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Air Flow Distribution in a Mechanically Ventilated High-Rise Residential Building

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Synopsis: Air flow measurements and simulations were made on a 13-story apartment building to characterize the ventilation rates for the individual apartments. Parametric runs were performed for specific conditions, e.g., height, orientation, outside temperature and wind speed. Our analysis of the air flow simulations suggest that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled, units at the lower level of the building have adequate ventilation only on days with high inside-outside temperature differences, while units on higher floors have no ventilation at all. Units facing the windward side will be over-ventilated when the building experiences wind directions between west and north. At the same time, leeward-side apartments will not experience any fresh air--the air flows enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. Even with the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments. In addition to the specific case presented here, these findings have more general implications for energy retrofits and health and comfort of occupants in high-rise apartment buildings.

1.0. Background

Airflow in high-rise apartment buildings has been the subject of sporadic research over the past three decades. From the early work by Shaw and colleagues in the early 1970s, researchers have tried to understand the driving forces for air flow in order to recommend energy efficiency measures that do not jeopardize the health and comfort of building occupants.

Our recent activity in this area came about through the DOE-HUD Initiative, a response to the U.S. National Energy Strategy's directive to improve the energy efficiency in public housing. Under the Initiative's guidance a collaborative project was established to demonstrate energy efficiency in public housing as part of a utility's Demand Side Management (DSM) Program.

The demonstration site is the Margolis Apartments, a modern 150-unit high-rise apartment building for the elderly and handicapped, located in Chelsea, Massachusetts, in the greater Boston, Massachusetts, metropolitan area.

2.0 Building Description

The Margolis Apartment building was designed in 1973-1974 and is typical of high-rise construction from that period. The building has thirteen stories and is of steel-frame construction. The individual apartments have electric-resistance heaters in each room, and double-pane windows and sliding balcony doors. A typical floor plan is shown in Figure 1.

The building has a mechanical ventilation system, with kitchen and bathroom exhaust fans for each apartment leading into separate vertical shafts that have additional exhaust fans located on the roof. The supply air system for the building is provided by a fan and heating unit on the roof which connects to a vertical shaft with supply registers to the main hallway on each of the floors. Supply air then enters the apartments by a slot under the front door of each unit.

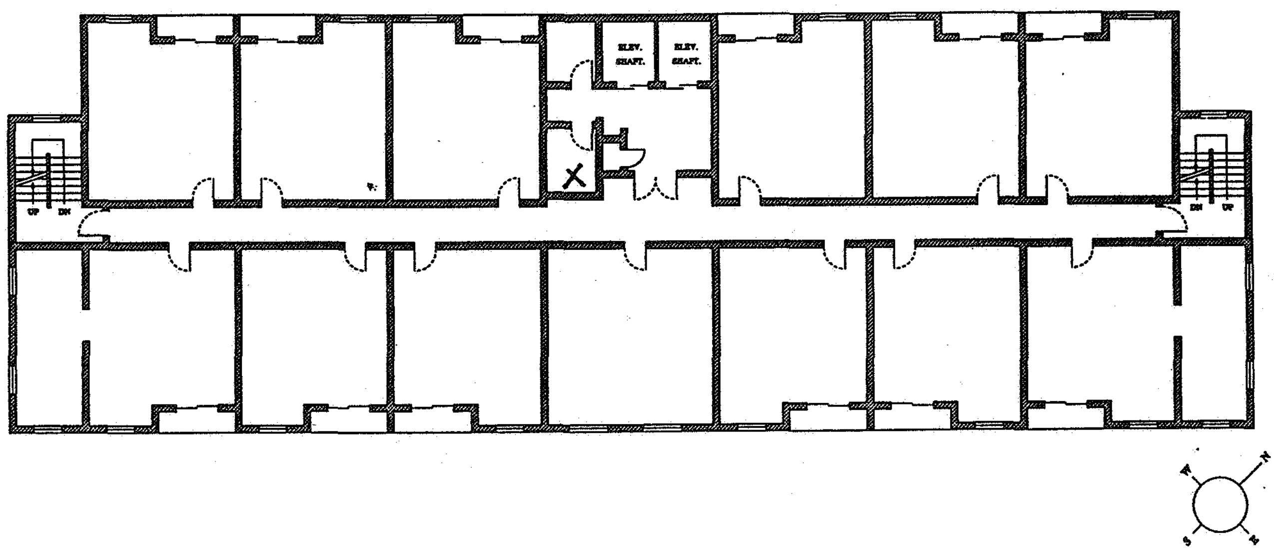

Figure 1. Typical floor plan (floors 2-5), Margolis Apartments, Chelsea, MA. The "x" shows the location of the supply ventilation register for each corridor.

The building is exposed on all sides to the wind, and is located less than 5 km from the airport weather station. Airport weather data records a mean annual wind speed of 6 m/s with up to 26 m/s wind speeds in winter. The winter wind is primarily from the northwest; the wind in spring through fall is from the southwest.

In December, 1993, the building underwent extensive retrofits. New double-pane, low-e windows replaced the old windows throughout the building. A computerized energy management system was installed that allowed for tracking and controlling of the thermostats in the individual apartments. Efficient light bulbs were installed in the individual apartments. A new sprinkler system was installed throughout the building. The balconies were screened in to prevent the pigeons from roosting. A second phase of retrofit activity a year later involved improvements to the abandoned ventilation system.

Prior to the window retrofit, drafts were a major complaints expressed by the tenants, but since the retrofit, there have been--according to building management--fewer complaints about window drafts. There was mention of the windows being hard to open for some of the residents, both from the latching mechanism and the effort needed to lift the double-hung sash. No problems with condensation on the windows were reported since the retrofit.

The northwest-facing units (weather side) continue to be the hardest units to maintain thermal comfort. Also the second floor units (above the open parking areas) continue to be a problem in cold weather.

3.0 Measurements & Preliminary Findings

The measurements and analysis that we are reporting here consist of two parts: 1) Air leakage measurements of the apartments measured pre- and post-retrofit, and 2) Computer simulations of the air flows in the building under different weather conditions.

3.1 Air Leakage Measurements

We measured using blower doors the air leakage in nine apartments, before and after the new windows were installed. The average pre-retrofit total effective leakage area for the one-bedroom apartments was 241 cm^2 and 256 cm^2 for the two-bedroom apartments. The post-retrofit total effective leakage area for the one-bedroom apartments was 230 cm^2 and 248 cm^2 for the two-bedroom apartments.

These measurements suggest little or no reduction in air leakage due to the new windows, which is surprising given that tenants who had previously complained of drafts were now satisfied. One explanation is that tenants were previously experiencing down drafts at the window due to cold surface temperatures, which no longer occur because of the new double-pane, low-e windows.

We also note that these measurements were made in very windy conditions--beyond the limits allowed for standard blower-door tests. While this problem is not uncommon in low-rise buildings, it is an even bigger problem in high-rise buildings, where wind speeds are often much higher than for buildings at ground level. Furthermore, the measurement technique used is based on a reference pressure describing the pressure field around the building. In large buildings, it is very difficult to find a pressure point which acts as the reference pressure for the apartment being investigated. There is also the possibility that the measurement technique itself, i.e., depressurization with a blower door, temporarily seals the windows and distorts the findings.

By way of comparison, Kelley et al. (Kelly 1992) measured the air leakage pre-and post-retrofit in a high-rise apartment in Revere, Massachusetts, a few kilometers north of the Margolis apartment. They found an average pre-retrofit leakage for 17 of the apartments of 904 m^3/h at 50 Pascals, and a post-retrofit leakage of 763 m^3/h at 50 Pascals, a reduction of 15%. The comparable flows at Margolis were higher, and showed no reduction after the retrofit, with an average of 1183 m^3/h pre-retrofit and 1214 m^3/h post-retrofit.

We also measured the leakage from one apartment to another, using tracer gases, and found little communication between units--less than 4% of the total leakage was to adjacent apartments. This was not altogether surprising given the concrete construction of the building.

3.2 Ventilation Simulations

Based on the measured air leakage data from the building we conducted extensive air flow modeling of the apartments using the multizone air flow model COMIS, a simulation tool, developed at Lawrence Berkeley Laboratory, which calculates air flows based on mass balance calculations for individual zones (Feustel, 1990).

In order to limit the amount of input needed for the simulation model, each apartment was modeled as one zone, assuming the internal doors to be open. In order to account for the stack effect and the inter-zonal flows between the floors, all 13 floors were modeled.

The results show, that with wind blowing perpendicular to the windward side and no stack effect present, air moves from the windward side facade through the corridors into the leeward side apartments. Under the previous conditions with no ventilation system present, only a small portion of the infiltration air is exhausted through the vertical shafts of the exhaust system. Dampers at the apartment level and on top of each of the shafts restrict the exhaust flow.
When the building is operating without the mechanical ventilation system, the air mass flow distribution for windward side apartments on different floors follows a predictable pattern (Figure 2). With increasing wind speed, the distribution of infiltration becomes more pronounced, showing a minimum at the level of the third floor and a maximum at the 11th floor. The leeward side apartments do not experience any infiltration.

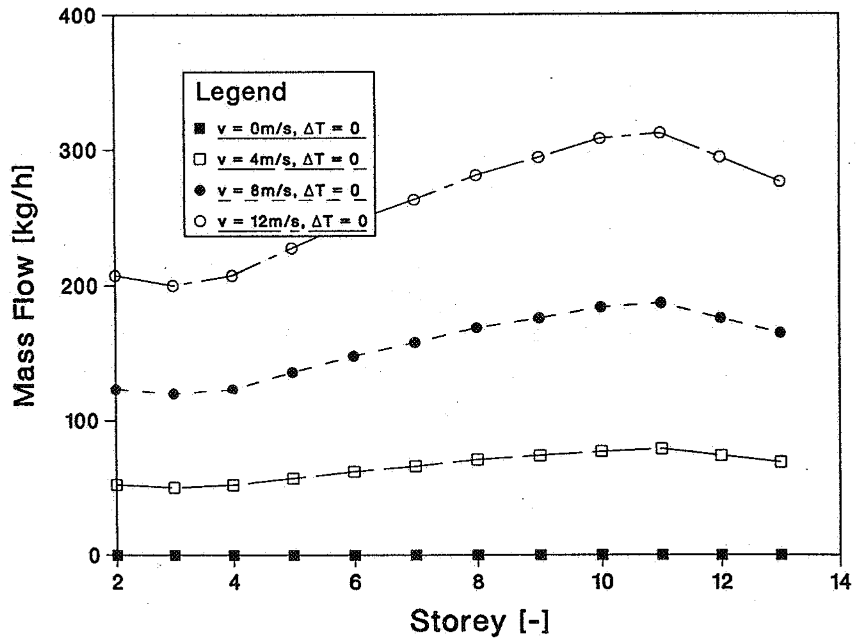

Figure 2. Mass air flow at different wind speeds and no inside/outside temperature difference for the windward apartments with the mechanical ventilation system off. The ASHRAE Standard 62 recommends a ventilation rate of 0.35 ACH, which corresponds to a mass air flow of 50 kg/h.

With a larger inside/outside temperature difference of 20 ^{0}C and zero wind speed, the air flow for the windward apartments decreases with height above ground from 100 kg/h (50 cfm) on the second floor to zero at the level of the 11th floor. With increasing wind speed the air flow curves show a more balanced air flow distribution until the velocity driven air flows override the stack effect (Figure 3). As the pressures forcing the air flow can be added, the air flows for any given wind speed is higher if stack pressure is present.

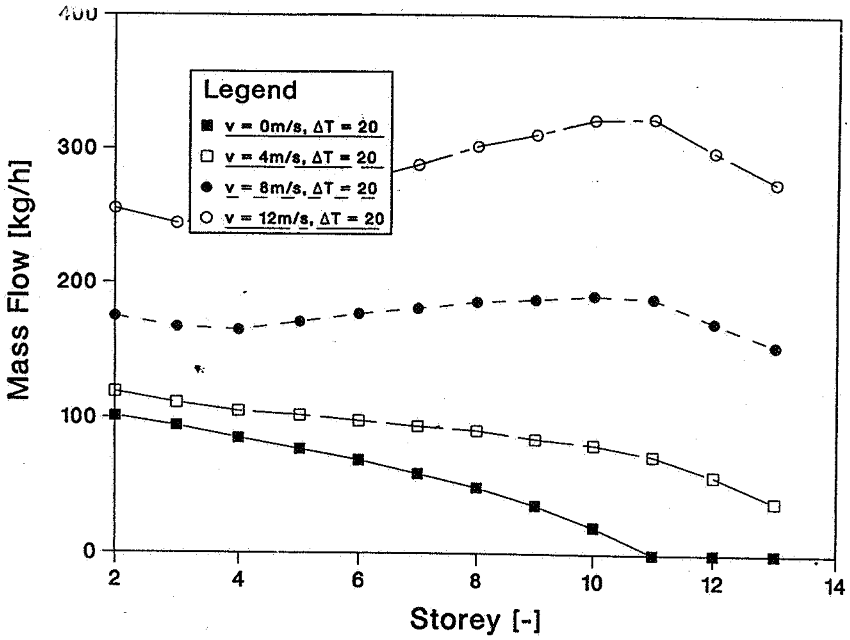

Figure 3. Mass air flow at different wind speeds and an inside/outside temperature difference of 20 K, for the windward apartments with the mechanical ventilation system off.

The air flows for the leeward side is shown in Figure 4. With increasing wind speed the air flow entering the apartments through the outside wall is getting smaller. The zero wind speed curve is the same for the windward side and the leeward side. The top floors do not experience any infiltration. Higher wind speeds cause higher negative pressures on the facade, which lower the level for the neutral pressure. At wind speeds of 12 m/s no infiltration occurs at the apartments facing the leeward side.

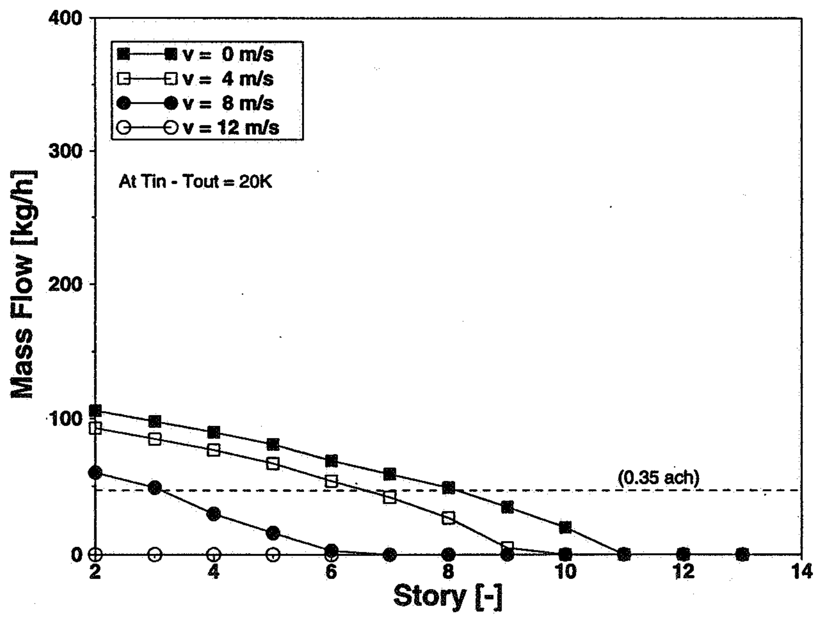

Figure 4. Mass air flow at different wind speeds and an inside/outside temperature difference of 20 K, for the leeward apartments with the mechanical ventilation system off.

Air flows into the apartments are slightly higher when the ventilation system is in operation. Figure 5 shows the air flows entering the apartments located on the windward side through the facade for different wind speeds when no stack effect is present. At low wind conditions, infiltration is almost independent of the height above ground. With higher wind speeds, we see that the infiltration flows follow the wind pressure profile.

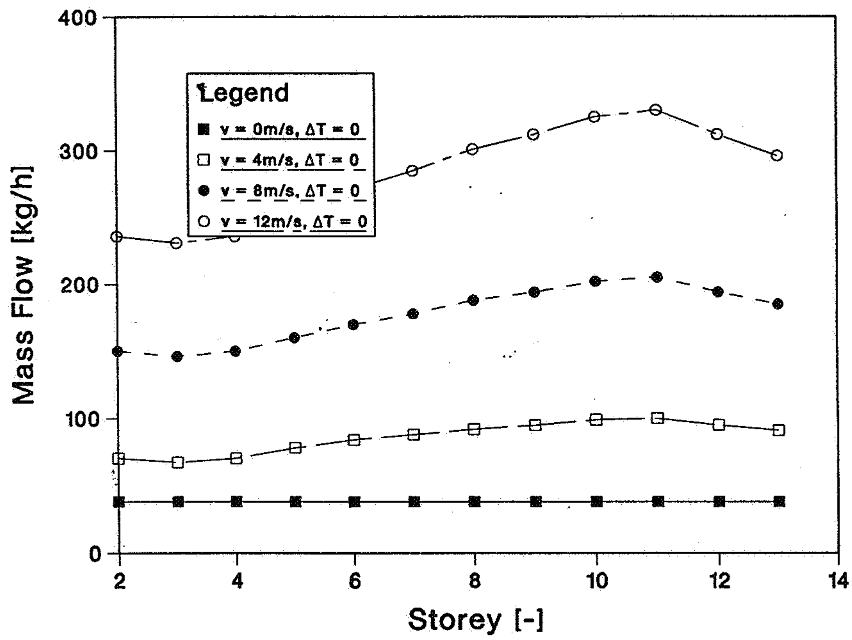

Figure 5. Mass air flow at different wind speeds and no inside/outside temperature difference, for the windward apartments with the mechanical ventilation system **on**.

The ventilation system is designed to provide the necessary "fresh" air by means of supplying the air to the corridor. The direction of the air flow through the doorway of the apartment door determines whether the supplied air is entering the apartments. For the two higher wind speeds, the air flow passing through the doorways are shown for the apartments on both sides of the corridor. We see, that at higher wind speeds the windward side apartments do not receive any of the air supplied to the corridor (see Figure 6). At lower wind speeds, the windward side apartments located on the lower floors participate slightly in the air exchange provided by the supply system. This means, that at lower wind speeds nearly all the air entering through the facade is being exhausted directly into the vertical exhaust shafts. At higher wind speeds, air from these apartments is being pressed into the corridor. All leeward side apartments receive between 50 and 75 kg/h air from the corridor. For higher wind speeds, this amount of air is smaller than the air which enters the corridor from the windward side apartments. The excess air is leaving the corridor through the elevator shaft (which has a large opening to the leeward side at the penthouse level).

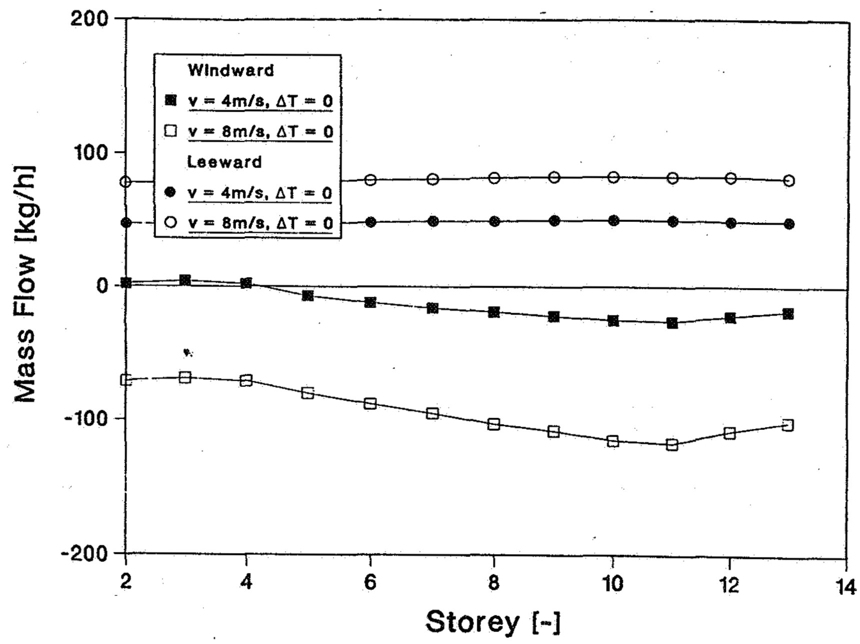

Figure 6. Mass air flow between the apartments and the corridor at different wind speeds and no inside/outside temperature difference, for all apartments and the mechanical ventilation system on.

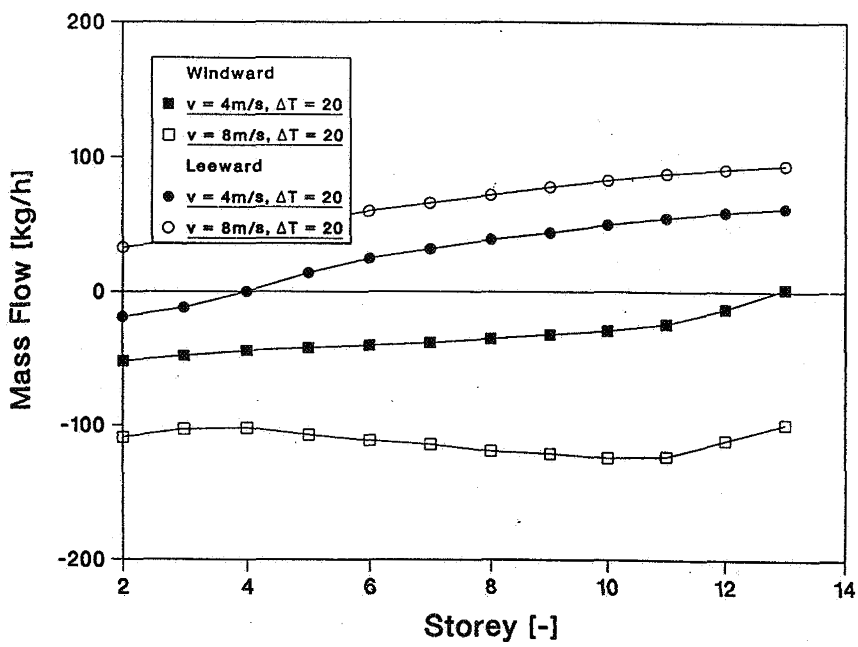

Figure 7. Mass air flow between the apartments and the corridor at different wind speeds and an inside/outside temperature difference of 20 K, and with the mechanical ventilation system on.

With larger temperature differences between inside and outside present (Figure 7), the infiltration flows for the lower windward side apartments increase significantly. The flows for the apartments on the higher floors keep constant. The stack effect also causes the distribution of air flow through the doors to change. At wind speeds of 4 m/s and temperature differences of 20 °C all apartments on lower floors provide air flow to the corridor, rather than receiving ventilation air. Higher up in the building, leeward side apartments receive air from the corridor while windward side apartments exhaust air into the corridor. With increasing temperature difference, the stack effect is amplified.

4.0 Conclusions

Our analysis of the air flow simulations shows that the ventilation to the individual units varies considerably. With the mechanical ventilation system disabled (pre-retrofit case), units at the lower level of the building had adequate ventilation only on days with high temperature differences, while units on higher floors had no ventilation at all. Units facing the windward side were over-ventilated when the building experienced wind directions between west and north. At the same time, leeward side apartments would not experience any fresh air--air flows would enter the apartments from the corridor and exit through the exhaust shafts and the cracks in the facade. Even with the mechanical ventilation system operating, we found wide variation in the air flows to the individual apartments.

A fundamental issue here is the design question of how to best supply ventilation to individual apartments in a highrise building. Using the corridor as the supply route has several challenges, including the control of the temperature of the supply air, the temperature of the corridor, the access from the corridor to the apartment, and the balance between supply and apartment exhaust.

On the exhaust side, studies have shown that when apartment occupants have local control over bathroom and kitchen exhaust, they use them less than one hour per day, if at all (Shapiro-Baruch, 1993), which makes it difficult to size the supply ventilation system. Continuous exhaust ventilation, however, presents the possibility of over ventilation and unnecessary use of energy.

Efforts to improve the energy efficiency of high-rise apartment buildings have been frustrated because of the lack of knowledge on air flows for individual apartments. Ventilation rates for individual apartments vary greatly due to height, orientation, and wind speed and outdoor temperature. Any recommendations for reducing air leakage will have to take these variables into account, so that efforts to tighten the shell for energy efficiency do not create health and comfort problems for the residents.

5.0 Acknowledgments

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