Soiling Patterns on a Tall Limestone Building: Changes over 60 Years

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Soiling of limestone caused by air pollution has been studied at the Cathedral of Learning on the University of Pittsburgh campus. The Cathedral was constructed in the 1930s during a period of heavy pollution in Pittsburgh, PA. Archival photographs show that the building became soiled while it was still under construction. Reductions in air pollutant concentrations began in the late 1940s and 1950s and have continued to the present day. Concurrent with decreasing pollution, soiled areas of the stone have been slowly washed by rain, leaving a white, eroded surface. The patterns of white areas in archival photographs of the building are consistent with computer modeling of rain impingement showing greater wash off rates at higher elevations and on the corners of the building. Winds during the rainstorms are predominantly from the quadrant SW to NW at this location, and wind speeds as well as rain intensities are greater when winds are from this quadrant as compared with other quadrants; the sides of the building facing these directions are much less soiled than the opposing sides. Overall, these results suggest that rain washing of soiled areas on buildings occurs over a period of decades, in contrast to the process of soiling that occurs much more rapidly.

Introduction

Air pollutants in combination with rain are known to damage buildings made of calcareous stone (1, 2). For example, SO_2 can react with limestone and marble when the surface is moist (3-5), resulting in higher oxidation states of sulfur such as SO_4^{2-} and forming species such as gypsum ($CaSO_4$) (6-8). Because gypsum occupies a greater volume than the original stone, the surface can crack and become pitted. The rough surface can then serve as a site for deposition of airborne particles that are responsible for discoloration. Gypsum is also more soluble in rainwater than the original stone, and thus the soiled surface can subsequently be washed away to leave a white, eroded area on the building. The rate at which the walls become soiled and the rate at which the soiled areas become white depend on pollutant deposition rates and the delivery of rain to the building walls. Although these processes have been known for some time, there have been few if any prior field studies on changes in soiling patterns on buildings over long periods of time.

Background and Methods

We have investigated soiling on the Cathedral of Learning, a 42-story Indiana limestone building on the University of Pittsburgh campus in Pittsburgh, PA. Building construction began in 1926, with the first stonework in 1929. Construction was completed in 1937 (9). The exterior has never been cleaned except by natural rainfall. In earlier work (10), we showed that airborne concentrations of gaseous SO_2, total NO_3^-, particulate SO_4^{2-}, and particulate elemental carbon were uniform with height between the 5th

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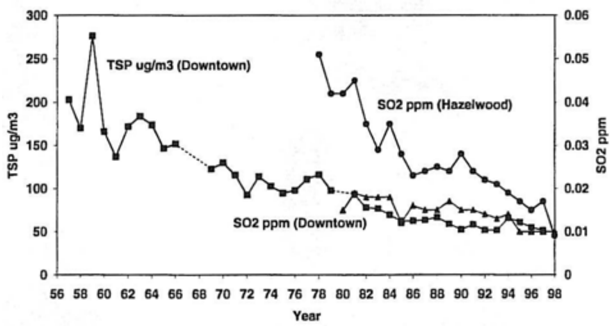


Figure 1. Annual arithmetic average concentrations of total suspended particles (TSP) and SO_2 in Pittsburgh. The TSP measurements were made with high-volume samplers at two downtown locations: the County Office Building (1957-1982) and Flag Plaza (1983-1997). The SO2 measurements were made with continuous monitors at Flag Plaza downtown (1980-1998) and in the Hazelwood section of the city (1978-1998). These measurements were conducted as part of the National Air Sampling Network and the Air Quality Program of the Allegheny County Health Department. Reliable TSP data are not available for 1967, 1968, and 1980.

floor and the roof. Dry deposition rates of SO_2 to perfect sink surfaces hung on the walls were only slightly greater on the 16th floor as compared with the 5th floor. Soiled surfaces on the building were examined by scanning electron microscopy by McGee (11) and found to contain gypsum as well as fly ash particles; white surfaces were found to contain much less gypsum and fly ash, implicating anthropogenic emissions as responsible for the soiling. In recent work, we used a computer model for airflow around the building to estimate the delivery of raindrops to the building walls (12). The results of these studies suggest that pollutant deposition occurs on the entire exterior surface of the building and that soiling patterns at specific locations on the walls are determined by competing processes of pollutant deposition and wash off by rain.

Here we extend the research on current soiling patterns at the Cathedral to consider changes in soiling over a period of several decades. We use historical air pollution records dating back to the 1930s, quantification of the amount of soiling on the Cathedral, and archival photographs to examine changes in soiling patterns since the Cathedral was constructed. We also consider the results of computer modeling of rain fluxes in comparison with archival and recent photographs.

Results and Discussion

Figure 1 shows annual average concentrations over time for total suspended particles (TSP) and for SO_2 in Pittsburgh (13). The TSP data cover the years 1957-1997 and are for downtown, 3.2 km west of the Cathedral. The SO_2 data are for downtown (1980-1998) and for the industrial area of Hazelwood, 3.3 km south of the Cathedral (1978-1998). The data show steady decreases in concentration over time, mainly due to reductions in emissions from heavy industry and from mobile sources. Data on visibility reduction due to smoke from the early part of this century to the present suggest that average TSP levels were much greater than 200 $\mu g/m^3$ in the 1930s and 1940s before regular TSP monitoring began (14). This is confirmed by archived data on dustfall in downtown Pittsburgh that show values decreasing from 30 ton/km^2 month in 1938-39 to 14 ton/km^2 month in the mid-1950s (14). The dustfall values have continued to decrease and are now less than 5 ton/km^2 month.

The excessive pollution that existed in Pittsburgh in the 1930s implies that soiling began while the Cathedral was still under construction. This is confirmed by archival photographs. Figure 2 shows a set of photographs of the Forbes Avenue side of the Cathedral (facing SE), beginning with a picture taken in 1930. This early photo shows a white buildingwithout evidence of soiling. In contrast, the second photo from the late 1930s shows extensive soiling by this time. The arrows in these two photographs point out the same place on the left side of the building, at which location later photos in Figure 2 show a sharp boundary between white and soiled areas in the form of a "notch" of white. This notch enlarges downward over time, which we hypothesize is due to rain wash off. Comparing the photographs in Figure 2 shows that this notch extends four floors below the 25th floor patio in the late 1930s, 5 floors in 1962, between 5 and 6 floors in 1989, and 6 floors in 1995. Records from the National Weather Service in Pittsburgh indicate that the annual precipitation has been roughly constant during these years (10), so reductions in pollution must have shifted the balance between pollutant deposition and wash off by rain in favor of the latter.

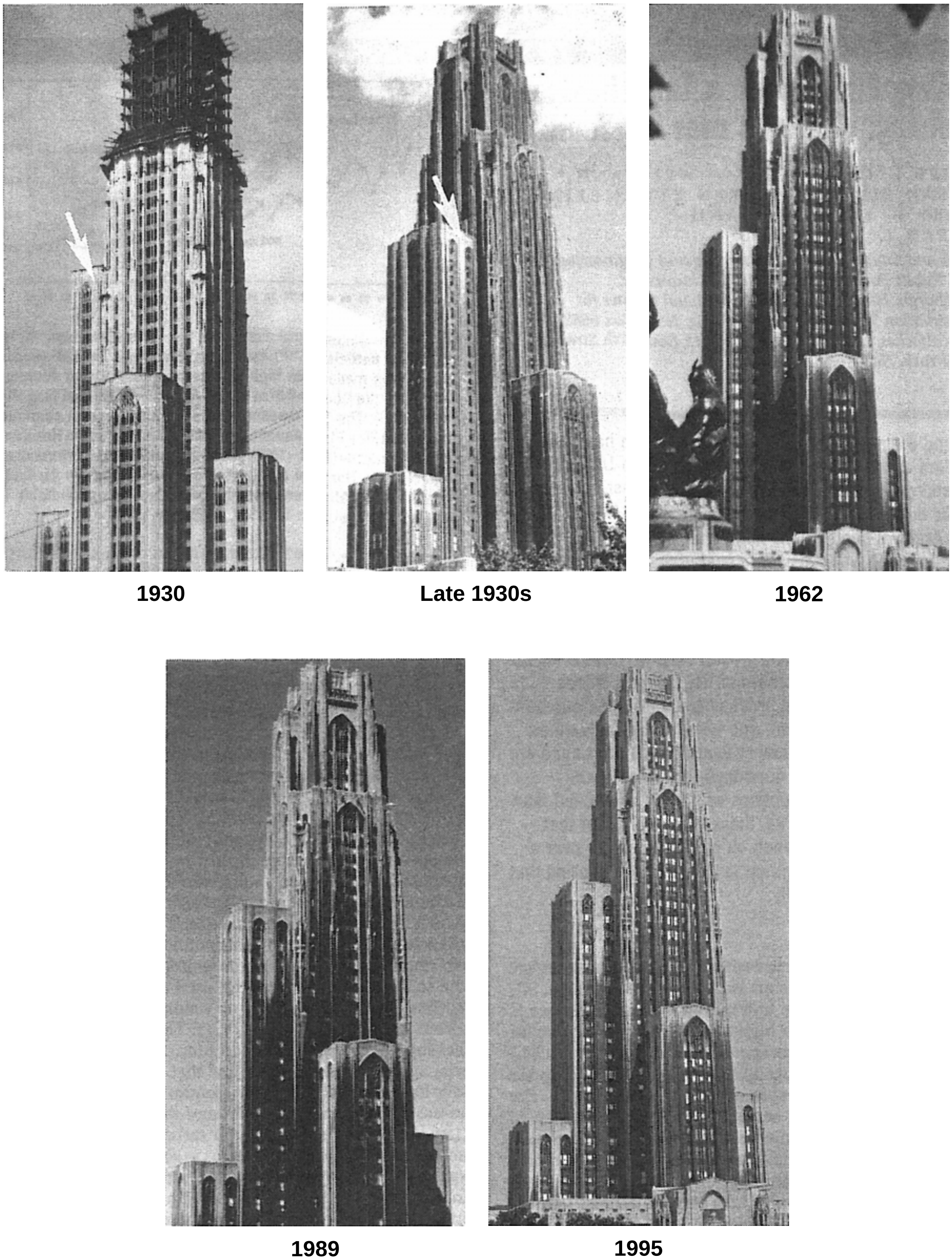
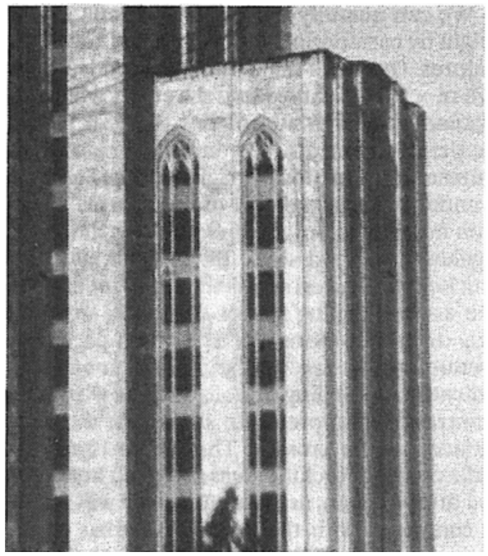
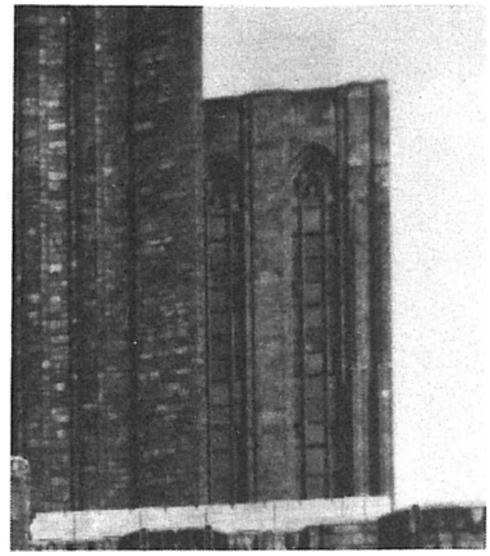


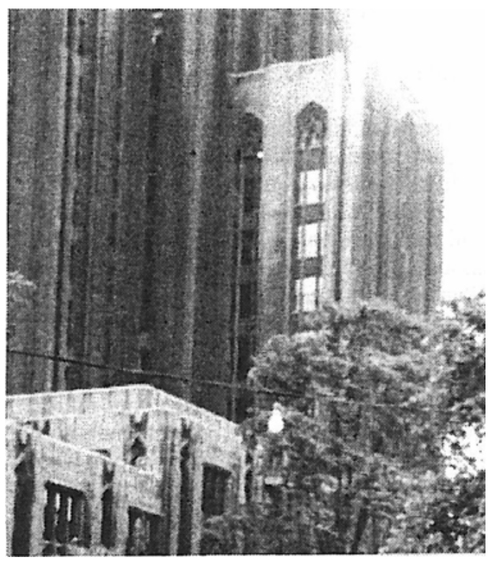
Figure 2. Archival photographs of the Forbes Avenue (SE facing) side of the Cathedral of Learning on the University of Pittsburgh campus. The arrows in the first two photos point to a wall section where the soiling patterns have changed with time. The wall below the arrow is unsoiled in 1930 but is mostly soiled by the late 1930s. The white "notch" at the top of the wall section has become enlarged in the downward direction over time as seen in the later photographs. Reprinted with permission from the following sources: 1930, University Archives, University of Pittsburgh; late 1930s, Carnegie Library of Pittsburgh; 1962, University Archives, University of Pittsburgh; 1980, Ferguson Photographic Enterprises; 1995, Justin Parkhurst.



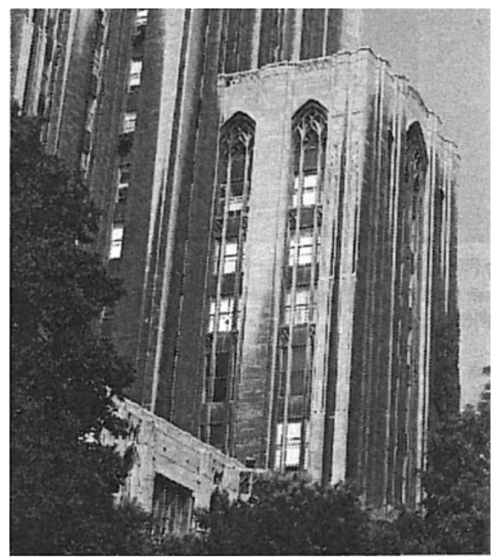
1930



1934



1950



1995

Figure 3. Enlarged photographs showing a wall section on the right side of the Forbes Avenue face of the Cathedral. There is no visible soiling in 1930, but the wall is completely soiled by 1934. The 1950 and 1995 photos show increasing areas of white, hypothesized to be from rain wash off. Reprinted with permission from the following sources: 1930 and 1934, University Archives, University of Pittsburgh; 1950, Carnegie Library of Pittsburgh; 1995, Justin Parkhurst.

Figure 3 compares enlarged photographs of a section of the Forbes Avenue face taken in 1930, 1934, 1950, and 1995. The first photo, taken from an enlargement of the 1930 photo in Figure 2, shows that the entire surface is unsoiled. By 1934, this area has become completely soiled. By 1950, the area has become partially white, as evidenced by the boundary between soiled and white areas. By 1995, the boundary has moved downward several meters. The same feature is barely visible in Figure 2 on the extreme right side of the photographs from 1962 through 1995. We hypothesize that the location of the boundary in the 1950 photo is the result of somewhat reduced pollutant levels by that time, such that rain wash off dominated over deposition of pollutants. Additional decreases in pollutants resulted in further wash off by rain, apparent in the 1995 photo. According to this hypothesis, the white areas in the 1950 and 1995 photos show stone that has become eroded by chemical conversion and rain wash off, in contrast to the white areas in the 1930 photo showing undamaged stone.

Figure 4 shows a photo of the Fifth Avenue side of the Cathedral taken in 1937. The photo is notable in that the main tower of the building, constructed in the early 1930s, is completely soiled. However, the stonework on the lowest four stories, which was installed later, is still white. It is clear that the time scale for soiling during the period of Pittsburgh's heavy pollution was only a few years at most.

We can gain insight into the competing processes of pollutant deposition and rain wash off by comparing soiling on different sides of the Cathedral and at different elevations. Figure 5 shows photographs of the four faces of the Cathedral as they appeared in 1999. The Fifth Avenue and Bigelow Boulevard sides show very little soiling as compared with the Forbes Avenue and Bellefield Avenue sides. The latter two building faces show less soiling near the top as compared with lower elevations, suggesting more efficient wash off at greater heights. The patterns also suggest more efficient wash off near corners on the building, with greater amounts of soiling near the center of the walls.

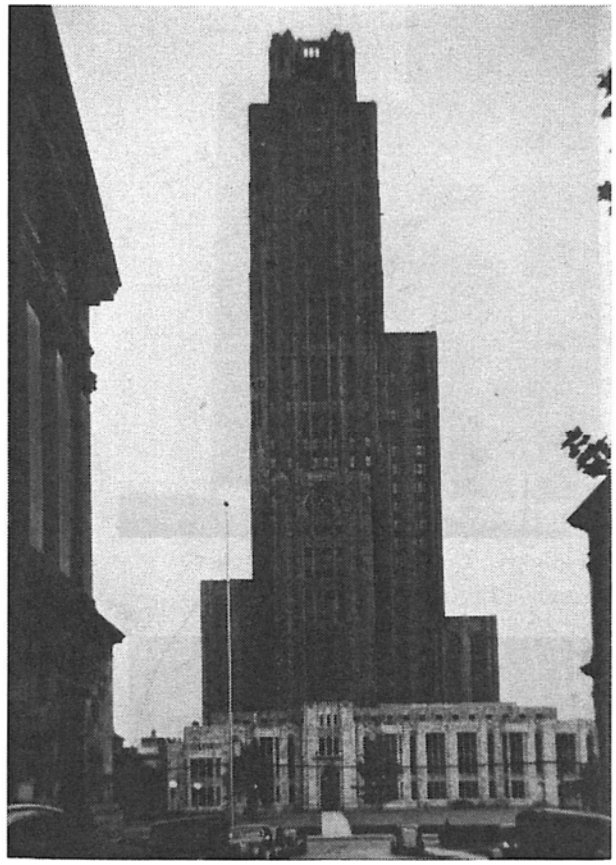
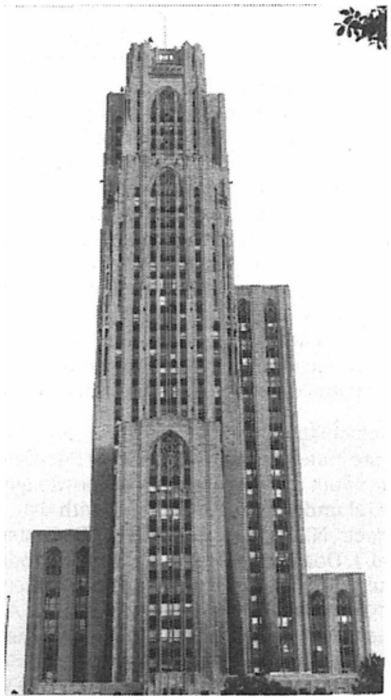


Figure 4. The Fifth Avenue side of the Cathedral in 1937. Reprinted with permission from the following source: University Archives, University of Pittsburgh.

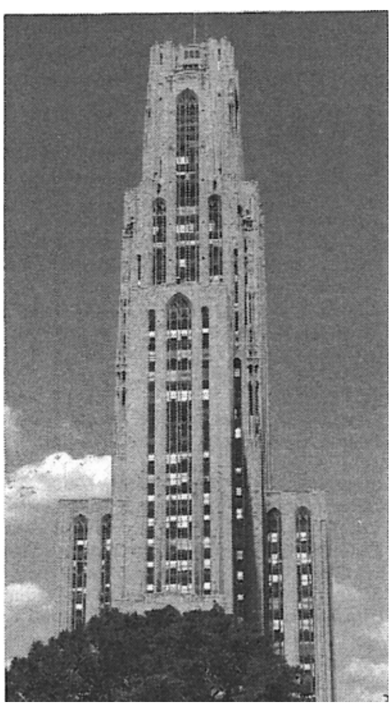
We can quantify the amount of soiling as a function of height by considering discoloration of specific architectural features. One such feature is a decorative cross measuring 0.75 m x 0.56 m carved into the stone, which appears at 226 locations on all four sides of the Cathedral. We have measured the percent of area soiled on each cross and have graphed the result as a function of height. For the Forbes and Bellefield Avenue sides, virtually all of the crosses are highly soiled, even near the top of the building. For the Fifth Avenue and Bigelow Boulevard sides, the amount of soiling decreases with height. Figure 6 shows the result for Bigelow Boulevard. The average soiling ranges from 64% on the lower floors (8th-14th) to 34% on the 37th floor; patterns for the Fifth Avenue crosses are similar. It is of interest that Figure 5 indicates little soiling overall on these two sides, despite the occurrence of appreciable soiling on the irregular carved surfaces of the crosses. This suggests that carved stone surfaces, which include areas sheltered from raindrop impact and dripping rain, are less effectively washed over the years as compared with the broad, flat areas of the stone that comprise much of the wall surface area. The abundance of soiling on the Forbes and Bellefield Avenue crosses is consistent with this hypothesis: the amount of rain reaching the highest elevations is sufficient to wash off flat areas of stone but not enough to wash the irregular surfaces of the crosses. The rain reaching the lower levels of the Forbes and Bellefield Avenue sides is insufficient to wash even the flat areas.

We can compare the soiling patterns discussed above with computer modeling of rain fluxes to the walls. The Cathedral has been modeled as a simple rectangular block, with each face divided into 15 sections of 10 m x 32 m. Wind speed, wind direction, and rainfall have been measured near the Cathedral over a 7-week period of generally typical meteorological conditions (April 29-June 18, 1998) and are used as model inputs. Two severe thunderstorms on June 2 that caused local flooding are considered outliers and have not been used in the computations shown here. The three-dimensional airflow field and associated raindrop trajectories have been modeled using a commercially available software package (FLUENT, Inc., Lebanon, NH), in which the Navier-Stokes and continuity equations are solved numerically. Raindrop sizes are approximated from an exponential distribution (15). The simplified distribution consists of three raindrop sizes, 1.25, 2.5, and 5 mm, where the amounts of rain associated with each size depend on measured rain intensity. The meteorological data are averaged over 15-min intervals for computing the amount of rain striking each section of the building. There are a total of 207 time intervals where rain was recorded; wind and rain data for these intervals have been used in the calculations. The total rainfall for



Fifth Avenue Side
(facing NW)

Bellefield Avenue Side
(facing NE)



Bigelow Boulevard side
(facing SW)

Forbes Avenue Side
(facing SE)

Figure 5. The four walls of the Cathedral of Learning in 1999. The Fifth and Bigelow faces are mostly white, while the Forbes and Bellefield faces have extensive soiling. Photographs by Wei Tang

these intervals, normalized to 1 year, is 1210 mm/year. This compares with the average rainfall in Pittsburgh of approximately 1000 mm/year, with May and June each receiving about 10% of the annual rainfall. Details of the modeling have been reported elsewhere (12). Resultant rain fluxes normalized to 1 year are shown in Figure 7.

The figure shows that calculated rain fluxes to the Fifth Avenue and Bigelow Boulevard sides are much greater than those to the Forbes and Bellefield Avenue sides. This is consistent with the greater amounts of soiling in Figure 5 for the Forbes and Bellefield faces. On all four sides, the fluxes at the top are considerably greater than those at lower heights. Furthermore, the fluxes on the sides are greater than those in the center sections. These results are in agreement with the observations of less soiling near the top and at the corners of the building. Comparing model results with the meteorological input data shows that the greater rain fluxes on the Fifth and Bigelow sides are due in part to the large fraction of time (0.50) when the wind is from the quadrant SW through NW. Furthermore, the rain intensities are high when the wind is from the SW, W, or NW (average 4.0 mm/h) as compared with all other directions (average 2.6 mm/h), and the wind speed is greatest when the wind is from these three directions (average 2.5 vs 1.7 m/s).

Although these conclusions are based on computations using only 7 weeks of meteorological data, comparison with the wind speed, wind direction, and rain intensity data for the full year from the National Weather Service in Pittsburgh suggests that conditions during April–June 1998 were quite representative of year-round conditions. Thus we conclude that the combination of frequent winds from SW through NW, greater wind speeds when the winds are from these directions, and greater rain intensities associated with these directions is believed to be mainly responsible for the soiling patterns on the Cathedral of Learning. The archival photographs suggest that soiling of the Cathedral occurred within a few years under highly polluted conditions. In contrast, the information presented here suggests that it has taken several decades for rainfall to remove much of the soiling and produce a white, eroded surface.

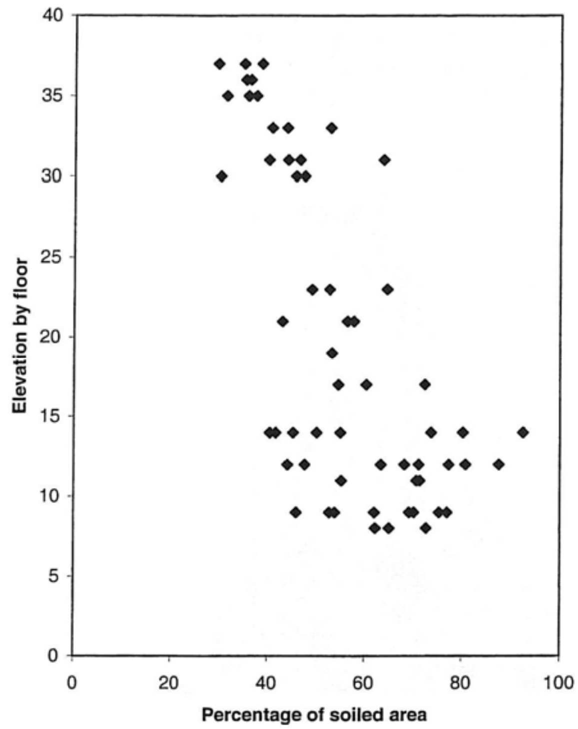


Figure 7. Elevation vs. percentage of soiled area for decorative crosses carved in the limestone wall on the Bigelow Boulevard (SW facing) side of the Cathedral of Learning.

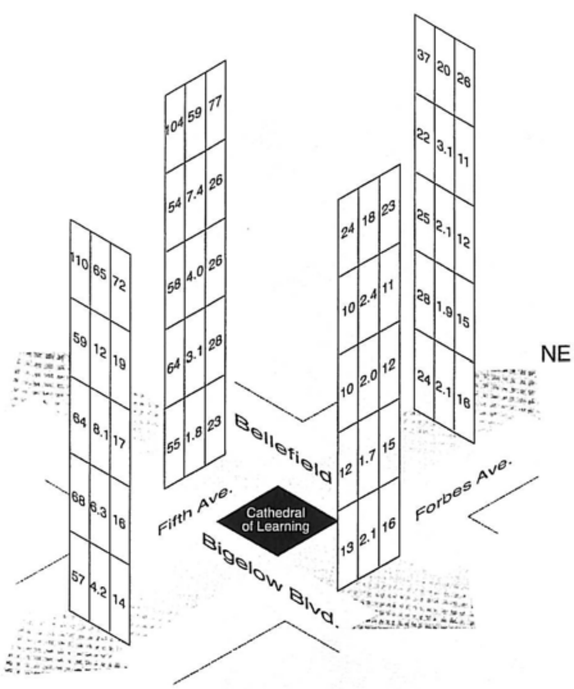


Figure 7. Computed rain fluxes in mm/year to the walls of a simple rectangular block with approximate dimensions of the Cathedral of Learning. The data suggest that much more rain strikes the Fifth and Bigelow faces of the building as compared with the Forbes and Bellefield faces.

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