Appendix 6

Building Pressurization Issues

Discussion

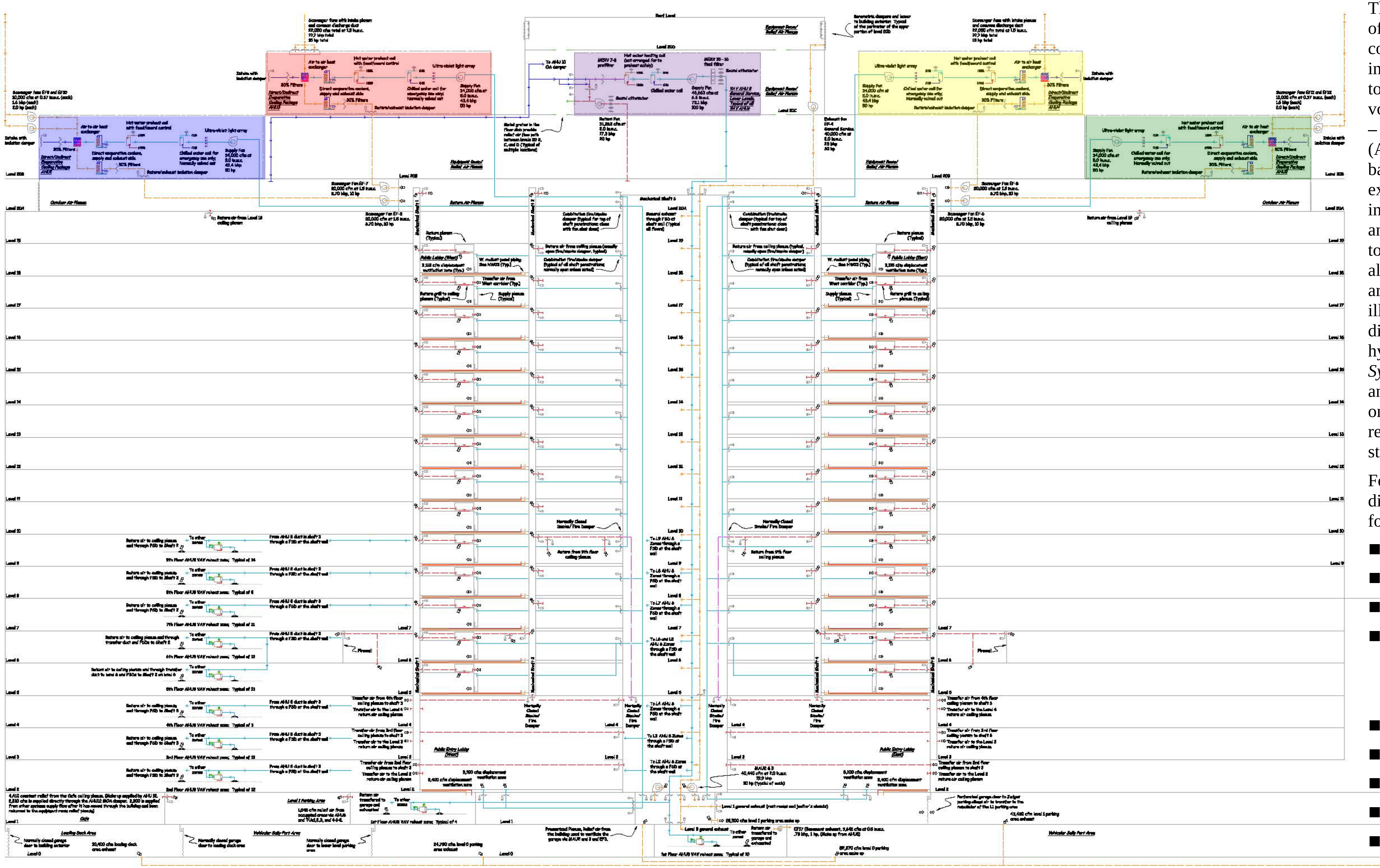
Building pressure control has been an ongoing issue for the facility and was one of the issues targeted for analysis during the kick-off meeting for the HVAC system study. Building pressurization is related to building geometry, envelope integrity, and building air flow patterns. For the courthouse, all of these things are quite complex.

Figure A6 - 1 illustrates typical envelope details as the curtain wall system was assembled. Note the many gaps and thermal breaks that are inherent in a structure of this type and must be treated and maintained properly to ensure a secure, air and water tight envelope.

Figure A6 - 1 - Typical Envelop Construction: This picture was taken in the East Wing early in construction, after the curtain wall had been hung but before the joints had been caulked and the interior finishes had been framed and installed.

Observations during the remainder of construction as well as the testing we have done during commissioning and to develop this report indicate that the gas and thermal breaks were properly addressed and that the building envelope is tight relative to some other facilities we have been involved with like the Hatfield Courthouse in Portland. We have simply included Figure A6 - 1 to illustrate the complexity of the envelope and what could go wrong, especially over time, in terms of the persistence of the integrity of the envelope.

Figure A6 - 2 illustrates the building schematically in cross section with several major air handling



This diagram represents a cross section of the high-rise portion of the courthouse with the section cut made in a manner that allows all of the shafts to be shown. The four constant volume systems in the facility (AHU1 – 4) and a typical VAV system (AHU8) have been overlaid on this background. The drawing has been extracted from the system diagrams included in the electronic Appendix, and while the font is generally to small to be legible in this figure, it does allow the general air flow patterns that are the topic of this discussion to be illustrated. To view the complete diagram with legible text, use the hyperlink provide in Appendix 1 under *System Diagrams* while working with an electronic version of the document on a CD, the CACEA portal, or a reproduced version of the project file structure.

For orientation purposes in the discussion in this appendix, note the following:

- Supply ducts are blue
- Return ducts are red
- Exhaust ducts are orange
- The exhaust duct leaving the drawing on the bottom left goes to garage exhaust fan EF3 on the top of the low rise structure.
- AHU1 is highlighted in blue
- AHU2 is highlighted in green
- AHU3 is highlighted in red
- AHU4 is highlighted in yellow
- AHU8 is highlighted in purple

Figure A6 - 2 -[redacted]Federal Courthouse Over-all Air Flow Patterns – Orientation: See Figure A6 - 6 for the section cut line associated with this diagram.

systems superimposed on it. A more detailed and legible version of the drawing can be found in the electronic appendix via the links in Appendix 1, but we have included it here to allow us to illustrate some of the air flow and building geometry relationships that we think are pertinent in light of the building pressurization issue as we move through our discussion

Vertical Shafts, Atriums, and Plenums

Note that the building geometry incorporates a number of shafts that interconnect many, and in some cases, all floors.

- Stairwells extend from the top to the bottom of the facility.
- Smoke and return air shafts extend from the top to the bottom of the facility.
- Elevator shafts extend from the top to the bottom of the facility and the elevators can act as pistons and move air in the shafts they travel in.
- Atriums interconnect many floors on the lower levels and also interconnect the office tower with the high rise.
- Portions of Level 20A serve as an outdoor air intake plenum while other portions serve as a return plenum that interconnects (short circuits) many of the shafts in the facility.
- Levels 20B, C, and D serve as a relief plenum to conduct air from the AHU relief dampers to the barometric dampers at the top of the facility for discharge to the atmosphere when operating on economizer cycle.
- MAU2 and 3 pull air from the high rise and use it to pressurize the lower portion of shaft 3 to provide make-up for garage exhaust fan EF3, which is located on the top of the low rise office tower.

In many cases, there are doors between the different plenums and shafts. For instance, there are doors from the stairwells into the 4 mechanical levels. Thus if a door is propped open while working or by an extension cord or hose passing through it, the pressure barrier it provides in the closed position is violated, which can impact how air will move through the facility.

Make Up Air Handling Units MAU2 and 3 Design Intent and Current Operating Mode

The original design intent behind MAU2 and 3 was to allow the relief air from the facility to be used to maintain a near neutral temperature in the parking garage without the use of additional energy. This is essentially a heat recovery strategy because relief air from an economizer process is air that is brought into a facility to cool it and then is relieved from the facility via the relief dampers at the average indoor temperature, having been heated by the internal gains.

While simple in concept, the implementation of this concept as shown in the contract documents, control drawings, and installed systems and equipment in the courthouse became quite complex and does not reflect the initial intent for a number of reasons.

1. The parking garage square footage and volume is large: High floor to floor heights and the large foot print covered by the parking garage drive the ventilation requirements for the garage upward.

2. The parking garage system is operated based on detected carbon monoxide levels vs. steady state operation: Carbon monoxide (CO) detectors located through-out the garage trigger the operation of:

   - EF-3, which removes a nominal 85,000 cfm through the garage.
   - AHU1, 2, 3, 4, 7, and 8, which are intended to supply the required make-up air for EF-3. Note that the amount of outdoor air introduced by AHU7 and 8 will vary with the operation of the economizer cycle and warm-up cycles and the loading of filters for all of the constant volume supply systems.[12]
   - *MAU2 and 3*, which transfer air from the high rise to the parking garage.

   Intermittent operation of these large systems places a step change into the building dynamics each time they start and stop. This impact undoubtedly ripples out and impacts other systems making all of them harder to control when a change in operating state occurs.

3. In our experience, give the size of the garage and the use patterns/traffic density; we suspect that the garage exhaust fan does not have to cycle much: The original intent would have flushed the garage continuously with some minimum level of flow any time the building is occupied. Our guess is this would have minimized or even eliminated the need for the system to cycle at full flow via the current sequence unless there was a major event that put a lot of traffic through the garage.

4. For the design flow balance to be achieved, AHU 1- 4, 7, and 8 must operation in conjunction with garage exhaust fan EF-3 and MAU2 and 3: During daytime hours, this probably doesn't make a difference because everything is running. But if the garage fan cycled during unoccupied hours this is a lot of equipment to start and get into the right mode and there are probably ripple effects associated with it at the boiler and chiller plant.

5. The air flow path associated with getting the makeup air from AHU1-4, 7, and 8 to the parking garage is complex: This is illustrated in Figure A6 - 3. The complexity introduces a number of dynamics into the garage exhaust process including interaction with other systems that are (in theory) not directly associated with the process, transportation delays, and restriction or loss of a flow path from make up to exhaust if a FSD or MAU fan were to fail.

6. The minimum outdoor air percentage for AHU 7 and 8 can vary with load condition and ambient temperatures: While the design intent appears to be that the systems provide a fixed minimum outdoor air quantity, our field observations and past experience with VAV systems that had passive rather than active control of minimum outdoor air indicates that this is probably not happening. In addition, if the systems are in a warm-up or cool down mode, the minimum outdoor air dampers are closed and thus, there would be a significant shortfall (35%) in makeup air until those processes terminated. This would tend to make the building more negative,

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[12] Even though the supply fans on the constant volume systems are equipped with variable speed drives, they operate as fixed speed fans since there is no control process in place to hold a constant static pressure and flow rate in the system as the filters load.

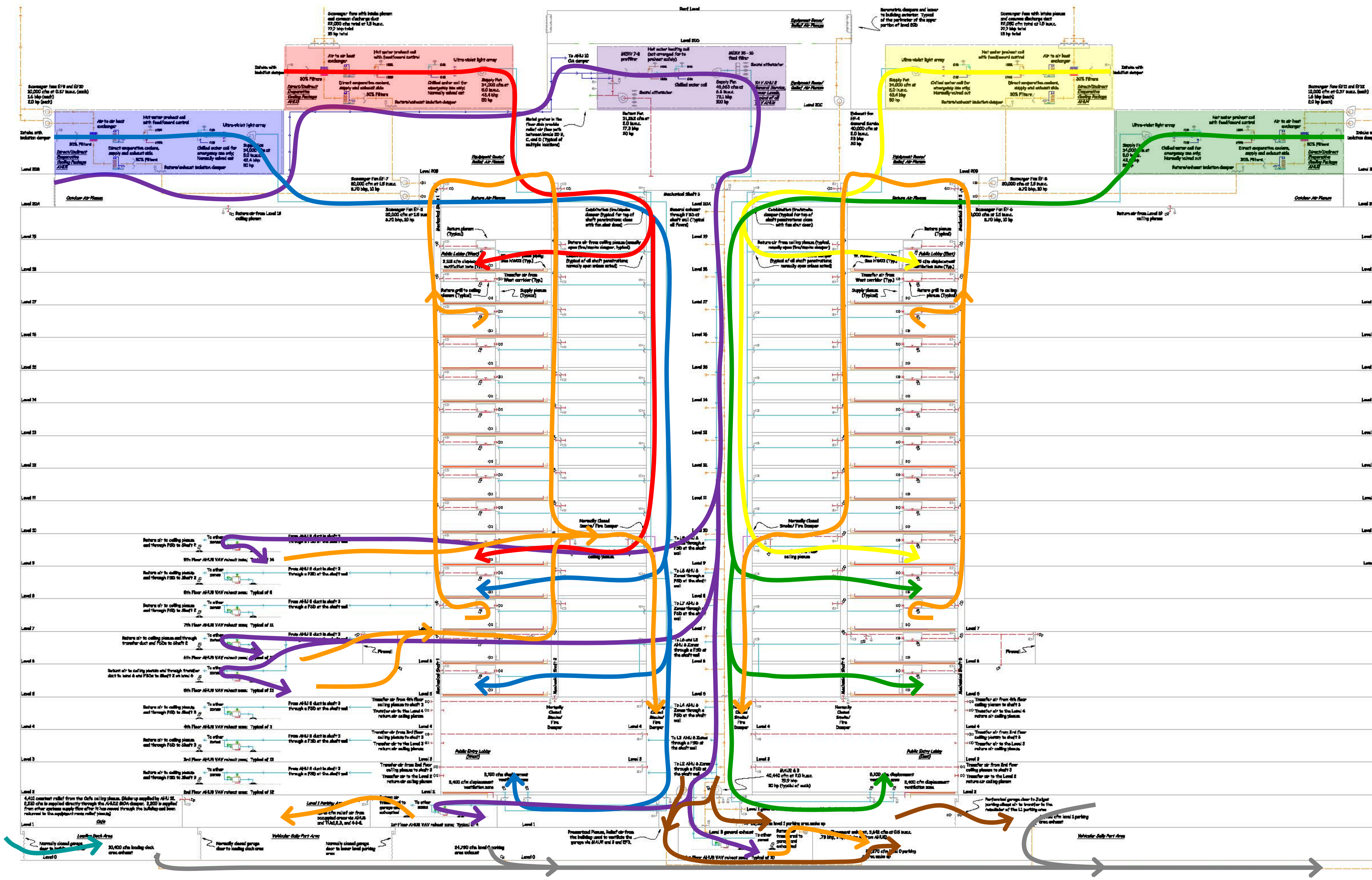

Figure A6 - 3 – Complex Make Up Air Flow Path for the Parking Garage Exhaust

This diagram overlays the air flow path required to bring the makeup air for the parking garage exhaust into the facility and transfer it to the garage for removal by EF-3.

- Air from AHU1 is **blue**
- Air from AHU2 is **green**
- Air from AHU3 is **red**
- Air from AHU4 is **yellow**
- Air from AHU8 is **purple**; note that AHU7 follows a similar path serving the opposite side of the building.
- Return air from the AHUs is **orange**
- Outdoor air pulled in through the slits in the parking garage doors is **teal**
- Air transferred by MAU2 and 3 is **brown**
- Exhaust air to EF-3 is **gray**; Note that EF-3 is located in the boiler room on the 8th floor of the adjacent office tower

Note the following in addition to the general complexity of the flow path:

- The air from the systems illustrated actually is mixed with air from the other 9 air handling systems serving the high rise tower on its way to the garage, primarily in the common return ceiling plenum, return shafts and return plenum on level 20A.
- There are several locations where an improperly positioned FSD could disrupt the flow path; this might happen if an actuator failed

introducing more infiltration, which could potentially prolong the warm-up and cool-down process.

7. As installed, the net outdoor air flow provided by AHU1 – 4 is significantly short of the design value: Both the TAB report and our testing reveals that AHU1, 2, 3, and 4 are short of supply flow as illustrated in Figure A6 - 5. FDE's tests say this is much more significant than indicated by the TAB report. The difference could be due to a number of factors including increased supply duct leakage since the balancing work was completed, restricted filters, evaporative media, or air to air heat exchangers, or measurement errors in the TAB report. Specifically our measurements indicate flow shortages in the 20-25% range on the supply side. On the exhaust side, near design flows have been achieved. Thus, from the standpoint of the over-all air balance envisioned by the design intent (see contract drawing M906), there will be a shortage of makeup air and a tendency to run negative, all other things being equal.

8. MAU2 and 3 have no back draft dampers: These fans have combination fire/smoke dampers (FSDs) in their discharge, but the dampers currently remain open unless there is a fire or smoke control event. This means that they are an uncontrolled opening to the parking garage and contribute to the stack effect issues. In addition, when EF-3 operates, these dampers allow it to influence the building static pressure, exacerbating the negative pressure problems in the lobby. Finally, with these dampers open, it is possible to introduce carbon monoxide from the garage into the building.

Make up For Garage Exhaust, Flow in cfm

System	Design	TAB	FDE
AHU1	13,999	13,618	8,500
AHU2	13,999	13,408	8,116
AHU3	13,999	11,838	5,689
AHU4	13,999	11,777	5,500
AHU 7 MOA	15,400	12,698	8,327
AHU 8 MOA	15,400	13,472	7,648
TOTAL	86,798	76,812	43,780
EF-3	84,999	81,200	81,200
Over/(Under)	1,799	(4,388)	(37,420)

Figure A7 - 3 – EF-3 Makeup Air Sources: This table contrasts the makeup air flow rates for the various sources that provided it. Note that the FDE values assume the exhaust flows for AHU1 – 4 and EF3 are about as measured by the TAB report. Supply flows are based on our actual field test measurements which were focused on the supply systems at the time. Note also that on the day of the measurements, AHU7 and 8 were forced to lower than normal MOA settings by the operators due to extreme weather. On a more normal day, we believe those flows are closer to design than not and thus, the shortfall is more along the lines of 22,595 cfm. This is still a significant shortage of air and a contributing factor to negative building pressures.

Item 2 above is particularly critical with regard to the building pressure control system as it currently exists. This is because of a number items related to how the control system manages the relief dampers and return fans. Based on our observations and the Johnson Controls drawings, the current control sequence:

- *Controls the relief dampers directly with the return and outdoor air dampers:* This is the traditional approach to controlling relief dampers in an economizer cycle for a constant volume system but has some limitations when applied to a VAV system.

Specifically, an economizer process can be thought of a temperature control strategy that achieves the desired supply temperature by bringing in more outdoor air than is necessary for ventilation. This extra air creates a building pressure control issue that must be dealt with by the relief system. For a constant volume system with well sized economizer dampers, the system flow rate is fixed and there is a fairly direct relationship between the amount of outdoor air that must be relieved from the building to control pressure and the amount that is brought in to control temperature.

But for a VAV system, total flow varies with load and the amount of air that needs to be relived to control pressure is a function of both the amount of air that is brought in to control temperature and the total supply flow rate in the system at the time.

To understand why this makes things more complicated consider a VAV system with a55°F discharge temperature requirement operating on a 55°F day but at 50% of capacity/supply flow. The economizer dampers would be at the 100% outdoor air position, but the amount of extra air that needs to be relieved from the building would be significantly less than it would be if the system were at full load. If the relief system was sized to handle the full load flow rate, the "hole" it represents in the building envelope at a partial flow rate is probably excessive, making it difficult to keep the building positive since it is the pressure drop associated with the air flow through the orifice represented by the relief system that generates the positive pressure. Or putting it another way, one can probably keep a small balloon with a pinhole leak inflated but would fail in the effort if the pinhole leak became a slit in the balloon.

- *Controls the return fans between 60% and 100% of supply fan speed based as building pressure with fan speed increasing as building pressure increases:* While at first glance, this seems logical (higher building pressure equals the need to move more air back to the air handling systems to be relieved from the building) there are a number of things that could work against success in the Courthouse.

  1. The relationship between fan speed and flow produced by different fans has more to do with the shape of their curve and the design operating point than it does the ratio of speeds. The PowerPoint® included in the electronic appendix titled *VAV Return Fan Tracking Control Example.ppt* illustrates this for a VAV system going through a step change in operating point. (Link to the PowerPoint® via Appendix 1).
  2. The return fans in the courthouse are located on level 20 and the relief system is at the top of that level. Bringing air back to the top of the building to eject it from the building takes the air from where it needs to be relieved to combat stack effect on a cold day and probably tends to make the lobby more negative as illustrated by the data we gathered while investigating the building pressure relationships (see the *Facility Dynamics Field Test Results and Recommendations* hyperlink in Appendix 1 to link to the folders containing this test data).

With the JCI control sequences in mind, consider what happens when the building is operating at near peak flow on 50% outdoor air via an economizer process when the garage exhaust fan cycles from off to on.

- Based on the design parameters when EF3 is started, 32% of the relief flow rate would shift from the AHU relief dampers to the garage exhaust path. Initially, the building would likely go fairly negative because EF-3 and MAU2 and 3 would start and come up to speed fairly quickly with the MAUs likely coming up faster than EF3 since they are across the line while EF3 has a VFD which likely has a modest acceleration time.
- The return fans would react to the building pressure drop reduction, but not very quickly since the information needs to be picked up and propogate through the control system and since the fans have acceleration and deceleration times programmed into their drives.
- In theory, the goal of having the return fans reduce speed is to have them move 32% less air up the return shaft and out the relief dampers (32% is the portion now taken by EF3 and ejected from the building via the parking garage). But when the return fan speed stabilizes at a new operating point associated with the relationship between return fan speed and building pressure that is programmed into the control system, there is no guarantee that the flow produced will be the right flow for the current operating mode since it depends on a number of variables besides fan speed.
- In theory, the starting EF3 should reduce the relief flow from the air handling systems by 32% since EFT3 is now ejecting that air from the building. But even if the return fan speed adjustment that occurred when building pressure changed did and in fact reduce return flow by 32%, there is no guarantee that the reduction in flow on the discharge side would occur entirely across the relief damper.
- In fact, since the relief dampers are controlled by the same signal that controls the outdoor air dampers and, since initially, nothing happened that would change the temperature at the sensor controlling them, the return and relief damper probably did not move, and the reduction in return flow is reflected as a proportionate reduction across both the relief and return dampers, not a reduction solely across the relief dampers.
- The reduction in air flow through the return dampers that was just discussed will cause the control point in the process that is controlling them to shift. How much of a shift occurs will vary with the percentages of outdoor air and return air and also with the difference between outdoor air and return air temperature. In other words, it is non-linear and will vary with operating conditions.
- In general terms, the reduction in return flow will cause the control system to close the outdoor air dampers and open the return dampers in order to compensate. While this finally impacts the relief path from the facility, it also changes the amount of outdoor air that is being brought into the facility, tending to reduce it and make the facility more negative, which is the issue that triggered the control process upset and response in the first place.

The bottom line is that we believe part of the problem with the current building pressurization control approach is that it does not directly control the relief system on the air handling units, an issue that is compounded by the complexities introduced by VAV system operating characteristics and the large step changes that can be made to air flow patterns when EF-3 and MAU2 and 3 cycle in response to a CO detector.

Stack Effect

From a fundamental physics standpoint, high rise buildings are a bit like chimneys with the top of the building representing the chimney cap and the lobby and main entrances representing the hearth and the shafts discussed in the preceding section representing the interconnecting flue. If it is cold outside, the air in the building is less dense than the air outside and tends to move into the facility at the bottom when doors are opened, travel upward through the facility via the shafts, and exit the building at the top. The reverse occurs when it is warmer outside than inside.

These air flow patterns occur because of pressure differences that exist between the interior and exterior of the building which are created by the differences in air density inside and outside. The density of the air is affected by both the temperature inside and outside and elevation, with density decreasing as temperature and elevation increase.

Returning to the winter case, when air comes into the bottom of the facility and exits from the top, the implication is that there is a natural, negative pressure relative to the outdoors at the bottom of the building and a positive pressure relative to the outdoors at the top. During one of our test sequences in mild weather, we measured the lobby pressure as being 0.07 in.w.c. negative relative to atmosphere with all of the systems in the building off.[13] This is the stack effect associated with the density differences inside to outside on the day we tested. Had it been colder, the lobby would have tended to be more negative and vice-versa.

If the pressures in the building is higher than atmospheric at the top and lower than atmospheric at the bottom, then it implies that at some point in the building, it is exactly equal to atmospheric pressure. This location is termed the "neutral plane" and it shifts position in the facility as a function of a number of different things.

- *Envelope integrity:* The integrity of the envelope impacts the location of the neutral plane because it impacts how easily air can enter or exit the facility. Related to this is the intentional envelope breaches created by doors on the lower levels and intakes, exhaust, and relief louvers on the upper levels as illustrated in Figure A6 - 6.
- *Indoor to outdoor temperature difference:* Temperature differences will shift the position of the neutral plane with the neutral plan shifting downward as the indoor temperature approaches the outdoor temperature.
- *Outdoor air percentage:* Increasing outdoor air flow will tend to shift the neutral plane down, all other things being equal. So, for a facility with economizer processes in place that vary the outdoor air percentage as a function of load, return temperature, and outdoor air temperature, the neutral plane can shift as a result of the economizer process operating state.

  The intent of the courthouse design appears to be to provide approximately 30% (of peak design flow) as minimum outdoor air when the systems are in operation (see Table A5 - 1 in Appendix 5). The economizer processes in the facility can drive this to 100% outdoor air if ambient conditions are suitable for free cooling and the loads demand it.

[13] Details of the building pressure profile measurements we made along with related recommendations can be found in the electronic appendix via the *Facility Dynamics Field Test Results and Recommendation* hyperlink in Appendix 1.

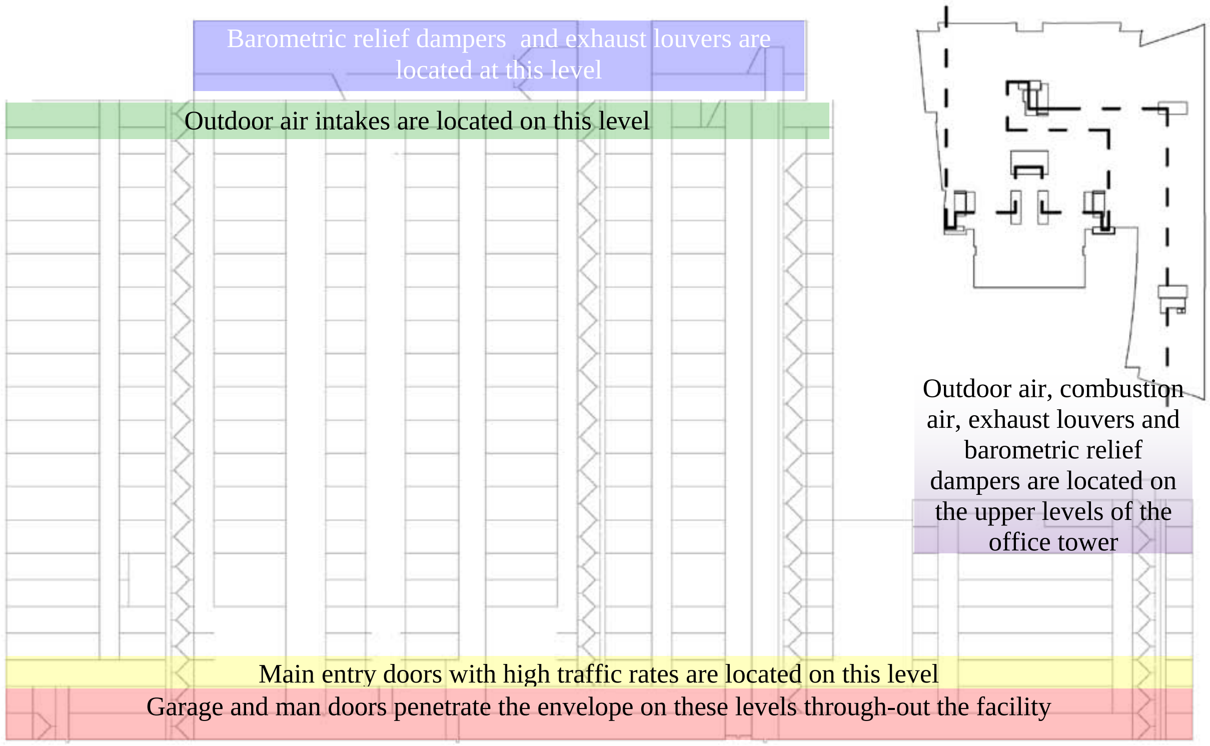

Figure A6 - 4 – Locations of Intentional Breeches of the [redacted] Courthouse Envelope: This drawing is the basis of the background for the air handling unit and air flow system diagrams that are used for Figure A6 - 3 and Figure A6 - 4. It includes a plan showing the section cut line and is used here to illustrate locations where the envelope is breeched intentionally to allow access or to support HVAC processes.

- *Exhaust and relief air percentage:* Increasing exhaust air flow will tend to shift the neutral plane up, all other things being equal. Note that for the purposes of our discussion, exhaust air is air that is removed for the purpose of ventilation and that was intended to be offset by makeup air by the design. Relief air is air that is removed to accommodate the extra air brought into the facility for “free cooling” by an economizer process.

  For a facility where there is an imbalance between make up air, exhaust air, and relief air the neutral plane will move around as a function of the drivers of the imbalance. For the courthouse, many of the issues discussed in this section could cause such an imbalance, making the neutral plane location and pressure control a very dynamic process.

Recommendations

1. Make every effort to keep doors between various pressure zones in the facility closed. With some regularity, while working on the mechanical levels, we would find doors propped open that were essentially short circuiting air from the return plenum to the relief plenum, from the outdoor

air plenum to the return plenum, etc. In addition to affecting building pressurization, this is often represents life safety issues since the doors are typically in rated assemblies.

2. Adopt a control strategy that returns the operation of MAU2 and 3 more in line with their original design intent. This is discussed in greater detail in *Appendix 7 - Control Optimization Opportunities*.
3. Adopt a control strategy that controls the relief dampers more directly based on building pressure, potentially shutting down the return fans when they do not need to run to move air to the top of the building. This is discussed in greater detail in *Appendix 7 - Control Optimization Opportunities*.
4. Calibrate the existing building pressure transducers and make calibration checks a semi-annual requirement, once during peak cooling season and once during peak heating season. Consider upgrading these sensors to velocity based sensors similar to the Iso-Tek SPM-2000 as manufactured by Tek-Air, either as a part of the proposed retrocommissioning process or as a repair option when existing sensors fail.
5. Related to the preceding, purchase a high quality air flow/air pressure measurement system similar to the Shortridge ADM-870C and associated measurement kit and flow hoods and train key personal associated with the facility in its use. Given the critical nature of flow and pressure in the facility, having such a tool and skill set available will be a valuable asset for troubleshooting and verifying system performance on a day to day basis.
6. Interlock the discharge fire and smoke dampers on MAU 2 and 3 so that they act as back draft dampers and close when the fans are off in addition to providing the smoke and fire separation. Note that this should be accomplished carefully and verified to ensure that the back draft function does not interfere with any smoke management functions.
7. Add a control loop to maintain constant flow in AHU1 – 4 as the filters load. Given that these systems are already equipped with variable speed drives on the supply fans and that the air flow they provide is critical to building pressurization, it is highly desirable to ensure that filter loading does not restrict system capacity to the extent possible by the available fan power. Field testing during the retrocommissioning process should target assessing the impact of restrictions on the exhaust side on building pressurization. Our feeling at this time is that while exhaust flow will vary some as the filter protecting the air to air heat exchanger load up, the reconfigured building pressure control strategy proposed above will compensate for this via the relief system.