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Resolving Duct Leakage Claims

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This report is from a study of the performance of eight exhaust systems of a large medical center in Tennessee. The mechanical contractor of the project initiated this study when confronted with a claim of unacceptable deficiencies in all building exhaust systems. These systems were reportedly exhausting 32% to 43% less than design airflow as a consequence of excessive leakage in the duct system.

The contractor explained that he had attempted to do high quality fabrication and installation of these systems and thought he had done so. Furthermore, he stated that these systems had been carefully inspected to verify that there were no visible cracks where large leaks could occur, and that none were found. Clearly puzzled and frustrated, he requested that an independent investigator evaluate the problem to confirm or disprove the findings reported in the testing and balancing (TAB) report, and to make recommendations necessary to resolve the issue.

More frustration and concern was observed at the job site. A high level of interest was evidenced by a task force of eight people who observed all activities, discussions and test work performed in this investigation.

Test Crew's Procedures

Nothing unusual was found in the procedures used by the TAB test crew. As they explained, their plan was:

- To measure and adjust all exhaust inlets to the design values.
- Measure total airflow by traversing the main duct.
- Compare a summation of the exhaust inlet airflow with the total airflow measurement in the main duct. These were expected to be equal.

Following this procedure, the crew found that a summation of inlet airflows was far less than the total airflow measurement. Thus, the difference of airflow as measured in the exhaust fan inlet minus the summation of the exhaust register measurements was 32% to 43% less than design airflow. They concluded that the difference of these two measurements was attributable to "leakage" in the duct system. These findings and analysis were published in the TAB Report.

Test Crew's Instrumentation

Instrumentation used by the test crew was not unusual:

1. A flow hood was used to measure exhaust inlets. The flow hood used was produced by a well-known and reputable manufacturer. It is capable of measuring either supply outlets or exhaust intakes. The hood was equipped with:

- A velocity pressure measuring device at the hood outlet. This device consists of a manifold with small holes drilled on the upstream side for sensing velocity pressure in the same manner as a Pitot tube.
- An electronic micromanometer readout device. This manufacturer claims that this meter (meter A) is capable of measuring pressure differentials: "plus or minus 2% of reading plus or minus one digit with four-place resolution from 0.0001 to 60.00 in. wc (0.02 to 14928 Pa). It is capable of translating velocity pressure to velocity reading in feet per minute. It can also make density corrections for both pressure and temperature and read out in either standard feet per minute (sfpm) or actual feet per minute (afpm). Because the hood outlet area is 1 ft², airstream velocity is equal to the airflow in cfm. Therefore, the hood readout is in cubic feet per minute.

The manufacturer of this hood claims an airflow measuring accuracy of "±3% of reading ±5 cfm (2 L/s) from 25 cfm (12 L/s) to 2500 cfm (1180 L/s)."

2. Total airflow of the system was measured by traversing the fan inlet duct. Traverses were made with a Pitot tube connected to an oil-filled, inclined gage. The gage scale had minor divisions of 0.005 inches of water (1.2 Pa). In suitable measuring locations, the expected accuracy would be about ±5%.

In view of this seemingly logical procedure, and the apparent quality of instrumentation that was used, significant duct leakage seemed to be a reasonable conclusion. In addition, with the magnitude of leakage that apparently existed, it seemed reasonable to expect to find very poorly constructed ductwork with openings that could be found readily by visual inspection.

Visual Inspection of Duct System

However, poorly constructed duct systems were not found by visual inspection. Instead, the systems appeared to be of high quality fabrication and installa-

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tion. All components had been manufactured by an automatic duct fabrication machine. Duct joints and seams were well made and appeared to be adequately sealed. No large cracks or gaping holes were found.

This lack of an obvious source of excessive leakage led to further investigation of individual systems in an attempt to locate the source of leakage.

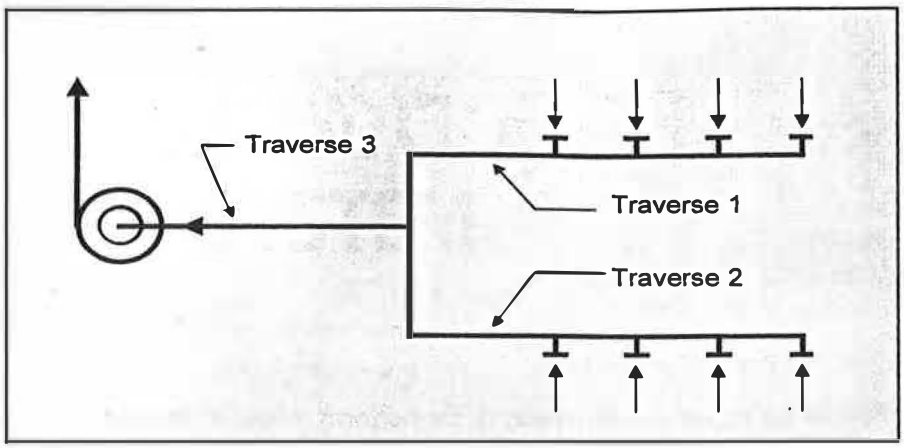

Figure 1: System EF-29.

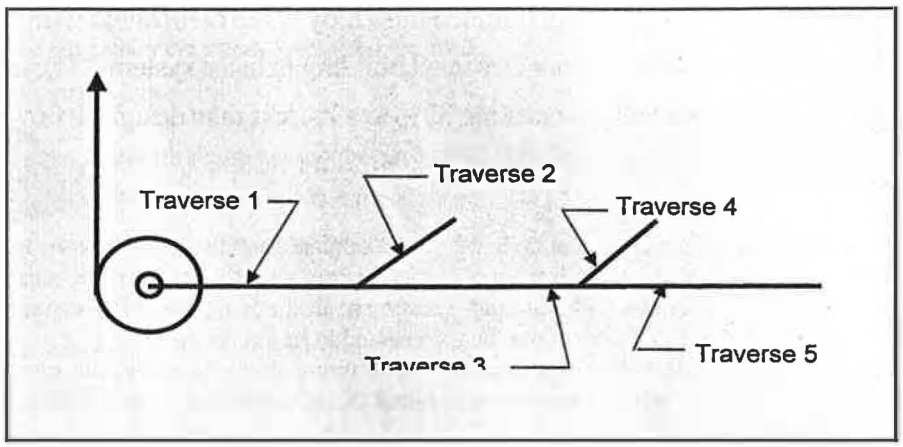

Figure 2: System EF-21.

Exhaust System Tests

System EF-29 first was selected for analysis because it was the one having the highest leakage rate. This system consisted of an exhaust fan located on the roof, a rather long duct system consisting of two major branch ducts on the first floor, and a large number of inlets. Design air volumes for inlets varied from 10 cfm (5 L/s) to 400 cfm (189 L/s).

The analysis of EF-29 was initiated by taking measurements of the airflow in the two major branch ducts (Traverse 1 and 2, *Figure 1*) on the first floor. These measurements were made with a Pitot tube connected to an electronic micromanometer (Meter B) that was provided by the independent investigator. Meter B is produced by the same company that manufactured Meter A and has the same alleged accuracy. This meter was a working piece of instrumentation that recently had been "field calibrated" but had not been "factory" calibrated in more than one year.

The sum of the airflows at these locations was slightly more than 50% of design. Because this measurement agreed with the test report, it was concluded that a major leak must exist somewhere between the measuring location and the fan inlet. It also was believed that a measurement at the fan inlet would be at design airflow in accordance with the test report, and would verify the conclusion that a large leak existed in the duct segment in question.

Accordingly, the investigation of system EF-29 was continued at the fan inlet. Here, the following observations were made:

1. Openings for making a duct traverse were not found in the fan inlet duct, but some were subsequently provided.
2. Fan static pressure was measured and found to be very low as compared to the specified design, and also the test report.
3. Motor amps were found to be near design values and also in agreement with values recorded in the test report.
4. Total airflow—as measured by duct traversing (Traverse 3, *Figure 1*)—was about 50% of design.
5. The fan was running backwards.
6. The arrow that indicates the direction of fan rotation had been modified with a pen to indicate an incorrect rotation for the fan.

The rotation of the fan was then corrected and measurements were repeated. Findings were:

1. Total airflow was slightly more than design.
2. Fan static pressure was near design.
3. Motor amps were near design.

From this data, it was concluded that the major problem with EF-29 was the rotation of the fan. In addition, a comparison of the branch airflow measurements with the total measured at the fan inlet indicated that duct leakage was not a major problem. Those present agreed that this system—except for balancing of the inlets—seemed to be satisfactory. Consequently, no further tests were made on this system.

System EF-21 was selected for the second step of the analysis because it had the second highest leakage rate. This system also consisted of an exhaust fan located on the roof, a rather long duct system consisting of several branch ducts and a large number of inlets. Design air volumes for inlets varied from 10 cfm (5 L/s) to 400 cfm (189 L/s).

With the expectation of finding another fan running backwards, testing of System EF-21 was started at the fan. Unexpected findings were:

- The existence of openings for making a duct traverse in the fan inlet duct. These openings were in a straight duct and were located a suitable distance from the fan inlet. Several di-

Inlet No	By duct Traverse with Meter B		Hood 1 with Meter A		Percent of Traverse
	cfm	L/s	cfm	L/s	
1	406	192	349	165	86
2	175	83	132	62	75

Table 1: Hood Test 1 results.

Inlet No	By Pitot Traverse with Meter B		Hood 1 with Meter A		By Hood 2 with Meter C	
	cfm	L/s	cfm	L/s	cfm	L/s
1	406	192	349	165	351	166
2	175	83	132	62	135	64

Table 2: Hood Test 2 results.

ameters of straight duct also existed upstream of the traverse location.

- Fan static pessure was found to be near the design value.
- Motor amps were found to be near the design value.
- Total airflow, as measured by traversing the fan inlet duct, was slightly above design and in good agreement with the test report.

Having established that the exhaust fan was running at design, and considering that the summation of measurements at the inlet registers (recorded in the test report) were 41% less, tended to substantiate the claim of significant leakage between the inlet registers and the exhaust fan. Accordingly, a series of duct traverses were made in an attempt to pinpoint the location of a very large leak or the existence or a lot of general duct leakage.

As illustrated in *Figure 2*, several traverses were made in both branch and main ducts, and a comparison of these measurements was made to determine if leakage existed. For example:

- It was found that the combined flow at the locations of Traverse 2 and Traverse 3 (*Figure 2*) was equal to the airflow at Traverse 1. Therefore, no significant leak existed between these measuring points.
- Similarly, it was found that the combined flow at the location of Traverse 4 and Traverse 5 (*Figure 2*) was equal to the flow at Traverse Point 3. Therefore, no significant leak existed between these measuring points.

This process was continued to the end of the system, but failed to reveal a significant leak. Because no leakage was found, the question arose as to the accuracy of measurements made at inlets. It was speculated that perhaps the flow hood used by the test crew might have been out of calibration.

Hood Calibration Tests

Three tests were made to verify the accuracy of hood measurements. All of these were made at the two final inlets of System EF-21. Here, ductwork was arranged suitably for measuring airflow by traversing the duct and comparing that with the measurement made with the flow hood. Both final inlets were ceiling registers connected to separate, vertical ducts, which had ample straight length for accurate measurements.

Hood Test 1

Airflow at the inlets were measured with Flow Hood 1 and compared to traverses of the duct. Flow Hood 1 was the one being used by the TAB test crew. It was equipped with Meter A as a readout device. Duct traverses were made with a Pitot tube and Meter B.

The results of Hood Test 1 are shown in *Table 1* and do indeed exhibit large discrepancies between measurements taken with the hood and those made by duct traverse. As seen, the hood measurement was 14% less than the traverse for Outlet 1 and was 25% less than the traverse for Outlet 2.

Tentative conclusions:

1. Hood 1 was out of calibration and therefore measuring inaccurately.
2. The error appeared to increase as the flow rate decreased.

Hood Test 2

This test consisted of re-measuring the inlets with a different flow hood. Hood 2 was equipped with an analog meter (C) having scale ranges of 0 to 2500 cfm (1180 L/s) and a "claimed" accuracy of ±3% of scale. This hood had been recently "factory" calibrated, and had not been used since calibration and therefore thought to be a reliable instrument. It was expected that this test would prove the inaccuracy of the hood being used by the test crew.

Unexpected results of Test 2 are recorded in *Table 2*.

These measurements were essentially the same as Test 1, and therefore invalidate the previous conclusion that Hood 1 was out of calibration. Instead, the results indicate that both hoods are measuring equally inaccurately.

This favorable comparison of hood measurements, led to speculation about the accuracy of Meter B that was used to make duct traverses. As previously noted, it had not been factory calibrated in more than one year.

Hood Test 3

Test 3 was made to determine the reliability of measurements with Meter B, the one used for making traverses.

This test consisted of re-measuring and comparing the same two inlets with a Hood 2 equipped with Meter B, and a traverse of the duct using a Pitot tube along with Meter B as a readout device. By using the same meter as a readout device for both the flow hood and for traversing the duct, it was believed that surely both measurements would be the same.

Unexpectedly, the measurements made with this hood were surprisingly close to measurements made in Test 1 and Test 2. In fact, all measurements by hoods for all three tests were almost identical.

Conclusions

1. All hoods-meter combinations are measuring the same, but consistently low.
2. Meters used as readout devices are not the problem.
3. Error increases as flow rate decreases.

Airflow Reading of Hood		Velocity Pressure at Sensor	
Cfm	L/s	Inches of Water	Pa
400	189	0.01	2.49
200	94	0.002	0.50
100	47	0.0006	0.15
50	24	0.000156	0.039
40	19	0.0001	0.025
25	12	0.00004	0.010
10	5	0.000006	0.0015

Table 3: Velocity pressures measured versus airflow readings of flow hoods.

Metered Airflow		500 cfm (236 L/s) Scale		1000 cfm (472 L/s) Scale	
cfm	L/s	cfm	L/s	cfm	L/s
100	47	100	47		
200	94	200	94		
300	142	302	143		
400	189	402	190	395	186
500	236	495	234	495	234

Table 4: Manufacturer's calibration report for Flow Hood 2.

Rationalizing the Outcome of Test Data

It is possible that flow hoods do not accurately measure small airflow. One reason might be that low airflow through hoods require an accurate measurement of some small velocity pressures. As seen in *Table 3*, these pressures become extremely small for flow rates less than 400 cfm and would, therefore, be subject to significant error. It seems logical that the likelihood of erroneous measurements increases with a decrease in velocity. However, it does not follow that the measurement will be consistently low as was experienced in this study.

Field Experience vs. Manufacturer's Guarantees

Experiences of this case do not compare well with the manufacturer's claims for flow hood accuracy. According to the manufacturer's specifications, the hood used in study has an accuracy of plus or minus 3% of reading or plus or minus 5 cfm (2 L/s) from 25 cfm (12 L/s) to 2500 cfm (1189 L/s). Furthermore, calibration is traceable to NIST standards. The calibration report for Hood 2 of this study is shown in *Table 4*.

As seen, this instrument is certified to measure the exact flow rate at 100 cfm (24 L/s) and 200 cfm (94 L/s) and very near exactly (about 1% or less) at 300 cfm (142 L/s), 400 cfm (189 L/s), and 500 cfm (236 L/s). Clearly, field experience (in this case) does not confirm the validity of the manufacturer's claims. Instead, these results do lead to further questions. Such as:

1. Are claims for accuracy of the instrument exaggerated?
2. Exactly, how was Flow Hood 2 calibrated?

Factory Calibration

During the discussion with the manufacturer regarding the calibration of Hood 2, the test setup was described as a wind tunnel that:

1. Was equipped with a "primary" measuring device, which was certified to comply with and is traceable to NIST standards. Furthermore, this device is re-certified annually.

2. Had one air supply diffuser located in a duct past the tunnel discharge. For calibration tests, the wind tunnel is operated at varying airflow rates. For each of these flow rates, airflow measurements are made and compared with both the primary measuring device and the flow hood that is being calibrated. All of these measurements are recorded for inclusion in the calibration report.

The manufacturer also reported that no calibration was done for measuring return inlets. He said, "we assume that the return measures the same as the supply. Consequently, we do not calibrate returns."

Factory Calibration Procedures

The equipment arrangement and test procedure followed by this manufacturer seemed to be in accordance with standard calibration lab practice. However, the author has a lingering concern about the accuracy of measurements of low airflow rates, which depend upon accurately reading very small pressures. The author questions the claim that Hood 2 measures airflow rates at exactly 100 cfm (47 L/s) and exactly 200 cfm (94 L/s) as was recorded in the calibration report! The author tends to expect some error in all measurements and an increase in instrument error as airflow becomes smaller. It did not happen that way during the calibration of Hood 2.

The author questions the manufacturer's assumption that "hoods measure return inlets the same as a supply outlet" because field experience with the calibration of "home-made" hoods indicates otherwise. In fact, when specially fabricated hoods are field calibrated, it is always necessary to calibrate for both supply and return because the effective area values are never equal.

Conclusions and Recommendations

1. Whereas excessive leakage was not found by comparing measurement made by traversing ducts in System EF-21 and whereas measurements made by traversing ducts is recognized as the most reliable method of measuring airflow,[1] claims of excessive leakage, as reported in the TAB Report, were judged to be false.

2. The flow hood used by the test crew and the hood provided by the independent investigator were measuring incorrectly. The results of this investigation indicate significant differences in measurements made with a flow hood and by duct traverse. In addition, it appears that the error becomes larger as the air volume decreases.

3. All inlets of these systems should be re-measured and

balanced in accordance with design requirements. Measurements should be made with a "specially fabricated hood" which has been calibrated for return measurements and for the range of airflow rates to be measured. To be acceptable, a summation of all air inlets should be equal to total airflow as measured by traversing the fan inlet duct.

Speculation and Questions

1. Test data found in TAB Reports and the conclusions that come from it are not beyond question. Although it's easy to assume that the test data is completely accurate and that conclusions reached are correct, it was shown in this case that errors do happen. Consequently, verification of test data accuracy should be a first step in the resolution of mismatched results. Testing and balancing personnel and reviewers of TAB Reports should question test data that is grossly missmatched.

2. It is unrealistic to expect that flow hoods will provide accurate airflow measurements of all air outlets and inlets regardless of size and configuration. However, some do. The test crew on this project seemed to have this attitude, because they did not question the test data that was grossly mismatched. In addition, the manager of this project's test crew expressed this attitude when he said, "How can you question these readings that were made with a 'signature' instrument?"

3. Realistically, flow hoods are still the best method for measuring airflow of outlets and inlets and should be expected to provide adequate accuracy where the configuration of the outlet is compatible with the design of the hood. However, test personnel and others should view measurements of unusually configured outlets (such as small inlets or outlets with small airflow) with some skepticism. Verification via a separate and different measurement is always a good plan.

4. Now that I know that Flow Hood 2 was not calibrated for "return" flows, I wonder about the reliability and the value of the calibration report that was provided. Is it worthwhile to return my instruments to the factory for periodic recalibration? Do I profit from including a "factory" instrument calibration requirement in engineering specifications?

5. Following this experience, I now have a better understanding of what to expect the next time. It's the unexpected of course. ■

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