APPENDIX A: AIR LEAKAGE TESTING PROCEDURES

Air leakage testing on the 7^{th} 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

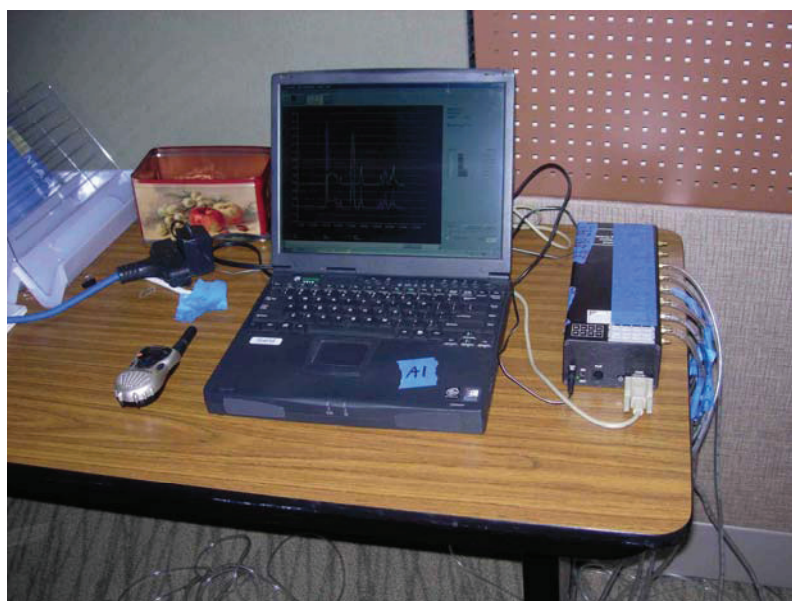

Figure 7: Plenum pressure measurement base station

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

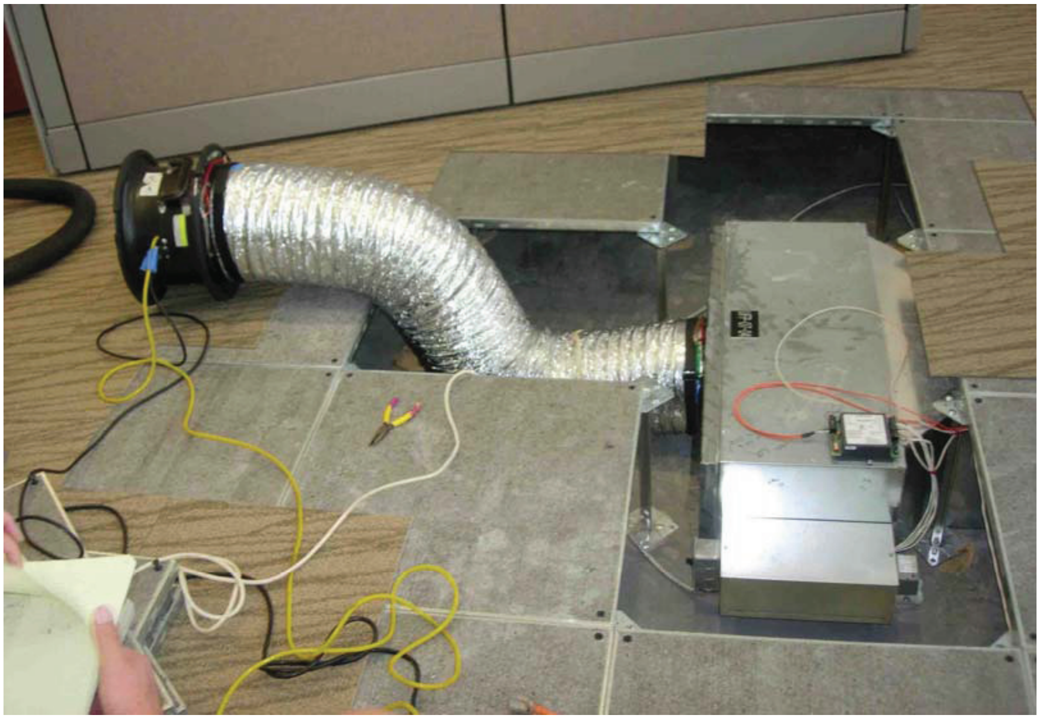

Figure 12: Duct Blaster connected to inlet of fan-coil unit for perimeter system testing

Figure 13: Sealed perimeter linear grilles

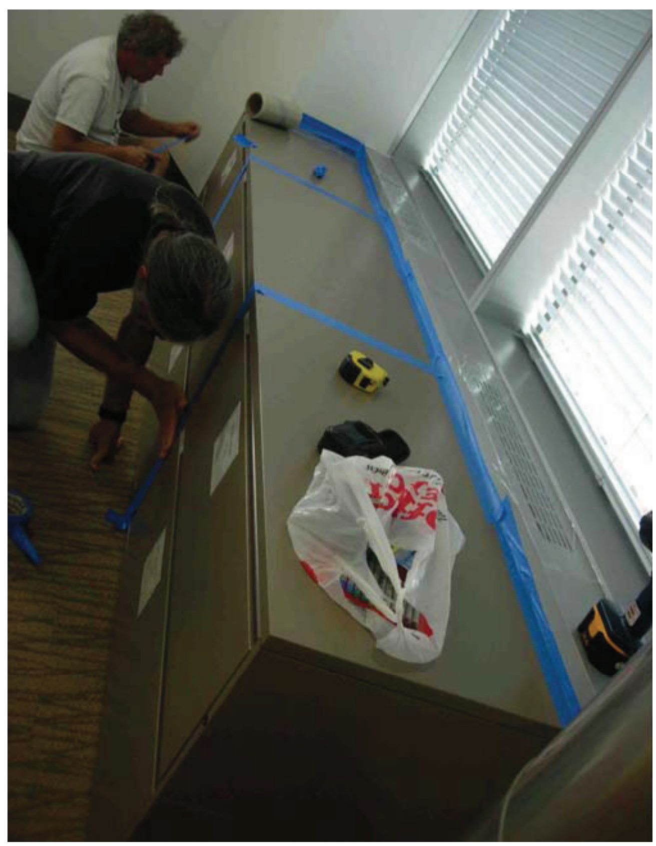

Figure 14: Taping cracks and cabinets at perimeter

APPENDIX B: CALIBRATION OF FLOW MEASUREMENT STATIONS

Purpose: The purpose of this test was to calibrate the eight airflow measurement stations serving the 7^{th} 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 7^{th} 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.

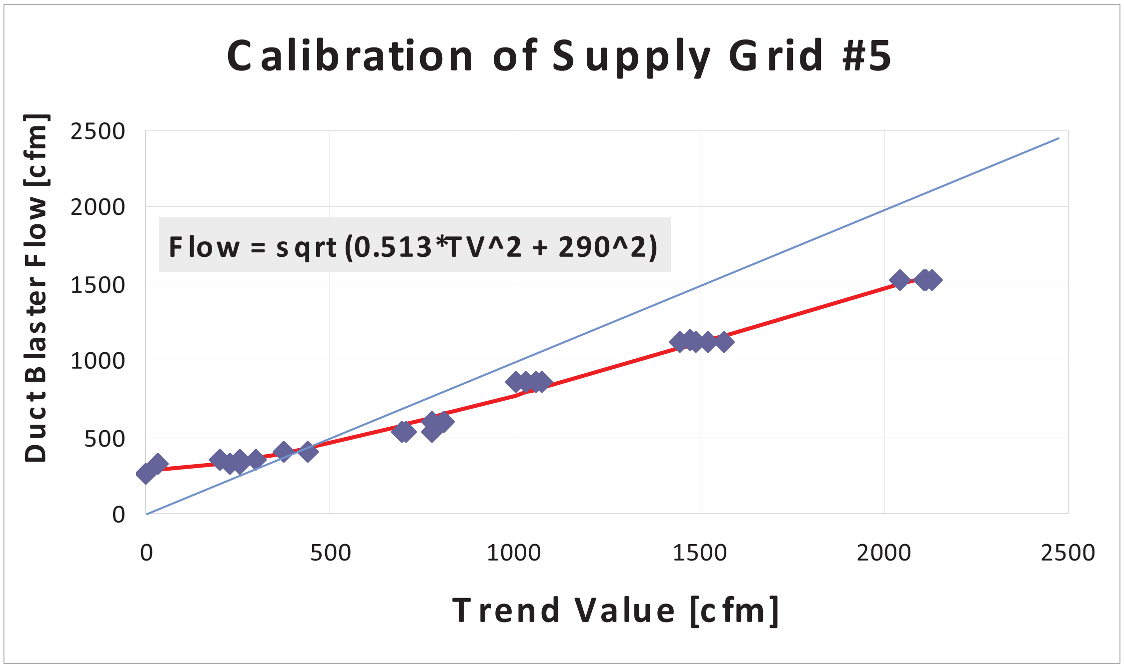

Figure B1: Example calibration data for flow station 5.

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