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Testing for Leaks In Underfloor Plenums

By **Steven Anticknap, P.E.**, and **Mary Opalka**, Associate Member ASHRAE

The Defense Information Systems Agency (DISA) provides the network, computing infrastructure, and enterprise services to support information sharing and decision making for the U.S. Department of Defense. For DISA's new 1.1 million ft^2 (102 193 m^2) office and computer/telecommunications lab complex in Fort Meade, Md., the design-build team chose to use an underfloor air-distribution (UFAD) system to help obtain LEED Silver certification (the project is LEED Gold certified) and fulfill other energy requirements.

The design-build team decided to use an 18 in. (450 mm) raised access floor (RAF) pressurized plenum system for cable management and air distribution. A positive pressurization at peak demand of 0.04 in. w.g. (10 Pa)[2] was specified for the UFAD system. Low-pressure underfloor ducts distribute air from the main supply shafts into chilled water (CHW) and heating hot water (HHW) underfloor terminal units (UFTs). Manually adjustable swirl diffusers provide comfort heating/cooling and are located adjacent to workspace areas in the open and private offices.

The perimeter (the area approximately 1 ft [310 mm] from the exterior walls) is treated as a "skin" system within which only exterior envelope heat gains and losses are handled. Perimeter UFTs have specialized solar-compensated outdoor air temperature controls to adapt to changing conditions and the air outlets are slot diffusers rather than swirl diffusers. Using this arrangement, a large cooling-only interior zone was created for the rest of the air-handling zone.

Each office floor was divided into three main zones each served by a custom rooftop air-handling unit (AHU) that feeds all floors in its zone via risers located in the core of the building. Full-height walls and duct sheet-metal zone dividers located beneath the RAF maintain a relatively constant underfloor plenum pressure for each zone by controlling dampers in the respective distribution duct.

Conference rooms, break rooms, training rooms, and other spaces with load

About the Authors

Steven Anticknap, P.E., is a quality control manager at Hensel Phelps Construction Company, Washington, D.C. **Mary Opalka** served as a joint venture engineer with Hensel Phelps Construction Company and is employed as a graduate mechanical engineer for SmithGroupJJR, Washington, D.C.

swings have dedicated UFTs controlled by space temperature and/or space CO_2 concentration with unique sequences of operations to maintain CO_2 concentrations with outside air volumes. These varying loads necessitated underfloor partitions to isolate them from the main plenum. As with the main spaces, swirl diffusers supply air to each room, and transfer air openings in the ceiling partitions connect to the general return air plenum.[1]

Telecom rooms are excluded from the main plenum by full-height gypsum board walls. Conduits, CHW piping, and other shared utilities have thoroughly sealed penetrations to ensure plenum integrity.

The many trades co-located in the underfloor plenum required extensive coordination prior to and during construction. Prior to construction, weekly coordination meetings were held with all trades. In these meetings, BIM software was used to find conflicts, which were reviewed by all members of the subcontracting team. Affected subcontractors resolved conflicts before the meeting concluded, eliminating an estimated 99% of all in-field interdisciplinary conflicts.

This coordination helped maintain the integrity of the underfloor plenum. Because the underfloor was not solely used for air distribution, clearances needed to be maintained so as not to create impediments to airflow. Because of the UFTs serving multiple spaces, and the security requirements of the end user (many full-height walls were used), sealing the zone partitions below the floor was important to ensure proper interplenum pressurization. Depending on the penetration location and size, a number of plenum partition fillers were used, including acoustical caulk, fire caulk, foil-backed tape, and fire barrier pillows.

After construction in an area was completed, underfloor inspections were conducted with the owner's representative (U.S. Army Corps of Engineers [USACE]) and the contracting team. These inspections verified that the underfloor was clean of construction debris and that all penetrations were sealed in a manner appropriate for the penetration type and location. UFAD testing could not proceed until an owner's representative had signed off on the area. This additional review helped ensure construction quality for long-term results of maintainability, as well as the short-term for test success.

Testing Procedure

Two different types of leakage tests were performed on this project: Type I and Type II.[3] Type I leakage is defined as leakage out of plenums and into spaces that do not provide occupant cooling. This leakage does little to contribute to occupant comfort and ultimately wastes energy. Per owner's requirements, the allowable leakage rate for Type I was established as 5% by volume.

Type II leakage is defined as leakage out of the plenum and into the zone being served (i.e., leakage through the RAF assembly) and is not necessarily detrimental to comfort heating and cooling. The allowable leakage rate for Type II was established as 10% more than the Type I leakage. For example, if a plenum had a Type I leakage rate of 3.1%, the Type II allowable leakage would be 13.1%. Both Type I and Type II were tested at 0.05 in. w.g. (12.5 Pa). The basis of design for

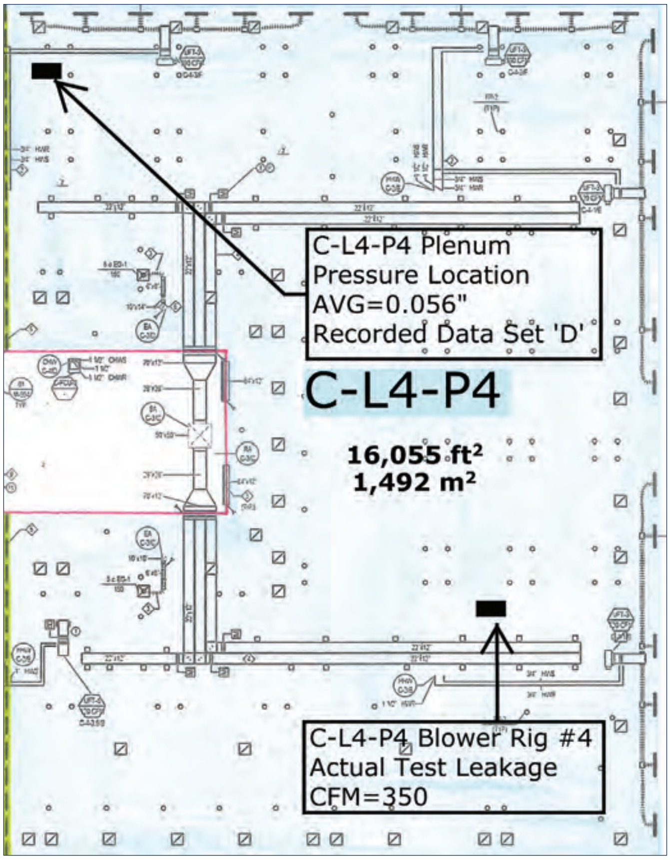

Figure 1: Floor plan layout.

the office spaces was 1 cfm (0.47 L/s) at 0.04 in. w.g. (10 Pa), therefore, the allowable Type I leakage for a plenum was 0.05 cfm per ft^2 (0.25 L/s per m^2) based on floor area.

The test equipment used consisted of calibrated digital manometers with 0.0001 in. w.g. (0.025 Pa) resolution and data logging capability and adjustable orifice-type duct leakage fans. The fans had flex duct connected to their outlet. This flex duct was fed into the floor plenum through holes intended for the swirl diffusers. Foil-backed tape was used to secure the flex duct and seal the opening. The manometers were placed under the floor to monitor the underfloor pressure. This rig can be seen in the photo on the facing page.

Each floor of the building tested has between four and seven plenums, depending on the full-height wall layout for each particular floor. Each plenum received its own calibrated duct leakage test equipment, and 60 data points measuring pressure were recorded in 15-second intervals.

Trial and error showed that the further from the supply air inlet of the test rig to the measurement point, the more stable the readings become, more quickly. Therefore, to avoid turbulence from the incoming airflow, the metering location was at least 50% of the way across the plenum from the air inlet, as shown in *Figure 1*.

Testing was performed for the entire floor at one time since all the floor's plenums share a direct or indirect connection. Each plenum's test apparatus and manometer were installed and sealed and once all plenums were ready they were turned on simultaneously and initial measurements were taken in each plenum. If the pressures were above the test pressure of 0.05 in. w.g. (12.3 Pa) the flow rates through each rig were adjusted. Pressures below 0.05 in. w.g. (12.3 Pa) would have been considered unacceptable as they did not meet design conditions and immediate remediation was performed by finding and sealing any remaining leaks until the plenum pressure met or exceeded the required test pressure.

All plenums tested were able to pass the required test pressure. The process for adjusting the fan volumes was complicated by slight leakage between plenums, the number of plenums on a floor, and the number of meters used to take readings. Lowering one plenum's volume would decrease pressure in adjacent plenums with a ripple effect to interconnected plenums. The most accurate results are achieved when the plenums were at nearly the same pressure, factoring in equipment tolerances and time delays between readings. However, with such small pressures and manual adjustments, it was not practical to get all plenums to precisely the same pressure values.

Field Testing

Successfully executing the UFAD leakage test and the described test procedure involved extensive field quality control during installation, cleaning, and preparation of the floor before testing. During construction of underfloor production a full-time field person was assigned to ensure that the plenums were being built to minimize leakage. This was done by ensuring that the bottom and edges of walls were sealed with plenum-rated caulking. Penetrations such as power and telecom conduits that entered the plenum boundaries had their below floor ends' sealed, as shown at right. These qualitative visual inspections proved vital in maintaining positive testing results, especially since troubleshooting was complicated by USACE requirements forbidding the use of smoke to determine leakage points.

After construction of the pedestal support system and before the flooring was installed, the underfloor was thoroughly vacuumed and mopped. Any necessary repairs were performed and a quality control close-in inspection was performed with the owner's representative.

The concrete floor tiles were installed, and the entire surface was thoroughly cleaned then covered in self-adhering carpet masking plastic in 3 ft (0.92 m) wide strips. At the edges of a plenum area and against walls a 2 in. (50 mm) wide packing tape was applied to seal the perimeter joint. Even with the additional care paid to these areas, the edge seals were a significant leakage point for Type I testing. Empirically, it was discovered that a plenum with a low perimeter-to-surface area ratio performed better than those with a high perimeter-to-surface area ratio.


Power and telecom conduits had their ends sealed.

Type II testing was performed after Type I testing was completed and the carpet and swirl diffusers were installed. The preparation required using 1 ft (30.5 cm) wide sections of carpet mask to cover the swirl diffusers and linear diffusers. Setup of the duct leakage test fans and measuring meters were the same as Type I testing with the exception being the increase in maximum allowable leakage, which was 10% greater than that measured for the same area for Type I testing.

Two Type II tests were conducted. The first Type II testing level was a completed floor with carpet and swirl diffusers installed. The second Type II test was also on a completed floor with carpet and swirl diffusers, but this floor also had a furniture spline wall installed, and there were numerous through-floor penetrations for power and telecom into the spline walls. The number of penetrations in the second Type II test required additional care in the pre-test prep work. A direct correlation was discovered between the time and caution spent with sealing and their related inspections and the resulting leakage rate.

Testing Results

A total of 20 UFAD tests were conducted according to the test methods described previously: 18 tests were Type I on 84 plenums covering 735,000 ft^2 (68 284 m^2), and two tests were Type II on floors covering 102,000 ft^2 (9476 m^2). The average leakage rate of the Type I and Type II results are presented in *Table 1*.

For Type I tests the average leakage for all Type I tests for the entire 735,000 ft^2 (68 284 m^2) tested was 4.1%. A typical test result for one of the levels tested is presented in *Table 2*. The best result was 1.1% leakage and was achieved twice on 15,950 ft^2 (1482 m^2) plenums.

For the Type II tests the average leakage for the 102,000 ft^2 (9476 m^2) tested was at 7.6% of allowable. The same plenums are shown in *Table 2* (Type I testing) and *Table 3*, (Type II testing). Type II testing was conducted with all furniture and spline wall penetrations, making this test a final as-built result. The results show that floor leakage was 6.2% higher than the Type I test on the same floor.

The difference in results between the Type I and Type II tests is an average 3.3% increase in leakage above Type I leakage. This was comfortably below the 10% allowable leakage rate for Type II tests. The other result for Type II leakage was a 1.3% increase above Type I and was achieved on a 16,100 ft^2 (1496 m^2) plenum.

Lessons Learned

During testing the project team learned how stringent the 5% leakage rate could be and the level of quality control vigilance required during construction. The first floor of Type I testing took several attempts with remediation work in between testing efforts to obtain a successful result. These remediation efforts taught the

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team that every penetration must be sealed and special attention must be paid to the conduits, which needed to be sealed on the edges and caulked on the sides.

With an 18 in. (46 cm) plenum, maneuvering and working under the RAF after tiles have been installed is very difficult, making it arduous to find and fill cracks. Learning this fact early drove all of the construction efforts and quality control and also led to the thorough underfloor pre-close-in process. These early experiences taught the team how sensitive every opening was and that even one small penetration could cause a plenum to not meet the required test pressure. Plenums that were below the required test pressure received immediate remediation to achieve passing results. The remediation work was difficult as problems could not be seen until floor tiles were pulled up.

The overall purpose of the testing was to meet the owner's project requirement, which was proven through individualized testing and reports for each level. Additionally, several experiments were conducted during testing to prove that the testing procedure and standard were accurate.

Test	Number of Plenums	Total Surface Area	Average Plenum Size	Average Allowable Leakage	Average Test Pressure	Average Leakage	
Type I	84	735,000 ft^2	8,750 ft^2	438 cfm	0.0567 in. w.g.	358 cfm	4.1%
Type II	9	102,000 ft^2	11,333 ft^2	1,700 cfm	0.0535 in. w.g.	844 cfm	7.4%

Table 1: Underfloor air distribution testing summary.

Plenum	Surface Area	Maximum Allowable Test Leakage	Actual Test Leakage	Average Test Pressure	Leakage (5% Max.)	Standard Deviation
C-L4-P1	14,940 ft^2	747 cfm	309 cfm	0.057 in. w.g.	2.07%	0.18%
C-L4-P2	9,137 ft^2	457 cfm	247 cfm	0.054 in. w.g.	2.70%	0.14%
C-L4-P3	10,370 ft^2	519 cfm	340 cfm	0.054 in. w.g.	3.28%	0.17%
C-L4-P4	16,055 ft^2	803 cfm	350 cfm	0.056 in. w.g.	2.18%	0.11%
Totals	**50,502 ft^2**	**2,526 cfm**	**1,246 cfm**		**2.56%**	

Table 2: Typical Type I test results.

Plenum	Surface Area	Maximum Allowable Test Leakage	Actual Test Leakage	Average Test Pressure	Leakage (15% Max.)	Type I to Type II Difference
C-L4-P1	14,940 ft^2	1,803 cfm	1,367 cfm	0.051 in. w.g.	9.15%	7.08%
C-L4-P2	9,137 ft^2	1,161 cfm	801 cfm	0.057 in. w.g.	8.77%	6.07%
C-L4-P3	103,70 ft^2	1,377 cfm	887 cfm	0.057 in. w.g.	8.55%	5.27%
C-L4-P4	16,055 ft^2	1,956 cfm	1,321 cfm	0.057 in. w.g.	8.23%	6.05%
Totals	**50,502 ft^2**	**6,297 cfm**	**4,376 cfm**		**8.67%**	

Table 3: Typical Type II test results with furniture penetrations.

The biggest question raised was the stability of the pressure across a singular plenum. During one test a 16,000 ft^2 (1486 m^2) plenum was selected and measurements were taken across the plenum in five locations and the results showed that the pressure was exactly the same across the entire plenum. This can be seen in *Table 4*.

Location	Pressure
A	0.0855 in. w.g.
B	0.0850 in. w.g.
C	0.0850 in. w.g.
D	0.0850 in. w.g.
E	0.0850 in. w.g.

Table 4: Floor-wide plenum pressure stability readings taken in five locations.

The testing team was observing a 15-minute stabilization period before recording data at the start of each test. After observing the stability of the pressure data on the early tests, the team questioned the length of the stabilization time.

An experiment was conducted to determine how long it takes a plenum pressure to stabilize. Several tests were done with the data logging manometer set to the shortest time interval, approximately 2 seconds. It was shown that the plenum pressure stabilizes within one or two data points. The quickness of pressure stabilization and the low standard of deviation suggested that the 15-minute stabilization period and 15-minute data logging period can be shortened significantly.

Conclusion

The data collected throughout the testing process empirically proved that the UFAD plenums had been built to meet and exceed the project's design requirements. The results for Type I testing, on average, surpassed the owner's criteria of 5% by 0.9%. For Type II testing, on the floor with the most penetrations (and therefore the most difficult to seal), the results show that the construction exceeded the owner's criteria of 10% more than Type I by 3.8%. Early results and improvements in performance after those first tests proved that the extra attention paid to the construction, inspection and close in of the plenums made the difference in repeatable successful tests throughout the nine months of testing.

All the work, the design, construction, inspections and testing proved valuable when the building HVAC systems were activated and the UFAD plenums' construction performed as expected and as required. Building performance during start-up and after turnover has shown that the UFAD system has performed as intended without plenum problems. This validates the testing procedure and the results obtained during field testing.

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