CASE STUDIES OF AIR-LEAKAGE EFFECTS IN THE OPERATIONS OF HIGH-RISE BUILDINGS

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ABSTRACT

Of the five thermal transfer mechanisms (conduction, convection, radiation, air movement, and phase changes of water) revealed in high-rise buildings today, air movement through the building envelope appears to be the most formidable threat to a building's operating efficiency. These mechanisms are causal mechanisms associated with deterioration of building components, particularly those conditions that produce condensation in roof and wall assemblies. Because most building envelope deficiencies are concealed from the conventional inspection procedures, new methods of building inspection are required. The application of infrared technology is a new evaluation technique for understanding the overall performance of the building envelope. Thermography is such a nondestructive diagnostic tool.

This paper is a comparative study of two 26-story high-rise buildings with hidden air leakage anomalies--a building envelope problem that may exist in a high percentage of commercial buildings today. Thermography revealed extreme exfiltration problems at top floor mechanical room levels of both buildings. Further investigation affirmed the presence of a severe stack effect fed by air infiltrating into each building's exposed central core through elevator and mechanical shafts, chaseways, and stairways.

INTRODUCTION

This paper discusses two high-rise buildings that had hidden air leakage problems. One building was initially studied to detect an obvious air infiltration problem. The other building was new construction and the owners specified an evaluation of the building's exterior to determine thermal integrity. Thermography used in the initial investigation disclosed areas where hidden problems existed. By combining the thermographic technology with other diagnostic methods, specific problems were determined.

CASE STUDIES

The two high-rise buildings in the case studies are located in a city in central Virginia. Both are 26 stories tall and stand within 300 yards of each other. Building A stands alone in an open setting, while Building B is surrounded by other city buildings. Building A is five years older than Building B, which was occupied in 1983. In August 1982 the management of Building A asked me to analyze a condition that had developed within the building's low-rise mechanical room during the winter. The building had experienced some severe air infiltration during the coldest part of January 1982. Temperatures in the second floor mechanical room area dropped to 16 F, some return air plenums on the third and fourth floors were recording return temperatures in the 40s F, while floor temperatures maintained 71 F. Apparently unknown to management at the time, the sudden drop in temperature caused severe freeze-up conditions in five air-conditioning units, which required replacement at a cost of $30,000.00. This condition was not discovered until April when mechanical personnel were preparing the air conditioning system for summer. In January, building designers were consulted concerning the air infiltration condition. They advised repositioning of a heavy mineral wool fire-saving material to act as an air barrier between the second floor concrete curbing and the exterior

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aluminum paneling to effect a tighter fit. They also recommended the addition of layers of fiberglass insulation. This was a retrofit measure that building personnel effected immediately. What the management wanted me to do was inspect the condition thermographically to determine if the retrofit had been effective because, they did not want a recurrence during the next winter's cold snap.

To make this kind of summer inspection was difficult. Parameters were set up that would induce hot air infiltration in through the building envelope at the second floor, which required a good thermal difference between indoor and outdoor temperatures. We selected a day in the mid-90s F. Building engineers created a negative pressure by opening air-handling chambers, and we were able to detect air movement into the mechanical area through the portion of the building envelope that had experienced the recent retrofit. Although we did not witness a rise in the inside ambient temperature of 77 F, we did see a drop in some second floor temperatures. We suspected that drop was influenced by colder air from other areas of the building that were under air conditioning. It appeared we were pulling more air down from the building central core than through the envelope, as we had attempted to do in this test. I informed management that, though it was inconclusive, we felt that the retrofit had retarded the flow of outside air into the second floor mechanical room. I encouraged them to authorize a broader building envelope examination in the winter of 1982-83 when the building's temperature differentials were at their greatest and the building would be under its maximum thermal stress. They approved, and arrangements were made for aerial and ground surveys. In the meantime, from August to January, I interviewed some of the people who worked in the building and talked with mechanical personnel who knew it best. We found it was a total electric building and operated on two electric boilers. It had about a million square feet of floor space, half of which was above ground and the other half below ground on three separate levels. Construction was poured concrete below grade, structural steel and concrete decks above grade; exterior was aluminum panels backed with insulation pads; and all windows were fixed. Building A had two mechanical rooms, a high-rise mechanical on floors 25 and 26 and a low-rise mechanical on the second floor. The building was under computer control and monitoring of all mechanical systems. Rising through the building's central core were stairways; mechanical, plumbing, elevator, and mail conveyor shafts; and electrical closets.

In January 1983, we started with a ground survey and discovered thermal anomalies across the outer enclosure. We identified heat transfer mechanisms of conduction, convection, and air movement. There was evidence of heat transfer by convection between insulated aluminum panels, which appeared to be scattered throughout the building's surface. Elimination of this heat transfer was not considered to be a high priority payback item. Conduction (thermal bridging) was inherent in the building's design with little hope for a practical solution. Air leakage in some east side columns was judged not excessive but would require further study. An aerial thermographic survey of the roof and upper floors with a reexamination of the second floor mechanical room followed in close sequence. Based upon collected preliminary data, investigative attention was quickly shifted to the 26th floor mechanical room and a corridor connecting it to a four-unit emergency generator room. A close examination of the original building plans disclosed the possible omission of a doorway partition between the 26th floor corridor and the emergency generator room. This opening, which measured 7' x 12', was experiencing high velocity movement of 71 F air into the generator room and out gravity louvers. Thermographic aerial survey data confirmed an apparent massive thermal anomaly of 70 F building core temperature air escaping through the louvered vents. While reexamining the second floor, it was found that areas of identified infiltration matched those detected in the August 1982 inspection. Now the air was moving up stairwells, mechanical and elevator shafts at such velocity as to create a high decibel, low frequency whistling sound. An interior floor by floor investigation traced this air movement up through the building to its point of exit through gravity and mechanical louvers at the 26th floor emergency generator room. We also discovered that the building had NDNPP syndrome (nondetectable neutral pressure plane). Within 24 hours, maintenance personnel had quickly sealed the 26th floor corridor with a wallboard partition and double doors. Other voids at wall corners and between partition wall plates and the corrugated roof deck were closed using styrofoam blocks and sealants.

Immediately, the building began to pressurize. Second floor ambient temperatures rose 3 F, and air movement noises subsided creating a noticeably quieter building. Perhaps for the first time in itshistory, the building experienced a neutral pressure plane currently located at the 17th floor level. With other floors recording temperature rises, mechanical personnel had to rebalance the heating and air conditioning systems. Since building warranties had expired, all corrective procedures were at the owner's expense. At this point, we began to realize the significance of being able to locate the building's neutral pressure plane. From now on in this paper, the neutral pressure plane will be referred to as NPP. As a general rule of thumb, the NPP of a high-rise building with a properly functioning envelope should be found between one-third to two-thirds of its height. Findings in this wintertime study led to the conclusion that severity of air leakage in the building can be judged based upon how high above two-thirds of its height the NPP is located. In the case of Building A, it was first located just under the 24th floor indicating an extreme condition. For all practical purposes, it was an unidentifiable NPP.

Although there were other factors involved, it was estimated that up to 4 billion BTU loss could have occurred each heating and air conditioning season during the previous five years. In light of the building now being pressurized, a proposed infrared inspection schedule for the coming winter of 1984 was predicted to disclose more points of air leakage on all sides of the tower. Also, it was theorized that if the 2nd and 25th floor mechanical room decks could be completely sealed at the perimeter, it would have the effect of putting a stopper in each end of the building. The in-between floors would be protected from air infiltration to those spaces by way of wall and column cavities. As we continued to work through the year, accessible portions of the soffit area below the second floor deck were physically inspected twice during the heating season and once in the cooling season. Under heating conditions, outside air was observed flowing into the building's wall cavity at the corner columns. While inspecting the soffit area, it was discovered that the building envelope of the central core was open to air movement, particularly heavy around a boxing that contained two overhead roll-up riot screens. An attempted retrofit, using a foam sealant, was in evidence but was judged to be only partially effective. As more of the building envelope's components came under inspection through some destructive testing, a poor quality of craftsmanship was observed. Loosely placed insulation, ineffective applications of sealants, incomplete air barriers--all seemed to reflect a need for understanding on the part of the building trade as to the importance of assembling a functioning building envelope.

All anomalies from the January 1983 aerial survey were reviewed and identified as normal mechanical system discharges, except for one unexplained anomaly discovered in the summer of 1983 during playback color analysis of the winter thermographic video data tapes. A secondary thermal response emitted from the window-washing equipment storage area was formerly undiscovered because of its location and other more intense roof-top thermal expressions. Without the use of thermography as a diagnostic tool, this secondary thermal loss condition would have gone undetected.

To complete the expanded investigation took a total of 12 months. This included inspection of shafts and stairways during both the heating and cooling seasons. Airflow meter readings taken in the 26th floor corridor revealed surges of air that correlated with the opening and closing of inside access doors on lower level B serving the main underground loading dock service area and the building's central core. Outside service doors usually remained open. Though other areas of the subbasement contributed, B level was analyzed to be the major point of massive air intrusion into the building's core. As we began to bring under control the building's envelope problems, we ran into another integrity problem that involved building personnel. This mainly had to do with leaving exterior doors open and also with leaving doors open that expose the central core of the building to an opened loop stack action. One example was the mail conveyor shaft and its enclosed vestibule on a subbasement level. Personnel found it difficult to open because of the pressure; therefore, it was left propped open. Management is now looking into the feasibility of air lock control systems at the key points.

After exhausting available nondestructive investigative techniques, the building management approved the opening of several wall cavities for inspection. One inspection disclosed the degree of ineffectiveness of the January 1982 retrofit at the second floor curbing in the 2nd floor mechanical room. Management brought in an industrial insulation contractor who has now sealed the envelope at this point using new resilient airtight state-of-the-art materials at a cost of less than $6,000.00. Incidentally, the door partition replacement in the corridor of the 26th floor was done by in-house maintenance personnel for less than $1,500.00. This work included the sealing around wall plates and the corrugated roof deck. The other destructive inspection, prompted by the delayed discovery of a thermal anomaly at the 26th floor window-washing equipment storage area, revealed a 14-foot-high void, 1-foot wide, at the junction of two outside wall cavities. The outside vertical structural I-beam, with an independent vertical support set between its flanges, formed a blind maze and created an air passage in the building's envelope. This was immediately corrected by building maintenance personnel for a few hundred dollars. In conclusion, this building has some inherent thermal deficiencies designed into it that management is learning to live with. However, there are other conditions within the building envelope that have a profound effect upon the building's operating performance that are within current technical capabilities to evaluate and correct.

Building B is five years younger than Building A and was first occupied in the summer of 1983. It is 26 stories tall with a 3-story pavillion to the north side and a 3-story parking deck to the west. It has two subbasement levels, which are below ground on the north side and at street level on the south side. All enclosed areas make up approximately 600,000 square feet of occupied floor space. Building B is constructed of structural steel with poured concrete decks and an exterior of polished Texas granite mechanically fastened to the steel structure. All exterior walls are blanketed with thermal insulation. Windows are fixed. The heat system is supported by gas/oil-fired boilers. The air-conditioning system is electrical. There are two mechanical rooms--one high-rise mechanical at the 25th and 26th floor levels and above that a penthouse that houses the emergency electrical generator and freight elevator equipment room. The low-rise mechanical is located between the 4th and 5th floors. Like Building A, this building is computer monitored and controlled. All utility shafts, elevators, and other mechanical chaseways rise through the center core of the building. When building construction reached completion, a building envelope evaluation inspection was conducted. In January 1984, accompanied by the building operations officer, we conducted the first aerial survey of the rooftop and penthouse area and upper floors. This was followed with a ground survey of all exterior surfaces and several sample interior surveys. No serious problems of conduction or convection were observed within the exterior wall or roof, nor did we identify anything from the exterior that would indicate condensation within the wall cavities. Aerial survey data did show many unexplained thermal expressions from the penthouse rooftop areas that required sorting out and identifying. Except for these unidentified thermal responses, it appeared to be a healthy building with good thermal integrity.

A computer controller is in moment-to-moment touch with the building's operating conditions. One weekday morning during our thermographic investigation, a smoke alarm signal was picked up in the computer control room. The operator calmly overrode the system by shutting off the alarm. He explained that this was a daily occurrence caused by diesel fumes from the trash truck that pulls into the building's loading dock area at the same time every morning. This was our first clue that there might be some serious air movement problems. If not related to the building envelope, certainly it was related to movements of air between interstructural spaces. What made the smoke alarm incident significant was the fact that the alarm was in an elevator shaft 300 feet from the loading dock area which supposedly was sealed off from the rest of the building. To add to the curiosity, the diesel fumes that flowed through the building had to pass a smoke alarm located at a low-rise elevator shaft on their course to the high-rise elevator shaft where the triggered alarm was located. At this point, a whole new facet to the investigation had opened up. It was discovered that the building suffered from the same nondetectable neutral pressure plane syndrome that had plagued the other building. The two high-rise public elevator shafts located to the north portion of the building and the freight elevator shaft located in the center of the building all exhibited high air velocity and high decibel sound levels at the top terminating floor levels. There was evidence that the north high-rise elevator shaft was moving more air at a higher negative pressure influence than did the south shaft. This indicated an air movement anomaly that required further examination. Upon investigation, the low-rise public elevator shafts located in the building nearest to the loading dock area revealed a surprising positive pressure at the lower shaft level. We were able to trace the positive pressure influence to the trash room exhaust system near the bottom of the low-rise elevator shafts. This also explained why the smoke alarm in the low-rise shafts was not triggered by the diesel fumes coming from the loading dock. They were repelled by the positive pressure.

The expanded investigation of air movement within the building disclosed air movement to the top of the building not only by elevator shafts but by mail conveyor shafts, stairways, bus duct risers through electrical closets, and other chaseways not designed for air movement. The terminal points for this movement of air, which could hardly be classified as air leakage, were through the 26th floor mechanical room and the high-rise elevator shaft equipment room. The two elevator rooms at the top of the building are equipped with exhaust fans that have gravity louvers. The stack effect was so strong at this location that the fans and louvers appeared to operate even though they were not under power. It was discovered that the air moving up the freight elevator shaft had an attraction for the 26th floor main mechanical room. With the help of building personnel, the vestibule passageway was sealed off with plywood. We were able to transfer the release pressure point which had been at the elevator doors, to the temporarily sealed passageway. Although the building is still under warranty, building owners have elected to perform the retrofit work themselves. They feel their personnel are better informed as to the function of the building envelope and are better suited to perform the task that will insure its integrity. However, the building contractor was assigned the job of sealing off the loading dock area from the rest of the building. The retrofits included installing a partition doorway at the 26th floor level, blocking openings in elevator shafts, and sealing up voids where penetrations occurred through walls and floors. An assessment of the retrofits to date will be conducted this winter, laying the foundation for further corrections in the air movement problem.

During the course of our internal investigation, we also learned of an apparent heat distribution problem in the building's southwest corner in the personnel offices on the first floor. The mechanical contractor was dealing with the problem by adding more air delivery to the area. Management personnel issued portable electric heaters to those who occupied the offices on the west wall. Interviews with personnel who occupied spaces on the west side from subbasement level through the second floor revealed a condition of general discomfort during cold weather days. During the days we investigated these complaints, the low nighttime temperature was 22 F with daytime temperatures in the low 30s F. Thermographic inspection of walls and floor in the personnel section disclosed a thermal gradient across the interior surfaces ranging from a 43 F to a high of 61 F in the office located in the extreme southwest corner. The heat loss mechanisms of conduction, convection, and radiation were present in this condition, and if this section of the building had been at 72 F design temperature and 40% relative humidity, we would have seen condensation on some wall and floor areas. Body heat of the occupants was radiating to the colder outside walls. One of these walls was polished Texas marble that connected to the building's facade. Thermography allowed us to map and trace a thermal bridging movement to the exterior. A similar pattern led us to investigate the space below the floor of this office. To our surprise, we found an uninsulated chamber open to the outside that was covered by a fixed louver panel. Apparently, this forgotten chamber was to have been part of a mechanical system that was deleted from the building plans. However, its presence was a contributing factor to a thermal deficiency in the envelope. Another contributing factor was the fact that a massive three-story concrete parking deck occupied a space on the building's west side corresponding to the offices where comfort complaints persisted. Building management is now considering methods to thermally isolate this radiation condition from influencing the inside environment.

SUMMARY

The building envelope deficiencies revealed in the study of Buildings A and B are illustrated in Tables #1 and #2. Included in this section is a list of conclusions not only related to Buildings A and B but a composite of conclusions derived from years of observing other building enclosure problems.

1. Most multiple story buildings existing today have some form of hidden thermal deficiencies within their enclosures not detectable through usual inspection practices. Thermography is an essential inspection tool.
2. Of the five thermal mechanisms responsible for energy losses through the building envelope of high-rise buildings, exfiltration of conditioned air (air leakage) through its core is the most threatening to thermal efficiency.
3. Mechanical systems designers and contractors need the assurance of a functioning building enclosure that is pressurized and will support and complement their systems.
4. Finding and analyzing the location of the building's neutral pressure plane holds the key to evaluating its air leakage integrity.
5. There is a need for writing into the architectural/mechanical specifications a complete building envelope evaluation inspection. In the case of buildings currently under construction, it is desirable for building owners to protect their interest through thermographic building inspections as part of the building commissioning process or before the expiration of the warranty period.
6. Investigation findings must be shared with building design professionals.
7. The general contractor's understanding of the function of the building's air/vapor barrier is important and there is a need for close supervision.
8. Craftsmen must understand the detailing required during construction to provide an effective air/vapor barrier.

TABLE 1
Building A - Thermal Deficiencies in The Building Envelope
Discovered During Cold Weather Conditions

AIR LEAKAGE

Exfiltration

- Major air movement through openings in the building envelope at the top floor mechanical room and generator room levels.
- Random scattering of small amounts of air movement across the exterior surface at the joints of false aluminum columns.

Infiltration

- Major air movement bypassing thermal and air/vapor barriers between second floor mechanical room deck and exterior aluminum panels.
- Secondary air movement through an assembled enclosure protecting the building's central core where it rises through a soffited space just below the second floor overhang.
- Air movement exposure to the building's central core through entrances located at the subbasement loading dock level.
- General air intrusion through building entrances.

Conduction (Thermal Bridging)

- Heat transmission from concrete decks through connecting metal support members to edges of aluminum wall panels. Condition exists across all exterior building surfaces.

Convection

- Convective currents flowing in voids between thermal insulation pads and exterior aluminum wall panels.
- Random convection identified in some existing false columns.

Phase Changes of Water

- Condensation and frost buildup on uninsulated aluminum exterior wall panels and steel support members at the top floor mechanical room level.

Radiation

- No evidence of radiation losses to other structures.

TABLE 2
Building B - Thermal Deficiencies in The Building Envelope
Discovered During Cold Weather Conditions

AIR LEAKAGE

Exfiltration

- Major air movement through a variety of openings in the building envelope at the top floor mechanical room and penthouse levels.

Infiltration

- Air movement into the building's central core through overhead door assemblies and voids in partitioned walls at the loading dock level.
- General air intrusion at building entrances.

Conduction (Thermal Bridging)

- Interior marble walls conducting heat to exterior marble walls at the main floor level.
- Concrete deck conducting heat energy into open chamber below west side office on the main floor level.

Convection

- Convective currents operating within the west wall cavity up to the third floor level.

Phase Changes of Water

None observed.

Radiation

- Severe heat loss through west wall adjacent to three-story parking deck.