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**Heating Loads:
Upstairs vs. Downstairs**

**Reducing Multifamily
Air Leakage**

Air-Sealing Tips



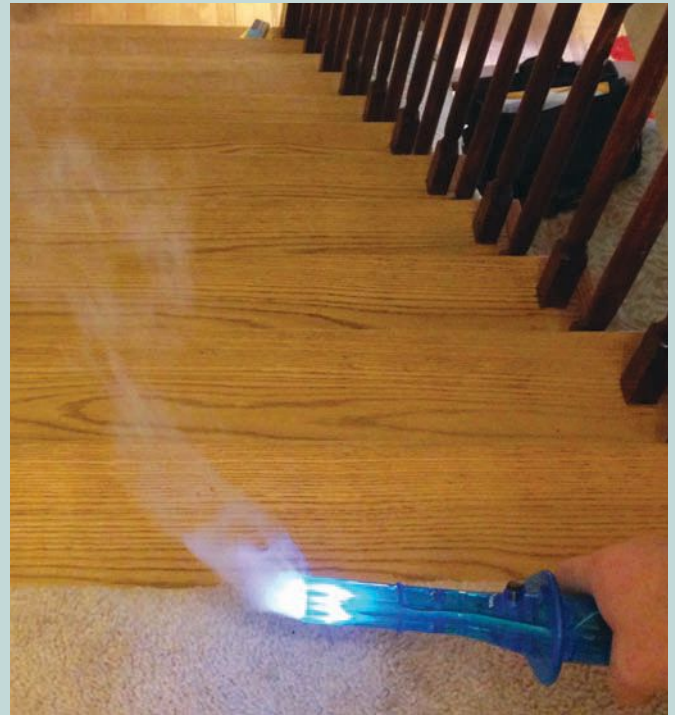
HEATING LOADS

Upstairs vs. Downstairs

by IAN M. SHAPIRO

Some time ago, my colleagues and I at Taitem Engineering observed that two-story buildings with open staircases used significantly more heat downstairs than upstairs. We saw this in two buildings. This led to further investigation to determine whether this phenomenon was replicable. We took measurements in two more buildings and confirmed that it was. All four buildings had two stories, had open staircases, and had separate heating controls downstairs and upstairs. Total heat used downstairs ranged from approximately 70% to 90%. Combining the results for all four buildings, we found that an average of 78.5% of total heat was used downstairs.

Why was more heat required downstairs? We found that this cannot be explained simply by stack effect. In other words, it cannot be entirely explained by the fact that the indoor-outdoor wintertime temperature difference causes indoor air pressures that drive cold outdoor air into a house downstairs (infiltration), and drive warm indoor air from the downstairs to the upstairs and then out of the house upstairs (exfiltration). Nor can it be explained by conduction up through the first-story ceiling. And it cannot even be explained by the combination of stack effect and conduction. We believe that a phenomenon we might call *thermosiphon airflow*, combining warm air rising and cold air falling, is primarily responsible for these vastly greater heating loads downstairs, and that this phenomenon occurs even in tight buildings (with low infiltration).



At floor level, cold air plummets downstairs.

Background

In most homes, we cannot separately observe the energy use of each of two stories of a house with an open staircase, because we do not usually meter energy use by story. One of the first two buildings we studied where we found that more heat was being used downstairs was part of a research project in Buffalo in the 1990s where the heat in every room was being monitored. In this house, a remarkable 89% of the heat in the house was used downstairs, and only 11% was used upstairs. More recently, we found that a two-story building with a retail store downstairs and residential apartment upstairs was using 69% of its heat downstairs. This was an unusual situation in which the downstairs tenant was inadvertently paying for much of the upstairs heat, because one of the downstairs radiators was located at the bottom of a separate staircase to the upstairs apartment. These two buildings prompted the current project.

We decided to focus on homes that had separate controls for heat downstairs and upstairs, so that we could eliminate indoor temperature as a factor, by maintaining the same temperature upstairs as downstairs.

Why Would More Heat Be Used Downstairs?

The first, and seemingly most obvious, answer to this question is the stack effect. We know that cold winter air is drawn predominantly into the first floor of two-story homes, so it adds mostly

to the load on the first-floor heating system. Warm air at the ceiling of the first floor naturally rises to the second floor—for example, up the stairs—and so delivers heat to the second floor, reducing the heating load on the second floor and adding to the load on the first floor. Finally, the interior air pressure upstairs is higher than the interior air pressure downstairs. This means that most of the air that leaves the building is upstairs indoor air, and that less outdoor air infiltrates upstairs to add to the load on the upstairs heating system.

But is stack effect enough to explain why 70–90% of the heating load is being carried by the downstairs heating system? We did a thought experiment and calculation to examine this ques-

systems, and this confirmed our back-of-the-envelope calculation: Its downstairs heating system uses 53.5% of the heating in the building, very close to our estimated 55%.

How about both stack effect and conduction? Analytically, still only 64% of the load is downstairs.

So neither stack effect alone, nor heat conduction, nor both of them together, is enough to explain an average 78.5% of the heating being used downstairs. What else could explain this phenomenon? How else could heat load from upstairs be shifted downstairs? We have looked at warm air rising and heat rising: There are no other ways for heat to get upstairs. Could cold be somehow “moving” downstairs? The only way for that to happen would be with cold air falling (see Figure 1).

Schematic Sketch

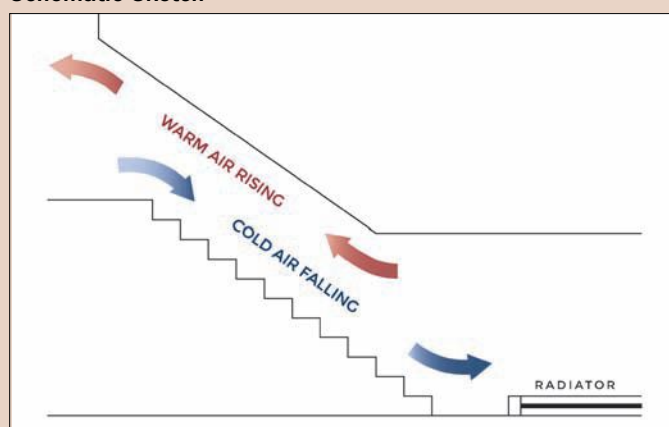


Figure 1. As heat rises, cold air also falls.

(Source: Florence Baveye)

tion. If we assume that a typical 2,000 ft² house has an infiltration rate of 0.5 ACHnat, this represents approximately 150 CFM of infiltration. Now if *all* of this outside air enters downstairs, and *all* of it rises upstairs with a typical 6.5°F air temperature difference between the first-floor ceiling and the second floor, in a house with a typical 84,000 Btu per hour load at a midwinter outdoor temperature of 0°F, this would explain only 59% being carried by the downstairs heating system. We simply do not get close to an average of 78.5% being carried by the downstairs heating system.

How about conduction, up through the floor? Again, we did a back-of-the-envelope calculation. Assuming that same 6.5°F temperature difference between air at the downstairs ceiling and air at the floor of the story above, and 1,000 square feet separating the two stories at a presumed R-value of about 3, we get only about 2,000 Btu per hour by conduction, which would in turn explain only 55% being carried by the downstairs heating system. We happened to find data for a two-story duplex, without a connecting open stairway, and with separate heating

Does Cold Air Fall, and If So, How Much?

We started out with a smoke test at the top of an open residential stairway, in a hydronically heated house, on a winter day with approximately 70°F indoors. First, we examined the airflow just below the ceiling, where we would imagine that warm air from downstairs is rising, and indeed the smoke test confirmed this: Air is moving upward, just below the stairway ceiling, rising from downstairs to the upstairs.

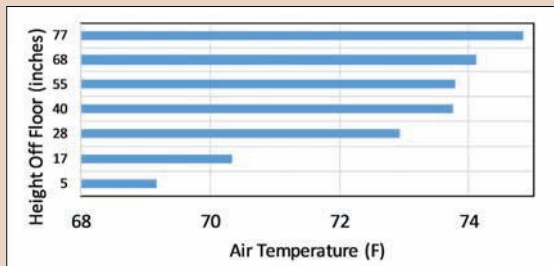
Then we lowered the smoke generator to the floor, at the top step of the stairway. If cold air is falling, this is where it would be falling. And the smoke test confirmed this: Substantial air is moving from the second story, down the stairs, at the level of the treads. We repeated the test in several other buildings, and observed the same phenomenon repeatedly.

Both of these airflows can also be observed by wetting a hand and holding it either at the ceiling (to feel the warm air rising) or at the floor (to feel the cold air tumbling downstairs). The direction of the airflow is felt by the side of your hand that is colder—that is the direction the air is coming from.

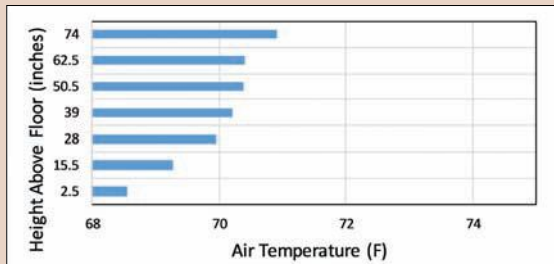
We videotaped the smoke test, and estimated the airflow rate by measuring the airspeed of the smoke moving in the video. The total airflow of cold air moving downstairs was estimated to be 350 CFM. This is a substantial airflow. Compare 350 CFM to the airflow of a typical bathroom exhaust fan (50 CFM), a typical kitchen exhaust (100 CFM), or a central forced-air furnace (approximately 1,000 CFM). The cold air falling downstairs has an airflow several times higher than a typical bathroom or kitchen exhaust fan, and about one-third as much as what a typical furnace circulates to heat a whole house.

For the upstairs cold air to substantially transport cold downstairs, and for the warm ceiling air downstairs to substantially transport heat upstairs, two things are required. The first is the substantial airflow that we found. The second is a temperature difference. So we measured a few floor-to-ceiling air temperature profiles, for both first floor and second floor. Examples are shown in Figures 2 and 3. Here's what we found:

Vertical Air Temperature Distribution —Downstairs



Vertical Air Temperature Distribution—Upstairs



Figures 2 and 3. The floor-to-ceiling temperature differences are far greater on the first story.

- The floor-to-ceiling temperature differences are far greater on the first story. Where the floor-to-ceiling variation upstairs typically ranges from 1.5 to 2.5°F, it's a much more pronounced 4–6°F downstairs.
- Heating with higher-temperature heat sources (such as a woodstove) causes greater temperature variations, just as we might expect.
- Ceiling air temperatures at the first story are in the 73–80°F range, and floor air temperatures at the second story are in the 68–72°F range. On average, this is the 6.5°F temperature difference we referred to earlier. This is the temperature difference that drives the delivery of heat from downstairs to upstairs, both by air transported upstairs from downstairs, and by conduction up through the floor, and also the transport of cold from upstairs to downstairs.
- Interestingly, whereas there does not appear to be a very cold surface layer within 2 inches of the floor, or conversely a warm layer right at the ceiling, there does appear to be a more pronounced temperature drop below about 24 inches above the floor, and a slightly more pronounced temperature rise above 70 inches. Air temperatures between 24 inches and 70 inches are slightly more uniform. In other words, there is a colder mass of air above the floor and a warmer mass of air below the ceiling.

Two More Houses

We decided to confirm the upstairs/downstairs heating split by examining two more houses. Specifically, we examined two relatively new and very tight (low-infiltration) homes in Ithaca, New York. Both homes are electrically heated and have open staircases. The electric heat allowed measurement of the heating use by room and by floor. We measured the temperature on top of the heaters, as a surrogate for measuring run time. One of the homes has only electric-resistance baseboard heaters. The other has mostly electric-resistance baseboard heaters, but it also has a one-on-one air source heat pump serving the downstairs living room. For the home with the heat pump, we measured electricity consumed by the heat pump, in addition to the run time of the electric-resistance heaters.

The reason we chose tighter homes is that if the thermosiphon airflow exists independent of infiltration-driven stack effect, we should see more heating downstairs even in very tight homes. The results of our experiment are shown in Table 1.

Interestingly, the downstairs heating system carries most of the load not only when the doors in the house are open but even when they are closed. This is where falling cold air helps to explain the phenomenon of more heating downstairs. Cold air can easily move below door undercuts, and keep moving to find the stairway to move downstairs. We do wonder how warm air from downstairs moves through the doors to deliver heat to the upstairs rooms, but we speculate that it can move around the edges of closed upstairs doors, which are typically loose and are not weather-stripped.

So much heat is rising upstairs, and so much cold is being transported downstairs to be heated, that we asked ourselves what would happen if we heated only the downstairs. How cold would it get upstairs? We tried this in both test homes. The results are shown in Table 2.

We reiterate that in these tests, 100% of the heat is being provided downstairs. We also note that both of these houses are high-performance buildings. From a baseline of 70°F, the upstairs temperature drops only 3°F when the doors are open, and drops about 5–7°F when the doors are closed. Why did we run this test? The thermosiphon airflow phenomenon offers the possibility of installing a high-efficiency heating system downstairs (for example a heat pump) and a low-cost but low-efficiency heating system upstairs (for example, electric-resistance heat). In such a case, we want to know what it takes to maximize use of the high-efficiency downstairs heating system; in other words, does it get unacceptably cold upstairs if we keep the heat off up there?

Implications

- Our finding that 70–90% of the heat in two-story homes is used downstairs has many implications: Our room-by-room sizing of distribution systems may have been way off,

Table 1. Downstairs Heating Percentages

	House 1	House 2
Heating provided by downstairs heaters (doors open)	82.5%	73.3%
Heating provided by downstairs heaters (doors closed)	76.9%	58.0%

Table 2. Upstairs Temperatures

	House 1	House 2
Heating provided by downstairs heaters (doors open)	67.0°F	Not tested
Heating provided by downstairs heaters (doors closed)	63.0°F	65.4°F


historically. Heat loss calculation tools probably give accurate results on a whole-building basis, but they probably far underestimate first-story room heating loads and far overestimate second-story room heating loads.

- In homes with a single temperature control, such as a first-floor thermostat, the second story may be overheated all winter, and the first-story heating system may not have sufficient capacity to deliver comfort in midwinter (at design conditions).
- Overheating upstairs offers an opportunity for energy conservation. This is achieved by rebalancing the heating distribution system, for example with manual dampers on forced-air systems or with radiator valves on hydronic systems.
- It is always advisable to provide separate temperature controls for upstairs and downstairs in new homes, and where possible as a retrofit in existing homes.
- Spaces at particular risk for being too cold downstairs include rooms at the bottom of open stairways, and low spaces such as sunken living rooms.
- For new homes, builders could deliver high efficiency with lower construction cost by installing efficient heating systems downstairs (for example, heat pumps) and low-cost inefficient heating systems upstairs (for example, electric-resistance heat). However, builders should take precautions—such as ensuring that doors have undercuts—to facilitate the thermosiphon airflow.
- Radiant-floor heating systems are probably less prone to the thermosiphon airflow effect than ducted systems. Since the floor itself is a heat source, cold air falling to the floor on the second story is far more likely to be heated, and so to be

a load on the second-story heating system. When heated, it will rise again, and so be less likely to tumble down the stairs. And the fact that the water in radiant-floor heating systems is cooler than the water in traditional radiator systems will reduce air temperature stratification, which means that warm air at the first story ceiling is lower in temperature than in traditional systems, which in turn means that there will be less air rising from the first story to the second.

Conclusions

This study was limited in scope, with rough measurements in just a few homes, and rough back-of-the-envelope supporting calculations. However, we are confident of the main conclusion: In two-story buildings with open stairways (a category that includes most homes), if the upstairs and downstairs heating distribution systems are separately controlled, the downstairs system carries 70–90% of the heating load. Our confidence derives from the replicability over our (admittedly) small sample of buildings, as well as several distinct physical phenomena, all of which support this unusually large difference in heating loads between the two floors. The physical phenomena in question are as follows. The air temperature increases from floor to ceiling on both floors of a house; the stack effect draws in cold winter air on the first floor; warm air rises; indoor air leaves the second story (preventing infiltration upstairs); and perhaps least recognized, cold air falls from the upstairs to the downstairs.

More research is needed, to determine how big a problem this poses, and to disaggregate contributing factors. Such research could be conducted by means of controlled testing, or of computational fluid dynamics (computer modeling of air temperatures and airflows and how these interact with heating systems), or both. We need to better understand the role played by different types of heating system (hydronic baseboard, hydronic radiant floor, hydronic panel or cast-iron radiation, forced air, ductless heat pumps, electric resistance); by different distribution system temperatures; by different building characteristics (ceiling heights, layout, tightness of doors); and by various other factors. We also need to understand how this phenomenon affects uncontrolled airflow in and out of attics, basements, crawl spaces, and other unconditioned spaces. Finally, we need to determine whether cooling has the reverse effect, placing more load on upstairs distribution systems, and creating a possible imbalance between heating and cooling needs. Better understanding these factors will help us to better design new homes and to conserve more energy in existing homes. 

Ian M. Shapiro is the founder of *Taitem Engineering*, in Ithaca, New York, and is the author of the blog **Building Evidence**.