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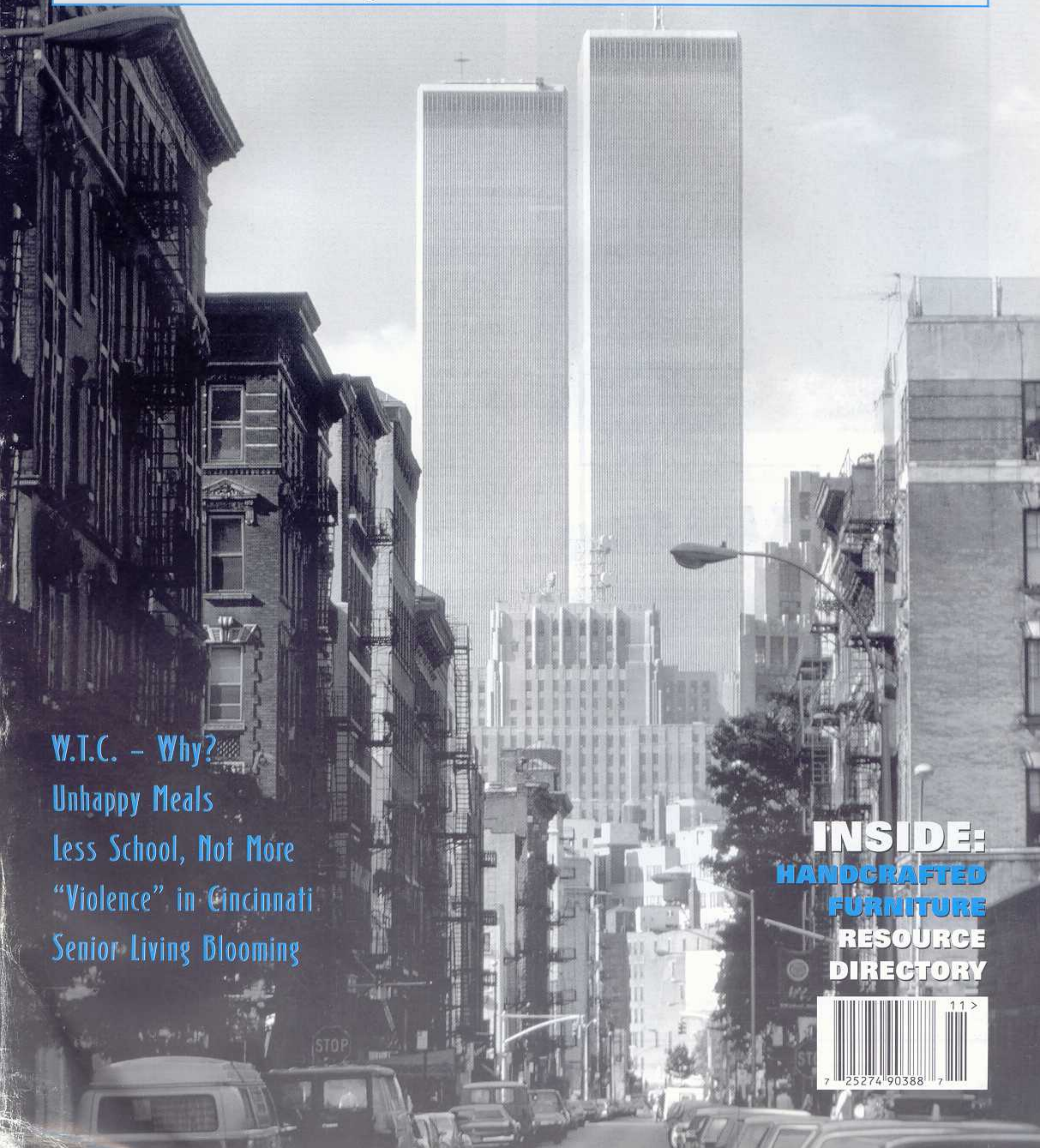

W.T.C. – Why?

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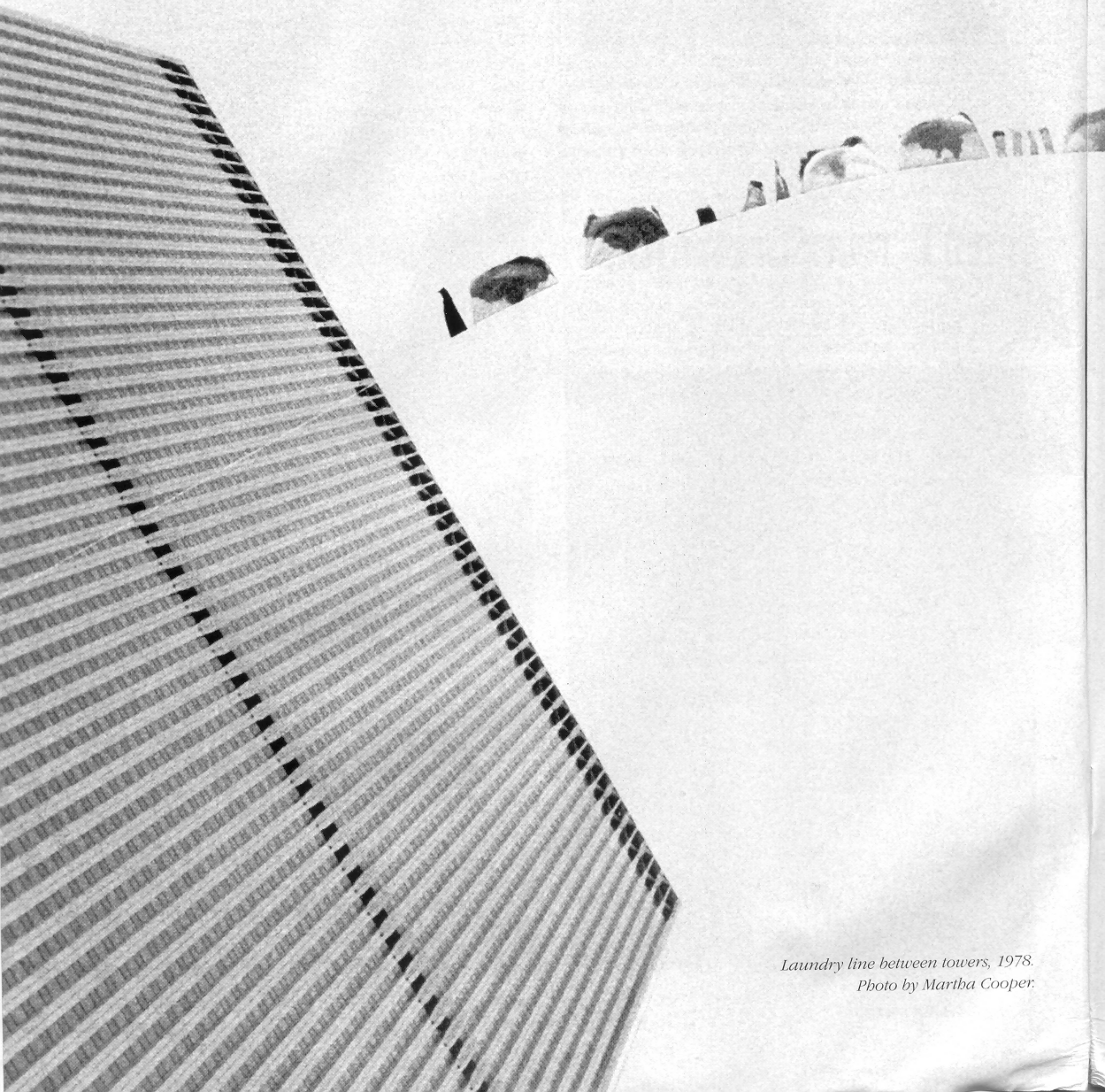
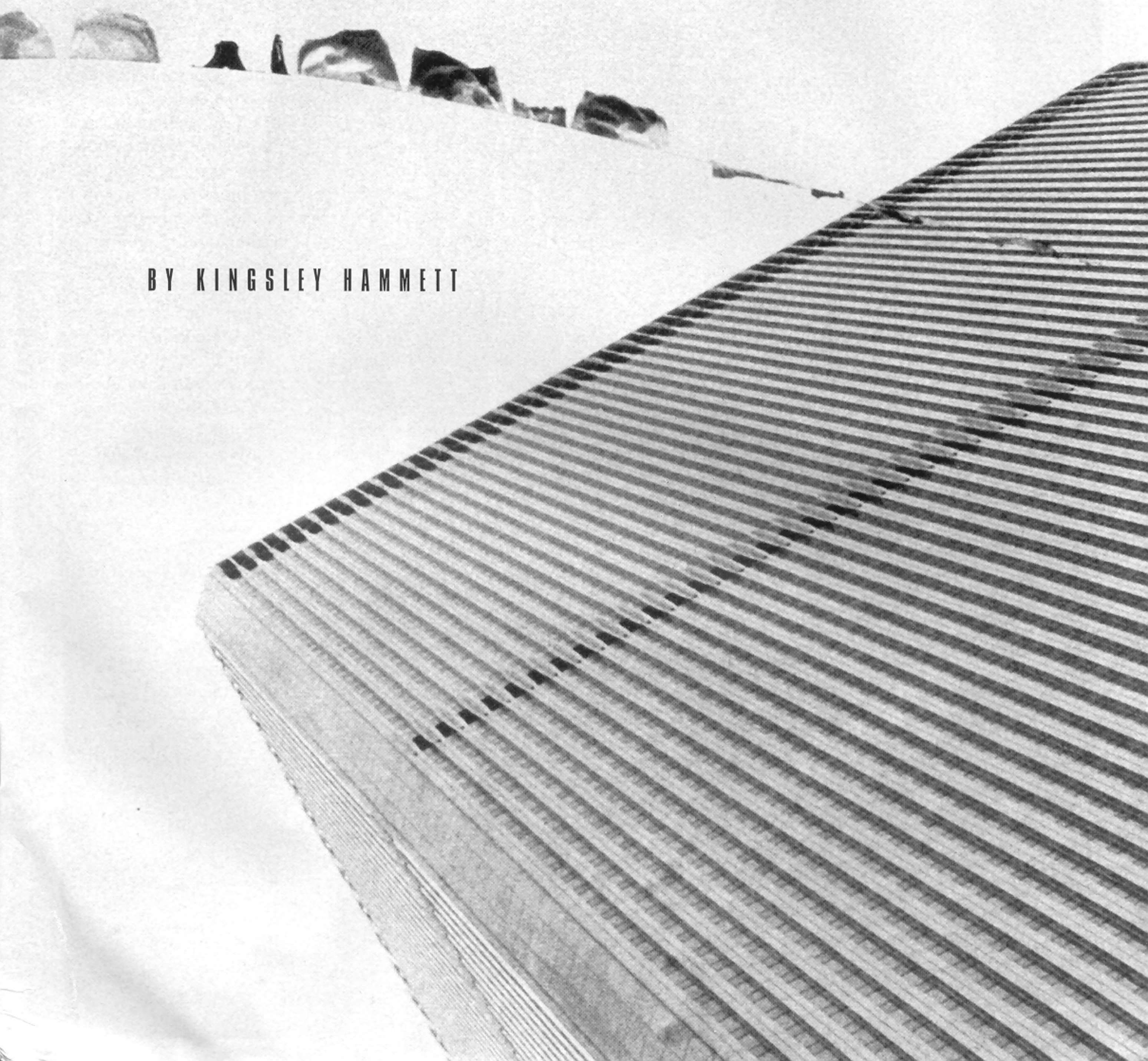
WHY THE WORLD



Laundry line between towers, 1978.
Photo by Martha Cooper.

TRADE CENTER COLLAPSED:

AN ARCHITECT'S ASSESSMENT



BY KINGSLEY HAMMETT

OPPOSITE PAGE: *The corner of the South Tower, 1966. Note how the base structure is framed conventionally, with columns spaced about thirty feet on center in each direction. These columns were wrapped in concrete, while the tower columns were only sprayed with fireproof mineral wool and wrapped with sheetrock. The designers and engineers did allow for the impact of a commercial jetliner, but they failed to allow for the impact knocking the fireproofing off the steel. (Photo by Jim Malott)*

Among the more shocking images of September 11 was the sight of millions of tons of steel, glass, and concrete collapsing into a mountain of rubble within a matter of seconds. Yet what failed to penetrate the blizzard of commentary about every aspect of the disaster and its aftermath was the answer to a simple question: Why?

Why did both towers of the World Trade Center, set afire in their upper floors, pancake to earth in a thunderous cascade of acrid smoke, crumbling concrete, and shredded gypsum to entomb more than 5,000 innocent victims? Was there something intrinsically flawed in the design and construction of the Twin Towers that hastened their complete collapse? Was there anything that could have mitigated the scope of the disaster? Are there lessons in New York for the future of high-rise construction? To Jim Malott the answer to these questions is "Absolutely."

"Everyone is looking at this and saying, "How horrible!'" Malott says. "The real story is "Why did the collapse happen?'"

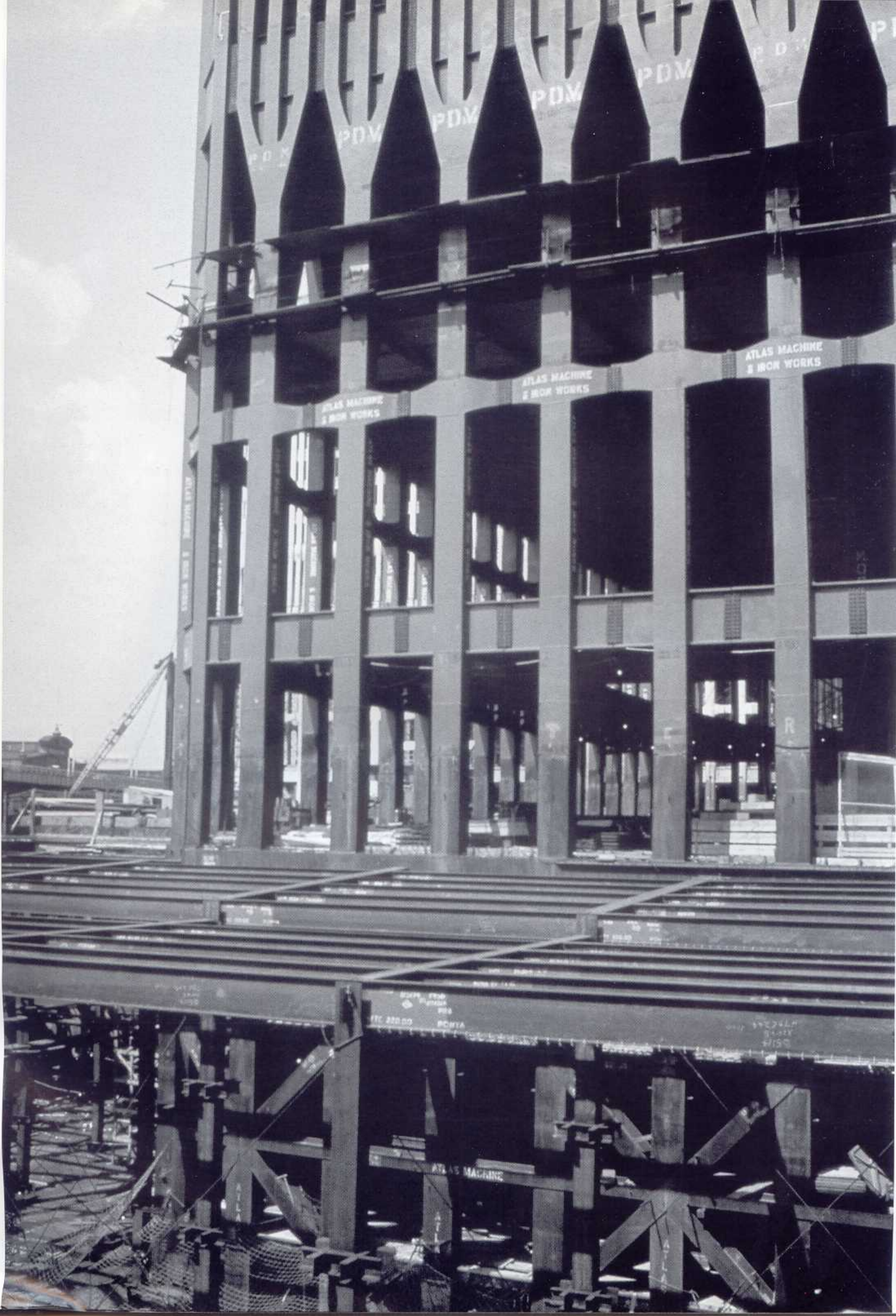
At the age of 61, Malott seems particularly qualified to assess the Twin Towers disaster. He holds a bachelor's degree in pre-architecture from Stanford. He spent four and a half years in the U.S. Navy, part of them as an officer aboard the U.S.S. *Enterprise*, where he witnessed more than one fiery jet plane crash. He is a skilled welder and studied the properties of steel-reinforced concrete while taking graduate courses at the University of Delaware. He has a master's degree in architecture from the Harvard Graduate School of Design. For the last thirty-one years he has been an architect in the San Francisco area, where he has helped design a number of high-rise buildings. And he has been a student of the World Trade Center since it first took shape on the east bank of the Hudson River in the mid-1960s, chronicling and photographing the towers' birth and growth. Fascinated by these gargantuan monuments to both revolutionary engineering and high-speed construction, he marveled as they were launched from their foundations at a tremendous rate, as much as one floor per week on each tower.

Prior to the advent of the World Trade Center towers, high-rise buildings shared two vital characteristics: they were supported by a grid of steel columns, generally spaced about thirty feet apart, and each interior column was encased in a tough cladding of concrete to create a fireproof skin designed to withstand a four-hour inferno. (The four-hour fire rating is the code rule for the columns and major beams in any large building.) As designed by architect Minoru Yamasaki, New York's Twin Towers incorporated neither of these traditional features. And as far as Malott is concerned, it was the failure of their substitutes – not the initial crash, not the exploding jet fuel, and not the subsequent fire alone – that lead to their collapse and the enormous loss of life.

The World Trade Center towers were the brainchild of Austin Tobin, director of the New York Port Authority, the Rockefeller brothers – David, the chairman of Chase Manhattan Bank, and Nelson, the governor of the Empire State – and other influential New Yorkers. Their plan was to clear a sixteen-block area of Lower Manhattan of small buildings housing small manufacturing, wholesaling, and retail firms to make way for many millions of square feet of office space for lawyers, brokers, financial services, insurance companies, and international trade. The builders first created a sheet piling dam around the old Hudson River piers and filled the area with both the demolished buildings and the World Trade Center excavation spoil, creating the twenty new blocks along the west side of Manhattan that became Battery Park City and the World Financial Center.

Writing in the January 2001 issue of this magazine, Eric Darton, author of *Divided We Stand: A Biography of New York's World Trade Center* (Basic Books, 2000), described the World Trade Center as "the manifestation, in steel and concrete, of an unprecedented alignment of political forces bent on ramping up Lower Manhattan's financial district into a gleaming 'heart pump' for the nascent global economy." This massive project – conceived, built, and operated by the Port Authority of New York and New Jersey – was seen as a twenty-million-square-foot "vertical port" to replace the rusting steamships and rotting piers that once lined the great river below.

Yamasaki designed a matched pair of square-tube cantilevers standing on their ends, each with a footprint that measured approximately 200 feet by 200 feet. To withstand the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powerful force of the 150-mile-per-hour hurricane winds that occasionally funnel through the Verrazzano Narrows and into New York's Upper Bay, Yamasaki set his bearing walls to the outside of the structure, creating in essence a 1,250-foot-high cage of steel columns spaced about six feet apart. Standing six times as high as they were wide, these cantilevers pushed the envelope of 1960s structural engineering almost to its limit.

The towers sprang from their massive seven-story-deep concrete foundations in three-story column lifts. Each set of three-story-high-by-three-column-wide sections was bolted and welded to the one below as the structure climbed into the sky. Rising in the center of this exterior column tube was a second, interior steel-columned tube, measuring about seventy-five feet by seventy-five feet, which housed the mechanical services, elevator shafts, and three stairwells.

Suspended between the inner and outer tubes were long-span steel bar joist floor panels that measured twenty to thirty feet wide, sixty to eighty feet long, and about three feet deep. The open-web steel bar joists were made from spot-welded, one-and-a-quarter-inch-diameter stock and steel angles about 3 by 3 by a quarter inches that were sheathed on top with a metal pan deck. The huge floor sections were fabricated in a plant in New Jersey, floated across the Hudson on barges, and lifted into place with cranes. Simple welded connections at the edges of the floor panels were all that held them to horizontal beams at the interior core and vertical columns at the exterior skin. The metal floor pans were covered with three or four inches of concrete flooring, and the bottoms of the bar joists held suspended sheetrock ceilings. The entire building, then, consisted of three parts: the central core, the exterior skin, and the lightweight, long-span floor sections between them. Thus every floor had unobstructed floor space with no interior supporting columns or beams.

To save time, weight, and money, Malott suspects, Port Authority officials exercised their political muscle to allow them to fireproof the steel columns of the interior core with spray-on mineral-wool fiber and layers of sheetrock instead of having to use the more traditional method of cladding the columns with several inches of reinforced concrete. While they tested the assemblies to convince New York building inspectors that this approach yielded the required four-hour fire rating, Malott points to this change in building technology as the key weakness that caused the buildings' rapid collapse.

"It's not devious, it's not nefarious," he says of the maneuvering required to win approval for the innovative approach. "It's the way everybody does business all over the world. But in this case they forgot – or failed to consider adequately – a few critical issues."

The elevator shafts within the central steel-columned core were made of shaftwall, a brand-new product developed specifically for these buildings, Malott says. Shaftwall consisted of two layers of inch-thick gypsum wallboard, two feet wide, that ran twelve to fourteen feet from one floor up to the next. The two layers of one-inch sheetrock were offset by about an inch and a half, and each slab was lapped to the next and screwed together through sheet-metal edge channels.

"The shaftwall was then covered with a layer of five-eighths-inch sheetrock on each side," he says, "so your entire interior wall system around the elevator shafts was made up of nothing but sheetrock."

As Malott watched the tragedy unfold, he surmised that the sequence of events went something like this: when the planes slammed into the exterior of the buildings, the fuselages and engines broke through a number of the outside columns while the wings disintegrated as though being forced through a cheese grater. The bodies of the planes crashed across the unobstructed floors, smashed into the central cores of the buildings, and blew the sheetrock off the supporting columns and from around the stairwells, completely destroying the elevator shaft walls. Thus, in the first seconds, the four-hour-rated fireproofing was stripped from the steel core structures and with it went all hope that the buildings could survive a fire.

The idea that witnesses saw two buildings consumed by flaming jet fuel is probably wrong, Malott says. As an officer-of-the-deck on an aircraft carrier he saw several Navy jet fighters crash into the flight deck and explode into balls of flame. Most of the fuel vaporizes on impact and ignites instantly, just as happened at the World Trade Center with the

OPPOSITE PAGE:
This stack of prefabricated floor sections, 60 to 80 feet long, was built in New Jersey, floated across the Hudson River on barges to what is now Battery Park City, towed by large tractors to the construction site, and lifted by cranes into position. By using three-story-high column lifts in sections and the huge floor sections, the builders were able to erect about one floor per week per tower. The floor sections were carried on the slender steel stock shown in this detail, welded to the interior core and exterior skin. The vertical dimension of the floor section is about three feet. All welds were spot welded. The top of the bar joist carried a pan slab with three inches of concrete, and the bottom carried a suspended ceiling of sheetrock. The assembly was supposed to have a four-hour fire rating, but with the sheetrock blown off the ceiling by impact or explosion, the floors could have failed within a few minutes. The steel sections were very thin and would have rapidly heated to 1,600 degrees and turned to butter. (Photo by Jim Malott)

OPPOSITE PAGE:
The North Tower from the south, about seventy stories high. Note the South Tower (about fifteen stories) climbing in three-story lifts.Each three-story column section was bolted temporarily, then welded in place. Photos after the collapse show that dozens, perhaps hundreds, of these welds failed, three in a row, just as they had been built, throwing into question the quality-control of the welds. Each column at the base split at the fifth floor into three smaller columns, creating a steel tube with a footprint of about 200 feet by 200 feet standing approximately 1,250 feet high, or six times its base dimension. Also note the fireproofing being sprayed on the steel columns on the bottom floors of the North Tower. The canvas wrapping around floors fifteen through twenty kept the spray from blowing off and contaminating the street below. (Photo by Jim Malott)

huge orange balls of fire seen outside the buildings. The subsequent smoke and flames seen billowing from inside were more likely from the burning contents of the building and a portion of the residual fuel.

"The mass of a 767 aircraft is less than half the mass of one floor of that building," Malott says, "so it wasn't an overwhelmingly heavy load, even at 300 miles per hour. In fact, the buildings withstood the impact very well"

The impact of the plane instantly ignited three or four floors, and he believes the majority of the damage should have stayed within those floors. But because the impact broke all the sheetrock off the interior support columns and elevator cores, the fuel shot both up and down the now-exposed elevator shafts and stairwells, which immediately filled with smoke and flame, trapping everyone on the floors above the impact zone.

After an hour of this inferno, the now-naked steel columns of the central core at the impact floors were heated to about 1,600 degrees, which is the point at which steel loses almost all of its structural strength. The relatively skimpy floor system, with hung sheetrock, small-diameter steel bar joists, and the thin layer of concrete, offered little barrier to the raging flames despite having been rated as fire-resistant for four hours. Three floors may have collapsed within the impact area, further tearing fireproofing away from the core columns. Once the first couple of core columns began to buckle, Malott speculates, they threw all of their load not onto a neighboring ring of strong columns protected with fireproofing (which in this design did not exist), but onto the adjacent columns in the exposed core, which were similarly denuded of fireproofing by the initial impact and also were failing under the intense heat.

"The outside of the building did not fail. It did not get hot enough," Malott says. "It was the core that failed."

As the interior core of the building at the impact zone began to settle downward, the floor sections were bent down at their spot welds along the exterior walls. The motion of the floors above now created a dynamic load on the column sections next below, and once the moving mass of the ten or twenty floors above the point of impact began settling downward around the buckling interior core there was no stopping it. The moving weight collapsed every successive core column in the building and smashed every floor panel down, pulling them inward and down and with them the outside walls of the building inward and down. A few of the floor sections pulled welds off the exterior wall columns, allowing them to topple outward.

"That's why you saw that curious collapse of the building," he says. "If you look carefully at the images you can see a bulging ripple going down the outside skin in advance of the collapsing floors. That was the bar joists tilting downward toward the interior core, which was probably moving two or three stories ahead of the collapse you saw on the outside of the building, pulling with them the exterior walls."

A building of this scale, in Malott's opinion, should never have been built in this way. The best proof is what happened to the 102-story Empire State Building when rammed by a B-25 in 1945. The plane, loaded with gasoline, hit between the seventy-eighth and seventy-ninth floors. The resultant fire burned for twenty-four hours and gutted five stories of the building. But the accident did not cause any catastrophic collapse of the structure because the tower had been built around a grid of interior columns and every one had been clad in concrete.

"It's a tough building," Malott says.

Weight is the enemy of any high-rise building, he says: the higher you go, the more weight and energy you have up in the air, the more your lower floors must support. In an attempt to cut weight, the designers of the World Trade Center towers eliminated the traditional grid of interior columns generally placed thirty feet on center, which can be found in most tall buildings built before the Twin Towers came along and changed the equation. Thus Malott catalogs a series of factors that combined on the morning of September 11 in the horrific tragedy the world watched on live television.

"First, the client wanted to be able to build cheaply and fast," he says. "Second, the engineers wanted as much of their structure on the outside of the building as possible to handle the wind loads. Third, the architect and engineers wanted it to be lightweight, so they substituted sheetrock fireproofing for concrete fireproofing. All of these decisions made back in the early 1960s were the precursor of this tragedy."


PARK


STOP

According to Darton, Yamasaki and his engineers had calculated the impact of a commercial jetliner shearing into the World Trade Center sometime in its projected lifetime of 200 years or more, something that might in fact have happened. What wasn't thought through, Malott says, is what would have happened if a plane rammed the building at 300 miles an hour, stripping the columns and elevator shafts of their sheetrock fireproofing. Without any tough fireproofing and without a redundant structural system of adjacent columns to pick up the failure of the damaged columns, the collapse was inevitable.

"There was nothing in this sixty-foot open span between the interior core and the exterior skin to even partially pick up the vertical load," he says. "Had there been, you might still have gotten the failure, but you should have had three or fours hours before the failure occurred. And the buildings might have stood and eventually been repaired."

It's time now to go back and rethink the entire concept of the high-rise structural system, Malott says. Buildings such as the World Trade Center towers cannot be built to minimum code specifications. And architects must now truly consider the impact of a fully loaded aircraft or other impact/explosion/fire combination striking another tower. Future high-rise buildings must be designed with a redundant system of interior support columns so no failure of any critical part – be it the core, the skin, or the floor – leads to the catastrophic collapse of the entire building.

"It's not reasonable to design a huge building where the failure of any one critical part leads to its total loss," he says. "That's not smart design."

But perhaps most important, Malott says, designers must also return to cladding their steel columns with concrete or some very tough substitute instead of fragile sheetrock. Ever since the World Trade Center became the global icon of capitalism, most high-rise buildings in America have followed its lead and wrapped their steel columns in some combination of mineral wool and gypsum board rather than concrete, leaving them susceptible to potentially devastating pancake failure not in four hours, for which they are theoretically fire rated, but in less than an hour.

"The culprit was not the jet fuel," Malott reiterates, as was repeated so often in the wake of the disaster. "And I say that as a former naval officer who witnessed a number of catastrophic aircraft accidents on the carrier. Those fires were out in minutes, even though they caused huge fuel fireballs. The jet fuel was part of the cause of the World Trade Center disaster, but the real culprit was that all the fireproofing was blown off on impact. It then took less than an hour to heat the unprotected steel columns to the failure point."

And to those who suggest that the fuel fire was so hot it burned through the sheetrock fireproofing, Malott says, "Try it. You can put a 3,000-degree welding torch to gypsum for hours and it will still be there when you're done. This fuel fire was not that hot."

It's interesting to note that while the enormous bomb that exploded in the parking garage of the World Trade Center in 1993 killed six people, injured almost 1,000, caused a massive fuel fire, and collapsed two garage floors, it did relatively little structural damage to the tower because the basement columns were encased in concrete. And that should be the primary standard, Malott says, for all steel columns in any high-rise structure.

"Even if the World Trade Center had been a total loss it should not have collapsed so quickly, if at all," he says. "There should have been enough time for the people to get out of the building. And those trapped on the upper floors should have had an escape mechanism – slide lines to adjacent buildings, fire- and smoke-shield clothing, parachutes, emergency breathing apparatus, and so forth."

In looking ahead rather than back, Malott says, we should reassess high-rise buildings and consider retrofitting them by wrapping their steel columns with a material as tough as concrete, even if this means huge costs.

"It might not take concrete cladding," he says. "Perhaps steel jackets around the gypsum board, somewhat like a seismic retrofit on overpass concrete columns, would suffice."

When writing last January about the 1993 bombing of the World Trade Center, Eric Darton made an eerily prescient observation:

"A traumatic event of this magnitude, with its horrific loss of life, opens up disquieting questions of how we have come to build and live in structures we are powerless to protect." Tragically, the worst was yet to come.

OPPOSITE PAGE:

A detail of the South Tower from the south with the five-story-high lobby completely open. Note the windows wrapping around the far side of the building that show the open-span floor plan with no interior columns other than the seventy-five-by-seventy-five-foot center core designed to hold the elevators, stairwells, and mechanical services. The lack of interior columns and lack of tough fireproofing constituted a nonredundant structural system. If any part of the system – the exterior wall, the floors, or the core – failed, the buildings would fall catastrophically. As it happened, on September 11, the core-column fireproofing was blown off on impact, and it took only about an hour for the thick steel columns to heat up to 1,600 degrees and collapse the core. Once the upper floors started moving downward in the core area, the dynamic energy collapsed each floor below in succession, while the floor panels pulled the exterior column skin inward and downward. (Photo by Jim Malott)