor area	0.03 cfm/ft^2 floor area
Building Floor Plenums	0.1 cfm/ft^2 floor area or 10% of the design supply air flow rate, whichever value is smaller	0.3 cfm/ft^2 floor area or 3% of the design supply air flow rate, whichever value is smaller