NIST NCSTAR 1-5A (Draft)

Federal Building and Fire Safety Investigation of the World Trade Center Disaster

Visual Evidence, Damage Estimates, and Timeline Analysis (Draft)

William M. Pitts
Kathryn M. Butler
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For Public Comment

NIST National Institute of Standards and Technology • Technology Administration • U.S. Department of Commerce

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ABSTRACT

This report summarizes the collection and analysis of visual material used for the National Institute of Standards and Technology (NIST) World Trade Center (WTC) Investigation. The task consisted of four major subtasks: 1) identification, collection, data basing, and cataloging of visual material, 2) timing of material incorporated into the NIST visual database, 3) development of fire time lines and additional analyses based on the visual material, and 4) documentation. Procedures used for subtasks 1 and 2 are summarized. Two data bases were assembled containing 6,899 photographs and 6,977 video clips, with 3,279 of the photographs and 2,772 of the videos timed with 3 second or better accuracy. The primary output of the task is a series of Excel data sheets describing individual window observations (fire, smoke, and whether window is open or closed) on the four faces of both towers as a function of time. Fire behaviors are discussed and documented by a large number of images. Additional analyses include initial façade damage and fire behavior due to aircraft impacts, aircraft speeds, and the motion of WTC 2 resulting from the aircraft impact. Unusual fire behaviors are documented for both towers. Several hanging objects (possibly floor slabs) observed inside WTC 2 and their changes with time are described. Other observations, including falling victims, falling streamers, and smoke marks on façade columns, are documented and related to the observed fire behaviors.

Keywords: Aircraft impacts, aircraft speeds, falling victims, fire behavior, fires, smoke marks, streamers, tower motion, World Trade Center.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronyms

ASTM	American Society for Testing and Materials
BPS	Building Performance Study
FEMA	Federal Emergency Management Agency
NIST	National Institute of Standards and Technology
PANYNJ	Port Authority of New York and New Jersey
SEAoNY	Structural Engineers Association of New York
USC	United States Code
WTC	World Trade Center

Abbreviations

°C	degrees Celsius
°F	degrees Fahrenheit
ft	feet
in.	inch
L	liter
m	meter
μm	micrometer
min	minute
s	second

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PREFACE

Genesis of This Investigation

Immediately following the terrorist attack on the World Trade Center (WTC) on September 11, 2001, the Federal Emergency Management Agency (FEMA) and the American Society of Civil Engineers began planning a building performance study of the disaster. The week of October 7, as soon as the rescue and search efforts ceased, the Building Performance Study Team went to the site and began their assessment. This was to be a brief effort, as the study team consisted of experts who largely volunteered their time away from their other professional commitments. The Building Performance Study Team issued their report in May 2002, fulfilling their goal "to determine probable failure mechanisms and to identify areas of future investigation that could lead to practical measures for improving the damage resistance of buildings against such unforeseen events."

On August 21, 2002, with funding from the U.S. Congress through FEMA, the National Institute of Standards and Technology (NIST) announced its building and fire safety investigation of the WTC disaster. On October 1, 2002, the National Construction Safety Team Act (Public Law 107-231), was signed into law. The NIST WTC Investigation was conducted under the authority of the National Construction Safety Team Act.

The goals of the investigation of the WTC disaster were:

- To investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of the WTC disaster.
- To serve as the basis for:
  - Improvements in the way buildings are designed, constructed, maintained, and used;
  - Improved tools and guidance for industry and safety officials;
  - Recommended revisions to current codes, standards, and practices; and
  - Improved public safety.

The specific objectives were:

1. Determine why and how WTC 1 and WTC 2 collapsed following the initial impacts of the aircraft and why and how WTC 7 collapsed;
2. Determine why the injuries and fatalities were so high or low depending on location, including all technical aspects of fire protection, occupant behavior, evacuation, and emergency response;
3. Determine what procedures and practices were used in the design, construction, operation, and maintenance of WTC 1, 2, and 7; and
4. Identify, as specifically as possible, areas in current building and fire codes, standards, and practices that warrant revision.

NIST is a nonregulatory agency of the U.S. Department of Commerce's Technology Administration. The purposes of NIST investigations under the National Construction Safety Team Act are to improve the safety and structural integrity of buildings in the United States, and the focus is on fact finding. NIST investigative teams are required to assess building performance and emergency response and evacuation procedures in the wake of any building failure that has resulted in substantial loss of life or that posed significant potential of substantial loss of life. NIST does not have the statutory authority to make findings of fault or negligence by individuals or organizations. Further, no part of any report resulting from a NIST investigation into a building failure or from an investigation under the National Construction Safety Team Act may be used in any suit or action for damages arising out of any matter mentioned in such report (15 USC 281a, as amended by Public Law 107-231).

Organization of the Investigation

The National Construction Safety Team for this Investigation, appointed by the NIST Director, was led by Dr. S. Shyam Sunder. Dr. William L. Grosshandler served as Associate Lead Investigator, Mr. Stephen A. Cauffman served as Program Manager for Administration, and Mr. Harold E. Nelson served on the team as a private sector expert. The Investigation included eight interdependent projects whose leaders comprised the remainder of the team. A detailed description of each of these eight projects is available at http://wtc.nist.gov. The purpose of each project is summarized in Table P–1, and the key interdependencies among the projects are illustrated in Figure P–1.

Table P–1. Federal building and fire safety investigation of the WTC disaster.

Technical Area and Project Leader	Project Purpose
Analysis of Building and Fire Codes and Practices; Project Leaders: Dr. H. S. Lew and Mr. Richard W. Bukowski	Document and analyze the code provisions, procedures, and practices used in the design, construction, operation, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of WTC 1, 2, and 7.
Baseline Structural Performance and Aircraft Impact Damage Analysis; Project Leader: Dr. Fahim H. Sadek	Analyze the baseline performance of WTC 1 and WTC 2 under design, service, and abnormal loads, and aircraft impact damage on the structural, fire protection, and egress systems.
Mechanical and Metallurgical Analysis of Structural Steel; Project Leader: Dr. Frank W. Gayle	Determine and analyze the mechanical and metallurgical properties and quality of steel, weldments, and connections from steel recovered from WTC 1, 2, and 7.
Investigation of Active Fire Protection Systems; Project Leader: Dr. David D. Evans	Investigate the performance of the active fire protection systems in WTC 1, 2, and 7 and their role in fire control, emergency response, and fate of occupants and responders.
Reconstruction of Thermal and Tenability Environment; Project Leader: Dr. Richard G. Gann	Reconstruct the time-evolving temperature, thermal environment, and smoke movement in WTC 1, 2, and 7 for use in evaluating the structural performance of the buildings and behavior and fate of occupants and responders.
Structural Fire Response and Collapse Analysis; Project Leaders: Dr. John L. Gross and Dr. Therese P. McAllister	Analyze the response of the WTC towers to fires with and without aircraft damage, the response of WTC 7 in fires, the performance of composite steel-trussed floor systems, and determine the most probable structural collapse sequence for WTC 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications; Project Leader: Mr. Jason D. Averill	Analyze the behavior and fate of occupants and responders, both those who survived and those who did not, and the performance of the evacuation system.
Emergency Response Technologies and Guidelines; Project Leader: Mr. J. Randall Lawson	Document the activities of the emergency responders from the time of the terrorist attacks on WTC 1 and WTC 2 until the collapse of WTC 7, including practices followed and technologies used.

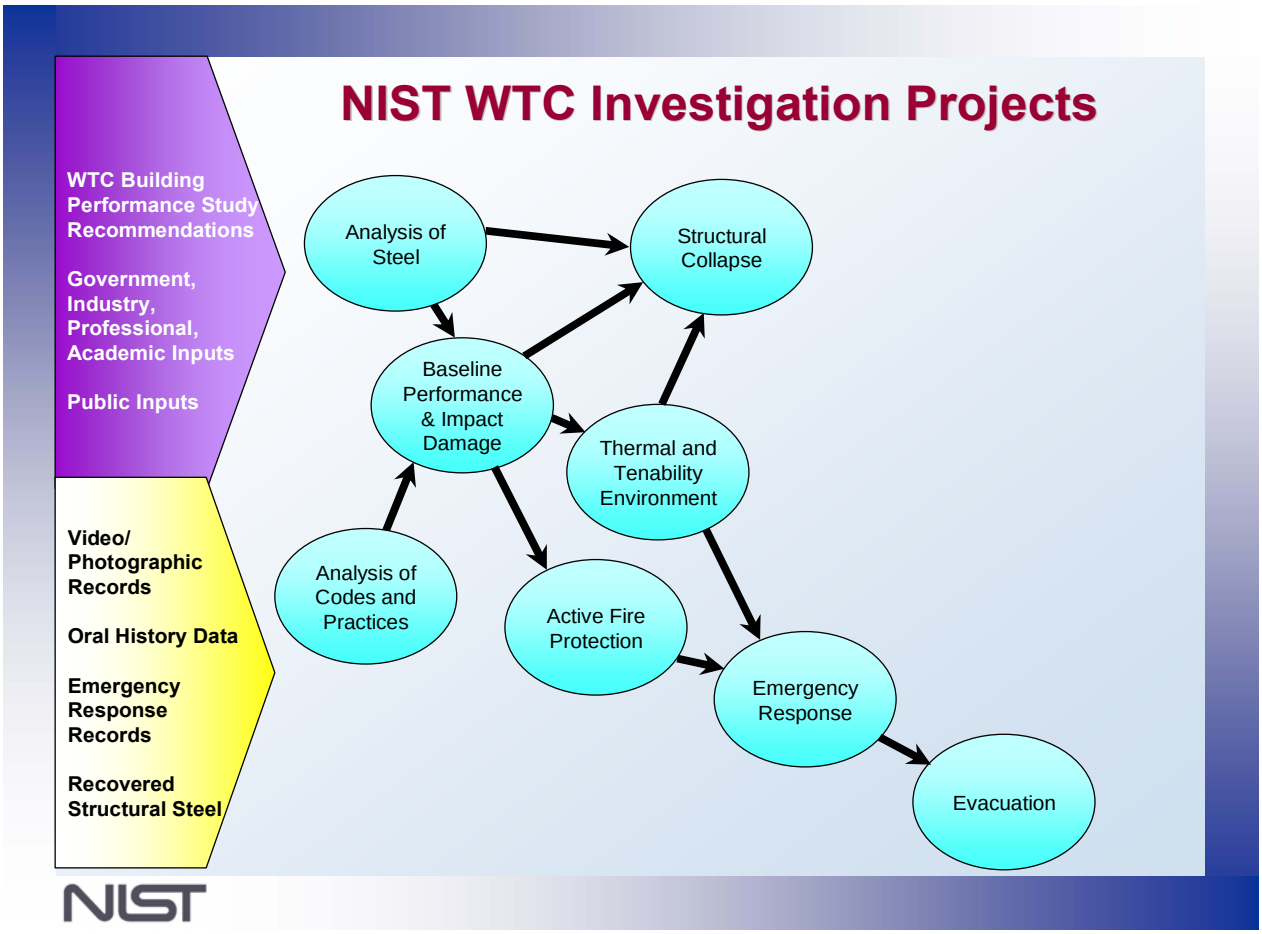

Figure P–1. The eight projects in the federal building and fire safety investigation of the WTC disaster.

National Construction Safety Team Advisory Committee

The NIST Director also established an advisory committee as mandated under the National Construction Safety Team Act. The initial members of the committee were appointed following a public solicitation. These were:

- Paul Fitzgerald, Executive Vice President (retired) FM Global, National Construction Safety Team Advisory Committee Chair
- John Barsom, President, Barsom Consulting, Ltd.
- John Bryan, Professor Emeritus, University of Maryland
- David Collins, President, The Preview Group, Inc.
- Glenn Corbett, Professor, John Jay College of Criminal Justice
- Philip DiNenno, President, Hughes Associates, Inc.

- Robert Hanson, Professor Emeritus, University of Michigan
- Charles Thornton, Co-Chairman and Managing Principal, The Thornton-Tomasetti Group, Inc.
- Kathleen Tierney, Director, Natural Hazards Research and Applications Information Center, University of Colorado at Boulder
- Forman Williams, Director, Center for Energy Research, University of California at San Diego

This National Construction Safety Team Advisory Committee provided technical advice during the Investigation and commentary on drafts of the Investigation reports prior to their public release.

Public Outreach

During the course of this Investigation, NIST held public briefings and meetings (listed in Table P–2) to solicit input from the public, present preliminary findings, and obtain comments on the direction and progress of the Investigation from the public and the Advisory Committee.

NIST maintained a publicly accessible Web site during this Investigation at http://wtc.nist.gov. The site contained extensive information on the background and progress of the Investigation.

NIST's WTC Public-Private Response Plan

The collapse of the WTC buildings has led to broad reexamination of how tall buildings are designed, constructed, maintained, and used, especially with regard to major events such as fires, natural disasters, and terrorist attacks. Reflecting the enhanced interest in effecting necessary change, NIST, with support from Congress and the Administration, has put in place a program, the goal of which is to develop and implement the standards, technology, and practices needed for cost-effective improvements to the safety and security of buildings and building occupants, including evacuation, emergency response procedures, and threat mitigation.

The strategy to meet this goal is a three-part NIST-led public-private response program that includes:

- A federal building and fire safety investigation to study the most probable factors that contributed to post-aircraft impact collapse of the WTC towers and the 47-story WTC 7 building, and the associated evacuation and emergency response experience.
- A research and development (R&D) program to (a) facilitate the implementation of recommendations resulting from the WTC Investigation, and (b) provide the technical basis for cost-effective improvements to national building and fire codes, standards, and practices that enhance the safety of buildings, their occupants, and emergency responders.

Table P–2. Public meetings and briefings of the WTC Investigation.

Date	Location	Principal Agenda
June 24, 2002	New York City, NY	Public meeting: Public comments on the *Draft Plan* for the pending WTC Investigation.
August 21, 2002	Gaithersburg, MD	Media briefing announcing the formal start of the Investigation.
December 9, 2002	Washington, DC	Media briefing on release of the *Public Update* and NIST request for photographs and videos.
April 8, 2003	New York City, NY	Joint public forum with Columbia University on first-person interviews.
April 29–30, 2003	Gaithersburg, MD	National Construction Safety Team (NCST) Advisory Committee meeting on plan for and progress on WTC Investigation with a public comment session.
May 7, 2003	New York City, NY	Media briefing on release of the *May 2003 Progress Report.*
August 26–27, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status of WTC investigation with a public comment session.
September 17, 2003	New York City, NY	Media briefing and public briefing on initiation of first-person data collection projects.
December 2–3, 2003	Gaithersburg, MD	NCST Advisory Committee meeting on status and initial results and the release of the *Public Update* with a public comment session.
February 12, 2004	New York City, NY	Public meeting: Briefing on progress and preliminary findings with public comments on issues to be considered in formulating final recommendations.
June 18, 2004	New York City, NY	Media briefing and public briefing on release of the *June 2004 Progress Report.*
June 22–23, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on the status of and preliminary findings from the WTC Investigation with a public comment session.
August 24, 2004	Northbrook, IL	Public viewing of standard fire resistance test of WTC floor system at Underwriters Laboratories, Inc.
October 19–20, 2004	Gaithersburg, MD	NCST Advisory Committee meeting on status and near complete set of preliminary findings with a public comment session.
November 22, 2004	Gaithersburg, MD	NCST Advisory Committee discussion on draft annual report to Congress, a public comment session, and a closed session to discuss pre-draft recommendations for WTC Investigation.
April 5, 2005	New York City, NY	Media briefing and public briefing on release of the probable collapse sequence for the WTC towers and draft reports for the projects on codes and practices, evacuation, and emergency response.
June 23, 2005	New York City, NY	Media briefing and public briefing on release of all draft reports and draft recommendations for public comment.

- A dissemination and technical assistance program (DTAP) to (a) engage leaders of the construction and building community in ensuring timely adoption and widespread use of proposed changes to practices, standards, and codes resulting from the WTC Investigation and the R&D program, and (b) provide practical guidance and tools to better prepare facility owners, contractors, architects, engineers, emergency responders, and regulatory authorities to respond to future disasters.

The desired outcomes are to make buildings, occupants, and first responders safer in future disaster events.

National Construction Safety Team Reports on the WTC Investigation

A draft of the final report on the collapses of the WTC towers is being issued as NIST NCSTAR 1. A companion report on the collapse of WTC 7 is being issued as NIST NCSTAR 1A. The present report is one of a set that provides more detailed documentation of the Investigation findings and the means by which these technical results were achieved. As such, it is part of the archival record of this Investigation. The titles of the full set of Investigation publications are:

NIST (National Institute of Standards and Technology). 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapses of the World Trade Center Towers.* NIST NCSTAR 1. Gaithersburg, MD, September.

NIST (National Institute of Standards and Technology). 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report of the National Construction Safety Team on the Collapse of World Trade Center 7.* NIST NCSTAR 1A. Gaithersburg, MD, December.

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Ghosh, S. K., and X. Liang. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Comparison of Building Code Structural Requirements.* NIST NCSTAR 1-1B. National Institute of Standards and Technology. Gaithersburg, MD, September.

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Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Fire Protection and Life Safety Provisions Applied to the Design and Construction of World Trade Center 1, 2, and 7 and Post-Construction Provisions Applied after Occupancy*. NIST NCSTAR 1-1D. National Institute of Standards and Technology. Gaithersburg, MD, September.

Razza, J. C., and R. A. Grill. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Comparison of Codes, Standards, and Practices in Use at the Time of the Design and Construction of World Trade Center 1, 2, and 7*. NIST NCSTAR 1-1E. National Institute of Standards and Technology. Gaithersburg, MD, September.

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Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Amendments to the Fire Protection and Life Safety Provisions of the New York City Building Code by Local Laws Adopted While World Trade Center 1, 2, and 7 Were in Use*. NIST NCSTAR 1-1G. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Post-Construction Modifications to Fire Protection and Life Safety Systems of World Trade Center 1 and 2*. NIST NCSTAR 1-1H. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., D. A. Johnson, and D. A. Fanella. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Post-Construction Modifications to Fire Protection, Life Safety, and Structural Systems of World Trade Center 7*. NIST NCSTAR 1-1I. National Institute of Standards and Technology. Gaithersburg, MD, September.

Grill, R. A., and D. A. Johnson. 2005. *Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Design, Installation, and Operation of Fuel System for Emergency Power in World Trade Center 7*. NIST NCSTAR 1-1J. National Institute of Standards and Technology. Gaithersburg, MD, September.

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EXECUTIVE SUMMARY

E.1 INTRODUCTION

The destruction of the World Trade Center (WTC) Complex in New York City on September 11, 2001, resulted in immense loss of life and property. Much of the loss was due to the collapses of the towers following the aircraft impacts. This task is a part of the Investigation of the technical causes for the disaster authorized by the United States Congress and performed by the National Institute of Standards and Technology (NIST). Details concerning the objectives and approach for the Investigation are included in the preface to the full report.

This summary describes the findings of one of the component tasks of Project 5—*Reconstruction of Thermal and Tenability Environment*. Project 5 was one of the eight projects that comprised the NIST WTC Investigation. This particular task, referenced as Task 5A, is entitled "Visual Evidence, Damage Estimates, and Timeline Analysis."

The objective of Task 5A was "to utilize photographs, videos, and other relevant information to develop detailed time lines for the spread and growth of fires at the peripheries of World Trade Center Buildings 1, 2, and 7 and to organize the information such that it can be utilized by other investigation team members." This report focuses specifically on the WTC towers, WTC 1 and WTC 2. In practice, the scope of the task was expanded, and this task provided significant technical support and analysis to Investigation Projects 2, 3, 4, 6, 7, and 8, while meeting the principal objective of developing time lines for the fires observed in the towers.

Task 5A consisted of four major subtasks: 1) identification, collection, data basing, and cataloging of visual material, 2) timing of material incorporated into the NIST visual database, 3) development of fire time lines and additional analyses based on the visual material, and 4) documentation.

This full report contains the documentation of Task 5A (subtask 4). Earlier interim reports released by the Investigation included updates on task progress.

E.2 COLLECTION AND HANDLING OF VISUAL MATERIAL

Even though the amount of visual material potentially available was immense, it was also diffuse, having been recorded by a large number of people. A variety of approaches were utilized to identify relevant imagery.

The identification of appropriate material was only the first step. It was then necessary to contact the source, request the material, and make arrangements for its transfer. There were often copyright and privacy issues that needed to be addressed. A strong emphasis was placed on receiving visual material in formats as close as possible to the original in order to preserve as much information as possible. NIST hired a visual media consultant, Mr. Valentine Junker, who acted as its representative in the New York City area and worked closely with Investigation staff to identify and obtain relevant material.

As anticipated, the amount of potentially useful visual material identified was huge. NIST ultimately collected and logged over 300 hours of video on nearly 150 separate tapes from a variety of organizations and individuals. Well in excess of 7,000 photographs were received from a variety of sources, including organizations and individuals.

The large amount of visual material was stored digitally in an electronic data system especially designed for the purpose. Once the material was available in digital form, the next step was to catalog and assemble it into a database. A commercial database program, known as Cumulus, designed specifically to handle visual material, was selected for this purpose. Each visual asset was catalogued using a number of attributes chosen to suit the needs of this task to track fire behavior and other relevant factors, including attributes identified by the other Investigation projects. Photographs and video clips were assembled into separate catalogs. Not all collected visual material was incorporated into the two catalogs. Even so, the photographic catalog includes 6,899 assets, and the video catalog includes 6,977 assets, representing over 75 hours of material.

E.3 TIMING OF PHOTOGRAPHS AND VIDEO CLIPS

Since the primary objective of this task was the development of time lines for fire growth and spread in WTC 1 and WTC 2, it was crucial that times of known uncertainty be associated with as many visual assets as possible. The visual material assembled during the Investigation can be classified into two broad categories with regard to time information—material that incorporates some indication of relative time and that for which no time information is provided. Generally, different approaches had to be employed in order to time these two classes of material. These are detailed in Chapter 3 of this report.

Recognizing that the majority of timing information available from the visual material itself was of high relative accuracy, but of unknown and variable absolute accuracy, a timing scheme was adopted in which all of the times for items in the databases were placed on a common relative time scale tied to a single well-defined event. Due to the large number of different views available, the moment when the nose of the second aircraft struck the south face of WTC 2 was chosen as the reference time. This event was defined to have occurred at 9:02:54 a.m. based on times for major events included in the earlier Federal Emergency Management Agency (FEMA) report (McAllister 2002) describing the events of September 11, 2001.

Once the reference time was chosen, it was possible to place times on videos that included the second aircraft impact. By matching other photographs and videos to these initial baseline videos, the assignments were extended to visual materials that did not include the primary event. By such a bootstrap process, it was possible to place photographs and videos extending over the entire period of the event on a single time line. An uncertainty estimate was included in the databases for each relative time assignment linked to an asset. Ultimately, 3,279 of the 6,899 catalogued photographs and 2,772 of the 6,977 video clips in the databases were timed with assigned relative uncertainties of 3 seconds or better.

To assist in the timing process, relative times for five major events of September 11, 2001--first aircraft impact, second aircraft impact, collapse of WTC 2, collapse of WTC 1, and collapse of WTC 7-- were determined with 1 s accuracies. These times are summarized in Table E-1. Many of the news broadcasts on September 11, 2001 had the current time imprinted on the screen. Based on four independent video recordings, the actual time of the second aircraft impact was determined to be 9:02:59 a.m., or 5 s later

than the time assigned in developing the database. The estimated uncertainty in absolute time is 1 s. These absolute times are included in Table E-1.

Table E-1. Times for Major Events of September 11, 2001.

Event	Relative Time from Visual Analysis	Adjusted Time from Television Broadcasts
First aircraft impact	8:46:25 a.m.	8:46:30 a.m.
Second aircraft impact	9:02:54 a.m.	9:02:59 a.m.
Collapse of WTC 2	9:58:54 a.m.	9:58:59 a.m.
Collapse of WTC 1	10:28:17 a.m.	10:28:22 a.m.
Collapse of WTC 7	5:20:47 p.m.	5:20:52 p.m.

E.4 DEVELOPMENT OF FIRE TIME LINES AND ADDITIONAL ANALYSES BASED ON THE VISUAL MATERIAL

The development of time lines describing the fire behaviors in the two towers was the principal objective of Task 5A. Other analyses performed by members of the task staff provided additional information concerning the aircraft impacts and the response of the towers to the impacts and subsequent fires.

E.4.1 Background Information

A substantial amount of background information is included in this report and its appendices that provides context and support for the analyses. Topics addressed include the local geography and wind direction on September 11th, along with relevant details concerning the towers such as dimensions, structural features, exterior architectural features, locations of mechanical floors, façade appearance, the nomenclature used to identify individual columns and windows, locations of intake and exhaust vents on mechanical floors, and details concerning locations of internal partitions. The vast majority of the available visual imagery was recorded from outside of the tower and, therefore, only provides information about the peripheries of the towers. The importance of tower geometry and camera location in interpreting information derived from external imagery is emphasized.

Different types of observations were used to provide insights into the fire behavior in the two towers. Details concerning the variety of observations utilized and how they were characterized are summarized in the relevant chapters of the report. The principal data collected were window-by-window assessments as a function of time for three properties often utilized to characterize fire behavior—1) presence or absence of fire, 2) whether or not smoke was coming from vents, and 3) whether ventilation pathways were open or closed. Data for a particular tower face and time were incorporated into individual Excel spreadsheets.

The intensity of a fire visible at a given window was further refined using a three-level rating scale with, the local fire intensity increasing with the number assigned. Similarly, smoke flow from windows was differentiated by two levels designed to characterize the amount of smoke present. There were often periods when certain windows were not observable due to effects such as smoke obscuration or the absence of an appropriate image. These windows were assigned “9”s in the data sheets.

While the data sheets provide indication for the fire intensities on the tower faces, it proved difficult to use these data to track changes without visualizing the results. Approaches were developed to provide color-coded representations of the various data sets on representations for the tower faces.

During the review of visual material, two behaviors associated with fire and smoke were identified that seemed to correlate with the local fire intensity at the faces of the towers. One of these was the frequent release of "streamers" during periods of active burning. Reviews of videos showed that streamers formed when a burning material (most likely polyurethane used for thermal insulation) located at the tops of windows fell. Once released, the flames quickly extinguished, but the material apparently continued to smolder, since intense white smoke was released that formed the streamer as the material floated downward. Observations of streamers have been tabulated in Appendix L of this report.

The second behavior was the formation of various types of distinctive smoke marks on the aluminum that covered the external steel columns made by flows of fire gases from adjacent open windows. The various types of marks provided additional evidence of the fire intensity near a given window. The most intense burning with external flames created marks referred to as "carets," based on their appearance.

During the review of imagery a number of observations were made of fire behaviors in the towers that were not characteristic of "typical" building fires. These included examples of extremely rapid apparent fire spread, based on the appearance of fires at windows on the façade; fires in the towers that burned for much longer periods than normal, perhaps indicating the presence of unusually high fuel loads; and occasional flame flare ups, which might indicate that changes were occurring within the towers. Such observations are described in Chapter 8 and Chapter 9.

In both towers there were occasions when large amounts of smoke and/or dust and sometimes flames were pushed simultaneously out of multiple open windows covering several floors and/or faces of a tower. These events were typically short lived (on the order of a few seconds) and are referred to as "puffs". The occurrence of puffs suggest the possible generation of pressure pulses within a tower that are transmitted through open pathways to remote locations and drive smoke and other material from the tower. The pressure changes required to create such puffs are not large and might be generated by events that result in relatively small volume changes, such as collapsing walls and ceilings, partial floor slab collapses, and sudden openings of ventilation pathways (e.g., an internal door). Some of the pressure pulses coincided with obvious events, such as the aircraft impact on or collapse of the adjacent tower, and are relatively easy to understand. Others occurred without outward indications of their sources. Since these puffs (pressure pulses) may have been indicators of structurally important changes taking place within the towers, their occurrences are documented in Chapter 8 and Chapter 9.

It was widely reported that numerous people either fell or jumped to their deaths on September 11th. People in the towers also took actions, such as breaking out window glass, which had the potential to influence the fires and even modify the effects of the fires within the towers. These human behaviors provide unique, albeit imprecise, insights into the local conditions within the towers. Observations of human behaviors are documented in order to better understand the behavior of the fires.

E.4.2 Observations and Analysis Related to the Aircraft Impacts

WTC 1

American Airlines Flight 11 struck the north face of WTC 1 at 8:46:30 a.m. Imagery was used to develop a time line for the events that occurred in the short period following the initial aircraft impact. Observations include the formation of external fireballs on the north, east, and south faces of the tower. Dust was visible exiting the north and east faces of the mechanical equipment room located at the top of the tower on the 108th and 109th floors.

By roughly 10 s after the aircraft impact, the fireballs that formed on the three faces of the tower dissipated, leaving "thermals" that continued to rise. A large amount of dust and debris created by the impact fell downward from the faces. By around 20 s after impact, the dust-filled cloud sinking below the impact area and the rising thermals had been blown to the southeast by the prevailing wind. Over this period the fires still present on the north, east, and south faces immediately following aircraft impact died down substantially.

An estimate for the aircraft speed at the time of impact, 443 mph ± 30 mph, was obtained by determining the period between the times when the aircraft first impacted the north face and when it fully entered the tower.

Close-up photographs and videos showing the area of the aircraft impact on the north face were used to generate the damage diagram shown in Figure E–1. Images show that substantial areas of the concrete floor slabs for the 95th through 97th floors were destroyed to an unknown depth within the tower in the immediate vicinity of the aircraft impact area. Locations where the two wing tips and the aircraft's vertical stabilizer struck the façade are represented by dashed lines in Figure E-1. The locations of the wing marks indicate that the aircraft struck between the 93rd and 99th floors. A properly scaled outline of a Boeing 767-200ER is superimposed on the damage diagram. The position of the aircraft has been adjusted to provide good agreement with the observed damage pattern and the wing and vertical stabilizer marks. The drawing indicates that the nose of the aircraft struck close to the center of the face near columns 129 and 130 at a height that was near the concrete floor slab for the 96th floor.

Views of the streets around the WTC complex revealed that a large amount of debris fell from the tower following the aircraft impact. Close-ups revealed a great deal of what appeared to be pulverized concrete. This is consistent with the aircraft impact cavity created on the north face.

Photographic evidence was also used to estimate damage to the east, south, and west faces of WTC 1 due to the aircraft impact and resulting fireballs. On the east face, a length of windows roughly half as wide as the tower face were broken on the 94th floor, starting just to the south of the face center and extending toward the north. Some of the aluminum facing on this floor was also dislodged. Even though part of the face was hidden by smoke coming from the open 94th-floor windows, it appeared that much less damage was done to the face on the other floors impacted by the aircraft.

Damage to the south face appeared to be localized to two principal areas. Following the aircraft impact, but prior to the collapses of the towers, a three-story steel panel section from the façade of WTC 1 was found to the south of the tower at the corner of West and Cedar Streets. Based on a review of photographs and videos, it is likely that this panel section originated from the center of the south face

between the 93rd and 96th floors, even though the area was obscured by smoke. The presence of an aircraft tire in one of the 95th-floor windows suggests how the panel was dislodged. Numerous windows were broken on the 96th floor over the area of the south face between the center and western edge. In contrast, in the area between the center of the face where the panel section was dislodged and the eastern edge, only a single window on the 94th floor was open.

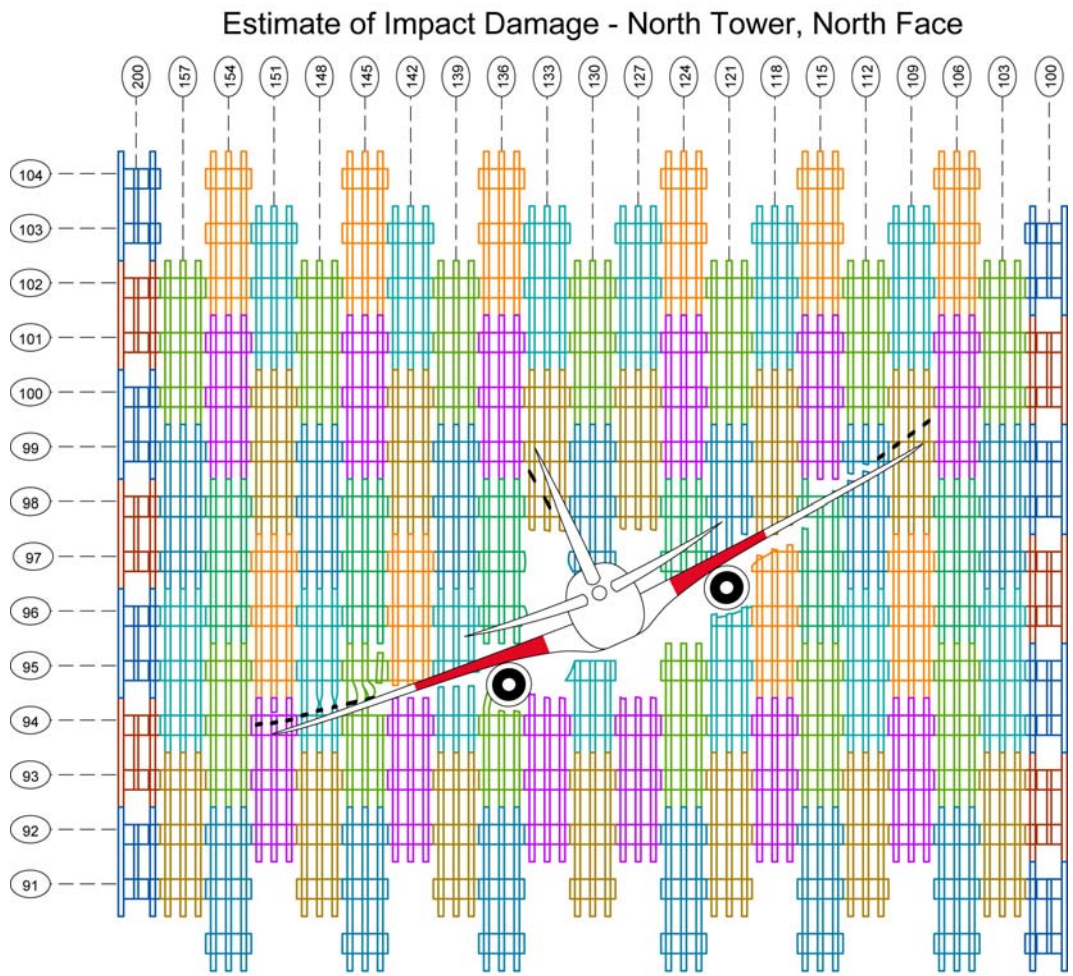

Figure E–1. A scaled outline of a Boeing 767-200ER is superimposed on the damage diagram for the north face of WTC 1. The position of the aircraft has been adjusted to best match the damage pattern and marks showing where the wing tips and vertical stabilizer struck. The red areas correspond to the approximate locations of fuel on the aircraft based on an analysis reported elsewhere (NCSTAR 1-2B).

Compared to the other faces, damage to the west façade of the tower appeared to be relatively light. With the exception of a small area of open windows and dislodged aluminum facing on the 96th and 97th floors near the south edge, damage to this face was limited to a few isolated broken windows.

The observed damage pattern in WTC 1 as the result of the aircraft impact and subsequent fireballs was somewhat asymmetric despite the fact that the aircraft struck near the center of the north face. On the east side of the tower most of the damage seemed to occur near the center of the east face, with very little observed damage in the southeast quadrant of the tower. On the other hand, the majority of external

damage visible on the west side of the tower was located on the western half of the south face and near the south edge of the west face.

As noted, fireballs formed on the north, east, and south faces after the aircraft struck WTC 1. The timing and the appearance of the fireballs indicate that they resulted from aviation fuel fires ignited inside the tower, which then rapidly forced large amounts of unburned atomized aviation fuel through openings created either by direct impact of the aircraft wreckage and/or building and contents debris or windows broken open as a result of the overpressures generated inside the tower by the fires. Note that the overpressures were associated with the thermal expansion due to combustion in a partially enclosed space. Previous studies have shown such overpressures can range from just above ambient to as high as 5 psi (Butlin and Tonkin 1974, Butlin 1975). An estimate from a simple analysis performed as part of the Investigation was consistent with this range. The overpressures generated in the tower were likely sufficient to break window glass and blow off sections of the aluminum curtain wall, but would not have been expected to be large enough to cause significant structural damage.

An analysis based on the limited amount of air available for burning on a given floor indicated that the maximum amount of aviation fuel that could have been consumed on a single floor (assuming that fuel was distributed over the entire floor) during the brief burning period was 365 gal. The amount of fuel on American Airlines Flight 11 when it struck WTC 1 has been reported as 10,000 gal (Barry 2003) distributed equally between tanks in the two wings. The approximate locations of this fuel on the aircraft are indicated in Figure E–1 (see NCSTAR 1-2B). Based on these fuel locations and assuming the fuel released from the fuel tanks moved over the floors directly in their paths, it is expected that roughly 5,000 gal of jet fuel were dispersed over portions of the 96th and 97th floors from the starboard fuel tank and roughly 5,000 gal over the 94th and 95th floors from the port tank. These considerations suggest that the upper limit for the amount of aviation fuel that could have been consumed by the initial burning within the tower was on the order of 15 %.

Some fraction of the remaining fuel was pushed out of the building by the overpressure, forming the fireballs when it mixed with additional air outside of the tower. It is likely that some of the fuel remained unburned on the impact floors. Flash fires were also observed at other location in the tower, including the ground-floor lobby, indicating that some fraction of the fuel was transported large distances, presumably via damaged ductwork and elevator shafts.

In the seconds immediately after the fireballs burned out, large fires were still present at damaged areas on the north, east, and south faces of the tower, indicating that aviation fuel was still being consumed. Between 40 s and 45 s after the aircraft impact these flames suddenly subsided, and the amount of visible flame decreased markedly. Such “damping down” of the internal fires is expected due to oxygen depletion and would be expected to continue until the air was replenished within the tower.

In the minutes immediately following the aircraft impact, relatively small fires were observed at isolated locations around the periphery of the building--in and near the aircraft impact cavity on the north face, near the center of the east face on the 94th floor, and on the west side of the 96th floor on the south face. These fires were likely burning small amounts of residual aviation fuel or building contents. They were not extinguished because they had direct access to outside air.

WTC 2

By the time United Airlines Flight 175 struck WTC 2 at 9:02:59 a.m., a large number of still and video cameras were trained on the WTC site. Many of these recorded the approach of the aircraft, its collision with the tower, and the events that immediately followed. More than 25 video clips of the aircraft impacting WTC 2, from all four sides, are included in the visual database. These clips were used to develop a time line for the events observed during the aircraft impact and the immediate aftermath.

Shortly after the aircraft impacted the south face of the tower and disappeared inside, signs of damage began to appear on the east and north faces. Very soon after the damage first appeared, flames were pushed out of openings in the façade, and fireballs began to grow rapidly outside the tower. The largest fireball formed on the east face, with flames appearing to come from across the entire width of the face. Large fireballs also grew on the north face, appearing to form from three separate, closely spaced locations on the east side. A fireball was also observed on the south face, coming from the cavity formed by the aircraft impact, but it seemed to be smaller and to last for a shorter period than those on the north and east faces. Videos showed that the fireball on the east face lasted the longest and was present for roughly 11 s. After the flames in the rising fireball were extinguished, the heated gases continued to rise, ultimately forming a distinct mushroom-cloud thermal.

Substantial amounts of dust and other debris were observed falling downward from the impact floors immediately following the aircraft impact. Dust was also pushed out of intake and exhaust louvers located on the north and east sides of the mechanical equipment room on the 75th and 76th floors. No fire, smoke, or dust was observed on the west face of WTC 2 during the aircraft impact and the period immediately following.

A particularly stable video shot from the east provided sufficient resolution to allow the nose and the tail of the aircraft to be tracked as a function of time as the aircraft approached the tower. Since the length of the aircraft is known, the speed was determined simply by dividing the length of the aircraft by the time required for it to pass a fixed point, yielding a value of 545 mph ± 18 mph.

Close examination of this video revealed a perceptible north-south movement of WTC 2 after it was struck by the aircraft. Image analysis of the video allowed the movement of the tower at the 70th floor to be determined as shown in Figure E-2. The maximum deflection was determined to be 12 in. ± 1 in. at this height, which extrapolates to a value of 22 in. ± 5 in. at the roofline. The primary period for the motion was 11.4 s ± 0.1 s, consistent with the fundamental natural mode of the building. Similar measurements using a brief video shot from the north yielded an amplitude near the roof line of 6 in. ± 1 in. for the east-west direction with a period of 5.3 s ± 0.1 s. This period and motion are consistent with the first torsional (twisting) mode of the tower.

The quality and number of visual images in the databases for the south face of WTC 2 were less than for the north face of WTC 1. Nevertheless, it was possible to characterize the initial damage to the façade as a result of the aircraft impact. The results are shown Figure E-3. Note that there was an area on the east side of the face where it was not possible to accurately determine the damage due to smoke obscuration.

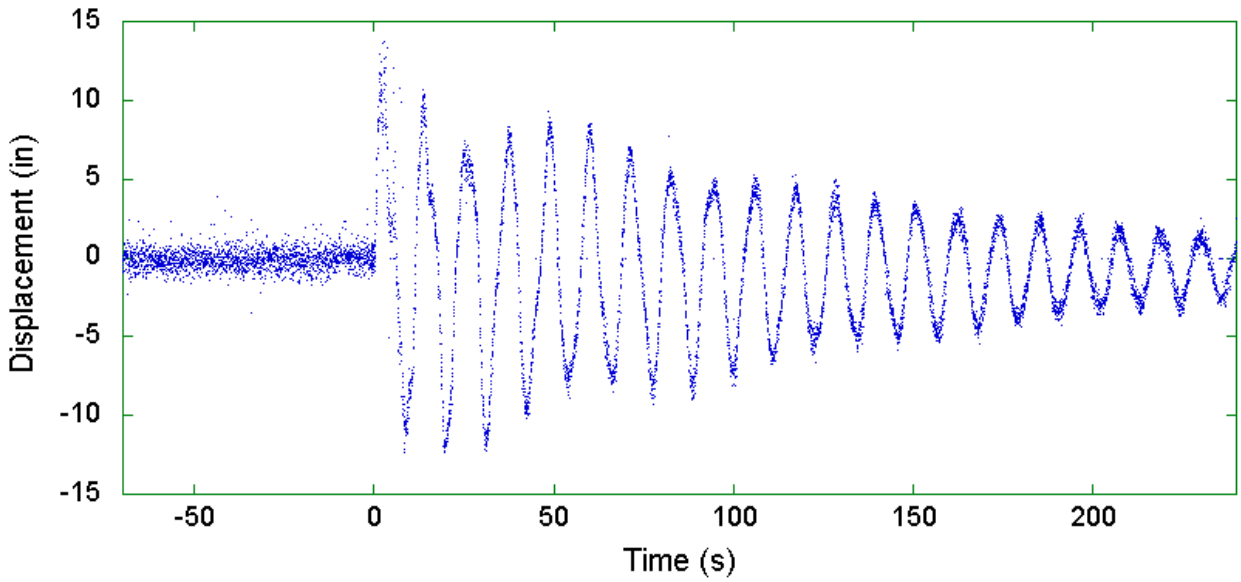

Figure E–2. The displacement of the first (left-most) window line on the 70th floor of WTC 2 determined using moiré analysis is shown as a function of time.

As was true for WTC 1, areas of the aluminum façade struck by the wing tips and the upper portion of the vertical stabilizer were marked. The locations for the left wing tip and vertical stabilizer are indicated in the figure. The area at the end of the right wing was obscured by heavy smoke. However, there were brief periods when the location of the last column struck by the wing tip could be discerned on column 404 at the 85th floor, as indicated in the figure. The left wing marks extend to the bottom of the spandrel located below the 78th floor. The location of the concrete floor slab for the 78th floor is above this point, which means the lowest point struck was on the 77th floor. Thus, the aircraft impact location on WTC 2 extended from the 77th floor to the 85th floor.

In Figure E–3 a scaled outline of a Boeing 767-200ER has been superimposed on the damage diagram for the south face. The position of the aircraft has been adjusted to provide good agreement with the observed damage pattern and the wing and vertical stabilizer marks. From the results it can be seen that the nose of the aircraft struck near column 422, i.e., to the east of the center of the face, at a height just below to the floor slab on the 81st floor. The port engine struck close to column 427 at a height just above the floor slab for the 79th floor, and the starboard engine struck near column 414 on the spandrel at the base of the 81st floor.

Close inspection of photographs and videos revealed a large amount of debris piled on the right-hand side of the cavity created by the aircraft impact. This debris, along with the depth of the cavity behind the opening, indicates that floor slabs in this area were partially collapsed or pulverized by the collision. Areas of the façade removed from the immediate vicinity of the impact appeared to be undamaged.

On the east face, substantial areas of the aluminum curtain wall were removed over multiple floors by the aircraft impact and resulting fireballs. A detailed map of this damage is included in Chapter 7 of the report. The areas of greatest damage were concentrated on the 80th, 81st, and 82nd floors. Large piles of debris near the north edge of the face could be seen through windows on the 80th and 81st floors. Aluminum panels covering the northeast corners of the 81st and 82nd floors were missing, and the resulting opening on the 81st floor was filled with debris.

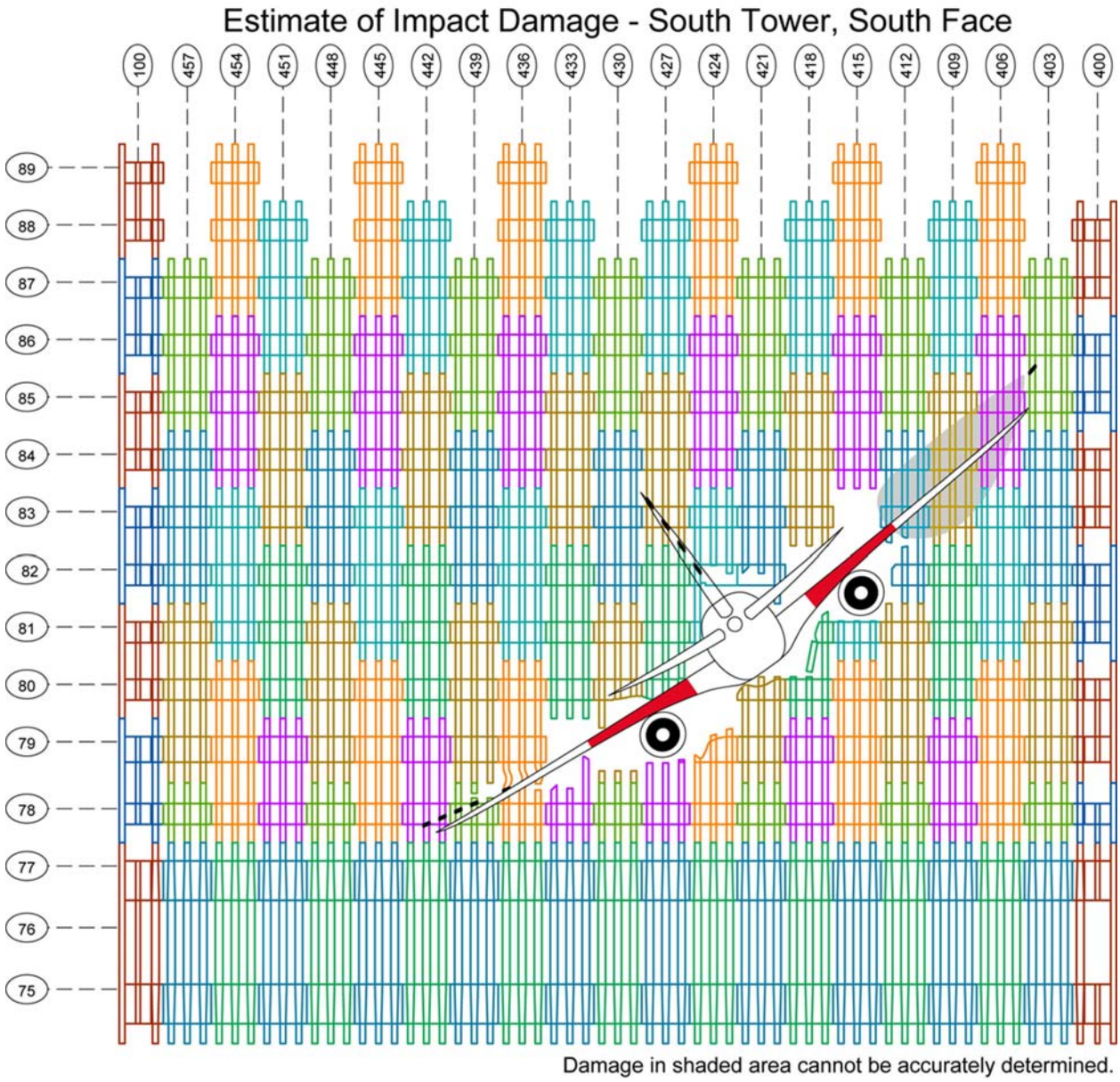

Figure E–3. A scaled outline of a Boeing 767-200ER is superimposed on the damage diagram for the south face of WTC 2. The position of the aircraft has been adjusted to best match the damage pattern and marks showing where the wing tips and vertical stabilizer struck. The red areas correspond to the approximate locations of fuel on the aircraft based on an analysis reported elsewhere (NCSTAR 1-2B).

Most of the initial damage on the north face due to the aircraft impact and resulting fireballs occurred on the east side. A substantial area of aluminum façade was removed in this area as detailed by a map for the face included in Chapter 7. The most prominent region of missing curtain wall was a roughly rectangular ten column wide area covering the 80th, 81st, and 82nd floors, starting eight columns in from the east edge of the face. This area coincides with the location where the largest nascent fireball formed on this face. As discussed below, very little flame was observed subsequently in this area, and temperatures in the vicinity were close to ambient well after the aircraft impact. For these reasons, this area is referred to

as the "cold spot". High-resolution photographs revealed that one of the steel columns to the immediate east of the cold spot was severed and that an adjacent column was severely distorted.

Three large piles of debris were evident through the windows on the north face. Two of these piles started at the northeast corner and extended out about eight windows toward the west on the 80th and 81st floors. These are the same floors where similar piles were observed on the east face at the north edge, suggesting that the debris had essentially filled up the northeast corners of the tower on these two floors. The third pile of debris was visible on the 79th floor, extending westward from near the center of the face over roughly nine windows.

There was no indication that the aircraft impact and resulting fireballs produced any visible damage to the west face.

Several pieces of the aircraft passed all the way through WTC 2 at the time of impact and exited at high speeds from the north side. Most of these pieces were relatively small, but at least two were of substantial size. It is likely that the two large objects were a portion of a jet engine that came to rest on a street corner roughly 1,500 ft to the northeast of WTC 2 and a landing gear that penetrated the roof of a building located at nearly the same distance. A large amount of small debris and dust was distributed on the streets around the WTC site following the impact. This material most likely came from portions of the dust clouds observed on the south, east, and north faces immediately following the aircraft impact. As for WTC 1, a significant fraction of this material appeared to consist of small pieces of concrete, suggesting that the aircraft impact pulverized a significant area of the concrete floor slabs as it entered the tower. This is consistent with the large scooped-out cavity seen at the aircraft impact point.

The majority of the fuel that formed the large fireball on the east face of the tower, as well as a substantial fraction that fueled the fireballs on the north face, appeared to come from the 82nd floor. This suggests that most of the aviation fuel that formed the fireballs was released from the starboard fuel tank of the aircraft (see Figure E-3). Much smaller fireballs appeared from the lower floors (primarily the 79th floor) struck by the port fuel tank.

During the 5 s to 10 s period following the aircraft impact, flames extended from windows on the south, east, and north faces of the tower. The most intense visible burning regions were on the south and east faces near the southeast corner of the 82nd floor and on the east and north faces floor near the northeast corner of the 81st floor. Areas of smaller flames were seen on lower floors at roughly the same time. Their locations included the south face near the bottom of the opening in the tower created by the aircraft impact and near the center of the north face where the smaller fireball had formed on the 79th floor. An interesting observation is that no flames were obvious on the east face below the 80th floor during this time.

Starting roughly ten seconds after aircraft impact, most of the large fires burning at the periphery of WTC 2 began to decrease in size and to recede back into the building. In many locations fires were no longer visible after about 30 s. Exceptions were fires in the northeast corner of the 81st floor and near the center of the north face on the 79th floor. Both of these flaming regions were in areas where large piles of debris were visible through the windows. The cold spot discussed earlier was located between the two fire zones on the north face and was essentially flame free.

A plausible description of the aviation fuel burning behavior following the aircraft impact was developed based on fire observations. Immediately after the aircraft struck the tower the fuel tanks were ruptured, and much of the jet fuel was atomized. The total amount of fuel involved has been estimated as 9,120 gal (Midgett, 2003), divided equally between the starboard and port wing tanks (a center fuel tank is believed to have been empty). This means that roughly 4,560 gal of fuel were dispersed in the vicinity of the 81st and 82nd floors and 4,560 gal in the vicinity of the 79th floor based on Figure E-3.

An estimate was provided earlier for the maximum amount of jet fuel that could be burned on a single floor of a tower using air already present on the floor. If the fuel was distributed completely over two floors and ignition of the entire volume occurred, it would be expected that about 730 gal of fuel would be consumed inside. In reality, it is unlikely that the fuel aerosol was distributed uniformly over two whole floors, so the total amount of fuel from one of the tanks burned inside was probably less than this amount, suggesting that less than 15 % of the fuel released from a fuel tank would have been expected to burn immediately within WTC 2.

The overpressure generated by the combustion taking place within the structure would be expected to break out window glass and possibly remove aluminum cladding and to induce flows of interior gas and aviation fuel aerosol out of the building. It was the aviation fuel expelled from the building that likely generated the spectacular external fireballs.

One interesting aspect of the observed fire behavior was that the fireballs on WTC 2 formed predominantly from fuel dumped on the 82nd floor. The lack of a large fireball emanating from the 79th floor, along with the observation that there was very little fire visible on the floor in the immediate aftermath of the fireballs, implies that most of the fuel from the port tank of the aircraft did not burn immediately following impact. There are two plausible explanations for this observation. One is that the fuel was transported elsewhere in the building, where it encountered fresh air and was then able to burn. There is no visual evidence that this took place. Another possibility is that the fuel was dumped in the vicinity of the 79th floor or into shafts within the core, and much of it failed to ignite. In this case, the fuel would have been expected to soak interior furnishings and perhaps form pools as the aerosol "rained out." The locations of these pools cannot be determined from the visual record.

Three estimates have previously been provided for the amount of jet fuel that burned outside of WTC 2 in the fireballs. The FEMA report (McAllister 2002) used fireball correlations to derive a value between 1,000 gal and 3,000 gal. Baum and Rehm (2005) reported consistent results between two analytical and computational approaches of 10 % to 25 % (roughly 900 gal to 2,300 gal) of the total fuel being consumed. Note that one of the approaches is summarized in Rehm et al. (2003). The consistency of the three calculations is good. Since most of the fuel that formed the fireballs came from the starboard fuel tank, this suggests that 20 % to 50 % of this fuel burned externally, with another few percent consumed inside the building. The remainder of the fuel was presumably left behind in the tower following the initial fire. This is also likely the case for almost all of the fuel released by the aircraft's port fuel tank, primarily on the 78th and 79th floors.

As already noted above, unlike WTC 1, several extensive regions of large fires were present after the initial rapid burn off of aviation fuel in areas of the tower where large piles of debris had been formed and for which the windows and large sections of the aluminum facing had been removed. The short-lived aviation fuel fires were apparently sufficient to ignite these debris piles. These fires were not efficiently damped down by the resulting oxygen depletion within the tower since they had ready access to oxygen

from outside air at locations where the façade had been breached. The large flame extensions observed for these fires are consistent with this conclusion.

E.4.3 FIRE TIME LINE FOR WTC 1

The following discussion of fire behavior in WTC 1 is broken into six time periods of roughly 15 minutes each. This summary focuses on fire observations. Details of the fire behavior as a function of time are documented in façade maps describing fire, smoke, and window condition observations included in Appendices C to F of this report. Detailed discussions of the fire observations, with numerous supporting images of the tower, and other related details such as window breakage, smoke flow, streamer formation, column smoke marks, and human behaviors are included in the report.

8:47 a.m. to 9:03 a.m.

This period spans the time between the first aircraft impact on WTC 1 and the second on WTC 2. As noted earlier, by 40 s after the aircraft impact on WTC 1, only relatively small fires were visible burning on the north, east, and south faces. During the following few minutes, only minor changes in these initial fire distributions were noted. After this lull, fires began to appear, grow, and spread on all four faces of the tower.

Within a few minutes of the aircraft impact, a substantial fire grew on the 97th floor to the immediate west of the aircraft impact cavity on the north face. Starting around 8:51 a.m., external flames also appeared on this floor from windows located a short distance to the east of the cavity and rapidly grew to fill several nearby windows. Around 8:57 a.m. smoke and flames suddenly came from windows on the east side of the 96th floor below the burning area on the 97th floor. The three fires on the 96th and 97th floors began spreading toward the edges of the face, with the fire on the west side of the 97th floor reaching the western edge of the tower by 9:03 a.m. and the two fires on the east side of the impact cavity spreading to the east before pausing outside of the walls of rooms located in the northeast corners of these floors. During the period, several small isolated fires were visible on other floors impacted by the aircraft.

On the east face of the tower the fire that was originally visible toward the center of the 94th floor spread and grew substantially. By 9:03 a.m. an intense fire was visible burning over a length of open windows that covered roughly a quarter of the face from a position on the north side to near the center of the face.

Just before 8:57 a.m., flames appeared from windows on the 97th floor located just to the south of the internal wall of the room in the northeast corner of this floor. This fire appeared to spread and grow rapidly, covering more than a quarter of the length of the floor by 9:03 a.m. By this time several small fires were also visible on the northern sides of the 92nd, 93rd, and 95th floors and had just appeared on the 96th floor. Near the end of the period, numerous people were observed falling from the 92nd and 93rd floors over a short period of time, which may have been an indication that conditions on the east sides of these floors were becoming untenable at this time.

The primary fire activity on the south face during the period was on the 96th floor. The fire on the western side of the face had grown and spread to cover nearly the entire western half of the floor. Flames were visible in the southwest corner of the floor where an aluminum panel covering the area had been

removed during the aircraft impact. Near the end of the period, relatively small fires began to appear on the western sides of the 95th and 97th floors.

No fires were visible on the west face until just after 8:55 a.m., when external flames and heavy smoke first appeared from a window on the 97th floor near the center of the face and then seemed to spread very rapidly in both directions. Within a minute, external flames were visible over a length of windows covering nearly a quarter of the face near the center. A second period of apparent rapid fire spread just after 9:01 a.m. increased this length to the south by roughly 50 % in 8 s. Shortly after 9:02 a.m., another period of rapid fire spread appeared to fill in most of the remaining gap between the existing fire and the north edge of the face. No fires were observed on other floors of the west face.

Fire observations for the period are summarized by the façade maps in Figure E-4, which show fire locations integrated over the period. The color coding indicates the highest fire intensity recorded during the period, with yellow representing a spot fire, red a more extensive fire burning inside the tower, and orange a fire with flames extending out of the window.

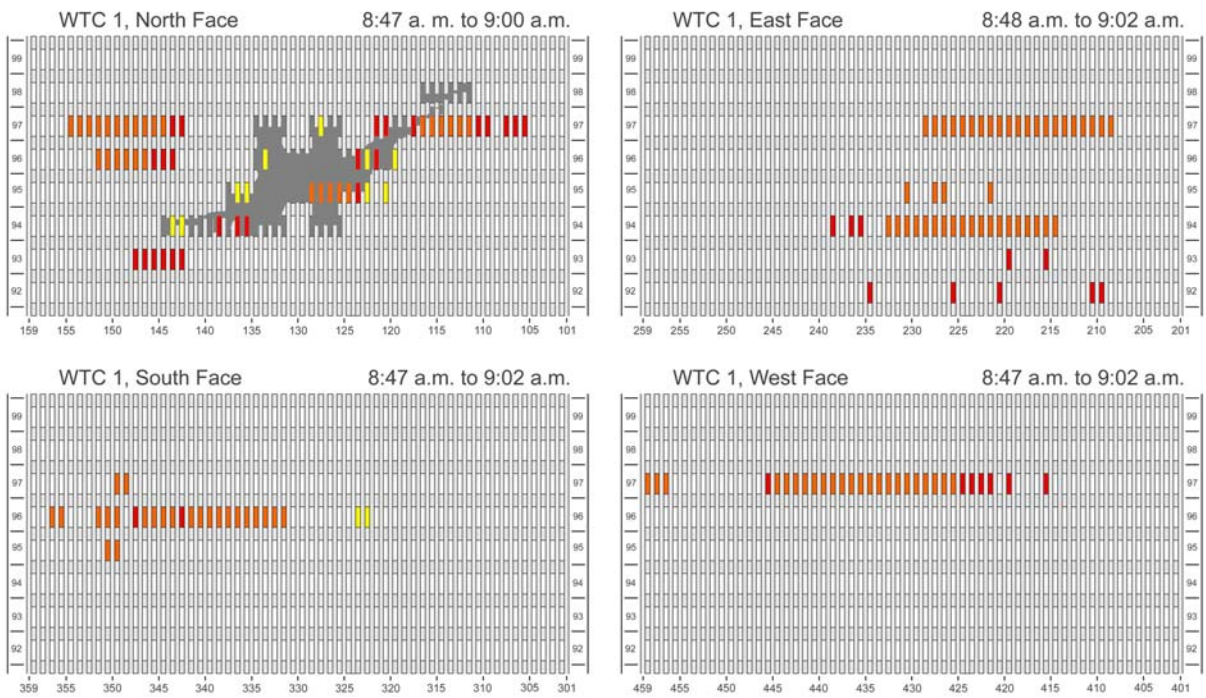

Figure E–4. Maps of integrated fire observations between 8:47 a.m. and 9:03 a.m. are shown for the four faces of WTC 1.

The most extensive fire growth took place on the 97th floor. The apparent rapid development of these fires, particularly on the west face, may be an indication that the fire growth and spread was accelerated by the presence of initially unburned aviation fuel that may have been dispersed over this floor during the aircraft impact.

Observations suggest that smoke from the developing fires was rapidly transported to the upper regions of the tower. Smoke was observed shortly after the aircraft impact coming from an area of intake vents for the fire floors located near the center of the north face in the mechanical equipment room on the 108th

and 109th floors. Starting around 8:52 a.m., trapped people began to break open windows on floors on each of the faces near the top of the tower, particularly on the 104th and 105th floors, and smoke began to flow immediately from many of these open windows.

Other observations summarized in this report are consistent with the observed fire behaviors during the period. A number of streamers were observed falling from façade areas where fires had recently appeared. The aluminum cladding next to windows where fires were present was marked by smoke in a manner which reflected the local fire intensity. In particular, distinct carets were present on the columns next to windows where flames extended from the openings.

Response of WTC 1 to the Impact of United Airlines Flight 175 on WTC 2

United Airlines Flight 175 struck WTC 2 at 9:02:59 a.m. The impact and subsequent fireballs briefly affected the fire behavior in WTC 1. The first effect was the sudden appearance of smoke, and in a few cases fire, from a number of open windows, indicating that a weak pressure pulse had passed through the tower. A portion of the fireballs that formed on WTC 2 were adjacent to the east face of WTC 1. As the fireballs initially expanded, they pushed smoke away from the east face of WTC 1 and revealed areas that had been hidden by smoke. As the fireballs grew larger, they entrained sufficient air that large amounts of smoke and air were drawn from open windows on the east face of WTC 1, while smoke flow was markedly decreased on the other faces. The disrupted smoke flow lasted for just over 10 s.

9:03 a.m. to 9:18 a.m.

Compared to the rapid fire spread observed on the north face periphery during the first time period, little additional fire spread occurred on this face during the following fifteen minutes. The intense fires that had grown on the 96th and 97th floors earlier retreated into the building and began to die down. Around 9:15 a.m. a fire appeared in windows on the west side of the aircraft impact cavity on the 94th floor. This was the first evidence for a fire in this area on this floor.

In contrast to the north face, the fires burning on the periphery of the east side of the tower continued to develop and spread during this time, initiating new areas of intense burning at the same time that areas ignited somewhat earlier were dying down. By 9:07 a.m. an extensive length of flame had appeared on the 92nd floor, extending over roughly 20 % of the width of the face to the north of the face center. Moderate fire growth had also occurred near the center of the 93rd floor, while an isolated fire was visible at the center of the 95th floor. An intense fire (with flames extended from windows) developed over a length running from just outside the wall of the room in the northeast corner to well pass the center of the face on the 96th floor. On the 94th and 97th floors, the fires at windows that had been burning intensely during the earlier period were dying down, while new areas of fire had spread to the south.

During the initial part of this time period, the fire on the western half of the 96th floor on the south face continued to burn intensely. At this time, flames were not visible on other floors. By the end of the period the appearance of the south face had changed dramatically. While the fires on the 96th floor had begun to die down and recede back into the tower, extensive areas of flame became apparent on both the 95th and 97th floors. The fire on the 95th floor was visible over roughly 10 % of the face width at a location to the west of the face center. On the 97th floor a fire developed that covered most of the western half of the floor.

The fires on the west face during this time period continued to undergo unusual and dramatic changes in behavior. During the early part of the period, heavy flames and smoke were observed coming from roughly the same locations on the 97th floor as just prior to 9:03 a.m. At 9:06:27 a.m. a short-lived, but intense, burst of flame appeared near the top of a window near the southern edge of the floor. Very shortly afterwards, the amount of smoke and flames coming from open windows along the length of the 97th floor decreased dramatically, and it was possible to see parts of the west façade that had been hidden by smoke just before. At this time flames were visible near the southern edge of the face. Later images during the period show an extensive fire across the entire length of the floor, but with flames that had receded well into the tower and with little smoke flow from the open windows. Around 9:08 a.m. a small fire became visible on the 96th floor near the southern edge of the face. By the end of the period a relatively low-intensity fire was visible in several windows in this area. No other fires were observed on the face during the period.

Figure E–5 shows integrated fire maps for the four faces of WTC 1 covering the period. Comparison with Figure E–4 reveals the changes in fire distributions between the two time periods. The most prominent feature in Figure E-5 is the extent of the fires on the 97th floor, with flames visible in a nearly continuous band running clockwise from just west of the center of the south face, along the western and northern faces, and reaching just past the center of the east face. Another feature which stands out is the general lack of visible fire in the southwest quadrant of the tower.

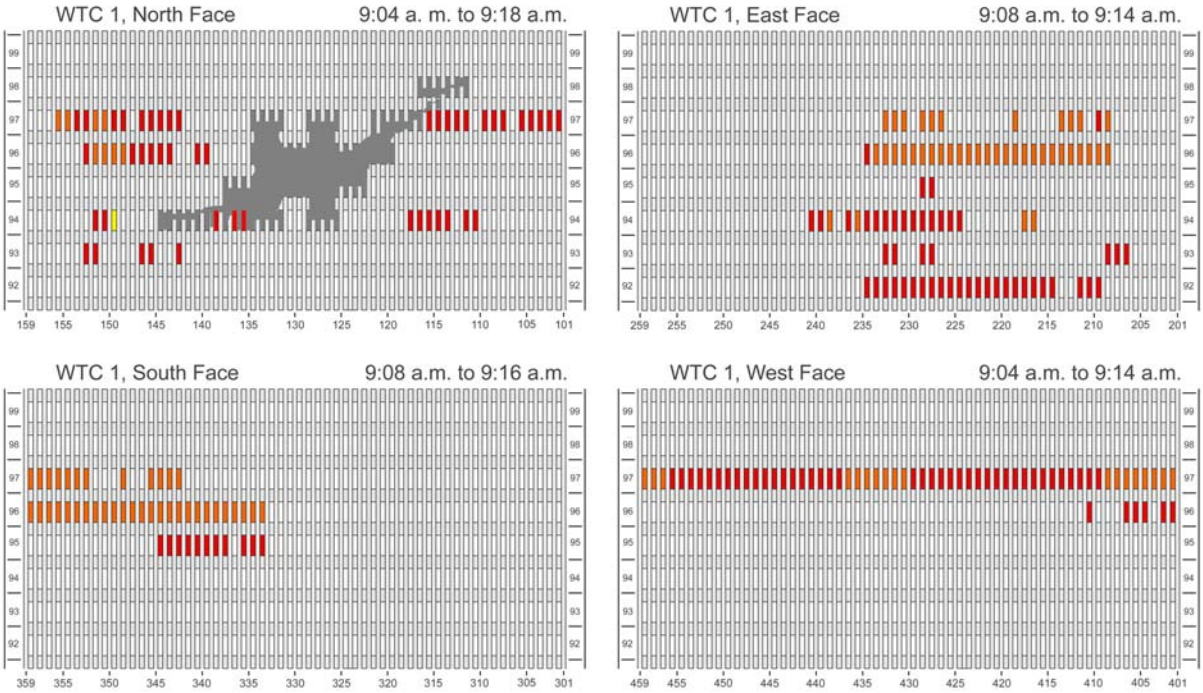

Figure E–5. Maps of integrated fire observations between 9:03 a.m. and 9:18 a.m. are shown for the four faces of WTC 1.

During this time period, fourteen people were observed falling from WTC 1. Unlike during the first time period, when a large number of people fell from windows at or below the aircraft impact floors, all of the people, for which the origins of fall are identified, came from above the aircraft impact floors, providing an indication that conditions on the upper floors were deteriorating. A number of these people were

observed falling from the south face. It is likely that many more fell on this face than were observed, since close-up visual coverage from the south was less complete than for the other three faces.

9:18 a.m. to 9:35 a.m.

Very shortly after 9:18 a.m., intense fires with external flames appeared at north face windows within the rooms on the northeast corners of the 96th and 97th floors. Similar flames were observed in the northeast corner room on the 94th floor around 9:25 a.m. Very shortly after these fires appeared, streamers began falling from the areas. The intense flames in these windows only lasted a few minutes, having died down by 9:35 a.m. The fire observed at the west side of the 94th floor on the north face at the end of the previous period spread significantly and filled the length between the aircraft impact cavity and eastern wall of a room in the northwest corner of the floor. Even though these flames were extensive, there was no external flaming and very little smoke came from nearby windows. By 9:35 a.m. this fire was also dying down. Around 9:28 a.m. a small fire became visible on the 98th floor. Over the next few minutes this fire spread and by 9:35 a.m. covered roughly one quarter of the floor width near the center of the face.

By 9:18 a.m. most of the fires observed earlier near the center of the face on multiple floors of the east face were dying down. As on the north face, fires were observed moving into rooms located on the northeast corners of the 96th and 97th floors around 9:19 a.m. and on the 94th floor around 9:23 a.m. A similar fire growth was observed in the room on the northeast corner of the 93rd floor starting near the end of the period. Fires which had recently spread west from the initial burning areas on the 92nd, 95th, 96th, and 97th floors continued to burn, but there was little additional fire spread during the period.

By the start of this period, intense fires with external flames were present on the west side of the south face on the 95th, 96th, and 97th floors. On the two higher floors, these flames extended from near the center of the face to the western edge, while on the 95th floor there appeared to be a barrier that prevented flame spread to the western edge. Over the course of the period the fires on the 96th and 97th floors began to die down, while those on the 95th floor remained intense. There was no indication of additional fire spread during the period on this face.

The fires on the west face were relatively quiet during this time. The extensive fire present earlier on the 97th floor continued to die down, becoming spotty by the end of the period. Meanwhile, the low intensity fire that had earlier begun to spread north on the 96th floor from the south edge continued moving methodically across the floor, reaching near the center of the face by 9:33 a.m. Unlike the earlier fires on the 97th floor, these flames appeared to be burning near the floor at separated locations. Their appearance was similar to the dying flames seen on the 97th floor.

Integrated façade maps for the fires observed during the period are shown in Figure E-6. In general, fire spread during this period was reduced compared to the first two periods. While intensely burning fires with extended flames developed in northeast corner rooms on several floors, most of the new fire growth involved less intense flames that did not extend from windows. Such fires included those on the west side of the 94th floor and the central section of the 98th floor on the north face and the south side of the 96th floor on the west face.

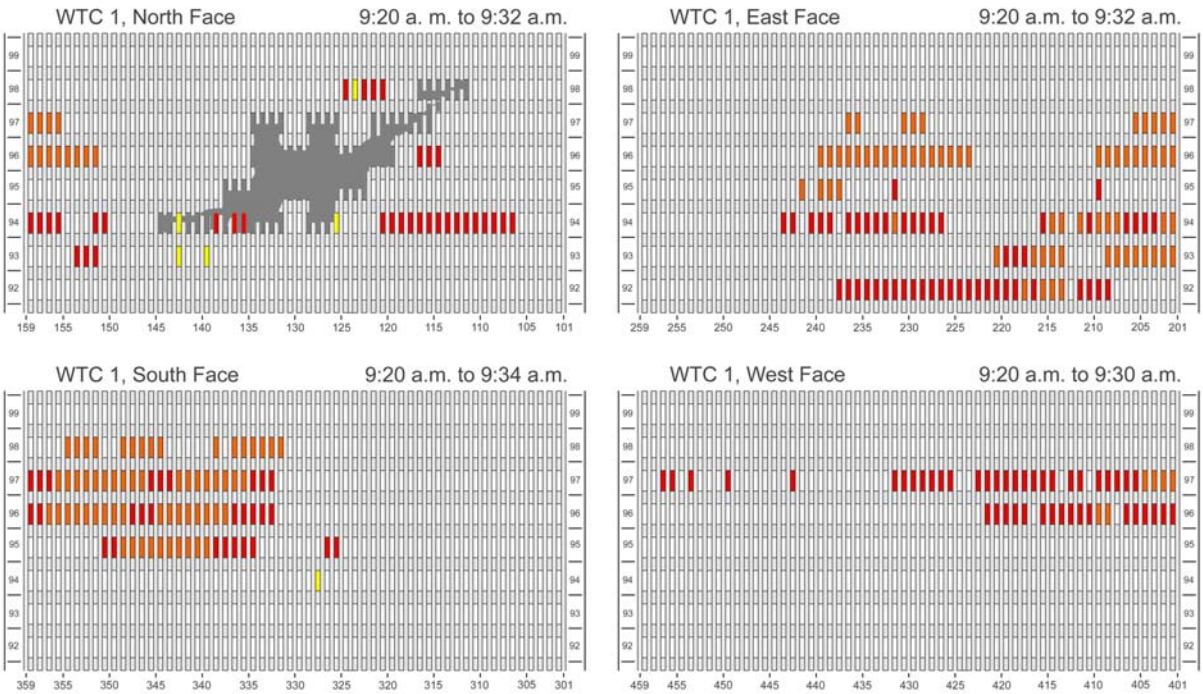

Figure E–6. Maps of integrated fire observations between 9:19 a.m. and 9:35 a.m. are shown for the four faces of WTC 1.

Most of the streamers during the period were observed falling from the north face early in the period when fires were spreading into the northeast corner rooms and on the west side of the 94th floor. Relatively few people were observed falling from the upper floors of WTC 1 during this time. These observations are consistent with the observations indicating that the fires present during this period were less vigorous and extensive than during the two earlier periods.

9:35 a.m. to 9:59 a.m.

This period takes the time line for WTC 1 fire behavior up to the time that WTC 2 collapsed.

The fires that appeared on the north face at the 98th floor near the end of the previous period continued to spread, and by the end of the period had reached the east edge and extended over two thirds of the face. Even though the flames were extensive, very little smoke and flame were evident coming from 98th floor windows. These fires were dying down by the end of the period. Around 9:40 a.m. smoke and flames appeared in windows at the western edge of the 94th floor, indicating that a nearby fire had entered a room in the northwest corner. At roughly the same time, a similar fire grew in windows at the eastern edge of the 92nd floor, apparently migrating into a northeast corner room from the east face. Another fire developed rapidly in a room on the northwest corner of the 96th floor around 9:53 a.m., seemingly moving from the west face. This fire would spread slowly to the east during the remainder of the period.

The most dramatic change in the fire distributions on the east face during this time was the growth and spread of an intense fire on the 98th floor. Around 9:38 a.m. a jet of flame erupted from a window located midway between the north edge and face center. By the end of the period intense flames were coming from 98th floor windows over the northern half of the face. Meanwhile, fires on the 92nd, 94th,

95th, 96th, and 97th floors continued to spread from locations to the south of the face center toward the south. Due to the growth and decay cycles of the spreading fires, the flames on these floors developed the appearance of waves moving slowly southward across the face. On the 93rd floor, flames were evident on the north side of the face, including in windows located inside a room on the northeast corner.

The distribution of fires on the south face also changed substantially during this period. The intense fires burning earlier on the west sides of the 95th, 96th, and 97th floors continued to die down during this time. Around 9:40 a.m. a flame jet suddenly erupted from the west side of the 98th floor. This new area of fire then spread and grew rapidly, covering most of the west side of the floor within a few minutes. This fire continued to burn until the end of the period. First indications for a fire burning on the south face well to the east of the center were observed on the 94th floor around 9:40 a.m. A separate area of small flames was observed in this area later in the period. These fires did not seem to grow substantially during the period.

The most dramatic changes in fire distributions on the west face took place on the 94th and 98th floors. Earlier there were no visible signs of fire on these two floors. Sometime around 9:38 a.m. flames appeared on the 98th floor and, within a few minutes, relatively low intensity flames could be seen over more than half of the length starting at the south edge. By 9:59 a.m. the flames covered more than three quarters of the floor width. Even though extensive, these flames were not intense since there was no flame extension, and very little smoke was flowing from nearby windows. At around 9:39 a.m. small fires appeared to develop rapidly near the center and northern edges of the 94th floor. Almost simultaneously eight people were seen falling or climbing down from windows on this floor near the center of the face. By the end of the period, relatively low intensity flames were visible in most windows on the floor from the north edge to well beyond the center. The northward movement of the low-intensity fire on the 96th floor continued during the period, finally reaching the north edge of the face around 9:53 a.m.

Figure E-7 shows integrated fire maps for the period. The effects of the apparent rapid fire growth on the 98th floor are evident, with flames visible in well over half of the windows around the tower. It is evident that burning was now taking place in the southeast quadrant of the tower, but large areas of the periphery near the southeast corner remained fire-free at 9:59 a.m.

The group of people who fell from the west side of the 94th floor around 9:40 a.m. was mentioned above. During the period, additional people were observed falling from higher floors on the north, east, and west sides of the tower.

Response of WTC 1 to the Collapse of WTC 2

At 9:58:59 a.m. WTC 2 began to collapse, and roughly ten seconds later debris reached the ground. Very shortly after the collapse began, fire and smoke were pushed out of the south face of WTC 1, presumably due to a pressure pulse transmitted to WTC 1 from the collapsing tower. The most prominent effect was on the 98th floor where flames were pushed out of windows along the west side of the face. There was also a distinct increase in the flame intensity on the west side of the 96th floor. It is likely significant that flames did not appear elsewhere on the face, perhaps indicating that large flames were only present near the periphery of the face at these locations at this time.

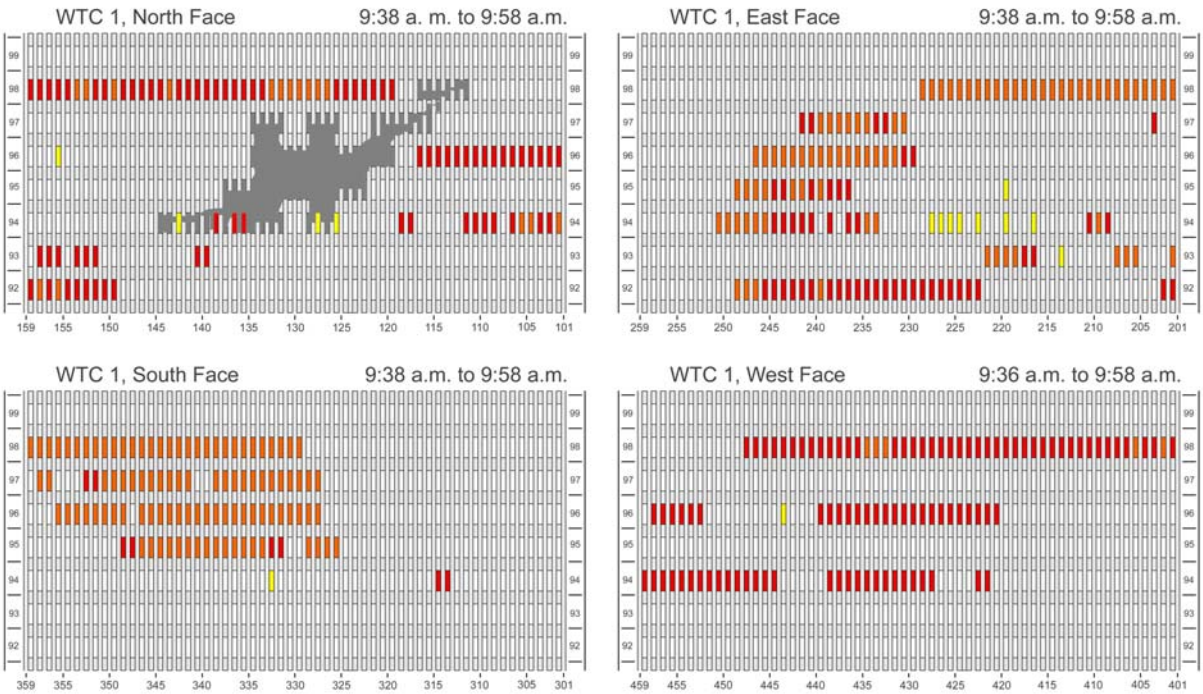

Figure E–7. Maps of integrated fire observations between 9:36 a.m. and 9:59 a.m. are shown for the four faces of WTC 1.

Videos show that no flames were pushed from open windows on the north face of WTC 1, but that fires burning on the 92nd, 94th, and 96th floors brightened noticeably. On the east face, flames near the south edge on both the 92nd and 96th floors flared out at roughly the same time the changes were observed on the north and south faces. Shortly after the collapse of WTC 2, the flow of smoke from the north face of WTC 1 stopped momentarily. The period of decreased smoke flow lasted for approximately 40 s.

Videos shot from the east show that debris from WTC 2 passed in an arc across the east face of WTC 1, creating damage on the façade of WTC 1 that is visible in images taken shortly after the collapse. The highest marks on the building were just below the mechanical equipment room on the 75th and 76th floors. The damage appeared relatively superficial, and it is unlikely that it affected the subsequent fire behavior in the tower. Videos and eyewitness accounts indicate that large amounts of dust and some debris entered the lower floors of WTC 1 during the collapse of WTC 2. It is not known if damage at these lower locations influenced the fires near the top of the tower.

9:59 a.m. to 10:18 a.m.

The collapse of WTC 2 resulted in decreases in the quantity and quality of visual material showing the faces of WTC 1. People near the site were forced to flee or seek shelter. Many photographers and videographers located further away changed their focus to the large dust clouds that covered much of lower Manhattan. The dust generated by the collapse reached levels near the top of WTC 1 and obscured the faces. This was particularly true on the downwind east and south sides. The loss of detail is unfortunate since significant changes in fire behavior and distribution took place prior to the collapse of WTC 1 at 10:28:22 a.m.

The most complete information for the current period is available for the north face. Images recorded shortly after 10:00 a.m. showed remarkably little visible fire on the face and that the flames that were visible had low intensities. During the period the fire burning on the east side of the 92nd floor continued spreading slowly to the west, apparently moving from room to room along the façade. By the end of the period it had reached roughly 2/3 of the way across the face. Only remnants of the earlier fires on the 94th and 96th floors were visible on the west side of the face. Starting around 10:10 a.m., an intense fire grew on the 98th floor near the west edge of the face.

Compared to the north face, it proved more difficult to characterize the fire behavior on the east face of WTC 1 due to the relatively few images available and obscuration due to dust. Just prior to the arrival of the dust from below, intense fires were visible coming from windows on the 94th, 96th, 97th, and 98th floors, with similar distributions to those seen just prior to the collapse . As the dust began to clear partially around 10:07 a.m., the only fire visible was the intense band of flames on the north side of the 98th floor. Over the next several minutes the limited imagery available suggests that the fire distributions on the east face remained similar to those present prior to the collapse. There is some indication that the fires burning on the 96th and 97th floors may have spread further south, perhaps reaching as far as the southwest-corner room on the 96th floor and three quarters of the way across the face on the 97th floor.

The quality of the imagery available for the south face of WTC 1 following the collapse of WTC 2 was similar to that for the east face. Shortly after 10:00 a.m., a long distance video showed an intense line of fire present on the west side of the 98th floor and a vigorous fire burning on the 97th floor near the center of the face. Shortly afterwards, dust rose from below and totally obscured the floors with fire. When the dust began to clear around 10:06 a.m., the fire distribution did not appear to have changed markedly. At around 10:11 a.m. the dust cleared sufficiently to detect the presence of fires on the east side of the 96th floor, extending from near the eastern edge to roughly one quarter of the way across the face, and on the 97th floor, concentrated toward the center of the face. Shortly afterward, flames were observed coming from the 99th floor on the west side of the face.

One of the more interesting fire spread behaviors associated with WTC 1 was observed on the west face shortly after the collapse of WTC 2, when a large fire developed rapidly on the south side of the 104th floor, i.e., well above floors where fire had been observed up to this time. A deep red glow along the 98th floor remained visible on the face, indicating that the interior fire on this floor was still burning. The fire reached across the entire width of the floor when it spread to the north edge during the period. Isolated flames were still visible on the north side of the 96th floor, while the low intensity fire burning on the 94th floor spread south to cover three quarters of the face width. Around 10:07 a.m., thirteen people were observed falling from windows near the center of the 95th floor. Shortly afterward, fire first became visible on this side of the floor, nearly simultaneously, at a number of windows. By 9:18 a.m. flames were visible over a three quarter length of the 95th floor, extending from near the north edge. Though extensive, these flames appeared to have relatively low intensities, similar to the fires below on the 94th floor.

Integrated fire maps of the four faces for the period are included in Figure E–8. These maps likely underestimate the actual extent of the fires due to the limited visibility on the east and south faces. The extensive fires on the 98th floor are a dominant feature. Keep in mind that the much of the fire on the north side of this floor had already died down. The intense fires that developed rapidly along the periphery of the southeast quadrant also stand out. The broad extent of the low intensity fires on the west

sides of the 94th and 95th floors is also evident. Note that the intense fire that grew on the south side of the west face of the 104th floor is not displayed in the façade map.

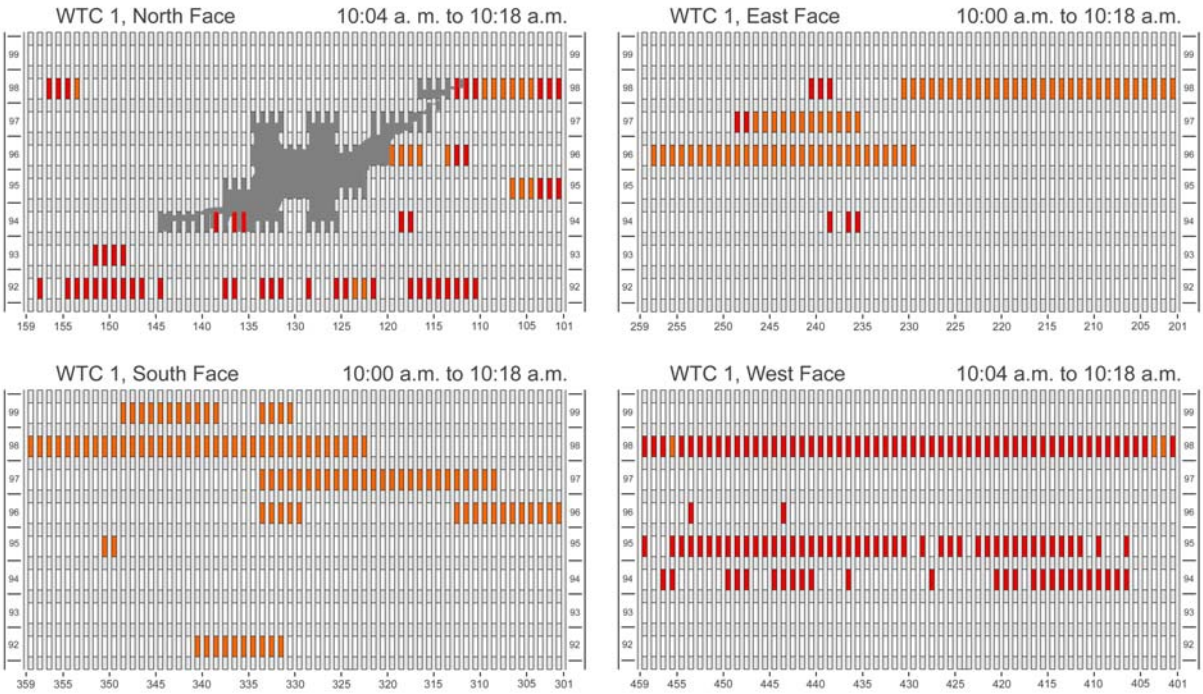

Figure E–8. Maps of integrated fire observations between 10:00 a.m. and 10:18 a.m. are shown for the four faces of WTC 1.

The large number of people observed falling from the 95th floor around 10:07 a.m. has already been discussed. Other people were seen falling from locations well above the fire floors on the north and west faces. Most of these fell near the end of the period, perhaps indicating that conditions on the upper floors had begun to deteriorate rapidly at this time.

10:18 a.m. to Collapse of WTC 1 at 10:28:22 a.m.

By shortly after 10:18 a.m. the fire spreading toward the west on the north face on the 92nd floor was approaching the edge of the face. Despite the presence of flames over a significant length of the floor, the

fire appeared to be burning with a low intensity at separated locations, with essentially no smoke coming from nearby open windows. An event took place within the tower at 10:18:48 a.m. that generated a pressure pulse with sufficient magnitude to force a large amount of smoke from the open windows on the 92nd floor, along with smaller amounts from open windows on other floors on the north face and on the other faces of the tower. While it seems likely that the pressure pulse was generated by some sort of collapse within the tower, e.g., a portion of the core settling or a partial floor collapse, it has not been possible to determine the nature of the event or even its general location based on the visual record.

Shortly after the pressure pulse, an intense fire appeared at the western edge of the 95th floor. Over the next several minutes, the fire on west side of the 92nd floor grew dramatically, with continuous internal flames visible in windows over most of the western half of the face. Fires present elsewhere on the north

face were dying down during this period. When the tower began to collapse, it acted as a piston, forcing air downward onto other floors and out through openings. As a result, large volumes of fire and smoke were pushed from windows on the 92nd floor at several locations across the face, confirming the presence of an extensive volume of fire. Flames were also pushed from windows in the northwest corner room on the 95th floor, indicating a significant fire was still present nearby. Flames were not expelled from elsewhere on the north face, providing additional evidence that intense fires observed earlier at other locations on the face had either died down or gone out.

Views of the east face during the final ten minutes were limited and partially obscured. A photograph of the face taken shortly after 10:18 a.m. revealed a similar fire distribution to that shown in Figure E–8. A small fire was burning near the center of the 101st floor. Several long-distance videos show that around 10:21:15 a.m. there was an intense burst of flame from the 98th floor at a location roughly half way between the center of the east face and the south end. This new region of intense fire rapidly expanded in both directions to cover about one quarter of the width of the face. This fire remained the dominant feature on the east face until the collapse. Roughly 3 s prior to collapse initiation, this line of fire brightened noticeably. During the collapse, bright flames were expelled from the southern side of the 98th floor, confirming the presence of an intense fire in this area. Expelled fire was not visible coming from the other fire floors on the face, suggesting the fires present elsewhere were much smaller than on the south side of the 98th floor.

Views of the south face of WTC 1 were also limited for this time period, but several photographs taken from a helicopter flying relatively close to the tower provided a good indication of conditions on this face roughly half way through the period. Figure E–9 shows a cropped view of one of these photographs shot from the southwest at 10:22:59 a.m. Fires are visible on the east side of the face on the 92nd through 98th floors. A long distance video showed that the particularly intense fire on the 98th floor moved into the area around 10:19 a.m. Closer inspection reveals that many of the columns on the south face in the vicinity of 95th floor to the 98th floors were bowed inward at this time. Somewhat smaller flames are visible on the west side of the face on the 92nd, 96th, 98th, 99th, and 100th floors. Around 10:25 a.m. heavy smoke and fire appeared from windows in a room located in the southwest corner of the 94th floor. Long distance videos show that during the period leading up to the tower collapse the line of fire on the 98th floor continued to burn vigorously. The fire on the 99th floor appeared to intensify and move toward the east, eventually reaching a location more than half way between the center of the face and the east edge. When WTC 1 began to collapse, a large amount of flame was pushed from openings on the south face, with flames appearing to come from three separate locations. The first was from the vicinity of the intense fire burning on the east sides of the 98th and 99th floors, the second was from the fire burning on the western edge of the 94th floor, and the third came from around the center of the face near the 94th floor.

Figure E–9. This photograph showing the south face of WTC 1 is a cropped version of a photograph shot from a helicopter at 10:22:59 a.m. It has been enhanced by adjusting the intensity levels, and column and floor numbers have been added.

Minimal fire spread took place on the west face during the period. Fire moved into two adjacent rooms located in the northeast corner of the 92nd floor and into a southwest corner room on the 94th floor. Fires observed earlier on the 94th, 95th, and 98th floors were generally dying down. The fires on the 96th and 97th floors appeared to have died out, since no flames were visible on these floors. The fire on the south side of the 104th floor continued to burn vigorously. A video showed that smoke was forced out of multiple west-face windows approximately two seconds before the collapse of WTC 1 began. As the tower collapsed, the resulting pressure increase pushed intense flames out of windows at the northern edge of the 92nd floor, at the northern edge of the 95th floor, at the southern edge of the 94th floor, and from the intensely burning region on the 104th floor, indicating the areas on the face where the most intense burning was taking place.

The integrated fire data for the period are shown in Figure E–10. A notable feature is the widespread presence of intense fire in the southeast quadrant of the tower following a long period when the area seemed to be isolated from fires burning elsewhere.

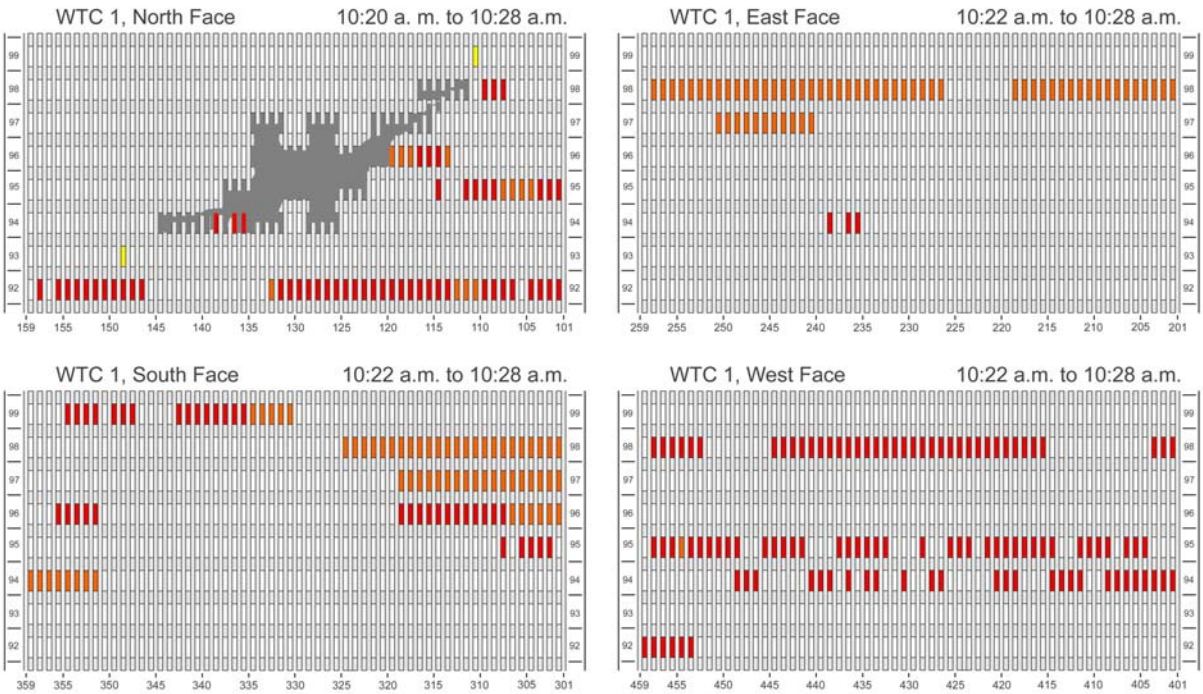

Figure E–10. Maps of integrated fire observations between 10:20 a.m. and 10:28 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure E-2.

During this final period people were observed falling from the upper floors of the north and west faces. It is likely that additional people fell on the other faces and were not identified due to the low resolution of the available imagery. The fact that people were still falling from upper floors suggests that conditions on these floors continued to deteriorate until the time of the tower collapse.

Summary and Additional Discussion of Observations for WTC 1 Fires

Fire growth and spread in WTC 1 was extensive during the 102 min between the aircraft impact and collapse of the tower. Figure E–11 shows the results for the four faces of integrating the fire observations over the entire event. Extensive fires were observed from the 92nd to 99th floors. (Note that fires were also present on higher floors, including the intense fire on the south side of the west face of the 104th floor.) Fires seem to have spread over almost all of the 96th to 98th floors, while some unburned areas were still present on lower floors. The largest unburned areas seem to have been on the 93rd and 95th floors.

An interesting aspect of the fire behavior in WTC 1 was the variation in burning behavior observed on the different faces. Fires at most locations on the west and north faces of the towers burned without flame extension or release of large amounts of smoke from nearby windows. In many cases the fires appeared to burn as relatively low intensity distributed flames. The preponderance of red in the north and west face

maps in Figure E-11 reflects this type of burning. In contrast, the fires burning on the east and south faces most often generated external flames and heavy smoke flows at nearby windows as indicated by the extensive areas of orange on the façade fire maps. Various explanations for the different burning behaviors were considered. The most plausible is the effect of the prevailing wind. On September 11, the wind was striking WTC 1 from the northwest and then flowing down the north and west faces. This wind created positive pressures at the windows on these faces that tended to resist gas flows out of the tower. On the east and south faces the effect of the wind was the opposite, creating low pressure areas at the windows that tended to draw gases out of the building. The net effect of these pressure forces was a tendency for gases to flow internally on a floor, if a pathway was available, from the west and north faces to the east and south faces.

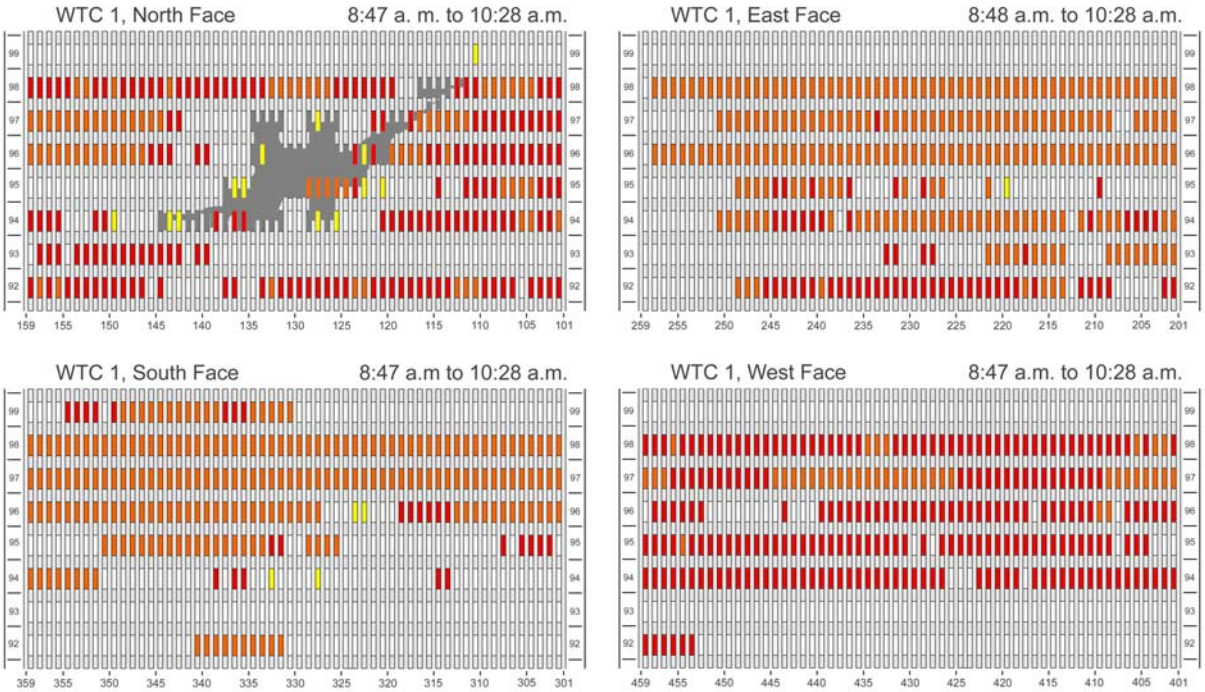

Figure E–11. Maps of integrated fire observations between 8:47 a.m. and 10:28 a.m. are shown for the four faces of WTC 1.

This summary has focused on the time variation of the fire distributions and intensities observed in WTC 1. This report also includes detailed time lines for window condition on the various floors and faces of WTC 1. Generally, as the fires spread into new areas, window glass in the immediate vicinity would break out. As a result, the number of open windows continuously increased. This, in turn, increased the amount of outside air available to support the fires burning inside. The total number of windows that were broken open by the aircraft impact and subsequent fireballs was estimated to be 236, with the majority located on the north face where the aircraft impact occurred. By the time of tower collapse this number had increased more than five-fold to 1,312, with roughly equal numbers on each face. This increase in the number of open windows provided an additional 12,470 ft^2 of ventilation area to the outside air. It is likely that window breakage played a pivotal role in the observed fire behaviors.

E.4.4 FIRE TIME LINE FOR WTC 2

The following discussion of fire behavior in WTC 2 is broken into four time periods of roughly 15 min each. This summary focuses on fire observations, but also includes some relevant structural observations. Details of the fire behavior as a function of time are documented in façade maps describing fire, smoke, and window condition observations included in Appendices G to J of this report. Detailed discussions of the fire observations, with numerous supporting images of the tower, and other related details, such as window breakage, smoke flow, hanging object (which may have been dislodged floor slabs) observations, and unusual intense burning phases, are provided in this report.

9:03 a.m. to 9:15 a.m.

As described earlier, immediately after the aircraft impact intense fires, located on piles of debris, were visible burning on the north face of the tower adjacent to (and within) the northeast corner on the 81st floor and just to east of the center of the face on the 79th floor. During the period it became clear that flames were also present on the 82nd floor immediately above the fire on the 81st floor and on the 80th floor immediately above the fire on the 79th floor. All of these fires continued to burn intensely during the entire period, but there was no indication of additional fire spread on the north face. Flames were not visible in a large rectangular area, which has been designated the cold spot, lying between the two burning piles of debris. The cold spot covered an area twelve windows wide on the 80th, 81st, and 82nd floors. Near the end of the period, closer images revealed that a number of objects were hanging across windows in and immediately adjacent to the cold spot on the 80th and 81st floors. As discussed further below with regard to the east face, one possible explanation for these hanging objects is that they were sections of floor slabs that had been dislodged from the outer wall and had settled down below the spandrels at the tops of the windows on the floor below.

In the immediate aftermath of the aircraft impact, extensive flames were visible on the east face of the tower coming from the 81st, 82nd, and 83rd floors. On the two lower floors, intense continuous fires were burning on debris piles that covered nearly one quarter of the floor widths extending to the south from the northern edge. The fire on the 83rd floor was intense, with external flames, and covered roughly one fifth of the tower width at a location slightly to the south of the face center. Much smaller fires were present at other isolated locations on the face. Very shortly after the aircraft impact, a hanging object was visible draped across the tops of 18 82nd-floor windows (i.e., nearly one third of the face width) near the center. This hanging object was observed numerous times in later images. While it proved difficult to identify the object with certainty, the evidence suggests that it was a portion of the 83rd floor concrete floor slab that had been dislodged from the spandrel located above the 82nd floor and had settled downward several feet, where it could be seen through the windows. The fact that the hanging object was visible so shortly after the aircraft impacted suggests that it was dislodged at some point during the impact and subsequent fireballs. In Chapter 9 of this report it is hypothesized that the separation of the 83rd floor slab from the spandrel may have resulted from the overpressure on the 82nd floor generated by burning aviation fuel. By 9:06 a.m., the intense flames burning on the south side of the 83rd floor were receding back into the windows and were less prominent than earlier. At the same time, a new area of fire was growing near the center of the southern half of the 82nd floor. By the end of the period, the fire on the south side of the 82nd floor had spread north to cover numerous windows, while the fire on the 83rd floor was no longer visible. The fires on the north sides of the 81st and 82nd floors had died down to the point where intense burning was primarily occurring near the northeast corner.

Shortly after the aircraft impact, only relatively small isolated fires were visible on the 78th floor, located just to the right of the aircraft impact cavity, and 79th floor, located within the cavity on the south face. During the following 12 min, similar small fires grew around the cavity on the 80th and 81st floors. More significant fires appeared in the windows between the aircraft impact cavity (see Figure E-3) and the eastern edge of the face on the 81st and 82nd floors starting around 9:07 a.m. Both of these areas were burning at the end of the period.

The west face of WTC 2 remained clear of smoke and fire until 9:10:29 a.m., when a plume of smoke appeared from a window on the south side of the 86th floor. This location was well above the floors with observed fire. The likely explanation for the appearance of this smoke is that people trapped in the tower broke out a window and released smoke that had built up on this floor. This would indicate that smoke was traveling upward through the tower. Several windows were open at this location at 9:15 a.m.

The fire data sheets for the period were integrated as a means for summarizing the fire distributions. The results are shown in Figure E-12. From these maps it is clear that the major visible fires were burning on the east and north faces of the tower. The most intense fires were on the 81st through 83rd floors, i.e., the upper portion of the floors impacted by the aircraft.

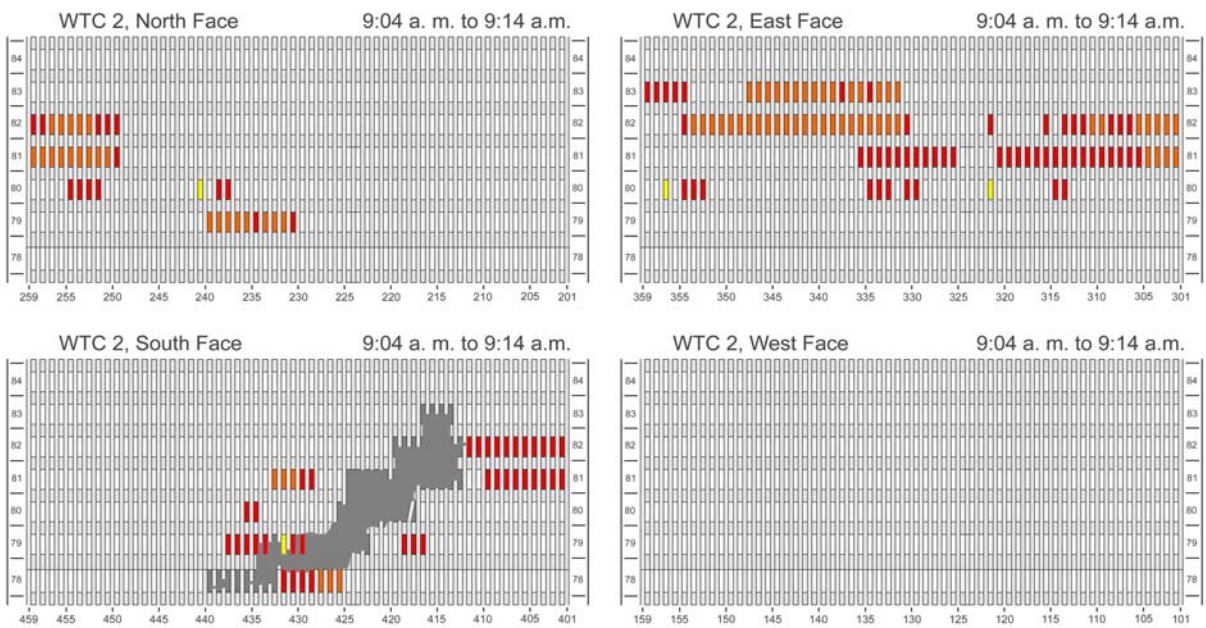

Figure E–12. Maps of integrated fire observations between 9:04 a.m. and 9:14 a.m. are shown for the four faces of WTC 2.

9:15 a.m. to 9:29 a.m.

Near the start of the period, an infrared image, which provided an indication of the heat distribution on the WTC 2 façade, was taken from the northeast. On the north face strong heating was evident from the fires burning on the 79th and 80th floors and the 81st and 82nd floors. The cold spot stood out in the image because the area was close to the ambient outside temperature. Standard photographs and videos showed that the primary fire distributions on the north face did not change dramatically during the period. The

fires in the northeast corners on the 81st and 82nd floors and near the center of the face on the 79th and 80th floors continued to burn intensely. Near the end of the period, a relatively low intensity fire became visible on the 83rd floor near the eastern edge of the face. Smoke was observed coming from windows on the west side of the face on the 93rd, 103rd, and 105th floors, indicating that smoke had migrated to the top of the tower. These windows were most likely broken open by people trapped at these locations.

The infrared image taken at the start of the period revealed strong heating across the entire width of the 81st floor on the east face, suggesting either that the fire observed on the north side of the face was heating the entire floor or that unseen fires were burning inside. Standard images showed that the fire burning on the south side of the 82nd floor was dying down somewhat while continuing to spread to the north. The fires in the northeast corner of the 81st and 82nd floors continued to burn intensely. A short-lived fire was present on the northern edge of the 83rd floor. Most often there was no smoke flow from open windows on the face below the 82nd floor, but increasingly frequent short-lived puffs of smoke were observed from multiple open windows on the 79th, 80th, and 81st floors. Sometime between 9:18 a.m. and 9:26 a.m. a portion of the hanging object visible through the 82nd floor windows on the east face settled down further in the windows, revealing that it had the plate-like structure expected for a floor slab.

Shortly after 9:15 a.m., a new area of fire grew on the 79th floor to the immediate east of the aircraft impact cavity on the south face, adding to the fires burning in the immediate vicinity of the cavity. The fire observed earlier on the 81st floor between the cavity and the east edge of the face was dying down, while the fire immediately above on the 82nd floor continued to burn intensely. This fire distribution changed little over the period. There were indications that smoke flows on the south face increased for short periods during at least some of the times when smoke puffs were taking place on the east face.

Early in the period, smoke was observed flowing from windows near the center of the 107th floor on the west face as well as from the location on the 86th floor seen earlier. The smoke flow from the 107th floor suggests that smoke had traveled to the top of the tower by internal pathways, and, due to its buildup, people trapped on the floor chose to break out windows to reach fresh air. These two smoke flows were the dominant features on the west face during the period.

Maps of integrated fire intensities over the period for the four faces are shown in Figure E–13. Comparison with Figure E–12 confirms that minimal fire spread was taking place during the period. The fire distributions on the east face for the two periods appear quite different due to the rapid changes in the fires observed near the beginning of the first period and the continued northward spread of the fire on the 81st floor, which initially developed on the south side of the face, while going through a cycle of growth, intense burning, and decay. As during the initial time period, the largest fires were in the northeast corners of the tower on the 81st and 82nd floors and near the center of the north face on the 79th and 80th floors. These fires had been burning since the aircraft impact and were slowly dying down.

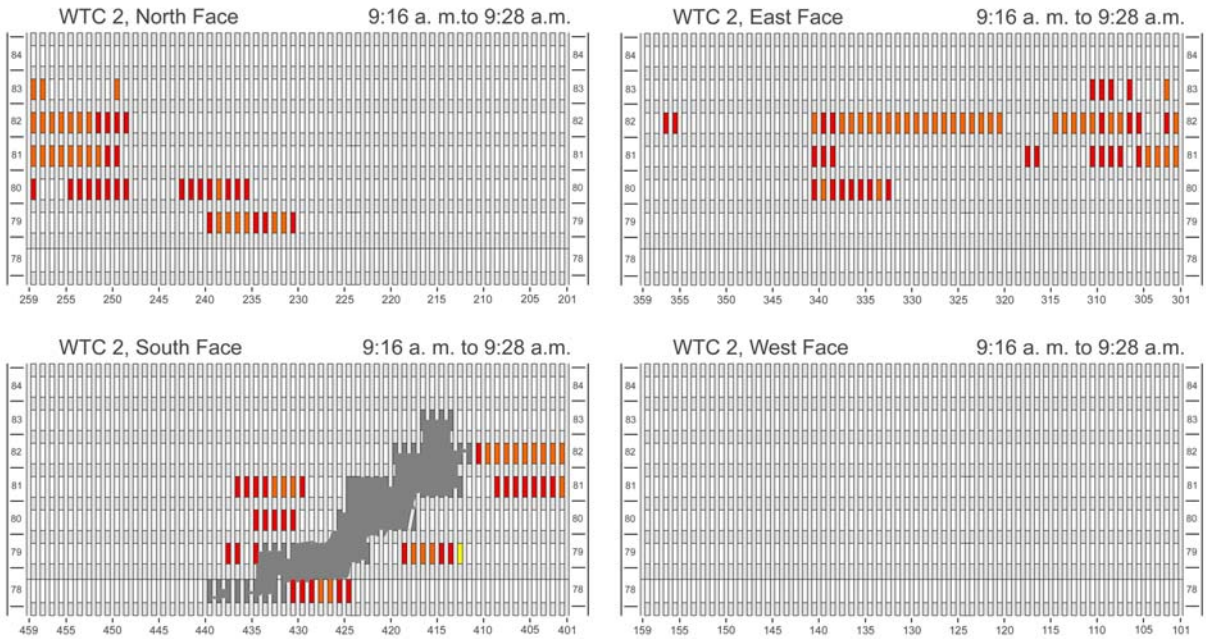

Figure E–13. Maps of integrated fire observations between 9:15 a.m. and 9:29 a.m. are shown for the four faces of WTC 2.

9:29 a.m. to 9:45 a.m.

Compared to the two earlier time periods, the fire behavior was more dynamic and difficult to characterize during this time period. A number of other related observations were made simultaneously.

Shortly after 9:29 a.m., an intense flame suddenly erupted on the north face from a window on the 83rd floor just above and to the right of the cold spot and quickly spread to cover several windows. Later a fire erupted on this floor several windows further to the west and again rapidly covered multiple windows. These fires were the first indication of significant fire spread on this face. Meanwhile, flames on this floor spread to cover most of the area between the east edge and the new fire area. Shortly after 9:30 a.m. there were indications that the fire on the 79th floor near the center of the face had also begun to spread to the west. The fires on piles of debris in the northeast corner and near the center of the face continued to burn throughout the period. Close up photographs shot near the end of the period revealed that the appearances of the hanging objects observed earlier through windows in the cold spot had changed. At the earlier time two objects were visible on the 80th floor, but now the lower object had apparently disappeared, while the second had dropped down lower. A similar change had taken place on the 81st floor.

Observations on the east face for the period were complex. The fire near the center of the 82nd floor continued moving toward the north, eventually approaching the north edge. Meanwhile, the fires in the northeast corners of the 81st and 82nd floors continued to burn, with that on the 82nd floor growing more intense. Shortly after 9:30 a.m., heavy smoke started to flow from a group of windows located near the center of the northern half of the 79th floor, where the glass had been in place minutes earlier, suggesting that a fire had recently grown in the immediate vicinity. Fire was later observed in this area in several

images and was still present at the end of the period. Around this time, three people either tried to climb down or fell from a window on the south side of the 79th floor, providing a possible indication that conditions were rapidly deteriorating on this floor. The unusual short-lived smoke puffs from windows on the face described earlier continued, apparently randomly, throughout the period. Some of these puffs released sufficient smoke to briefly obscure the face. In some instances smoke was also pushed simultaneously from windows on the north and south faces. Another type of transient behavior was first observed starting around 9:35:45 a.m. Heavy smoke began flowing out of numerous windows over the face and was particularly heavy near the centers of the 79th and 80th floors. Unlike observed during the short-lived smoke puffs, intense flames were also visible coming from many of the these windows and, instead of lasting only a few seconds, the heavy smoke and flames were present for just over a minute before they abated as quickly, seemingly, as they appeared. This roughly one minute widespread release of heavy smoke and flames represents a distinct type of behavior from the short smoke puffs and more typical burning behaviors seen up to this time. This unusual event was not unique. Two similar releases of smoke and fire, each lasting roughly one minute, were observed, with one starting just before 9:40 a.m. and the other after 9:41 a.m. A photograph taken around 9:38 a.m. showed that the hanging object (possibly the 83rd floor slab) visible earlier through open windows on the 82nd floor of the east face had once again dropped further down and that some intermediate portions had disappeared from view. The windows where the object first appeared below the 83rd-floor spandrel had moved further toward the edges of the tower on both the north and south ends. Figure E-14 shows a photograph of the east face taken just before 9:45 a.m. during a period when there was very little smoke flow from the face. Closer inspection reveals that the columns near the center of the face on the 80th and 81st floors are bowed inward. Similar bowing was identified in other images of the face starting as early as 9:22 a.m.

On the south face, several low intensity fires continued to burn on multiple floors around the aircraft impact cavity. The fire on the 82nd floor located between the cavity and the eastern edge was still burning. Near the start of the period, a small fire became visible near the center of the 83rd floor. Roughly half way through the period, smoke began to flow and flames became visible on the 80th floor near the eastern edge. A view of the upper part of the tower revealed heavy smoke flowing from numerous windows on the 105th floor just to the west of face center. This is another location where trapped people apparently broke open windows.

On the west face, the number of open windows with smoke flow continued to increase, with smoke now observed on the 84th, 86th, 88th, and 107th floors. Smoke was also visible near the top of the tower next to the southwest corner. This smoke appeared to be flowing from a location on the lower level of the mechanical equipment room on the 108th and 109th floors, where there was a nearby fresh air intake for the 107th floor observation area, suggesting that the smoke was back flowing from the 107th floor. There was still no indication of fire burning on this face of the tower.

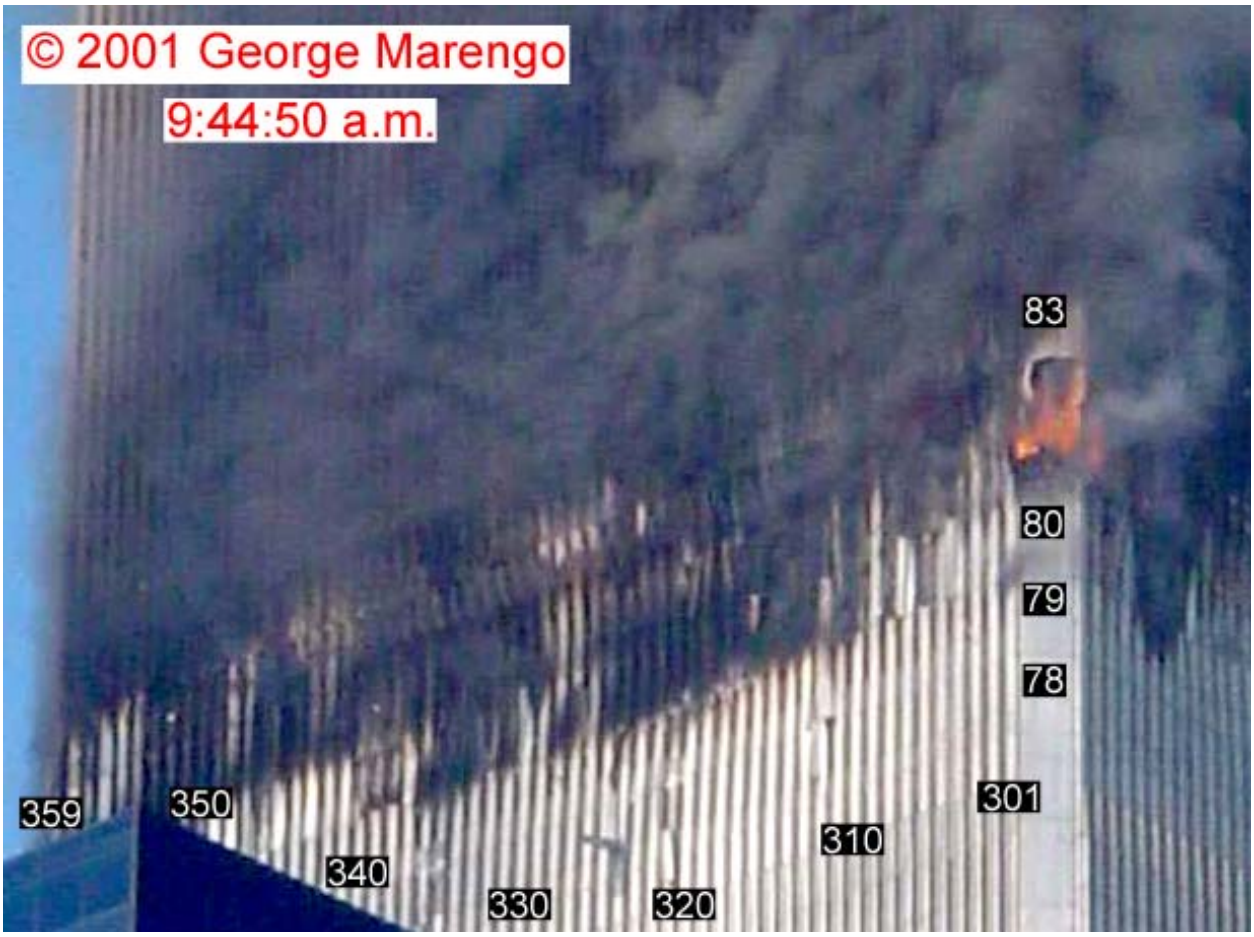

Figure E–14. This cropped photograph was shot from the northeast and shows the east face of WTC 2 at 9:44:50 a.m. The original intensity levels have been adjusted, and column and floor numbers have been added.

Figure E-15 shows integrated fire maps for the period. The new areas of fire that appeared on the 79th and 83rd floors of the north face are evident. Extensive new areas of fire were also present on the 79th and 80th floors of the east face. It should be remembered that a fraction of the observed fire indicated on the maps for these floors was associated with the three roughly one-minute-duration periods during which heavy smoke flows and fires were present.

9:45 a.m. to Collapse of WTC 2 at 9:58:59 a.m.

Near the start of this period, several small fires were observed for the first time near the center of the cold spot on the north face at the 81st and 82nd floors. Fires elsewhere on the face were generally dying down at this time. During the period, the fire burning on the 79th floor continued to spread to the west. By the time of collapse, the flames were approaching, but had not yet reached, the west edge of the face. Around 9:54 a.m. a fire grew just to the west of the cold spot on the 82nd floor and began to spread westward, covering eight windows by the time of collapse. The fire that had earlier spread in the same direction on the 83rd did not appear to migrate further. A small spot fire was observed near the center of the 84th floor, suggesting that the fire on the 83rd floor had spread upward. Close-up photographs and videos during the period revealed a distinct outward budge of the steel columns in the vicinity of the debris pile

near the center of the 79th floor. Just before 9:52 a.m., puffs of smoke and/or dust were expelled from multiple locations on the north face near the east edge. Almost immediately a bright spot appeared at the top of a window on the 80th floor four windows removed from the east edge, and a glowing liquid began to pour from this location. This flow lasted approximately 4 s before subsiding. Many such liquid flows were observed from near this location prior to the collapse of the tower. Several were accompanied by puffs of dust and smoke that were now occurring frequently. The composition of the flowing material can only be hypothesized, but it is likely that it was molten aluminum that came from aircraft debris, located immediately above on the 81st floor, that had been heated to its melting point by the fire burning on that floor. Shortly after 9:53 a.m., the fire that had been burning on the eastern edge of the 81st floor since the aircraft impact suddenly died down, revealing the windows above on the 82nd floor. A hanging object was visible through these windows that appeared to be a dislodged corner section of the 83rd floor slab. The hanging objects present in and near the cold spot were also visible in images taken during the period. At 9:58:59 a.m., WTC 2 began to collapse. Videos show that the only place flames were pushed out of windows on the north face was from the burning area near the western edge of the 79th floor.

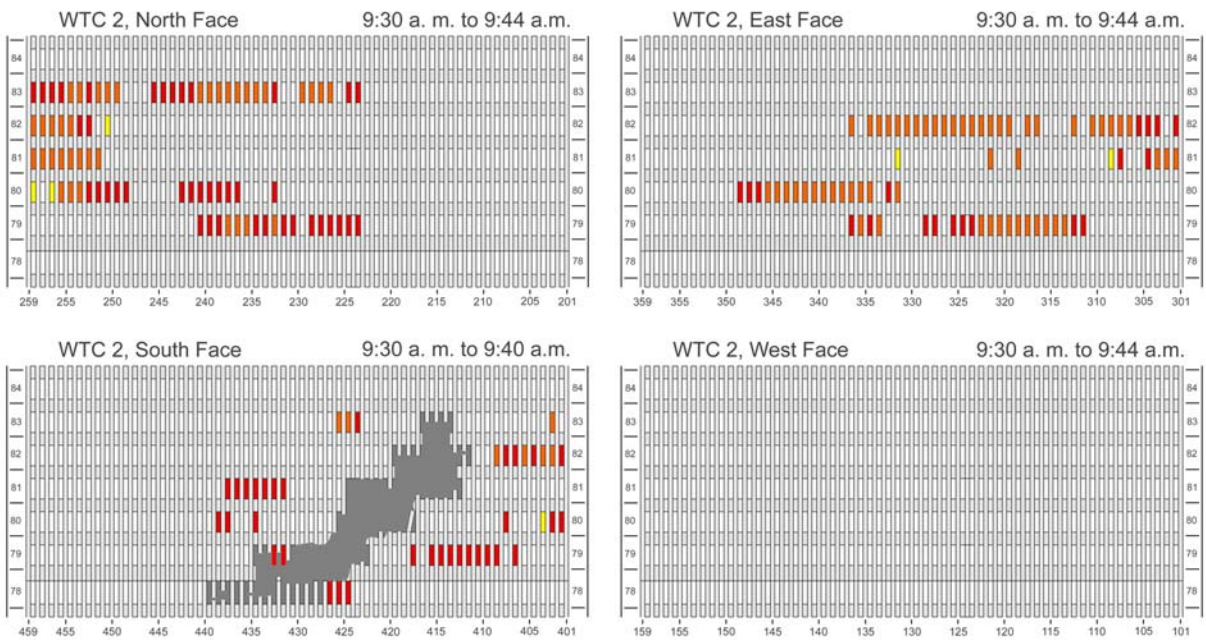

Figure E–15. Maps of integrated fire observations between 9:30 a.m. and 9:45 a.m. are shown for the four faces of WTC 2.

A fourth short-lived (again roughly a minute) release of heavy smoke and flame from windows on the 79th and 80th floors of the east faced occurred around 9:45 a.m. Three additional, somewhat less intense, releases lasting similar lengths of time occurred around 9:47 a.m., around 9:52 a.m., and just before 9:56 a.m. Smoke puffs, similar to those seen earlier, occurred multiple times during the period. At the start of the period, the fire located at the center of the northern half of the face on the 79th floor continued to burn vigorously, only dying down near the end. A similar burning area became visible on the 80th floor, just to the south of the fire on the 79th floor, around 9:55 a.m. Much of this area had been hidden up to this time by smoke coming from below. A substantial fire continued to burn on the 82nd floor near the northern edge of the face. The fire in the northeast corner of the 81st floor was generally gently burning, but would occasionally flare up. During the period, the position of the hanging object visible

through windows on the 82nd floor changed again, with the northernmost window where the object could first be seen located slightly further the north. A prominent feature on the east face during the period was the inward bowing of the outer wall. This can be seen clearly over the 79th to 82nd floors in Figure E-16, which was taken less than a minute before the collapse started. During the 20 s prior to the collapse, a large number of pieces of debris fell from the northern sides of the 80th and 81st floors. The falling debris coincided with a heavy flow of molten metal from the north face. When WTC 2 collapsed, very little flame was expelled from the east face windows. Based on observations elsewhere on the two towers, regions of intense burning would have been expected to generate short-lived jets of flames. Their absence suggests that large fires were not burning near the east face at the time of collapse.

Figure E–16. This cropped image shows the east face of WTC 2 at 9:58:02 a.m. The intensity levels have been adjusted, and column and floor numbers have been added.

At the beginning of the period, a number of small fires were visible on several floors of the south face at locations surrounding the aircraft impact cavity. Their positions suggest that these were continuations of the slow spreading fires that had grown around the cavity shortly after impact. The fire that had grown earlier between the cavity and the east edge on the 82nd floor continued to burn gently. Around 9:48 a.m. a brief flash of flame was observed from a window to the west of the impact cavity on the 80th floor, and just before 9:53 a.m. a substantial amount of smoke was released from windows still further to the west. Shortly afterward, flames were observed spreading across the floor at this location from east to west. By the time of collapse, an intense fire was burning near the center of the western half of the 80th floor and extended over roughly one fifth of the floor width. As WTC 2 began to collapse, the only significant flames pushed out of open windows on the south face came from this fire area.

Views of the west face during the period showed smoke flowing from open windows on the 84th, 86th, 88th, 91st, 105th, and 107th floors and from the southern edge of the mechanical equipment room on the

108th and 109th floors. There were no visible indications that fires capable of breaking out window glass had reached the west face of WTC 2 prior to the collapse.

Façade maps of integrated fire intensities for the period are shown in Figure E–17. Many of the fires present during earlier periods were either no longer visible or were dying down during the final interval prior to the tower collapse. Some fire spread to the west had taken place on several floors on the north face. Areas with substantial fires included those on the north sides of the east face on the 79th and 80th floors (recall that the observed fires are combinations of sustained fires and short-lived flame releases) and the intense fire that grew on the west side of the south face on the 80th floor.

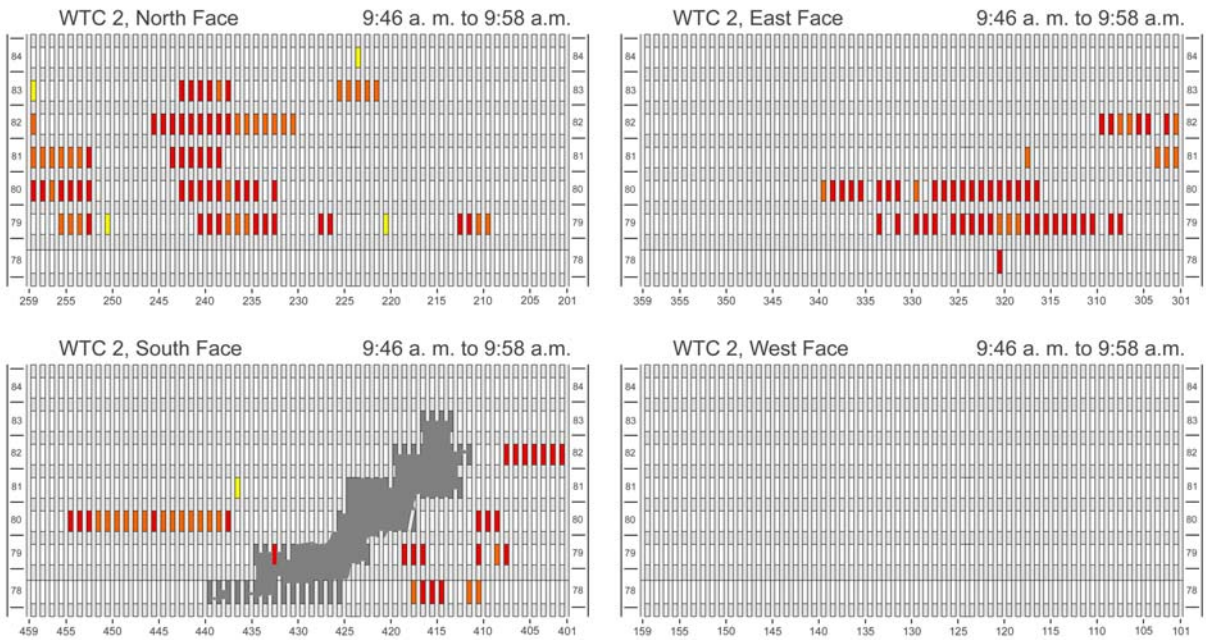

Figure E–17. Maps of integrated fire observations between 9:45 a.m. and 9:59 a.m. are shown for the four faces of WTC 2.

Summary and Additional Discussion of Observations for WTC 2 Fires

Compared to WTC 1, there was less observed fire spread in WTC 2, even when the difference in available time (102 min for WTC 1 and 56 min for WTC 2) is taken into account. Figure E-18 compares WTC 2 integrated façade maps of fire observations for the entire 56 min period with fire distributions present shortly after the aircraft impact. Primary areas of fire growth and spread include the east side of the 83rd floor and locations to the west of the cold spot on several additional floors of the north face, much of the 81st floor and extensive areas toward the centers of the 79th and 80th floors on the east face, and areas on either side of the aircraft impact cavity on the south face, particularly to the west side of the 80th floor and to the east on the 81st and 82nd floors. The absence of visible fire indicates that substantial fires did not reach the west face of the tower during the available time.

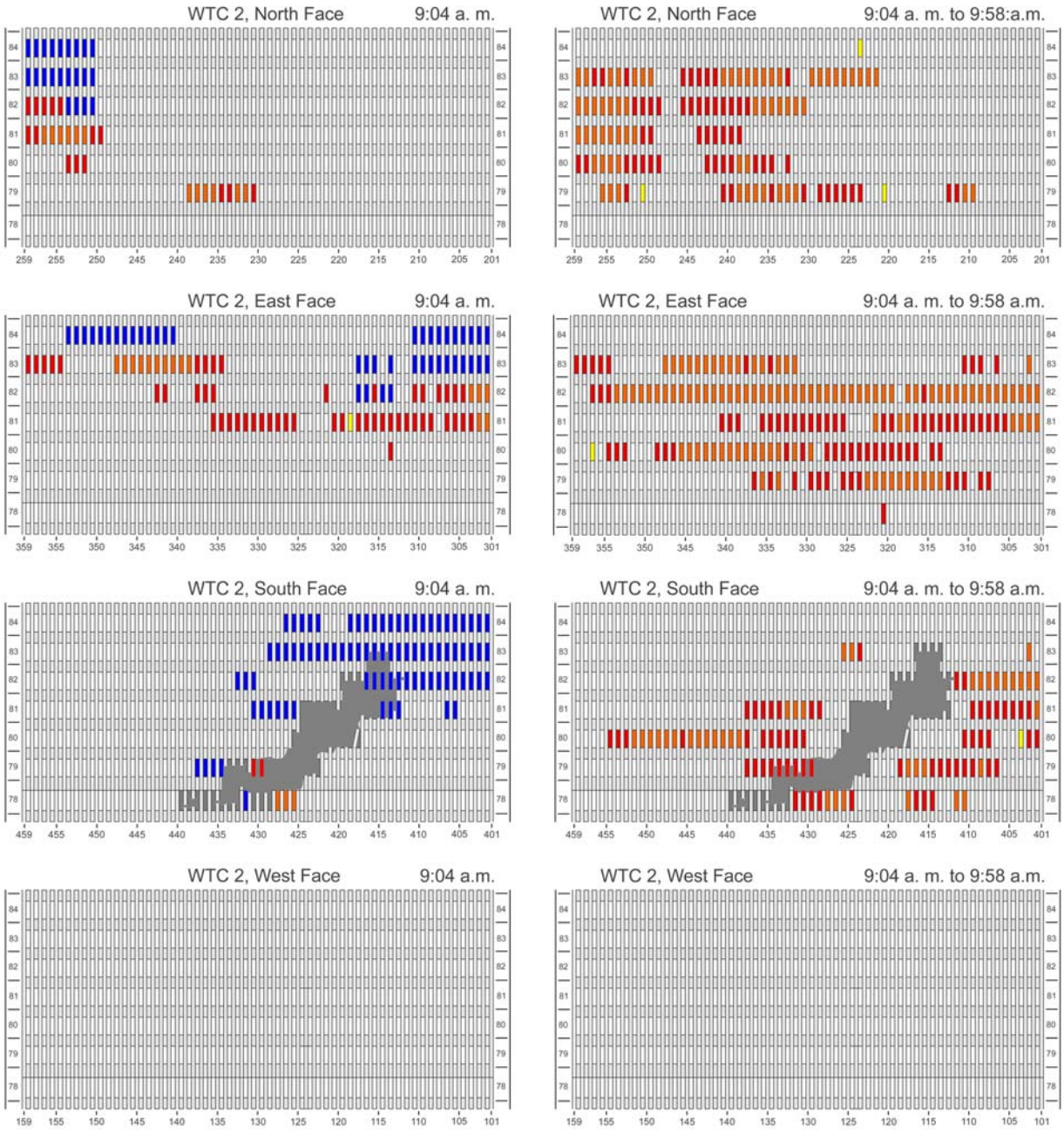

Figure E–18. Maps of observed fire distributions on the four faces of WTC 2 shortly after the aircraft impact (near 9:04 a.m.) are compared with the corresponding integrated fire observations for the entire period between 9:03 a.m. and 9:59 a.m. Blue represents windows where observations were not possible.

Additional differences between WTC 1and WTC 2 became apparent when changes in window condition (discussed in detail in Chapter 8 and Chapter 9) were considered. Recall that for WTC 1 the number of open windows following the aircraft impact (roughly 236) increased by more than a factor of five as a result of fire spread. For WTC 2, the number of open windows (estimated as 433) immediately following the aircraft impact was considerably larger, mostly due the fact that the aircraft struck toward the east side

of the south face and caused extensive façade damage and window breakage along the east face and east side of the north face. When WTC 2 collapsed, the estimated number of open windows was 620, having increased by less than 50 %, reflecting the limited fire spread that had taken place.

A curious aspect of the fire behavior in WTC 2 was the presence of the cold spot on the north face, which covered three floors over a length equal to one sixth of the face width. The existence of the cold spot implies that little fuel was available in the immediate vicinity to support burning. A number of possible explanations were considered for the absence of fuel. One is that the area was vacant and that there was limited fuel present prior to the aircraft impact. NIST is unaware of information supporting such a conclusion. A second possibility is that the fireballs that exited through the area were so intense that they pushed most of the available fuel in the area to the sides or out through the opened windows. A third possibility is that the floor slabs, particularly on the 81st and 82nd floors, in the immediate area collapsed locally during the aircraft impact and fireballs, in effect, creating a cavity behind the steel frame. The available visual evidence can be used to support and argue against all three possibilities. NIST has concluded that insufficient information is available to allow a likely formation mechanism for the cold spot to be postulated.

Additional unusual behaviors observed for WTC 2 include the correlated smoke puffs observed over large areas of the east façade and the roughly one-minute periods during which the smoke flows increased dramatically, often accompanied by external flames. These events were usually most evident on the 79th and 80th floors of the east face, but could often be detected on other floors and faces as well. At least 65 occurrences of smoke puffs were documented along with seven occurrences of the one-minute-long smoke releases.

The evidence suggests that the smoke puffs resulted from pressure pulses, generated within the tower and transmitted to other locations. It is considered likely that while the pressure pulses were of sufficient magnitude to affect smoke flows over multiple faces and floors, they were much too small to affect the tower's structural components. For most of the smoke puffs, there was no visual indication of the event that generated the pressure pulse or its location. In a few cases, such as when molten metal poured from the tower, circumstantial evidence indicated that the puffs were associated with specific observed events.

The roughly one-minute-long periods of heavy smoke flow were easily distinguished from the smoke puffs due to their persistence and the presence of flames. The short-term release of large amounts of smoke along with external flaming over large areas of a building façade is not a typical building-fire behavior. Solid-fueled fires in buildings more typically go through the stages of growth, sustained burning, and decay observed elsewhere in both towers. It has been hypothesized that burning of isolated pools of aviation fuel deposited inside the building during the aircraft impact was the likely explanation. Given the likelihood that a large amount of aviation fuel from the aircraft's port fuel tank was spread across the 79th floor during the impact, perhaps the most noteworthy observation on the east face was the absence of large fires on the 79th (with the exception of the debris pile on the north face) and 80th floors for the initial 25 min of the fires. The fire behaviors during the short periods of heavy smoke release are those expected following the sudden ignition and rapid burn out of aviation fuel at interior locations within the tower. The identification of seven such occurrences suggests that, if the aviation fuel was indeed responsible, it had collected at multiple locations that separately ignited and burned.

Numerous visual observations suggest that important changes, which might have had structural relevance, were taking place in WTC 2 in the period following the aircraft impact until collapse. These observations

include hanging objects, at least some of which, based on appearance, were likely locally dislodged floor slabs that had settled down below the associated spandrel, at several locations on the north and east faces; observed changes in the positions of the hanging objects; the occurrence of numerous pressure pulses identified by smoke and/or dust puffs generated over multiple windows and floors; the appearance of molten metal pouring from the tops of open windows; and bowing of the outer steel framework on the east face.

The general picture that emerges from the observations is that WTC 2 possibly underwent a prolonged series of subtle structural changes that began shortly after the aircraft impact and that these changes continued until the tower collapsed. Presumably, these changes occurred as the structure adjusted to the initial damage inflicted by the aircraft and associated fireballs and the additional deformations caused by the fires that subsequently developed. While there was similar direct evidence in WTC 1, e.g., bowing columns and events, such as smoke puffs, that might be possible telltale signs of internal structural changes taking place within the tower, these were considerably less frequent in WTC 1 than observed for WTC 2.

It has been noted that the fire events in WTC 1 and WTC 2 had different characteristics. These differences extended to human behaviors, which provide additional indications about these differences. In WTC 1, people broke out numerous windows above the immediate floors that were burning and were often observed in open windows. While some windows were broken open in WTC 2, the locations were limited, and people were infrequently observed. Numerous people were observed falling from the upper floors on the four faces of WTC 1, while the three people observed falling from WTC 2 came from a single window on the east side of the 79th floor. These differences suggest that conditions on the upper floors in WTC 2 did not degenerate as quickly, nor become as dire, as on the upper floors of WTC 1.

In WTC 1, a large number of streamers were observed falling from the tops of windows. These were attributed to smoldering polyurethane that was originally located above the window head casings. In contrast, very few streamers were observed falling from WTC 2. The absence of streamers is likely due to the relatively limited fire spread that occurred in WTC 2 and because large areas of the aluminum curtain wall that contained the polyurethane insulation were removed by the aircraft impact and resulting fireballs.

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Daily News	Digimarc	
Federal Emergency Management Agency	Fire Department of New York	Firehouse Magazine
Goldfish Pictures	Jersey Infrared Consultants	Magnum
NBC	New York 1	
New York Police Department	New York Times	
Port Authority of New York and New Jersey		Reuters
Star Ledger	Steeple Chase Films	Village Voice
WABC	WCBS	WNBC
WNJU	WNYW	WPIX
Wonderlust		

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Chapter 1
INTRODUCTION

The destruction of the World Trade Center (WTC) Complex in New York City on September 11, 2001, resulted in immense loss of life and property. Much of the loss occurred as a result of the collapse of the towers following the aircraft impacts. This task is a part of the Investigation of the technical causes for the disaster authorized by the United States Congress and performed by the National Institute of Standards and Technology (NIST). Details concerning the objectives and approach of the Investigation are incorporated in the preface to this report.

This report summarizes the results of one of the component tasks of Project 5—*Reconstruction of Thermal and Tenability Environment*. Project 5 was one of the eight projects that comprised the NIST WTC Investigation. This particular task, referenced as Task 5A, was entitled "Visual Collection and Analysis."

The objective of the task was "to utilize photographs, videos, and other relevant information to develop detailed time lines for the spread and growth of fires at the peripheries of World Trade Center Buildings 1, 2, and 7 and to organize the information such that it can be utilized by other investigation team members." This report focuses specifically on the WTC towers, WTC 1 and WTC 2. In practice, the scope of the task was expanded, and its staff provided significant technical support and analysis to Investigation Projects 2, 3, 4, 6, 7, and 8, while meeting the principal objective of developing time lines for the fires observed in the towers.

Based on media coverage on September 11, 2001, and afterward, it was evident that the World Trade Center disaster had been visually documented to a degree that was unusual for such an emergency. An extraordinary number and variety of photographs and videos were shown publicly, starting with live television coverage shortly after the first aircraft impact. There are a variety of factors that contributed to the creation of this extensive visual record, including the location of the disaster in the of a center major metropolitan area, the overwhelming magnitude of the attack and loss, and the length of time the event lasted.

Members of the NIST technical staff recognized that this visual record might offer an unparalleled opportunity to document the disaster and contribute to understanding its technical causes. Very shortly after September 11, informal efforts to collect visual material that might prove useful to an eventual investigation were initiated. Prior to the formal authorization and funding of the Investigation by the United States Congress, NIST had initiated several small, internally funded projects related to the September 11 disaster. One of these projects was a more organized effort to begin the identification and collection of relevant visual material. These efforts accelerated greatly once the formal Investigation was authorized, and these activities became a formal part of the Investigation.

This task consisted of four major subtasks: 1) identification, collection, data basing, and cataloging of visual material, 2) timing of material incorporated into the NIST visual database, 3) development of fire time lines and additional analyses based on the visual material, and 4) documentation.

This report is the documentation of this task (subtask 4). Earlier reports released by the Investigation include interim updates on progress on the task. (NIST SP-1000-3, 2003; NIST SP-1000-4, 2003; NIST SP-1000-5, 2004)

The report is organized as follows:

Chapter 2 provides a general description of the visual material that was recorded on September 11, 2001, and approaches that were developed for identifying, collecting, data basing, and cataloging the material that was collected (subtask 1). Since a major focus of the task was the development of time lines, it was necessary to assign accurate times to the photographs and videos incorporated into the database. Chapter 3 describes the approaches developed for timing and an assessment of their effectiveness (subtask 2).

Chapter 4 provides background information about such topics as the local geography, wind direction, relevant tower structural and architectural details, a numbering system for describing window locations on the towers, and some interior details, such the locations of air intake and exhaust louvers on mechanical equipment room floors and floor plan layouts for certain affected floors. The tower geometry affected the accuracy of findings based on visual analysis. Such effects are discussed in the last section of this chapter.

Chapter 5 includes details concerning the various types of analysis and procedures employed to develop time lines for fire behavior in the two towers. The primary output was a series of numerical data sheets as a function of time that provided window-by-window assessments of whether or not a fire was present, and, if present, a measure of the local intensity, whether or not smoke was flowing from a particular window and, if observed, an indication of whether the flow was light or heavy, and whether or not glass was in place for a given window. The criteria and the key used for these assessments are discussed. The usefulness of the datasheets was enhanced by visualizing the contents using various types of color façade maps. In addition to the window-by-window data sheets, a number of other observations related to the fire behavior were documented, including the formation of streamers, smoke marks on column covers, unusual burning and smoke behaviors, and human observations (subtask 3).

Chapters 6 and 7 contain time lines describing external observations related to the aircraft impacts and subsequent fireballs for WTC 1 and WTC 2, respectively. The aircraft impacts caused significant damage to the towers and released aviation fuel, which ignited inside the towers, leading to the formation of external fireballs immediately afterwards. Even those these aviation-fueled fires rapidly burned out, they ignited nascent fires within the towers that were the sources for the fire spread and growth observed following the aircraft impacts. These chapters also include descriptions of the damage inflicted by the aircraft based on observation of the exteriors of the towers and debris observed on the ground. Observed fire distributions shortly after the aircraft impacts are documented. Estimates for the speeds of the aircraft at the time of impact are provided that are based on video analysis of the impacts. For WTC 2, additional analyzes of available videos allowed the motion of the tower in response to the aircraft impact to be assessed (subtask 3).

Chapter 8 and Chapter 9 provide detailed discussions of observed fire behaviors in WTC 1 and WTC 2, respectively. The results presented in these two chapters, along with the associated data sheets, fulfill the primary objective of the task (subtask 3).

A number of additional details are incorporated into appendices for this report. Appendix A includes diagrams for the locations of air intake and exhaust louvers at the peripheries of mechanical equipment rooms located on the 108th and 109th floors and the 75th and 76th floors. Appendix B provides floor plan layouts for a number of floors in the vicinities where the aircraft impacted the towers. Appendix C to Appendix J include detailed façade maps incorporating window data on fire, smoke, and window condition as a function of time for the four faces of each tower. Appendix K provides additional details concerning an analysis of the motion of WTC 2 that resulted from the impact of the aircraft. Appendix L includes a table of observations of streamers released from WTC 1 during the fires, and Table M summarizes observations concerning people falling from WTC 1.

1.1 REFERENCES

May 2003 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST Special Publication 1000-3.

December 2003 Public Update on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST Special Publication 1000-4.

Appendix H: Interim Report on Evolution of WTC Fires, Smoke, and Damage Based on Image Analysis, in June 2004 Progress Report on the Federal Building and Fire Safety Investigation of the World Trade Center Disaster, NIST Special Publication 1000-5.

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Chapter 2
COLLECTION AND HANDLING OF VISUAL MATERIAL

2.1 BACKGROUND

The New York City area is a major center in the United States for the media, being the home for several newspapers, numerous local television stations, and the national headquarters for several television network news organizations. It is a large city, and there are numerous freelancers who make their living shooting photographs and video. The American fashion industry, which supports additional photographers and videographers, is centered in New York. City. New York City is also a major tourist destination, attracting thousands of visitors daily who bring along their cameras to record their experiences. As a result of these traits, the New York City area, and particularly Manhattan, likely has one the highest concentrations of cameras per area in the world, along with people skilled in their use.

On September 11, 2001 numerous events were taking place in New York City that increased the number of cameras in the vicinity of the World Trade Center. A primary election was being held in the city, and numerous news organizations were covering it. It was Fashion Week, and the number of fashion photographers was higher than usual. School had just opened for the fall, and numerous parents carried cameras when they took their children to school that morning.

The fact that this event occurred in lower Manhattan in the midst of a sea of cameras, resulted in incredible fireballs and smoke plumes that immediately attracted people's attention, was visible from vast distances due to the heights and sizes of the towers, and took place over several hours meant that thousands of people, both professional and amateur, turned their cameras toward the World Trade Center and recorded some type of visual record of the events of September 11. As a result, the World Trade Center disaster is one of the most photographed events in world history. Portions of this visual record were shown publicly starting on September 11, 2001 and continue to be shown today. The dramatic images have molded public perceptions of what occurred on that day in a way that written or verbal descriptions could not have accomplished.

Due to the location, certain types of imagery are more available than might have been anticipated. As an example, aerial images were recorded from at least nine different helicopters. Several video cameras were stationary, and in some cases long uninterrupted views of the towers were recorded. These video recordings have not only proven invaluable for timing purposes, but have allowed analysis approaches that provide unprecedented details concerning certain aspects the disaster. In an unlikely occurrence, an infrared camera was trained on the burning towers for brief periods.

The WTC towers (WTC 1 and WTC 2) were immensely tall, and they dominated the New York City skyline. When WTC 1 was struck by American Airlines Flight 11 at 8:46:30 a.m., the approach of the aircraft was captured by at least two videographers who were coincidentally filming nearby. Other photographers and videographers in the vicinity began recording within a few seconds after the impact. As fires grew in the tower, smoke pouring from the building formed a plume that could be seen for miles in all directions in the clear sky of September 11, 2001. People in Manhattan, Brooklyn, Queens, and New Jersey began to turn their cameras toward the WTC complex. The major news organizations began

coverage almost immediately and began moving professionals into position to cover the event. Numerous other videographers and photographers, both professional and amateur, started moving toward the WTC in order to create their own visual records.

When United Airlines Flight 175 struck WTC 2 at 9:02:59 a.m., the approach and collision of the aircraft were recorded by numerous cameras from a variety of directions. Many people continued to record images until WTC 2 collapsed at 9:59:59 a.m. Following this collapse, the amount of visual material decreased markedly as people rushed to escape the area and the huge dust clouds generated by the collapse obscured the site.

Even as the disaster unfolded, it was clear that a large amount of visual material was being recorded. The resulting visual record offered an unparalleled opportunity to contribute to the technical understanding of the tragedy of September 11. Even though it was clear that an extensive visual record of the events of September 11 existed, approaches for obtaining access to photographs and videos and cataloging the material had to be developed. These critical tasks are discussed in the following sections.

2.2 SOURCES FOR VISUAL MATERIAL

Potential sources of visual material were identified in a number of ways. Recordings of newscasts from September 11, 2001 and afterward, documentaries, and other remembrances provided information directly, but also pointed toward other potential sources of material. The major photo clearinghouses, such as AP, Reuters, and Corbis, have World Wide Web sites that were reviewed for material related to September 11th. Members of the media suggested sources. Several collections of visual material have been assembled for charitable or historical purposes. Collections from the Here is New York City exhibition and the September 11 Digital Archive were reviewed. Many photographs and videos began appearing on the World Wide Web as early as September 11, 2001. These could often be identified by Web searches, and in many cases contact information was provided. Public appeals for visual material were made during Investigation news conferences and updates. News accounts of these events led many to contact NIST using the toll-free number or by e-mail. Frequently, a new source would provide suggestions about other potential sources. Members of the New York City Police and Fire Departments recorded numerous photographs and videos that were made available to NIST for review.

NIST hired a visual media consultant, Mr. Valentine Junker, to act as its representative in the New York City area. In addition to interacting with a number of individuals, his efforts were particularly valuable in interfacing with the major television networks and local New York City stations, as well as the major photographic news services.

2.3 COLLECTION PROCEDURES

The identification of sources was only the first step in the collection process. It was then necessary to contact the source, request the material, and make arrangements for its transfer. Special considerations such as copyright and privacy issues often needed to be addressed. Once an agreement was reached, arrangements were made to review and transfer copies of the material to NIST.

In the collection process, emphasis was placed on obtaining material in a form that was as close as possible to the original in order to maintain as much spatial and timing information as possible. In the

case of digital photographs and videos, this implied a direct digital copy. For film or slide photographs, it would be a high-resolution digitized version of the original media, and for analog video, a direct copy from the original source. While it was not always possible to maintain these standards, the majority of material ultimately collected was handled in this manner.

2.4 GENERAL DESCRIPTION OF VISUAL MATERIAL COLLECTED

As expected, the amount of visual material from September 11 was immense. NIST was able to obtain access to a significant amount of relevant imagery. In excess of 300 hours of video on nearly 150 separate tapes were assembled and logged. Video footage was provided by NBC, CBS, ABC, CNN and local New York City stations WABC, WCBS, WNBC, WPIX, WNYW and New York City One. In many cases, the videos provided not only included material broadcast (known as air checks), but also material that was recorded but not broadcast (known as outtakes). Additionally, videos recorded by more than 40 individuals were received.

Photographs have been provided by a number of sources including commercial photo services, the New York City Police Department (NYPD), The Fire Department of the City of New York (FDNY), and individuals. Well in excess of 7,000 photographs, representing more than 200 photographers, were received. Professional news organizations that provided material include AP, Corbis, Reuters, the New York Times, the Daily News, and the Star Ledger. Many of these organizations also provided access to unpublished photographs. The majority of photographs came from individual photographers, both professional and amateur.

It is difficult to estimate the actual amount of relevant visual material recorded on September 11, 2001, and thus, to estimate how complete the collection efforts were. There is certainly material that has not been identified and collected. However, NIST believes that the extraordinarily large collection of video material that it assembled is sufficient for purposes of the Investigation.

2.5 DATABASING AND CATALOGING

It would have been impossible to effectively use the vast amount of visual material collected for the Investigation without some means of organizing and cataloging the material. This section summarizes the approaches and procedures used for these purposes.

2.5.1 Digital Storage

Very early in the task, the decision was made to save all material in digital format on large digital data storage devices. This approach had several advantages. Because the material was in digital form, it could be assessed quickly. It was not necessary to search for a particular photographic collection or videotape, and no special equipment was required to display it. Because most material was received in other forms, the digital storage was, in effect, a backup system for the original. Additional redundancy was provided by backing up the entire digital storage system at regular intervals. Because videos were saved digitally, they could be analyzed using a variety of commercially available editing software.

Various storage solutions were considered. An approach was adopted in which a central server along with two 325 gigabyte and one 160 gigabyte external hard drives were connected with eight personal

computers equipped with 70 gigabyte hard drives. The personal computers not only provided additional disk storage, but also served as workstations for data entry and analysis. All of the systems were connected by high-speed ethernet to form a single network configured such that the entire system became, in effect, a single mass storage device. The total amount of storage available was roughly 1.4 terabytes. Due to security concerns related to the sensitive nature of some of the visual material and copyright issues, the computer network was set up with its own dedicated connections and was isolated from the internet backbone of NIST. Policies were adopted that required all viewing and analysis of the material to be done in secured rooms using secured networks.

2.5.2 Digitizing Techniques

When new visual material was received at NIST, it was stored digitally on the dedicated system. If the material was already in digital form, this simply required copying and saving it on the system. Analog material had to be first digitized in some manner. For instance, a photograph might be scanned and digitized, or an analog video might be converted to a digital video format (typically mini-DV) and then copied to the data storage system.

Each arriving video was logged into VideoList, a Microsoft Access database application that was written specifically for this task. Each video entered in the database was assigned a unique identification number. Pertinent information concerning the tape was recorded, including its duration, the network and broadcast date, if applicable, its format (e.g., VHS, Hi-8, or mini-DV), where the physical tape was stored, whether the tape was an original or a copy, its source, whether it had been digitized, whether it contained embedded time code, and general notes on its content.

Figure 2–1 shows an example of the entry sheet for the VideoList database. Videos to be stored digitally were copied onto mini-DV media, and each copy was also logged into the database. VideoList also contained a calculator for assisting in the calculation of clip timing as described in Section 3.1.2. Selected video material was then transferred to hard disk for storage.

Video material was often found to have natural breaks, such as when the camera was turned off and on (e.g., by an individual videographer) or when multiple cameras were used (e.g., during a newscast). It is advantageous to treat each of these breaks as the end of an individual video. This was accomplished by a process known as “clipping.” By using Adobe Premiere software and a personal computer to control the video player, it was possible to identify and note such breaks in a “clip file.” The clip file could also contain notes related to the material. Once a clip file was generated for an entire tape, the software could take control of the video player and go through and automatically generate multiple data files containing the video material. The material that was clipped was stored in “avi” format, which maintained all of the digital information. The maximum video file size that could be handled by this system was 1 gigabyte. This corresponds to slightly more than 4 1/2 min of avi video. Longer continuous video segments were broken into lengths having roughly this period. Breaking up longer videos in this manner also made them easier to search and catalog.

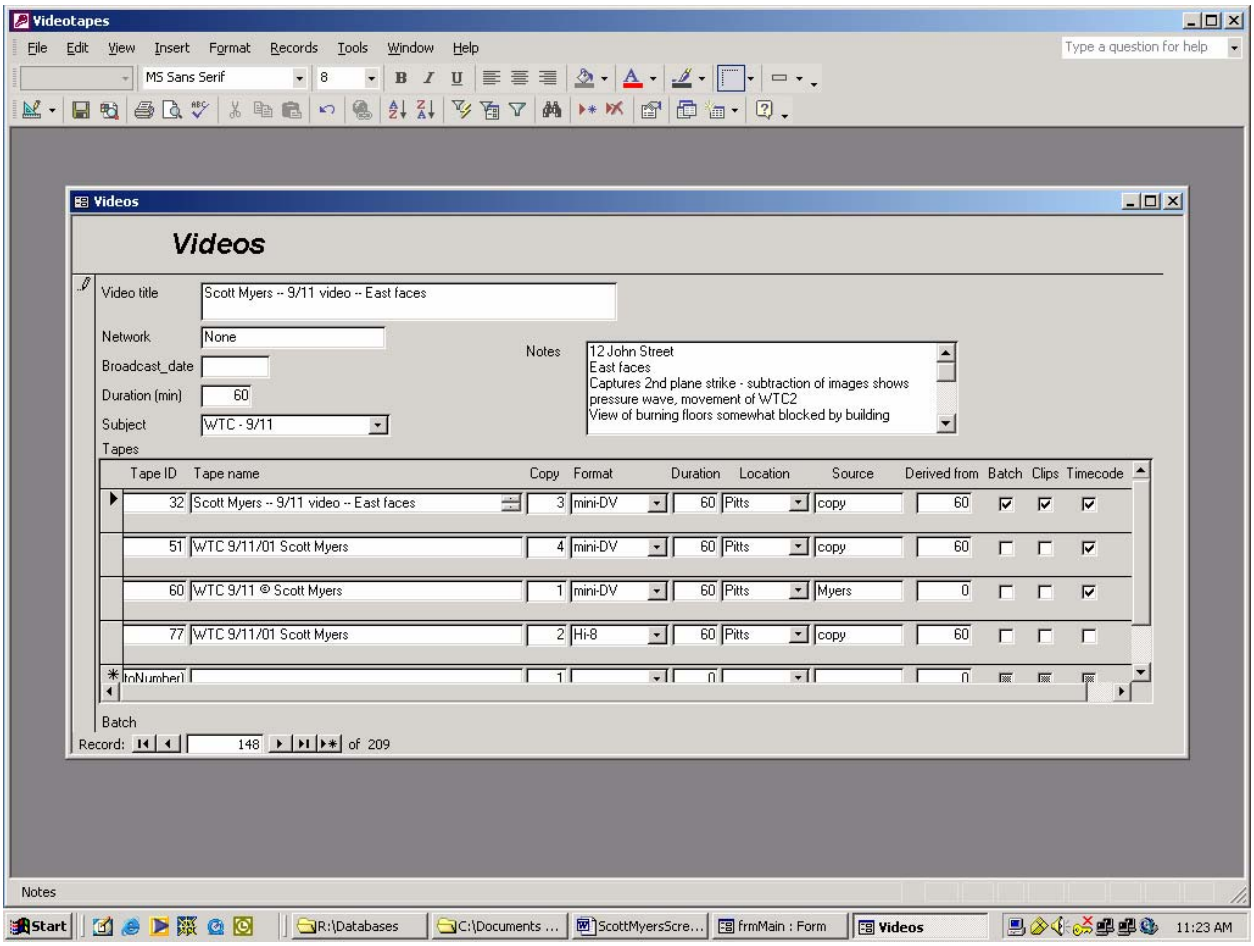


Figure 2-1. An example of the VideoList data entry sheet for video assets is shown.

2.5.3 Searchable Database

As noted earlier, a vast amount of visual material was collected and saved digitally as part of the investigation. Without some organization, it would have been impossible to use this material effectively. A commercial database program written specially for organizing visual material, Cumulus, was chosen for this purpose. This software is designed to collect individual "assets" in specified catalogs and to allow the assets to be characterized with a variety of attributes. It is possible to generate specific attributes and include these in specially designed forms for data entry. Once a catalog had been assembled, it was possible to search for assets having a specific attribute or combinations of attributes. Quite sophisticated searches could be created. It was also possible to order assets based on a particular attribute. As an example, when dates and times were assigned, the assets could be ordered in chronological order.

Two separate catalogs, one for photographs and one for video clips, were created for visual materials collected as part of the Investigation. Each catalog had a similar set of attributes that was used to characterize the assets that were included. These attributes were chosen based on the needs of this task, dealing with fire conditions within WTC 1, WTC 2, and WTC 7, and by consultation with staff of other Investigation projects. Table 2–1 and Table 2–2 list the attributes used for the photographic and video catalogs, respectively. A description of each attribute is provided along with details on how information

concerning the attribute was input into the worksheet. Figure 2–2 shows an example of the first screen for the photographic data entry form.

Table 2-1. Attributes for photographic assets.

Attribute	Definition	Entry Choice
Asset Reference	Location of photograph in file system	Set by Cumulus
Categories	List of categories under which the photograph is listed, typically the photographer's name or source	Set by Cumulus
Record Name	File name of photograph	Set by Cumulus
Photographer	Photographer's name	Text
Received from	Where photograph was obtained ("Other" may refer to a third party, for example)	Photographer WWW Other
Original Source	How photograph was added to the collection	Digital Copy of Original Digital Copy from Program Digitized Slide or Negative Digitized Photograph Uploaded from Web
Use Limited	Photographer has requested that use of the photograph be limited	Checkbox
Copyright	A copyright exists	Checkbox
Copyright Agreement	Usage agreement with NIST	Text
Shot From	Location of photographer	Text
Date Recorded	Date and time of shot	Date and time
Time Uncertainty (s)	Number of seconds uncertainty in the time assigned	Integer
View Direction	Location of photographer with respect to the WTC	North Northeast East Southeast South Southwest West Northwest
WTC Faces WTC 1 North Face WTC 1 East Face WTC 1 South Face WTC 1 West Face WTC 2 North Face WTC 2 East Face WTC 2 South Face WTC 2 West Face WTC 7 North Face WTC 7 East Face WTC 7 South Face WTC 7 West Face	Building face(s) visible in the photograph	Checkbox for each choice

Attribute	Definition	Entry Choice
Distance Near Medium Far	Clarity of the photograph Near = Can make out details within windows Medium = Can count windows Far = Unable to count windows	Checkbox for each choice
Building WTC 1 WTC 2 WTC 7 Other Building	Building(s) visible in photograph	Checkbox for each choice
1st Plane Strike	Photograph shows the plane strike on WTC 1	Checkbox
2nd Plane Strike	Photograph shows the plane strike on WTC 2	Checkbox
WTC 1 Collapse	Photograph shows the collapse of WTC 1	Checkbox
WTC 2 Collapse	Photograph shows the collapse of WTC 2	Checkbox
WTC 7 Collapse	Photograph shows the collapse of WTC 7	Checkbox
Street	Street scene, or a street is visible in the photograph	Checkbox
Debris Aircraft Debris Collapse Debris Debris Inside Building Street Debris	Debris is visible in the photograph Type of debris: Aircraft = Can be identified as plane debris (e.g., tires, engines) Collapse = Resulting from collapse Inside Building = Visible through windows or openings Street = On street	Checkbox for each choice
Fireball	Initial fireball from plane strike is visible	Checkbox
Thermal	The thermal is a tall region of the smoke plume that results from the lift caused by the hot gases of the initial fireball	Checkbox
Plume	Smoke plume generated by the fires within the towers and blown downwind. This marker is checked if the smoke plume in the photograph extends farther than a single tower width.	Checkbox
Flames Visible	Flames are visible in the photograph	Checkbox
People Inside Falling Outside	The photograph includes people Inside = People inside the buildings, at the windows or climbing down Outside = People on the street	Checkbox for each choice
Falling building component	The photograph shows a building component falling (e.g., aluminum cladding)	Checkbox
Streamers Falling	The photograph shows a streamer, an object that emits smoke as it falls and leaves a trail	Checkbox
Dripping	Molten material dripping from WTC 2 is visible	Checkbox
Hanging Floor	A sagging or hanging object suggesting a floor is visible within the windows	Checkbox

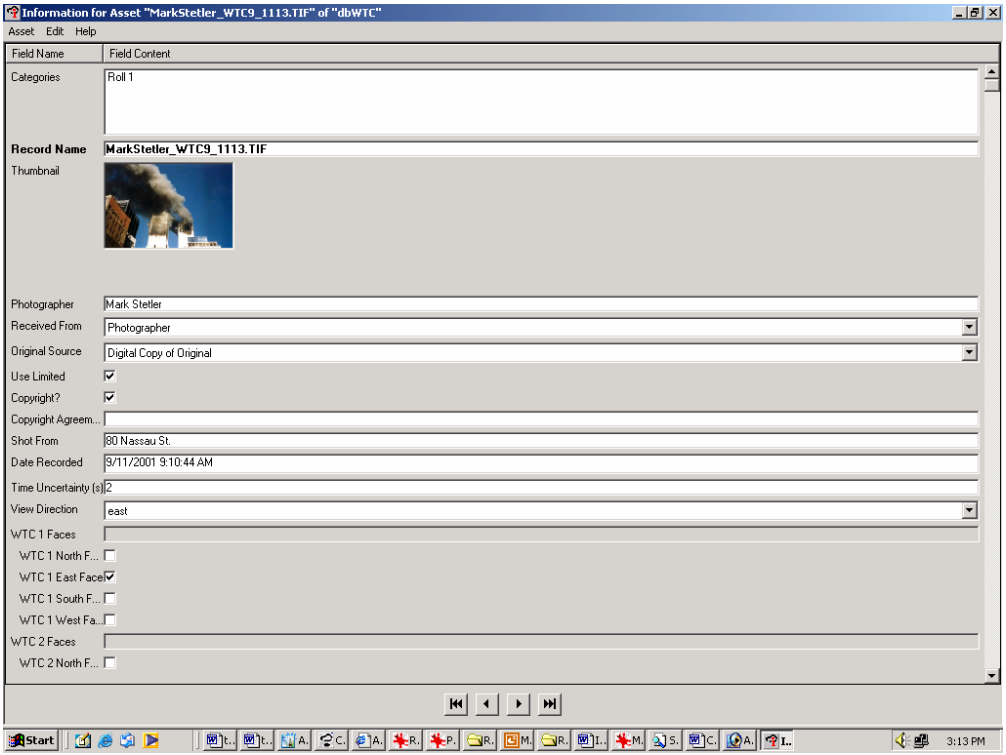
Attribute	Definition	Entry Choice
Building Core	Photograph shows the core of WTC 1 or WTC 2 — both remained standing briefly during collapse before falling	Checkbox
FDNY FDNY Apparatus FDNY Personnel	FDNY personnel or vehicles are visible, including EMTs, fire trucks, and ambulances	Checkbox for each choice
NYPD NYPD Apparatus NYPD Personnel	NYPD personnel or vehicles are visible, also includes FBI and other police officials	Checkbox for each choice
Impact Aircraft	Photograph shows aircraft approaching WTC 1 or WTC 2 before or during the strike	Checkbox
Other Aircraft	Aircraft other than the impact aircraft are included in the photograph, such as helicopters or fighter jets	Checkbox
Good for Analysis	Mark photograph for possible window-by-window analysis	Checkbox
Analyzed	The photograph has been used for window-by-window analysis	Checkbox
Notes	Notes, including a description of how the photograph was timed	Checkbox

Table 2-2. Attributes for video assets.

Attribute	Definition	Entry Choice
Asset Reference	Location of video clip in the file system	Set by Cumulus
Categories	List of categories under which the video clip is listed, typically the photographer's name or source	Set by Cumulus
Record Name	File name of video clip	Set by Cumulus
Videographer	Videographer's name	Text
Content	Content of video clip WTC 9/11 Footage = Events before collapse of WTC 7 Street Scene (no timing) Debris field = Ground Zero after WTC 7 collapse Construction = Construction of WTC towers from documentary Normal Operation = Normal operation of building, usually from documentary Animation = Animation of 9/11 events from documentary Still(s) = Photographs contained within documentary Interview = Clip only shows interview	WTC 9/11 Footage Street scene (no timing) Debris field Construction Normal operation Animation Still(s) Interview
Use Limited	Videographer has requested that use of the videotape be limited	Checkbox
Copyright	A copyright exists	Checkbox
Copyright Agreement	Usage agreement arrangements with NIST	Text
Shot From	Location of videographer	Text
Date Recorded	Date and time of beginning of video clip	Date and time
End Recording	Date and time of end of video clip	Date and time
Duration	Number of minutes:seconds contained in clip	Real number
Time Uncertainty (s)	Number of seconds uncertainty in the time recorded / end recording	Integer
View Direction	Location of videographer with respect to the WTC	North Northeast East Southeast South Southwest West Northwest

Attribute	Definition	Entry Choice
WTC Faces WTC 1 North Face WTC 1 East Face WTC 1 South Face WTC 1 West Face WTC 2 North Face WTC 2 East Face WTC 2 South Face WTC 2 West Face WTC 7 North Face WTC 7 East Face WTC 7 South Face WTC 7 West Face	Building face(s) visible in the video clip	Checkbox for each choice
Distance Near Medium Far	Clarity of the video clip Near = Can make out details within windows Medium = Can count windows Far = Unable to count windows	Checkbox for each choice
Building WTC 1 WTC 2 WTC 7 Other Building	Building(s) visible in video clip	Checkbox for each choice
1st Plane Strike	Clip shows the plane strike on WTC 1	Checkbox
2nd Plane Strike	Clip shows the plane strike on WTC 2	Checkbox
WTC 1 Collapse	Clip shows the collapse of WTC 1	Checkbox
WTC 2 Collapse	Clip shows the collapse of WTC 2	Checkbox
WTC 7 Collapse	Clip shows the collapse of WTC 7	Checkbox
Street	Street scene, or a street is visible in the video clip	Checkbox
Debris Aircraft Debris Collapse Debris Debris Inside Building Street Debris	Debris is visible in the video clip Type of debris: Aircraft = Can be identified as plane debris (e.g., tires, engines) Collapse = Resulting from collapse Inside Building = Visible through windows Street = On street	Checkbox for each choice
Fireball	Initial fireball from plane strike is visible	Checkbox
Thermal	The thermal is a tall region of the smoke plume that results from the lift caused by the hot gases of the initial fireball	Checkbox
Plume	Smoke plume generated by the fires within the towers and blown downwind. This marker is checked if the smoke plume in the video clip extends farther than a single tower width.	Checkbox
Flames Visible	Flames are visible in the video clip	Checkbox

Attribute	Definition	Entry Choice
People Inside Falling Outside	The video clip includes people Inside = People inside the buildings, at the windows, or climbing down Outside = People on the street	Checkbox for each choice
Falling building component	The video clip shows a building component falling (e.g., aluminum cladding)	Checkbox
Streamers Falling	The video clip shows a streamer, an object that emits smoke as it falls and leaves a trail	Checkbox
Dripping	Molten material dripping from WTC 2 is visible	Checkbox
Hanging Floor	A sagging object suggesting a floor is visible within the windows	Checkbox
Building Core	Video clip shows the core of WTC 1 or WTC 2 – both remained standing briefly during collapse before falling	Checkbox
FDNY FDNY Apparatus FDNY Personnel	FDNY personnel or vehicles are visible, including EMTs, fire trucks, and ambulances	Checkbox for each choice
NYPD NYPD Apparatus NYPD Personnel	NYPD personnel or vehicles are visible, also includes FBI and other police officials	Checkbox for each choice
Aircraft Impact Aircraft Other Aircraft	Aircraft are visible in the video clip Impact: Shows aircraft approaching WTC 1 or WTC 2 before or during the strike Other: Helicopters or fighter jets	Checkbox for each choice
Major Change Major Fire Change Major Smoke Change Windows Opened	One of the following events takes place in the video clip: Major Fire Change: Fire flares up, dies down, or spreads to a new region Major Smoke Change: Smoke bursts, dies down, or spreads to a new region Windows Opened: Window breaks open, either due to fire or to people	Checkbox for each choice
Good for Analysis	Mark video clip for possible window-by-window analysis	Checkbox
Analyzed	The video clip has been used for window-by-window analysis	Checkbox
Notes	Notes, including a description of how the video clip was timed	Text

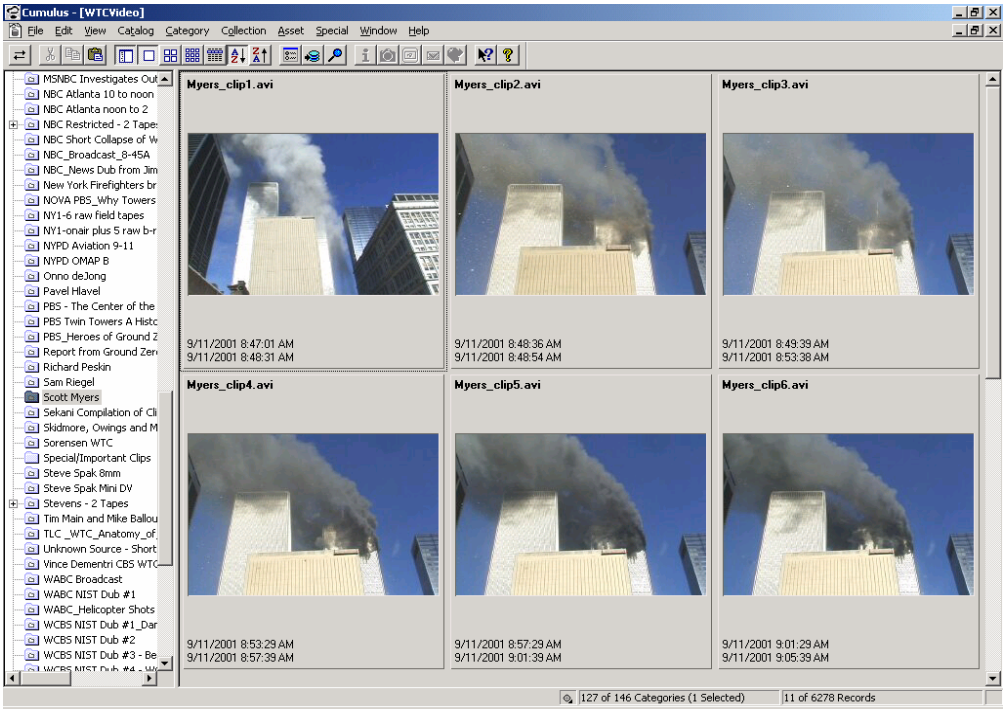


Source: Thumbnail © 2001 Mark Stetler.

Figure 2-2. An example of the first page of the Cumulus data entry sheet for photographic assets.

Cumulus allows thumbnails of entire catalogs or selected subsets to be displayed. This made it possible to review large numbers of photographs and video clips quickly and to decide which were most likely to be useful for a particular purpose. A variety of asset characteristics could also be shown simultaneously. Typically, the asset name and the time the asset was recorded were displayed. Figure 2–3 shows an example of thumbnails taken from the video database.

Not all collected visual material was incorporated into the two catalogs. Photographs and videos judged not to contain information directly relevant to the Investigation were not included. Even so, the number of photographs and video clips added to the catalogs was large. The photographic catalog includes 6,899 assets, and the video catalog includes 6,977 assets representing over 76 hr of material.



Source: Thumbnails © 2001 Scott Meyers.

Figure 2-3. An example of a Cumulus asset screen display for the video database. Thumbnails are shown along with the time and dates when the recording started and ended.

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Chapter 3
TIMING OF PHOTOGRAPHS AND VIDEO CLIPS

Since one of the major goals of this task was the development of time lines for fire growth and spread in World Trade Center (WTC) 1 and WTC 2, it was important to assign times of known accuracy to assets included in the two image catalogs. This task was greatly complicated by the absence of accurate times for the majority of visual material collected.

The visual material assembled during the Investigation can be classified into two broad categories with regard to time information—material that incorporates some indication of relative time and that for which no time information is provided.

3.1 VISUAL MATERIAL INCORPORATING TIMESTAMPS

Modern photographic and video digital cameras often record camera clock times as part of their output. For photographs, this information is usually stored as an integral part of the image in a header known as an Exif file. Similarly, digital video cameras often embed a variety of information, including the camera clock time, as part of what is known as meta data. Software is available for reading these clock times from Exif and other meta data media file formats. While a great help, these times usually still required some adjustment because people do not generally set their camera clocks accurately. In some cases, clocks were found to be off by days or even years. Even so, the relative times over the short time period of the events of September 11, 2001, were quite accurate.

Occasionally, analog photographic and video cameras imprint a time stamp on their outputs that can provide relative times similar to Exif or meta data.

The following subsections describe approaches and tools that were developed to partially automate the assignment of accurate times to series of photographs and videos containing integrated time information.

3.1.1 Photograph Tools

In order to make the best use of the information embedded in digital photographs, software was required to retrieve the Exif file information and to adjust the recorded clock times. The commercial software package CatDV is able to retrieve meta data embedded in a variety of media formats, including digital photographs and mini-DVs. The Access database PhotoTiming was written for the purpose of determining the actual times for a set of photographs given the relative Exif time for each and a single accurate time reference. For a set of photographs sharing a common clock from the same digital camera, an accurate time for a single photograph was sufficient to set the relative times for the entire set.

Figure 3–1 shows a PhotoTiming data sheet for a selected set of photographs. A file generated by CatDV containing the Exif data for each photograph, if available, was read into PhotoTiming. The equivalent Exif and known relative times were entered into the appropriate fields at the upper right of the data sheet.

Selection of the Calculate Photo Times button filled the Actual Time column with the appropriate values for each Exif time. In this example, the Exif times were found to be off by 102 s.

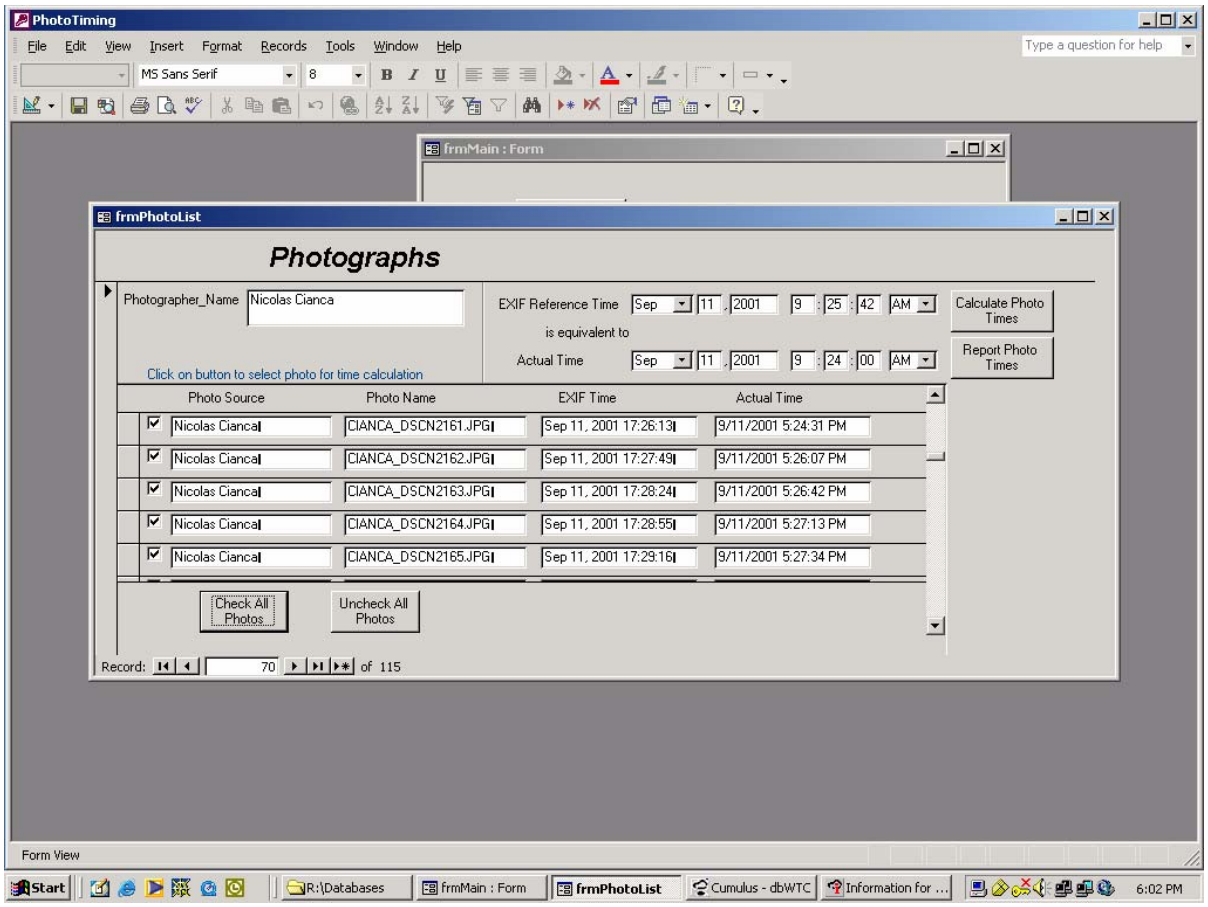


Figure 3-1. An example of the PhotoTiming sheet for calculating times for photographs containing Exif meta data is shown.

3.1.2 Video Tools

In addition to containing the video database described in Section 2.5.2, VideoList also assisted with timing the clips taken from a videotape. This function was similar to that in the PhotoTiming tool. For a broadcast video that was filmed in real time, the timing of every clip in the video, except for replays, could be set from knowing the time at a single point. An example of this use of VideoList is shown in Figure 3–2 A clip file generated in Adobe Premiere for a specified video was read into VideoList. The mini-DV time of an event in the video whose timing was known, such as the moment of the second aircraft impact on WTC 2, was identified. Both times were entered into the appropriate fields at the upper right of the data sheet. Clips to be timed (excluding replays) were identified by a check mark, and the requested calculation resulted in the actual times in and out for each clip as shown in Figure 3–2. This tool was also useful in calculating start times for continuous video segments broken into multiple clips.

For each mini-DV video that contained meta data, CatDV was used to extract the clock times for the In and Out points for each clip. These values enabled the timing of every clip in the video from a single reference time.

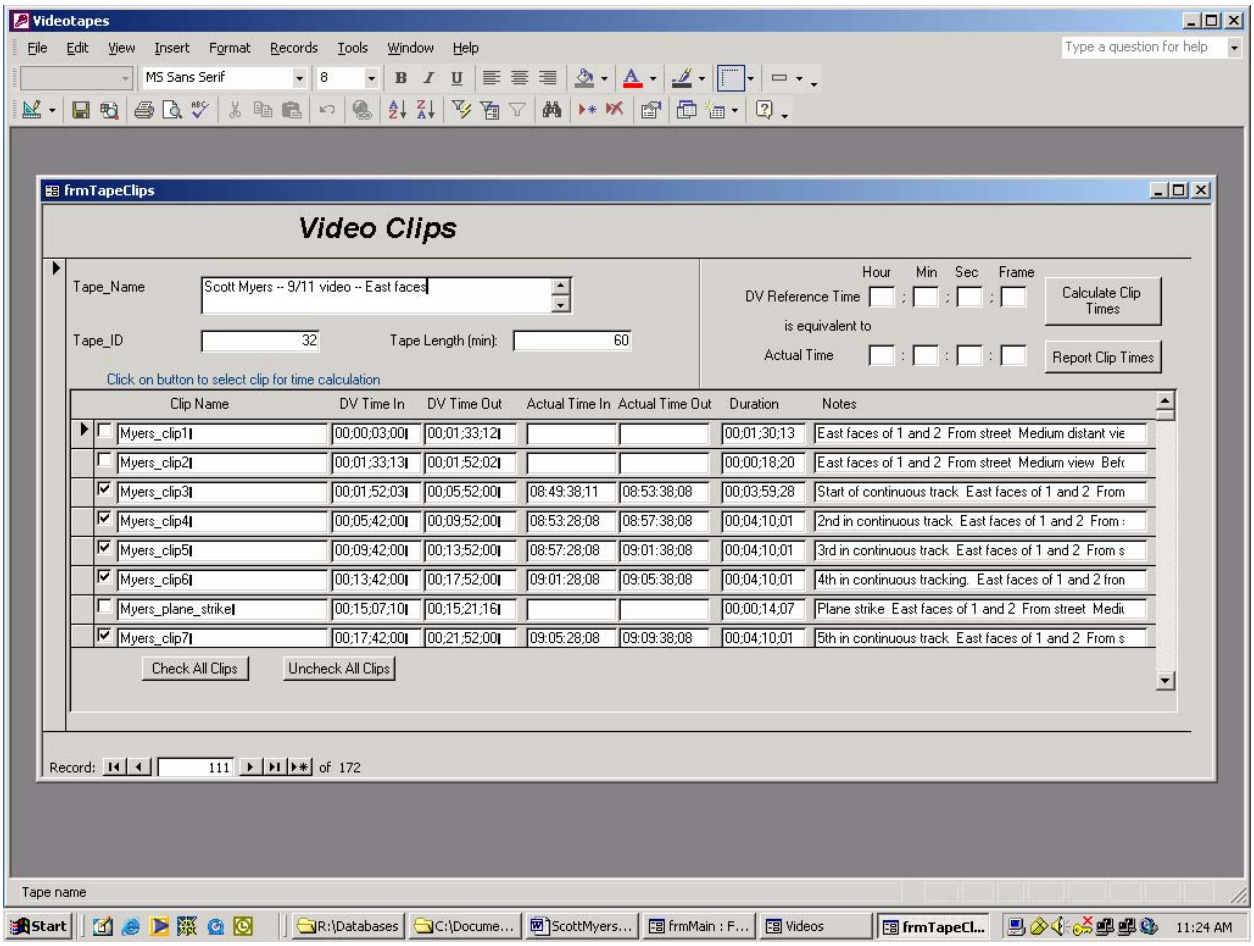


Figure 3-2. An example of the VideoList sheet for calculating clip times for video assets.

3.2 VISUAL MATERIAL WITHOUT TIME STAMPS

Most analog visual devices, such as film-based photographic and video cameras and analog video recorders that record on tape, do not provide a clock output that is recorded. For these cases it was necessary to assign times using approaches such as those described below. In the case of photographs, this required assigning a time to each individual photograph. The situation is similar for video recordings, but with a major difference. Video can be thought of being comprised of a series of closely spaced images, known as frames, having very well defined and known time spacing. As long as the camera records continuously, the times for the entire video could be assigned by simply determining the absolute time for a single frame.

3.3 REFERENCE TIME

Recognizing that the majority of timing information available from the visual material itself was of high relative accuracy, but of unknown and variable absolute accuracy, a timing scheme was adopted in which all of the times for items in the databases were placed on a common relative time scale tied to a single well-defined event. Due to the large number of different views available, the moment when the nose of the second aircraft struck the south face of WTC 2 was chosen to be this time. This event was defined to

have occurred at 9:02:54 a.m. based on times for major events included in the earlier Federal Emergency Management Agency (FEMA) report (McAllister 2002) describing the events of September 11, 2001.

3.4 TIMING TECHNIQUES

Once the reference time was chosen, it was possible to place times on videos that showed the second aircraft impact. By matching other photographs and videos to these initially assigned videos, the assignments were extended to visual materials that did not include the primary event. Using this process, it was possible to place photographs and videos extending over the entire period of the event on a single time line. Sets of photographs containing Exif times and video clips that either contained meta data or were continuous over relatively long periods were particularly useful for this purpose, because a single time assignment would allow the entire series to be timed. Sets of photographs recorded on film or analog videos that were frequently turned on and off were the most difficult items to time since individual matches were required for each photo or video clip.

Matching visual images and assigning times turned out to be a demanding task, requiring unique approaches. A variety of characteristics were employed to match times in different photographs and videos. These include distinct shadows cast on the buildings by the smoke plumes, the appearance and locations of smoke and fire plumes, the occurrence of well-defined events such as a falling object or the sudden appearance of smoke, and a variety of other unlikely clues such as a clock being recorded in an image.

3.5 TIMES FOR THE FIVE MAJOR EVENTS OF SEPTEMBER 11, 2001

To assist in the timing process, relative times for the five major events of September 11, 2001--first aircraft impact, second aircraft impact, collapse of WTC 2, collapse of WTC 1, and collapse of WTC 7--were determined with 1 s accuracies. These times are summarized in Table 3-1. Note that the building collapse times are defined to be when the entire building was first observed to start to collapse. In the case of WTC 7, a penthouse on the roof sank into the building before the main collapse started.

Table 3-1. Times for major events of September 11, 2001.

Event	Relative Time from Visual Analysis	Adjusted Time from Television Broadcasts	Time Reported in the FEMA Study	Time Based on LDEO Recent Analysis
First aircraft impact	8:46:25 a.m.	8:46:30 a.m.	8:46:26 a.m.	8:46:29 a.m.
Second aircraft impact	9:02:54 a.m.	9:02:59 a.m.	9:02:54 a.m.	9:02:57 a.m.
Collapse of WTC 2	9:58:54 a.m.	9:58:59 a.m.	9:59:04 a.m.	9:59:07 a.m.
Collapse of WTC 1	10:28:17 a.m.	10:28:22 a.m.	10:28:31 a.m.	10:28:34 a.m.
Collapse of WTC 7	5:20:47 p.m.	5:20:52 p.m.	5:20:33 p.m.	5:20:42 a.m.

It is not only important to assign relative times for photographs and videos, but also to provide an indication for how accurately they are known. For this reason, timing uncertainties were estimated for each time determination and included in the databases.

The timing process was initially difficult. However, Task staff timing skills improved with practice while more visual material became available, and the number of timed assets increased. Ultimately, 3,279 of the 6,899 catalogued photographs and 2,772 of the 6,977 video clips in the databases were timed with assigned relative uncertainties of 3 s or better.

3.6 ABSOLUTE TIME ACCURACY

Many of the news broadcasts on September 11, 2001, had the current time imprinted on the screen. These imprints are known in the industry as "bugs." As these broadcasts were timed, it became apparent that there were small differences between times for the second aircraft impact based on these bugs and the time used as the basis for the database. Checks with several broadcasters indicated that the bugs should be quite close to the actual time because the clocks used as sources for the bugs are regularly updated from highly accurate sources, such as geopositioning satellites or the precise atomic-clock-based timing signals provided by NIST as a public service. Careful checks showed small time differences between different video recordings, but these were generally less than 1 s. These small discrepancies were likely due to variations in transmission times resulting from the different pathways that the video signals took to the sites where they were recorded. Based on four independent video recordings, the actual time of the second aircraft impact was determined to be 9:02:59 a.m., or 5 s later than the time assigned in developing the database. The estimated uncertainty is 1 s. Table 3-1 compares times for the major events taken from the database, adjusted to television time, and reported in the FEMA report (McAllister 2002).

The times listed for the major events in the FEMA report (McAllister 2002) were based on seismic signals (and analysis) recorded by the Lamont-Doherty Earth Observatory (LDEO) of Columbia University at a location 21 miles from the WTC site in Palisades, New York. These signals have subsequently been reanalyzed by LDEO, working under a contract from the NIST WTC Investigation. (Kim, 2005) A reinterpretation of the types of seismic signals received resulted in slightly revised times for the major events. The results of this recent analysis are also included in Table 3-1. The uncertainty for the first aircraft impact on WTC 1, the collapse of WTC 2, and the collapse of WTC 1 were reported by LDEO to be 1 s, while that for the aircraft impact on WTC 2 is 2 s. Recalling that uncertainties for times of the major events based on the television broadcasts are estimated to be 1 s, it can be seen from Table 3-1 that the two aircraft impact times derived by NIST and LDEO now agree within the combined uncertainties.

Times listed in Table 3-1 for the collapses of the two towers based on the television records and the revised LDEO analysis appear to differ significantly. These differences are likely due to different definitions used for the collapse times. The times based on visual analysis refer to the time when the collapse of a tower first became evident, while the times based on seismic records likely indicate the time when the falling debris first struck the ground. The differences between the two times were estimated to be approximately 9 s for WTC 2 and approximately 11 s for WTC 1 based on videos of the collapses. When the times required for falling debris to reach the ground are subtracted from the LEDO times, the collapse times also agree within the reported uncertainties.

Since the times derived from television broadcasts (i.e., those in column 3 of Table 3-1) are believed to be accurate and also agree with the most recent analysis of seismic signals, 5 s were added to times included in the NIST WTC databases when precise times were reported for the Investigation.

3.7 REFERENCES

Kim, W.X., 2005 "Analysis of Seismogram Data Recorded on September 11, 2001 during the World Trade Center, New York City Disaster, Final Technical Report to the Building and Fire Research Laboratory," Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York, January 31.

McAllister, T., ed. 2002. World Trade Center Building Performance Study: Data Collection, Preliminary Observations, and Recommendations. FEMA 403. Federal Emergency Management Agency. Washington, DC, May.

Chapter 4
BACKGROUND INFORMATION

This chapter provides background information and nomenclature that will be useful for the detailed characteristics, analyses, and discussion that are presented in later chapters. Such aspects as local geography, wind direction, and tower design are considered. The interdependence of these characteristics and the visual record is emphasized. Nomenclature that will be used in the remainder of the report is introduced. Most of the information related to the towers themselves is taken from design drawing and additional information provided to NIST by the Port Authority of New York and New Jersey.

4.1 LOCAL GEOGRAPHY AND WIND

Figure 4–1 shows a map of the World Trade Center (WTC) complex and the immediate surrounding streets as they existed on the morning of September 11, 2001. Figure 4–2 indicates the location of the WTC complex on Manhattan, an island that forms one of the five boroughs of New York City. An extended map of the area, including nearby areas in Brooklyn, Queens, and New Jersey, is shown in Figure 4–3.

As is evident in Figure 4–2, Manhattan is elongated with the upper end of the long direction aligned roughly to the northeast. Even though not strictly true, New Yorkers view Manhattan as running north-south, and areas uptown are considered to be located to the north. This nomenclature has been adopted for this report, so references are to the north and south towers as well as the north, east, south, and west faces of WTC 1 and WTC 2. For each of these cases, north refers to the building or side that faces uptown. It should be kept in mind that the north faces of the two towers were actually oriented roughly 29 degrees clockwise from true north (NIST NCSTAR 1-2).

Figure 4–1 shows that the western sides of the towers were located close to the Hudson River shoreline. As a result, most of the images of the towers from the west were taken from New Jersey or the Hudson River, and fewer close-up images have been collected from this direction than from other directions. In contrast, the area toward the east between the World Trade Center complex and the East River was roughly ten blocks wide and was traversed by several major streets, including Broadway, which was located one block to the east of the WTC site. For this reason, the visual record, including close-up images, up to the time of the collapse of WTC 2 is much more complete from this direction than from the west.

Figure 4–2 shows that the towers were located toward the southern end of Manhattan, with roughly 15 city blocks between the WTC complex and the tip of Battery Park, located at the southern end of the island. On the other hand, there are well over a hundred blocks to the north of the complex site. As a result, while views of the disaster from the north are prevalent, the visual record from the south is more limited, and ground views became nearly nonexistent after the first tower collapsed.

As pointed out above, the majority of the visual material showing the western sides of the towers was shot from the New Jersey shore. Figure 4–3 provides indications of the rough distances between the WTC

complex and various locations on the other side of the Hudson River. While a large number of videos and photographs showing the east face were taken from nearby locations in Manhattan, there was also a great deal of visual material recorded from Brooklyn and Queens. Figure 4–3 also provides an indication of the distances and orientation of various locations in these two boroughs relative to the WTC complex.

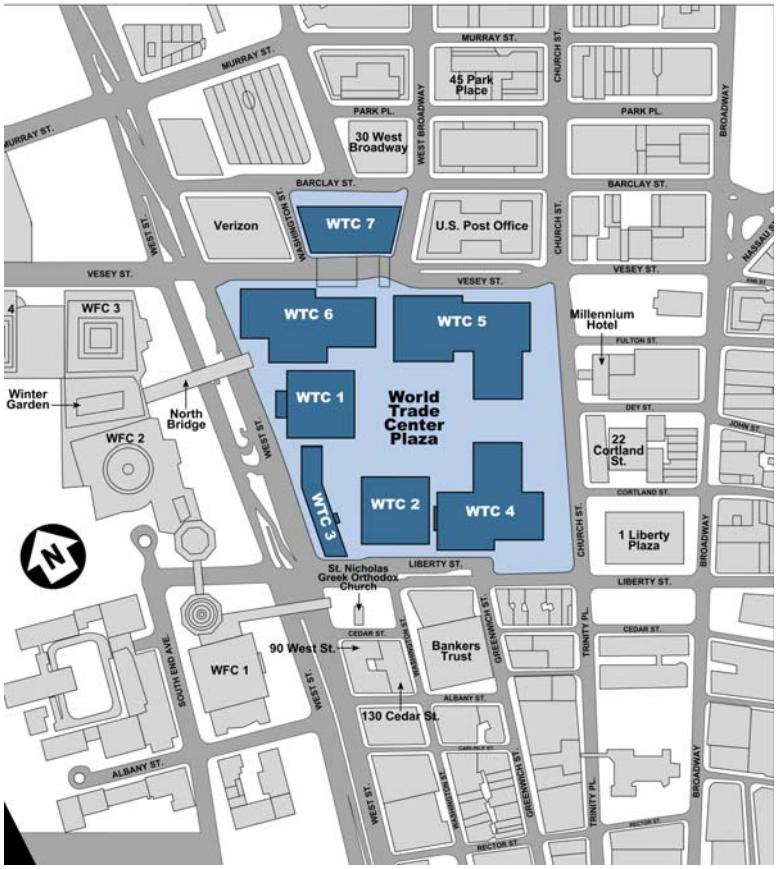


Figure 4-1. A pictorial representation of the area of the area of Manhattan in the immediate vicinity of the WTC site is shown.

Map not yet available

Figure 4-2. This map of the lower portion of Manhattan shows the location of the WTC complex relative to the island.

Map not yet available

Figure 4-3. This map shows the location of the WTC complex on Manhattan in relation to the Hudson and East Rivers, the New Jersey shoreline, and Brooklyn and Queens.

On September 11, 2001, the wind in New York City was primarily from true north. Rehm et al. (2001) used wind records recorded by aircraft in the New York City area on the morning of September 11, 2001, to estimate that the wind direction was from the north (within a few degrees) and had a speed between 11 mph and 22 mph at the heights where the aircraft impacted the towers. Accounting for the difference between true north and building north, the wind was, therefore, striking the towers from roughly 29 degrees west of north (building coordinates). As the wind came in contact with WTC 1, it flowed along the north and west faces and then "shed" from the northeast and southwest corners. As a result of this wind pattern, low-pressure recirculation zones were created on the east and south faces. As can be seen in Figure 4–1, WTC 2 was positioned such that it was shielded to a great degree from the prevailing wind by WTC 1. The wind flow patterns across this tower were more complex and variable.

Numerous images and videos available in the NIST data base show that when the towers collapsed, huge amounts of dust were generated that mixed with the air. Since the dust-air mixture was much heavier than the surrounding air, the dense fluid formed gravity currents at ground level that flowed much like a liquid along the streets and around buildings. The flows started at the point of the collapse and spread outward, reaching distances of several blocks. As a result of these flows, dust clouds covered much of lower Manhattan following the collapses of WTC 2 and WTC 1. The dust that formed the clouds was so dense that for a period following a collapse it became totally opaque. Eyewitnesses caught in the dust clouds describe being trapped in total darkness, even when on the street on a bright sunny day. For viewers outside of the clouds, the dust obscured views and limited visual recordings.

The first tower to collapse was WTC 2 at 9:58:59 a.m. Immediately following the collapse, the resulting dust cloud almost totally obscured the lower portion of WTC 1, with only the upper portions being

visible. However, due to the prevailing wind direction, the dust cleared relatively quickly to the north and west of the tower, and the north and west faces could be seen again shortly afterward. However, on the east and south sides dust was drawn upward into the low pressure areas generated by the wind, and these sides were partially obscured during the entire period between the collapses of WTC 2 and WTC 1.

4.2 TOWER CHARACTERISTICS

This section provides a general description of the World Trade Center towers and introduces some of the nomenclature that will be used in later chapters.

4.2.1 Tower Dimensions and Some Structural Features

Each of the towers was 110 stories above ground. The North Tower, also known as WTC 1, was 1,368 ft tall at the roofline, and the South Tower, also known as WTC 2, was 1,362 ft tall. WTC 1 was easily identified because it was topped with a 360-foot tall television and radio transmission tower. There was an outdoor observation deck on the roof of WTC 2. An additional six stories of each tower were located below ground level.

The towers were nearly square in shape. The distance from outside column cover edge to outside column cover edge was 208 ft 10 in. Note that the width of the towers is often quoted as 207 ft 2 in., which is the distance between the outer walls. Each corner was chamfered 6 ft 11 in.

The steel structural system for the towers was different from those typically used in steel buildings at that time. The design of the towers is sometimes referred to as a frame-tube system because it consisted of outside walls formed by closely spaced steel columns interconnected by bands of spandrel beams that were designed to act together like a flexible tube. The perimeter walls surrounded a steel-frame core located at the center of the tower. Various building services, including mechanical and electrical systems, stairways, and elevators were located in the core. With the frame-tube design, it was possible to accommodate large open-span floor areas between the perimeter walls and the core.

The cores had 47 steel columns and interconnecting steel floor beams. Even though not evenly spaced, the steel columns were arranged roughly in a grid of eight columns by six columns (note that one of the long column lines contained only 7 columns). The cores were rectangular in shape with nominal dimensions of 87 ft by 137 ft. The distances between the rectangular outer core walls and the perimeter walls were roughly 35 ft and 60 ft. In WTC 1 the long dimension of the core was aligned in the east-west direction, while in WTC 2 it was aligned in the north-south direction.

Above the fifth floor, each of the four outer walls of each tower was formed from 59 steel columns that were roughly square in shape with 14 in. sides over most of the height of the tower. These columns were placed 40 in. on center. The columns were interconnected at each floor by horizontal steel spandrel beams that were 52 in. high on most floors. Spandrels at the chamfered corners provided continuity between the perimeter faces. On each floor two additional columns were placed at the chamfered corner centers on alternate corners. At the 5th floor, three columns from above came together as a fork to form 19 base columns 10 ft on center from the 57 inner perimeter columns. The two columns at the ends of a given wall ran from bottom to top.

Steel trusses overlaid with 1½ in. fluted metal decking typically supported four inches of lightweight concrete that formed the floor slabs in the area between the core and perimeter walls. Pairs of trusses were spaced 80 in. on center. Perpendicular bridging trusses were used to provide additional support.

At the outer wall, the trusses were connected to steel seats welded to the columns. At the core, the seats were attached to steel channel welded around the outer edge of the core. The seats were placed such that the top of a finished floor slab on a typical floor was located 13½ in. below the top of the spandrel.

Mechanical services and elevators in the towers were vertically zoned. As a result, the locations and termination points of vertical shafts varied from floor to floor. Two-story mechanical equipment rooms were located at four locations, 7th and 8th floors, 41st and 42nd floors, 75th and 76th floors, and 108th and 109th floors, with an additional mechanical floor located at the 6th basement level. The areas of the mechanical equipment rooms between the core and perimeter walls were two stories high since the intermediate floors were not present. In the core area the intermediate floors were included.

Electrical and heating and air conditioning connections served floors located near a given mechanical equipment room. Of particular relevance to the current Investigation is the division above the 76th floor. Services for floors 77 to 91 were connected to the mechanical equipment rooms on the 75th and 76th floors, while floors 92 to 110 were connected to the 108th and 109th floors.

Elevator passenger service was broken into three zones, using a combination of high-speed express elevators and local elevators. The high-speed elevators connected the ground floor with sky lobbies located on the 44th and 78th floors. The sky lobbies served as transfer points to local elevators. The local elevators connected the ground floor and the two sky lobbies with other floors within a given zone. In each zone the local elevators were arranged into four banks of six elevators, with each bank connecting to a group of adjacent floors within the zone. For instance, above the 78th floor sky lobby, the groups of local elevators went to the 80th to 86th floors, 87th to 93rd floors, 94th to 100th floors, and 101st to 107th floors. Once above the floors serviced by a given bank of local elevators, the shafts would end, freeing up additional floor space. A single freight elevator and two passenger elevators ran the full length of each tower.

The vertical spacing between most floors was 12 ft. Exceptions included the mechanical floors, the sky lobby floors, and the 107th floor.

The construction techniques used for the perimeter wall steel structure influenced the damage patterns that resulted from the aircraft impact on the towers. The perimeter walls were formed by joining shop-fabricated panel sections. Most panel sections were three stories, 36 ft, tall by three column separations,10 ft, wide. They were formed with three 36 ft length box columns and three 10 ft long spandrel plates in the configuration shown in Figure 4–4. Bolt holes were provided so that each spandrel and column end could be attached to its nearest neighbor.

Just above the mechanical equipment room floors, all of the columns terminated at the same height. By using alternate panel sections that were one, two, or three floors tall, as the next panels put in place, it was possible to ensure that no more that one third of the connections on a given higher floor were bolted. An example of the arrangement of panels on the south face of WTC 2 above the mechanical floors on the 75th and 76th floors is shown in Figure 4–5.

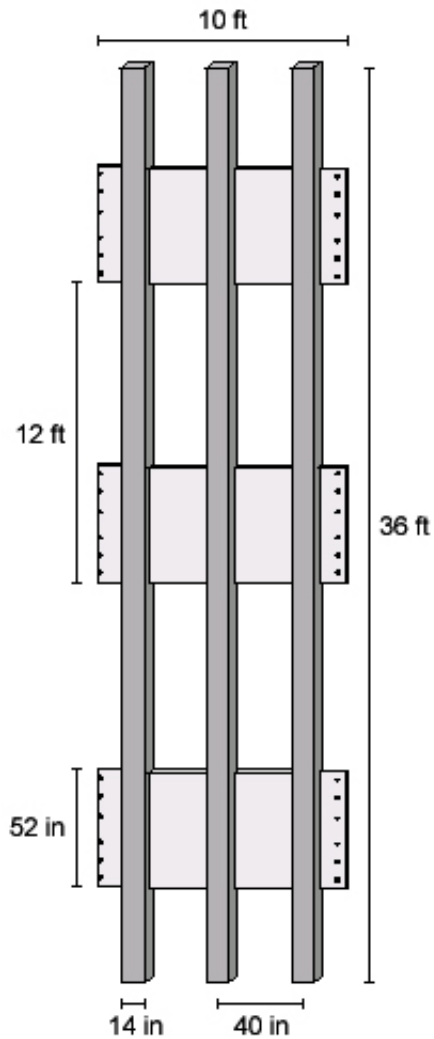


Figure 4-4. A representation of a typical steel panel section used in the construction of the WTC towers is shown. Dimensions are included.

Figure 4–5 introduces the numbering system used to identify column and floor locations for this report. It is based on nomenclature used for design drawings of the towers. The 59 columns that formed each perimeter wall were designated by numbers 1 to 59 moving from right to left as viewed from the outside. Faces for the towers were also assigned numbers as follows; WTC 1—north: 1, east: 2, south: 3, and west: 4, and WTC 2—west: 1, north: 2, east: 3, and south: 4. By combining the floor number, the face number, and a column number, a specific column on one of the floors can be identified. As an example, for WTC 1, the number 94-214 refers to the fourteenth column from the right on the east face of floor 94. Note that for the purposes of this report, a floor refers to the space between adjacent floor slabs. Vertical connections between panel sections were made roughly midway between floor slabs.

As shown in Figure 4–5, the three-story panel sections were used for columns numbered 02 to 58. Nineteen panels were required to span a given perimeter wall. The chamfered corners were formed from two-story prefabricated sections assembled from two 24 ft long columns (numbered 01 and 59) and two bridging spandrels. A third column spanned the shorter distance between the two spandrels. When

assembled into the perimeter wall, the shorter columns appeared on alternate floors and corners and were numbered “00” in conjunction with the appropriate face number.

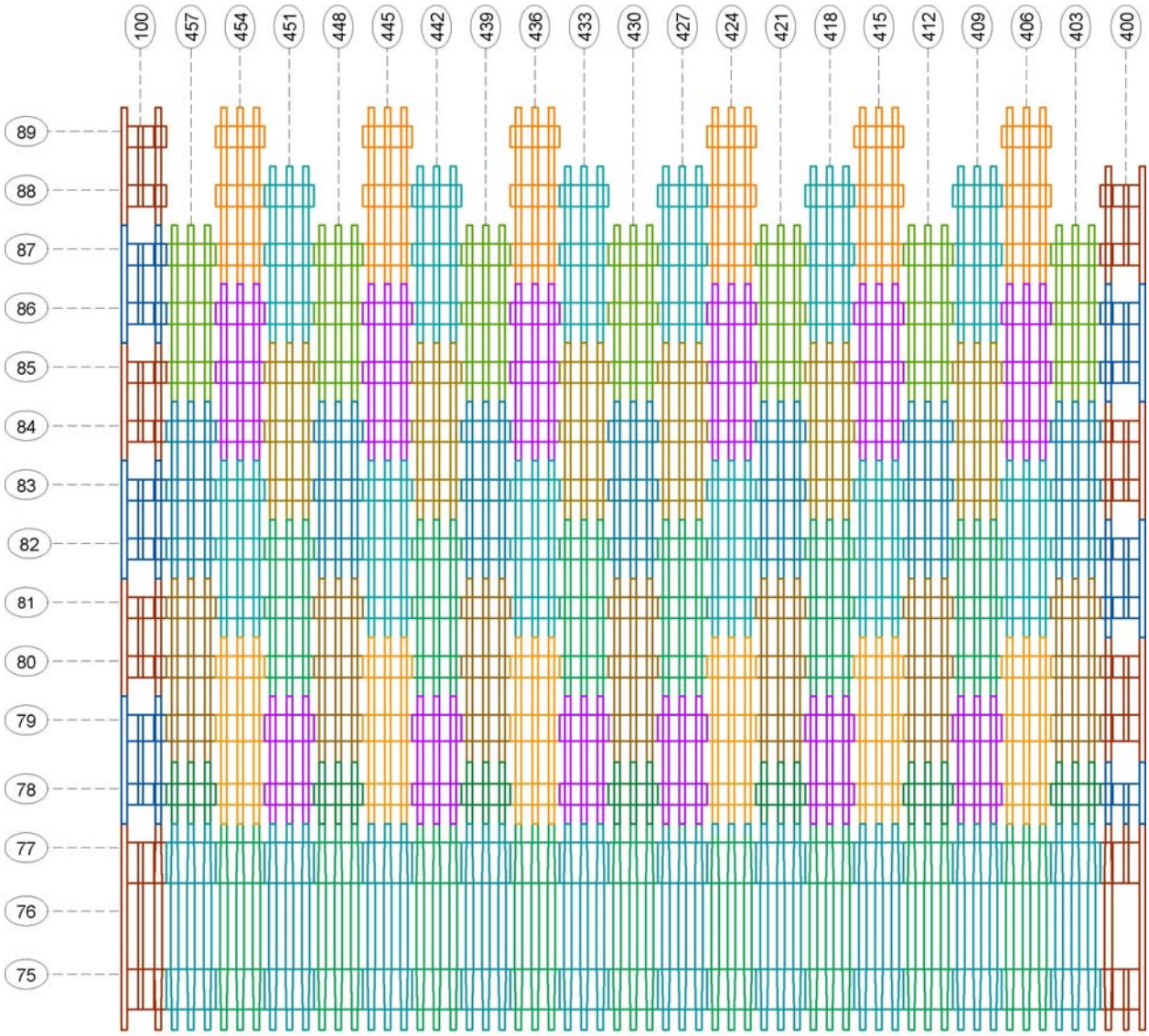


Figure 4-5. The arrangement of steel panel sections over the 12 floors above the mechanical equipment room on the 75th and 76th floor of the south face of WTC 2 is shown. Column and floor numbers are indicated.

4.2.2 Tower Curtain Walls and Interior Finish

The steel structural system described in the last section provided the strength necessary to support the weight of a tower and its contents and to resist wind forces applied to the building. However, the outward appearance of the towers was determined by the covering, often referred to as a curtain wall, which was applied over the steel frame-tube structure. The curtain walls also included glass that covered the windows.

The primary materials used to form the curtain walls were aluminum and glass. The aluminum was shaped to enclose the steel columns and spandrels and to provide support for the glass that was placed in the window openings. One-story high aluminum covers were placed over the steel columns and their coverings of fireproofing material. The nominal width of these covers was 18¾ in., as compared to the14-in. width of the underlying steel columns. The distance between adjacent columns was 21¼ in. A recessed 1.5 in. wide stainless steel window washer track with a ⅜ in. opening ran down the center of each column cover.

The aluminum spandrel covers and window frames were placed between two column covers. The interconnected column and spandrel covers were attached to the steel-perimeter structure by two aluminum mounts bolted to the spandrel plate, as well as by clamps that attached to the tops and bottoms of the spandrels and at the sides to the edges of the columns.

The spandrel covers extended 1½ in. above and below the ends of the steel, which were 52 in. high on most floors. The total height of 4 ft 7 in. resulted in the vertical distance between spandrel covers being 7 ft 5 in. on floors with 12-ft floor slab spacing.

Window glass was mounted inside the 21¼ in. × 7 ft 5 in. openings in the aluminum curtain wall. They were recessed 11½ in. from the outer edges of the aluminum column covers. A 1 in. wide aluminum window frame attached to the columns and spandrels held ¼ in. thick bronze-tinted glass that was sealed with neoprene seals. The aluminum column covers were mounted such that their bases were at the tops of windows. A narrow expansion joint was included at the base.

Polyurethane thermal insulation was placed around the window frame to reduce thermal conduction between the outside air and the building interior. Of particular relevance for the later discussion is the configuration at the tops of the windows. A thin aluminum head casing was attached to the window frame and bridged a distance of about 6 in. to the point where it joined to the interior ceiling, passing just below the steel spandrel. A 3 in. layer of polyurethane was placed on top of the head casing between the outer portion of the spandrel cover and the steel spandrel. The layer of polyurethane thinned down as it passed under the spandrel and the fireproofing applied to it. The dimensions of the polyurethane layer above a head casing was approximately 6 in. (w) × 21 in. (l) × 3 in. (h).

The distance from the outer edges of the column covers to the inner walls was 18 in. The top of a floor was located 15 in. below the base of the window. A 17 in. wide by 15 in. high metal enclosure equipped with grilles was located at the bases of the windows and was used for air conditioning. A false ceiling was mounted flush with the tops of the windows, giving a ceiling height of 8 ft 8 in. The 36 in. high area above the false ceiling was used to route electrical and environmental services and also served as a plenum for the return airflow.

4.2.3 Tower Appearance

The repeating pattern of the columns and windows in the horizontal direction and the floors in the vertical direction gave the towers a very uniform appearance over much of their height. As a result, modifications in the exterior appearance associated with changes in the column configuration at the base of the towers, at the mechanical floors, and at the 107th floors stood out and gave the towers their distinctive appearance when combined with the regular repeating patterns. This can be seen clearly in Figure 4–6 which shows the upper portions of WTC 1 and WTC 2 in a photograph taken from the north northwest. The dark

Figure 4-6. This cropped photograph shows a view of WTC 1 and WTC 2 taken from the north northwest at 8:57:05 a.m. The intensity levels have been adjusted.

bands on WTC 1 and WTC 2 near the bottom of the photograph are at the location of the two-story mechanical equipment room on the 75th and 76th floors. At the top of WTC 1 the dark band is created by the Windows on the World Restaurant on the 107th floor and the mechanical equipment room located on the 108th and 109th floors. The 360-foot tall television and radio transmission tower stands out on the top of WTC 1.

Horizontal lines are visible running across the towers. These lines are due to the expansion joints that typically separated the one-story tall aluminum column covers. These lines provide a convenient means for identifying and counting floors on the towers. However, it must be kept in mind that the expansion joints were located at the tops of windows and, as a result, were placed below the floor slabs that represented the true boundaries between floors.

Since both aircraft struck the towers above the mechanical equipment rooms on the 75th and 76th floors, this discussion focuses on the towers from this level upward. The steel columns on the 75th and 76th floors were wider than on the standard floors, as were the aluminum column covers. The aluminum cover widths for columns located between the top of the spandrel at the base of the 75th floor and the bottom of the spandrel at the base of the 77th floor (recall that were no spandrels at the 76th floor) were 24½ in. Since the columns were 40 in. on center, the distance between columns was 15½ in. The spaces between the columns were open. The total length of a column between the spandrels was 17 ft.

The column covers passing over the spandrel at the base of the 75th floor were 8 ft 10 in. tall, and the ones at the top were 8 ft 9 in. As the column covers passed upward over the lower spandrel cover they widened linearly from the 18¾ in. typical column cover width at the bottom of the spandrel to the 24½ in. width of the mechanical equipment room floor column covers. At the upper spandrel the process was reversed, and the column cover width narrowed back to 18¾ in.

The column covers between the spandrels on the 75th and 76th floor included fins in the center of the column. These fins were 5 in. wide and extended 7 in. out from the column cover. Window washer tracks ran down the centers of the fins. The fins began at the bottom of the lower spandrel and increased linearly in height across the spandrel, reaching the full 7 in. height at the top of the spandrel. The process reversed at the top spandrel.

The combination of the wider column covers and fins allowed the mechanical equipment room floors to be easily visually distinguished from the typical floors. They usually appeared as dark bands around the towers as in Figure 4–6.

The windows for the 77th floor began at the top of the spandrel on the upper side of the mechanical equipment room. The spacing between columns and the window heights for this floor were the typical values. The spandrel cover heights at the top of the 77th floor, which were also the base spandrels for the 78th floor sky lobby, were the typical 4 ft 7 in. height. On the other hand, the height of the window openings for the 78th floor was 8 ft 5 in., a foot longer than a typical window. The spandrel covers at the top of 78th floor were 5 ft 7 in. high, i.e., 1 foot longer than on most floors. As a result, the distance between floor slabs on the sky lobby floors was 14 ft.

Figure 4–7 shows the appearance of WTC 2 in the vicinity of the mechanical equipment room on the 75th and 76th floors at the northeast corner. The changes in column cover widths and the fins as they pass the mechanical equipment room floors, the variation in spandrel cover heights, and the appearance of

standard floors starting at the 79th floor are easily identified. The horizontal dark lines on the aluminum column covers are the expansion joints discussed earlier. On most floors the expansion joints were located just above the tops of the windows. However, the column covers were divided with additional expansion joints as they passed over the spandrels at the top and bottom of the 78th floor, as can be seen in the photograph. Recall that the floor height of the 78th floor was 2 ft greater than for the standard floors.

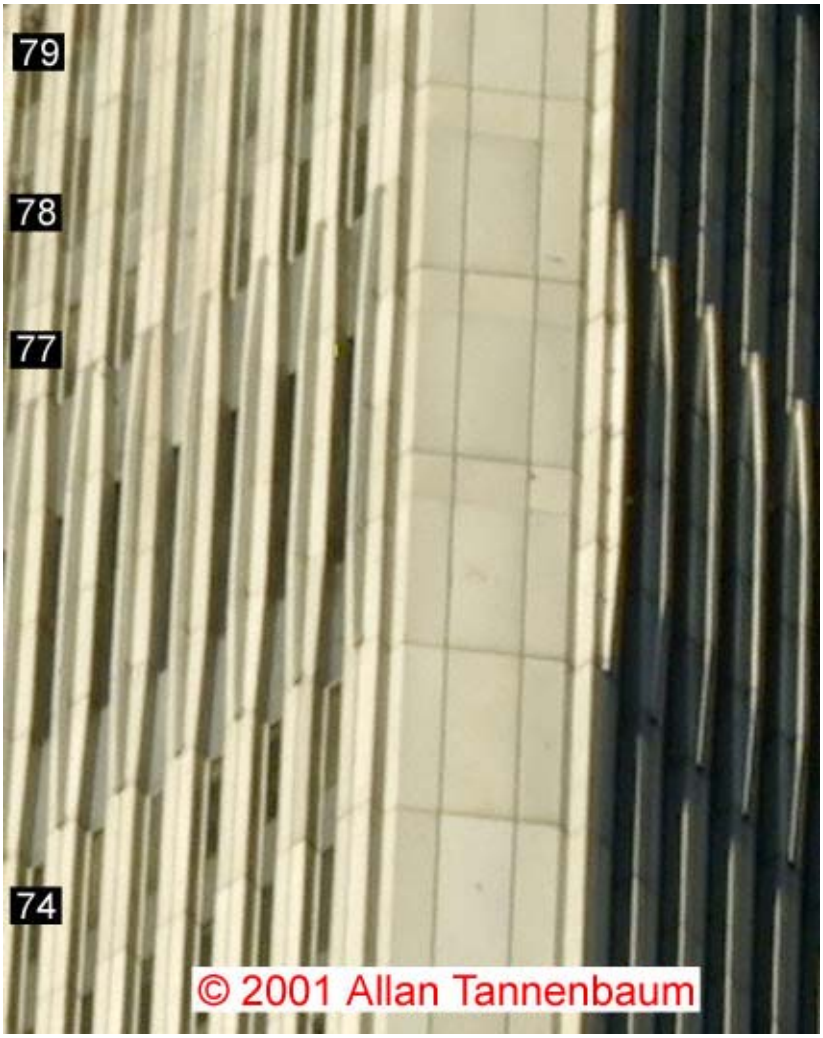


Figure 4-7. This cropped photograph shows the northeast corner of WTC 2 in the vicinity of the mechanical equipment room on the 75th and 76th floors. Floor numbers have been added.

On the tower corners the aluminum covering for a one-story height was formed from 3 sections, as can be seen in Figure 4–7. There were also distinctive expansion joints at the corners, separated by one-story heights. On the typical floors these expansion joints lined up with those on the column covers. The expansion joints on the corners also proved useful for identifying and counting floors. The same caution concerning their location relative to the actual floor slab locations applies as for the aluminum column covers.

The 79th to 106th floors had the typical floor geometry, with 12 ft slab spacing and 4 ft 7 in. high spandrel covers. A view of a portion of the façade in an area on the east face of WTC 1, where the floors had the standard repeating configuration, is shown in Figure 4–8. Portions of six floors are visible. The oblique view of the image allows many of the details concerning the façade design discussed earlier to be identified. The configuration of the aluminum column and spandrel covers relative to the windows can be seen. The 1 in. wide window frames are visible, and the depth of the recessed windows relative to the column covers is clear. The expansion joints for the column covers stand out as a line running along the tops of the windows.

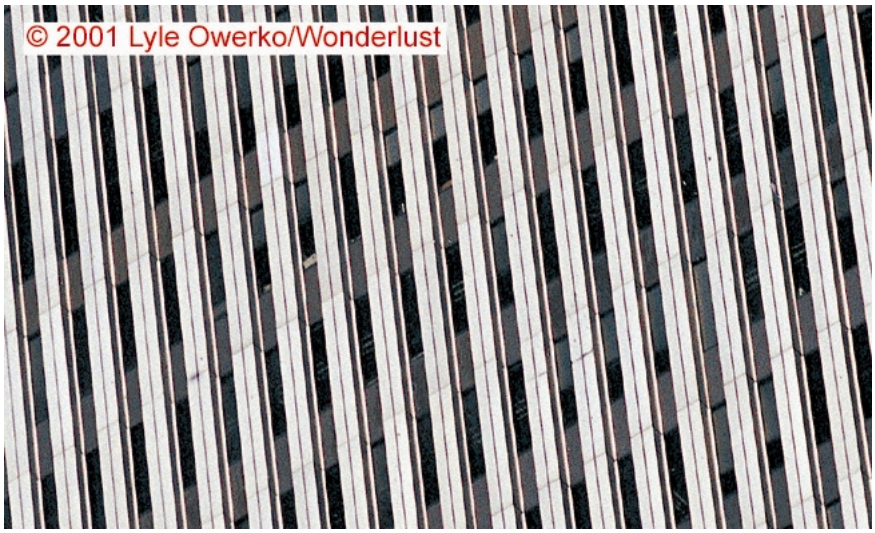


Figure 4-8. This cropped photograph shows an oblique view of a portion of the east face of WTC 2 in an area where the floors have the standard repeating configuration.

The tower structure changed at the 107th floor. In WTC 1 this floor housed the Windows on the World Restaurant, and in WTC 2 it served as an indoor observation deck and visitor center. The spandrel cover height at the base of these floors was 7 ft 1 in. The floor slab was located 17 in. below the top of this spandrel cover. As the column covers passed over the spandrel they narrowed down at the top to their 12 in. width for the 107th floor. The window openings on these floors were, therefore, 28 in. wide, and the heights were 11 ft 7 in. Five sixteenths inch tempered glass was installed in these windows.

The two floors above the 107th floor formed the upper mechanical equipment room. The 109th floor slab was only present in the core. The surrounding area was two stories high. The spandrel covers at the base of the 108th floor were 6 ft 2 in. high. The steel structure changed at the upper floors and alternated between adjacent columns. The column covers reflected this change. One set of column covers passing over the spandrel at the bottom of the 108th floor were the same width as those on the 107th floor, while the other set abruptly narrowed down to 7 in. at the base of the spandrel. Strips of decorative aluminum were added to the outside of the wider columns, yielding a total column cover width of 17 in. As a result, the spacing between column covers on the mechanical equipment room floors was the same as on the 107th floor, 28 in., over most of their length. As the column covers passed over the 7ft 2 in. high spandrel cover at the top of the 109th floor, the process was reversed, and the column covers once again became 12 in. wide as they terminated at the top of the spandrel cover.

Figure 4–9 is a photograph of the upper northwest corner of WTC 1 from the 105th floor to the top of the building. The details described above are clearly seen. The large object on the top of the tower at the corner is a window washer.

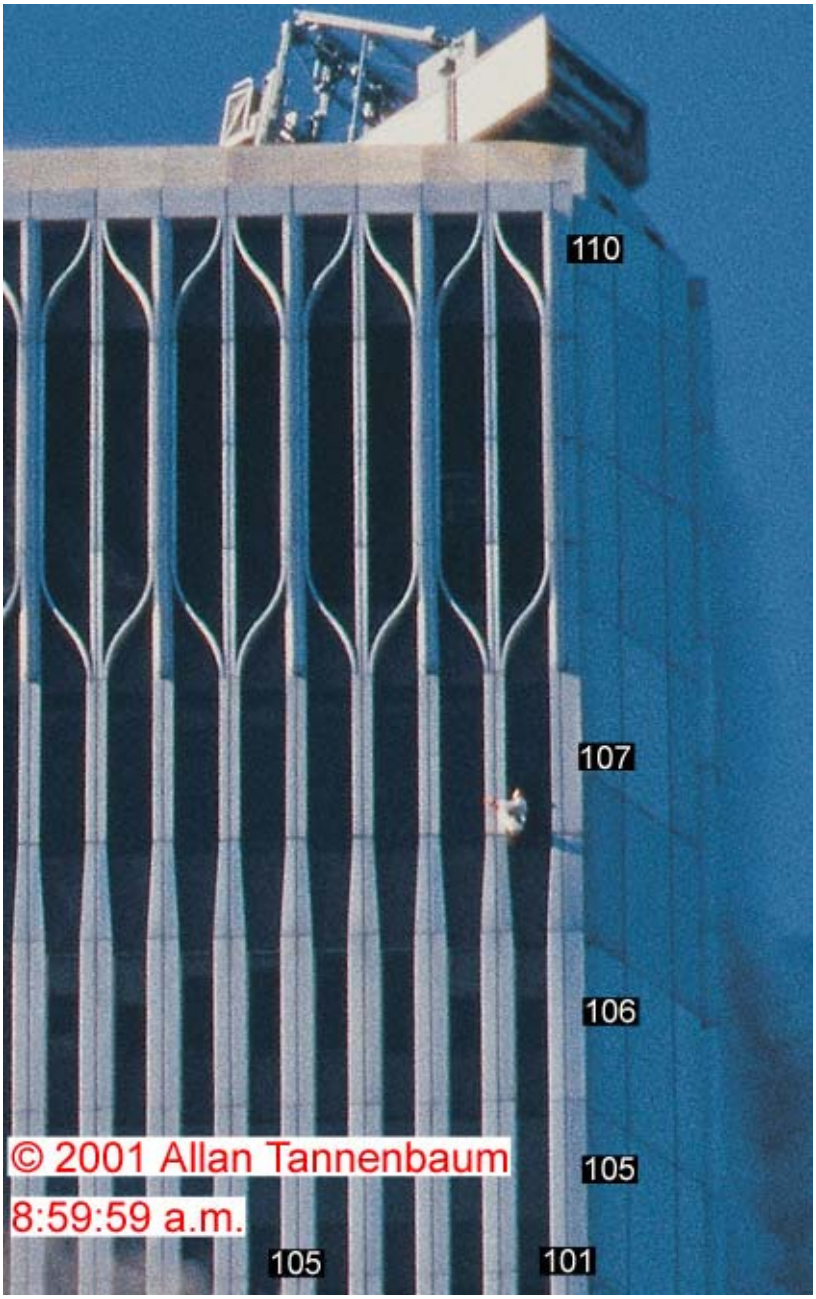


Figure 4-9. This cropped photograph showing an area of the façade on the north face of WTC 1 near the top of the tower was taken at 8:59:59 a.m. A mechanical equipment room is present on the 108th and 109th floors. Column and floor numbers have been added.

4.2.4 Window Numbering

Much of the characterization of the fire behavior in the two towers is based on visual observations related to individual windows in the towers. In order to identify windows, a numbering system based on the column numbering described earlier was adopted. On a given face of each tower the 59 vertical columns formed 58 windows per floor. These windows were assigned the same number as the column to their immediate right, as viewed from the outside. Thus, windows are numbered 1 to 58 from right to left across the face. As for the columns, a particular face is identified by including a 1, 2, 3, or 4 before the window number, and the floor number is included first, separated from the combined face/window number by a hyphen.

4.2.5 Intake and Exhaust Duct Arrangements on Mechanical Equipment Room Floors

Shortly after the aircraft impacts and during the subsequent fires, smoke and/or dust were observed coming from various locations on the mechanical equipment room floors. The smoke was carried to the air intakes and exhausts from the interior by a series of ducts and shafts. The outer façade on the mechanical equipment room floors simply provided openings to a volume located between the façade and an inner wall that contained the louvered intake and exhaust vents for the ventilation system. The distance between the inside of the façade and the inner wall was 4 ft.

Drawings showing the locations of the air inlets and exhausts relative to the façade are included in Appendix A for the mechanical equipment rooms located on the 108th and 109th floors of WTC 1 and the 75th and 76th floors of WTC 2. The locations of the sets of louvers on the corresponding floors in the other tower can be obtained by a clockwise rotation between WTC 2 and WTC 1.

Note that separate intakes were provided for the cores, interiors and peripheries of the floors.

4.2.6 Interior Floor Plan Layouts

For the NIST Investigation some tenants provided detailed plan layouts for many of the floors in WTC 1 where fires were observed. Similar layouts were available for multiple floors in WTC 2. These detailed floor plan layouts were used to generate more simplified layouts that indicate core and perimeter column positions, show locations of elevators, stairways, and vertical shafts in the core and perimeter space, and show the positions of floor-height partitions (e.g, internal walls and column enclosures) in the core and perimeter areas.

These diagrams are collected in Appendix B. Color coding, explained in Appendix B, is used. The partitions near the outer perimeter walls of WTC 1 are particularly relevant because, as shown in Chapter 8, fire spread along the outer periphery of the tower was often slowed by the presence of a room-height partition that terminated at an outer wall.

4.2.7 Tower Geometry and Visual Analysis

There are several features of the towers and their geometry that must be kept in mind when the visual record of the September 11, 2001 disaster is used for technical analysis. The nose of American Airlines

Flight 11 struck WTC 1 near the 96th floor, which was located roughly 1,175 feet above the ground, while United Airlines Flight 175 struck WTC 2 near the 80th floor, which was roughly 990 feet above ground level. As a result, photographs and videotapes shot from the ground were necessarily taken looking upward at angles that decreased as the distance from the towers increased. For locations within roughly a fifth of a mile of the towers, this angle exceeded 45 degrees, and views through windows at the heights of the aircraft impacts were essentially directly observing only the upper regions of the interior at locations very close to the exterior wall. As distances from the towers increased or shots were taken from raised elevations (including aerial shots from helicopters), the depth within the building that could be observed increased. These considerations have particular importance with regard to observing interior fires, as will be discussed further below.

The design of the tower curtain walls also played a crucial role in what could be observed at interior locations from outside the buildings. As already discussed, the aluminum column cover widths on most floors were 18.75 in., and their depths were 16.5 in. For these floors, the open window widths were 19.25 inch, when the one inch frame that held the window in place is accounted for. The open heights of the windows were 7 ft 5 in. on most floors. The windows were located above air conditioning registers that reached a height of 15 in. above the floor and extended 17 in. into the room from the base of the interior walls. The large depth of the columns relative to their spacing meant that they partially obscured the interior for any observations that were not made exactly perpendicular to the façade. This had the effect of further limiting the depth of the interior that could be directly observed. The height of the windows above the floor meant that objects or fires near the floor could not be observed, except by looking down through the windows or as reflections from the ceiling.

The practical effect of these geometric considerations was that the results of visual observations could, and did vary, with the distance and direction from which a given image was taken. The most sensitive characteristic to these effects was the visual determination of the presence of low-level fires burning inside the towers at locations away from the windows. It was often observed that fires that were visible from long distances or when looking down on the towers from helicopters were not visible in images shot from locations closer to the towers or from larger angles relative to the tower face normal.

On the other hand, such characteristics as smoke flowing from windows and flame extension from windows are relatively insensitive to these geometric factors, since these properties are based on observations made outside the windows. The ability to accurately characterize such properties as these depends primarily on the effective distance from which the image was taken, i.e., the resolution of the image. In the context of this discussion relative image distance (near, medium, and far), such as used to characterize image quality in Table 2–1 and Table 2–2, refers to how far away a tower appears to be and not to the actual distance from which a given image was taken. To a large degree, the effective resolution depends on a combination of the distance of the camera from the subject and the magnification used to record the image. Some of the best-resolved (near) images of the towers in the databases were shot from long distances.

4.3 REFERENCES

Rehm, R. G., W. M. Pitts, H. R. Baum, D. D. Evans, K. Prasad, K. B. McGrattan., G. P. Forney. 2002. Initial Model for Fires in the World Trade Center Towers. *Proceedings of the Seventh International Symposium on Fire Safety Science*, International Association for Fire Safety Science, pp. 25-40.

Chapter 5
FIRE CHARACTERIZATION

A number of different observations have been used to provide insights into the behaviors of the fires that developed in the towers after the aircraft impacted World Trade Center (WTC) 1 and WTC 2. The observations utilized and how they were characterized are summarized in the following sections.

5.1 FIRE, SMOKE, AND WINDOW GLASS BREAKAGE

The presence or absence of fire, whether or not smoke is coming from vents, and whether ventilation pathways are open or closed are three properties often used to characterize fire behavior. As discussed below, observations related to smoke flow and the presence of fire were broken into broad classes of smoke flow rate and fire intensity. Windows were characterized as open or closed. Note that these three properties are not independent. As examples, smoke flow generally occurs from open windows, and it is possible for smoke to hide an underlying fire from view.

Since the vast majority of the visual record from September 11, 2001, was created from outside of the towers, the characterizations are based on observations at the peripheries of the towers and provide information primarily for fires burning near the outer walls. The only ventilation pathways characterized were windows on the outer curtain walls of the towers.

For the towers, sufficient visual evidence was available to allow relatively complete time lines to be developed on a window-by-window basis. A goal was adopted to provide determinations in two-minute increments from the time an aircraft struck a tower until the tower collapsed. Not surprisingly, there are certain time periods and building faces that could not be analyzed with such detail due to a lack of suitable images or obscuration. This is particularly true for WTC 1 after WTC 2 collapsed. As a result of the northerly wind direction on September 11, areas to the east and south were enveloped in the smoke and dust cloud generated by the collapse. Images of WTC 1 from these directions are limited following the collapse of WTC 2. The number of images is also limited because most people were fleeing the area at that time.

5.1.1 Window-by-Window Assessment

The key in Figure 5–1 was used as the basis for the window-by-window assessment of fire behavior in the towers. The results were coded in three separate data sheets using Microsoft Excel. The floor and window locations were identified using the numbering system described in Section 4.2.4. Separate files containing the three data sheets were generated for each face of a tower and time analyzed.

KEY FOR ANALYSIS

Sheet #1: Fire Visible

0	No fire		(white)
1	Spot fire		(yellow)
2	Fire visible inside		(red)
3	External flaming		(orange)
9	Not visible		(blue)

Sheet #2: Smoke

0	No smoke evident		(white)
1	"Light smoke"		(gray)
2	"Heavy smoke"		(black)
9	Not visible		(blue)

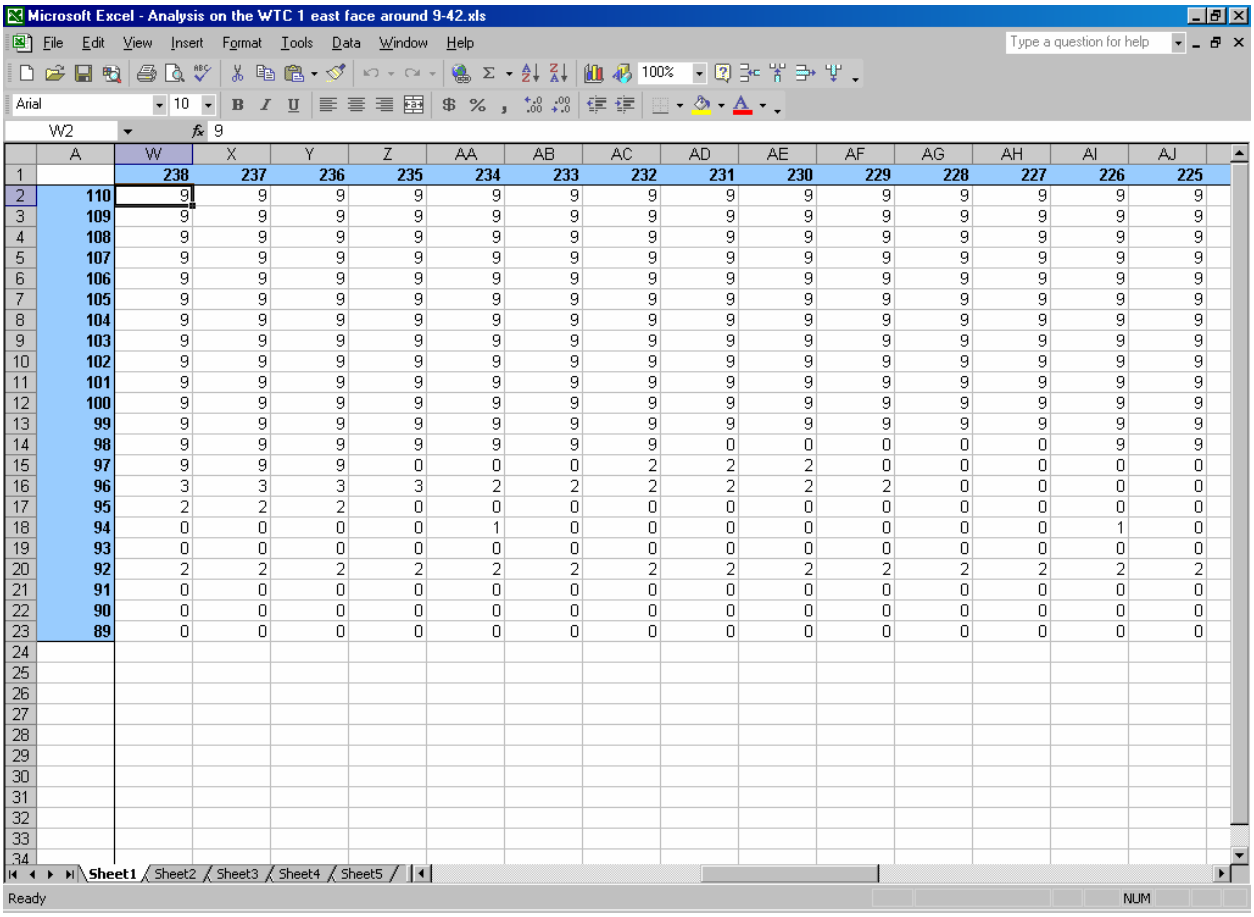
Sheet #3: Windows

0	Window open		(black)
1	Window glass intact		(white)
9	Not visible		(blue)

Figure 5-1. This key was used to describe observations with regard to fire, smoke, and window breakage in Excel data files for individual windows in the two towers. The color codes used to represent the data in façade maps are shown to the right.

The first sheet characterizes observed fire condition. If a particular window could be observed, it was first determined whether a flame was visible or not (assigned a "0"). If a flame was visible, it was further characterized using a scale related to fire intensity. If a small, isolated fire was present, it was identified as a "spot fire" and assigned a value of "1". If a larger fire covering two or more contiguous windows was visible through the window, and flames were not coming out of the window, the fire was identified as "fire visible inside" and assigned a value of "2". If flames were coming out of the window, the fire was identified as "external flaming" and assigned a value of "3". There were many instances where the fire condition could not be determined for a given window for a variety of reasons, including smokeobscuration, insufficient image resolution, or lack of a suitable image for analysis. These windows were assigned values of "9".

As an example, Figure 5–2 shows a portion of an Excel data sheet describing fires (i.e., sheet one) on the east face of WTC 1 around 9:42 a.m. Floors are indicated by the column of vertical numbers along the left-hand edge of the worksheet, and window locations are indicated by the horizontal row of numbers at the top.



	A	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH	AI	AJ
1		238	237	236	235	234	233	232	231	230	229	228	227	226	225
2	110	9	9	9	9	9	9	9	9	9	9	9	9	9	9
3	109	9	9	9	9	9	9	9	9	9	9	9	9	9	9
4	108	9	9	9	9	9	9	9	9	9	9	9	9	9	9
5	107	9	9	9	9	9	9	9	9	9	9	9	9	9	9
6	106	9	9	9	9	9	9	9	9	9	9	9	9	9	9
7	105	9	9	9	9	9	9	9	9	9	9	9	9	9	9
8	104	9	9	9	9	9	9	9	9	9	9	9	9	9	9
9	103	9	9	9	9	9	9	9	9	9	9	9	9	9	9
10	102	9	9	9	9	9	9	9	9	9	9	9	9	9	9
11	101	9	9	9	9	9	9	9	9	9	9	9	9	9	9
12	100	9	9	9	9	9	9	9	9	9	9	9	9	9	9
13	99	9	9	9	9	9	9	9	9	9	9	9	9	9	9
14	98	9	9	9	9	9	9	9	0	0	0	0	0	9	9
15	97	9	9	9	0	0	0	2	2	2	0	0	0	0	0
16	96	3	3	3	3	2	2	2	2	2	2	0	0	0	0
17	95	2	2	2	0	0	0	0	0	0	0	0	0	0	0
18	94	0	0	0	0	1	0	0	0	0	0	0	0	1	0
19	93	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	92	2	2	2	2	2	2	2	2	2	2	2	2	2	2
21	91	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	90	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	89	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 5-2. A portion of the Excel spreadsheet describing fires on the east face of WTC 1 around 9:42 a.m. is shown. The numbers at the left refer to floors, and those at the top are the window numbers.

The local intensity of a fire burning in the towers is roughly correlated to the value it is assigned. In general, a spot fire is gently burning with relatively low heat release. The intensity of fires assigned a value of "2" can vary widely from relatively small fires burning over a range of windows to fires in which flames are large and fill many windows, but do not extend outside of the window. In general, flame extension from open windows, "3", is indicative of an intense fire.

Fire intensity is also related to the ventilation characteristics of a fire. When sufficient air is available in the immediate vicinity of the fire to react with all of the gaseous fuel being generated, the fire is referred to as "overventilated". In some situations it is possible for more gaseous fuel to be generated by solid fuel pyrolysis than can be completely consumed by the available air. In this case, only part of the fuel is burned, and the remaining unburned gaseous fuel can flow to other locations where, if it remains sufficiently hot or an ignition source is available, additional burning can take place when the partially burned fuel encounters gas with sufficient oxygen to support burning. Underventilated burning is often

observed for fires burning in enclosures where fuel can be generated from solid fuels at higher rates than it can be consumed by air flowing into the enclosure. Such unburned fuel can be transported to external vents, such as windows and doors, where additional burning can take place when it comes in contact with fresh air. For such conditions, it is common for flames to extend out of the vent.

The generation of gaseous fuel from a liquid or solid fuel requires heat input that is supplied by heat transfer from the fire. In an enclosure fire, much of the heat released by the fire rises and can fill the volume above the fire. As the temperature of this upper layer increases, it begins to radiate heat back to its surroundings, which in turn can lead to more fuel pyrolysis and, thus, more heat release. This generates a positive feedback situation that can lead to a rapid fire growth process known as flashover. Flashover can be very dangerous because it is possible for a relatively small fire that is burning on a single item in an enclosure to heat the upper layer to a point such that, in a very short period of time, fuel pyrolysis begins to take place on all exposed fuel surfaces below the upper layer, and the entire enclosure fills with flames. So much fuel is generated in a flash over fire that the air entering the enclosure is usually insufficient to burn all of the gaseous fuel that is generated, and external burning takes place at distant locations where the partially burned fuel encounters fresh air. Long flame extension at external doors and windows is one indicator for the presence of a flash over fire within a building.

The second worksheet was used to identify whether or not (assigned a “0”) smoke was flowing from a window. If a smoke flow was observed, it was characterized as being either “light”, assigned a “1”, or “heavy”, assigned a “2”. These designations are qualitative in nature, but, in practice, it was found that consistent ratings were provided by a number of individuals who participated in the generation of the data sheets. Light smoke generally flows from the very top of a window and was often light in color, while heavy smoke flows fill up a larger fraction of a window and was often dark in color. If a particular window could not be observed for some reason, the worksheet cell for this window was assigned a value of “9”.

The third and final worksheet described the condition of windows. If the window glass was broken out it was assigned a value of “0”, and if the glass was intact it was assigned a value of “1”. If a given window could not be observed, it was assigned a value of “9”. The identification of window condition required fairly close up imagery. Since fires and smoke were more easily observed, the number of 9s assigned for the window worksheets tended to be greater for a given time and face.

5.1.2 Worksheet Data Visualization

While the data sheets captured the fire behaviors, it proved difficult to use them to track changes without visualizing the results. Two approaches were developed and used for rapid day-to-day visualization. The first employed a Web-based system that generated color-coded maps of the results. Figure 5–3 shows such a map for the fire data included in the data sheet shown in Figure 5–2. The second approach used the program Smokeview (Forney and McGrattan 2003; Forney, Madrzykowski, and McGrattan 2003) to generate time-dependent animated visualizations of the results. Smokeview was developed at NIST to display the results of fire dynamics calculations. For the current application, it was used to visualize the properties of interest on a three-dimensional representation of a tower façade as a function of time. Because Smokeview allows the point of view to be varied at will, this approach is a powerful means for visualizing the time-dependent behaviors on different faces of a tower. Figure 5–4 shows a frame taken from a visualization in which results from the fire and windows data sheets for WTC 2 were combined.

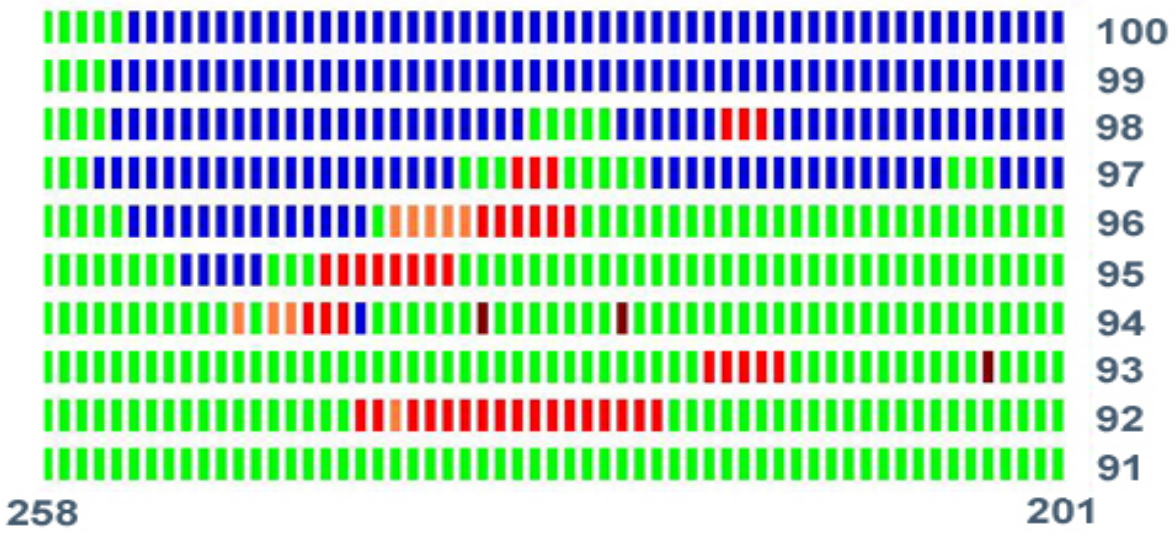


Figure 5-3. A representation of fires for floors 91 to 100 on the east face of WTC 1 around 9:42 a.m. is shown. Results are taken from the Excel spreadsheet shown in Figure 5-2. The color coding is based on numbers assigned in the data sheet as follows: 0-No fire, 1-Spot fire, 2-Fire visible inside, 3-External Flaming, and 9-Can't see.

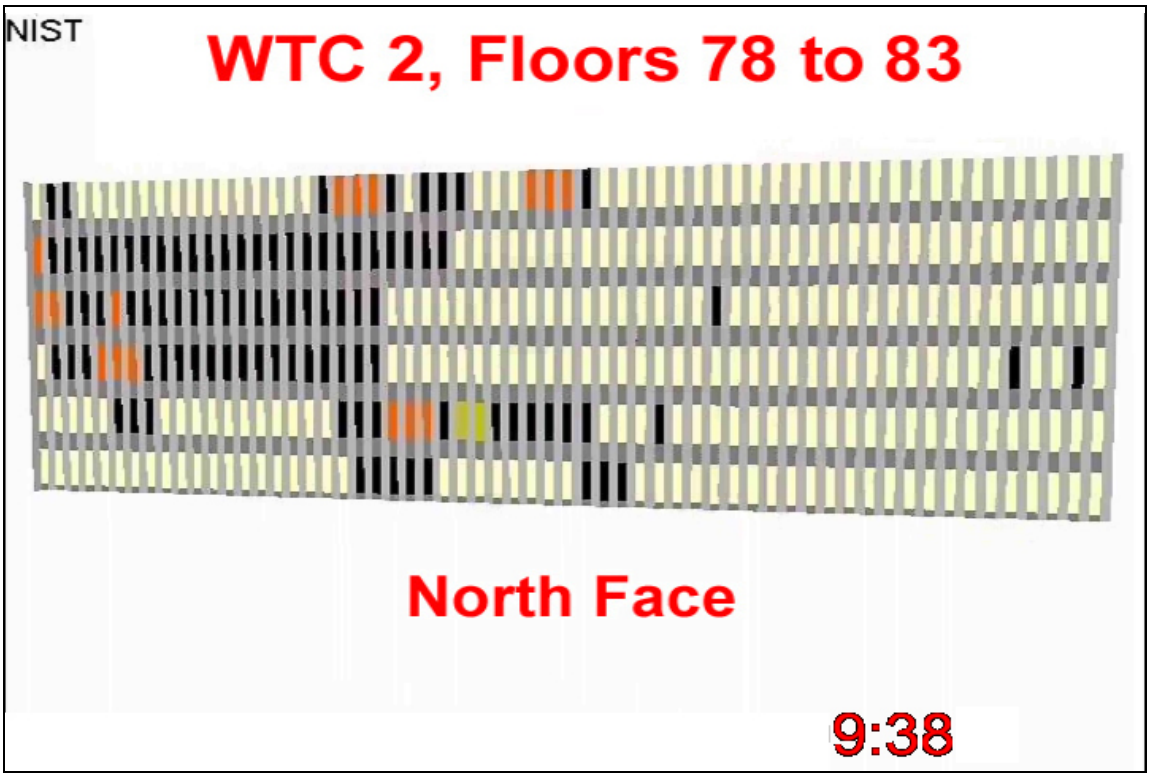


Figure 5-4. A single frame from a time-dependent visualization generated by Smokeview is reproduced. The animation is a three-dimensional representation of the condition of windows and fires on WTC 2 from the time of the aircraft impact at 9:02:59 a.m. until the tower collapsed at 9:58:59 a.m. The color assignments are: – window in place, – missing window, – external flaming, – fire inside, and – spot fire.

For the purposes of this, report a more detailed visualization approach was developed to display the data contained in the worksheets. The properly scaled drawing of the tower façade shown in Figure 5–5 was used as the basis. The dimensions used for the columns and spandrels are those for the aluminum covers and, thus, reflect the actual appearance of a tower. This particular drawing is for WTC 1 and shows the top 22 floors of the tower. It extends from just below the height where the aircraft struck the tower to the top. Column and floor numbers are included for reference. The lines on either side represent the floor slab locations.

Color coding has been used to map the data included in the data sheets onto the façade. Figure 5–1 includes the key used for mapping the different types of data. Figure 5–6 shows an example of a map that combines datasheet results for windows and fires. Individual windows are coded such that if a fire is present or if a value cannot be assigned its color code is displayed. Otherwise, the window code is displayed. For the vast majority of time, this is equivalent to displaying the window data since fires were typically observed only when the window glass had been removed. Very seldom was fire observed through window glass that was still in place.

Appendices C to J provide maps based on all of the data sheets that were generated. Two façade maps are provided for each tower face and time analyzed. The first combines window and fire results in the manner shown in Figure 5–6. The second displays the smoke results using the color coding shown in Figure 5–1.

5.2 FORMATION OF STREAMERS AND SMOKE MARKS ON COLUMNS

During the review of visual material, two additional behaviors were identified that seemed to correlate with the local fire intensity at the periphery of the buildings. One of these was the frequent release of "streamers" during periods of active burning. Figure 5–7 shows three streamers that fell nearly simultaneously from the south face of WTC 1. The exact time of this photograph is not known. As is clear from the photograph, when the lighting was correct the streamers could be observed from long distances.

The source of the streamers was identified by observing their formation and behavior in videos. Close-ups showed that the streamers formed when a flaming material located at the top of a window fell. Once released, the flames quickly extinguished, but the material apparently continued to smolder, since intense white smoke was released that formed the streamer as the material floated downward. These streamers were particularly visible when illuminated by sunlight.

Figure 5–8 shows a series of four frames taken from a video that recorded the formation of a streamer on the north face of WTC 1. At 8:56:43 a.m. two small areas of flame are visible at the tops of windows 97-142 and 97-143. At 8:56:54 a.m. the flame at the top of window 97-142 was still in place (note that window 97-143 was out of the frame at this point). Very shortly afterward, the flame at the top of window 97-142 began to fall. The frame at 8:56:55 a.m. was taken 1.2 s later. The flaming object can now be seen near the base of window 97-142. This object extinguished very rapidly and formed the streamer that is visible curving downward at 8:56:56 a.m. near the base of the 96th floor. Note that the area of fire at the top of window 97-143 is still in place.

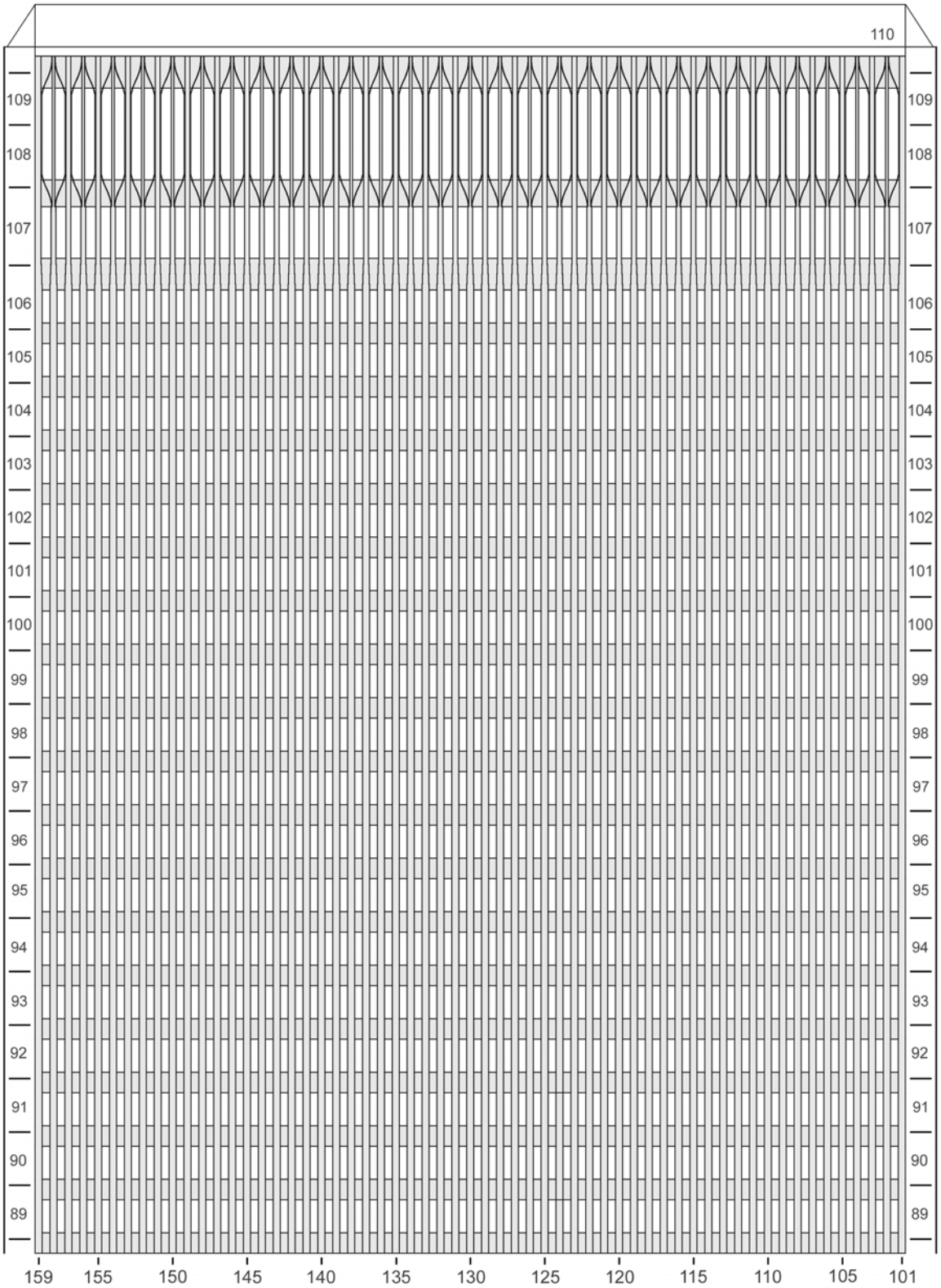


Figure 5-5. A properly scaled representation of the northern façade of WTC 1 is shown. Column and floor numbers are included. Horizontal lines on either side indicate the locations of floor slabs.

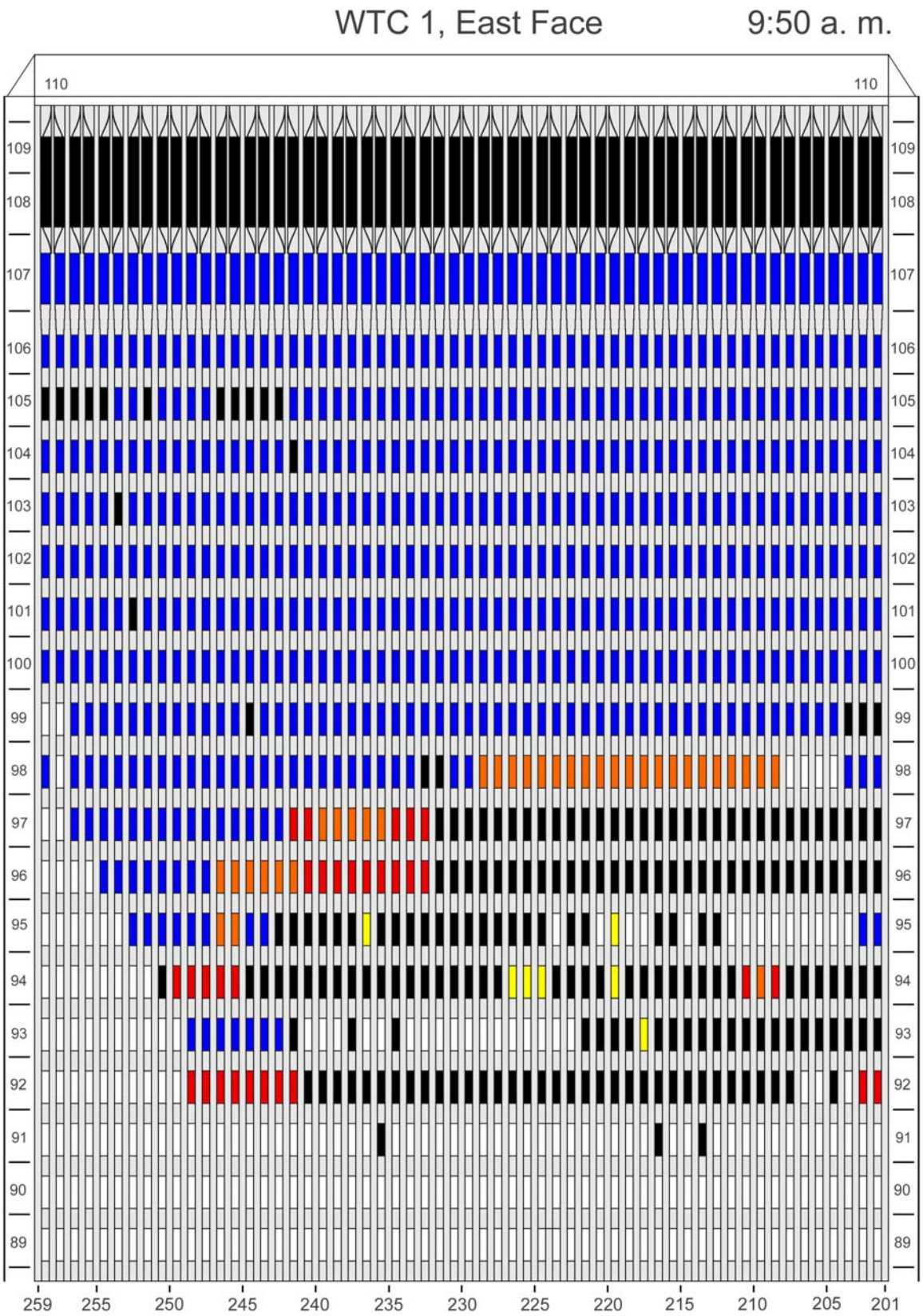


Figure 5-6. An example of a façade drawing combining data for window condition and fires is shown. The data is for the east face of WTC 1 around 9:50 a.m.

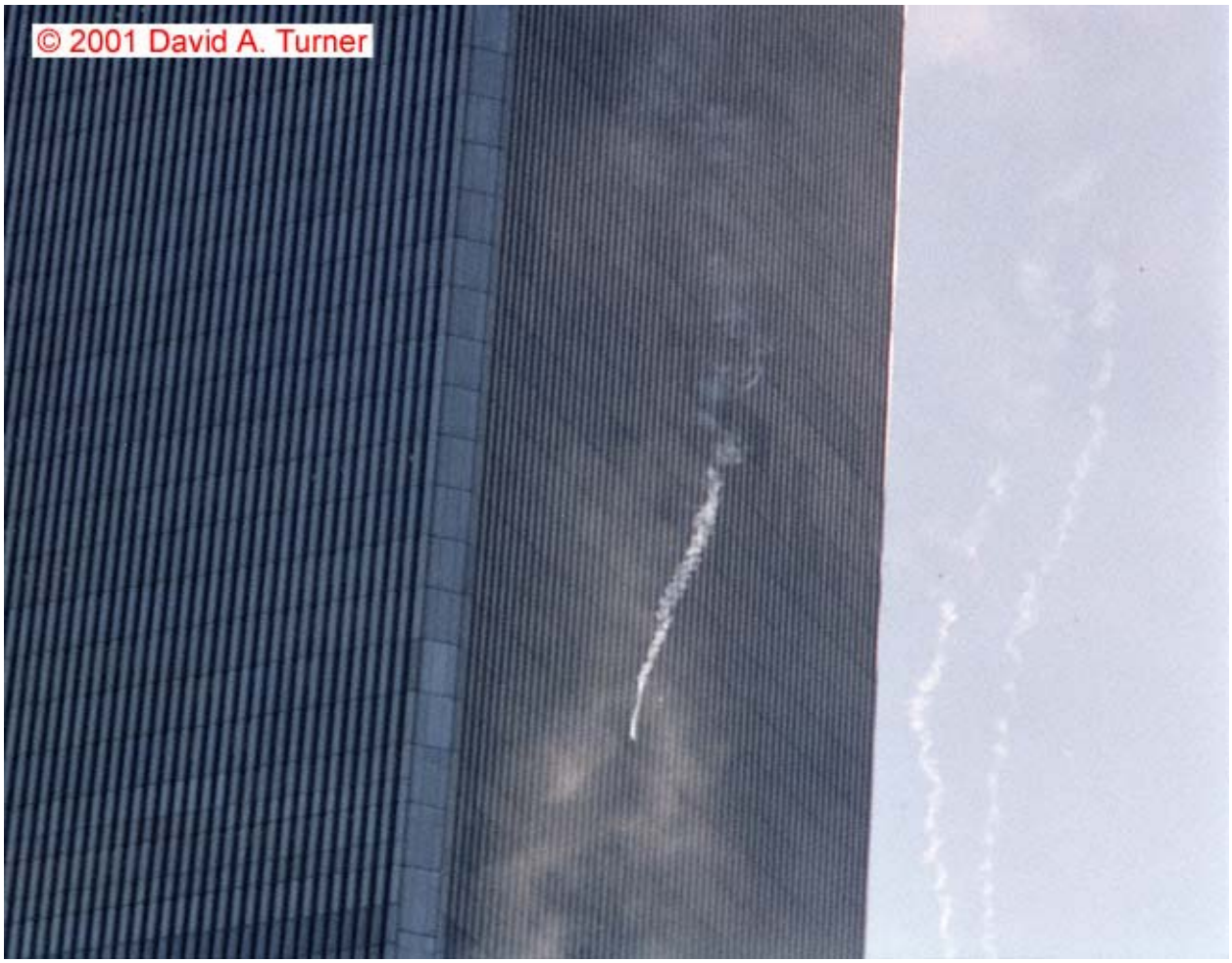


Figure 5-7. This cropped and enhanced photograph shows the west and south faces of WTC 1. An intense streamer is falling near the south face of the tower, and two additional streamers have already fallen through the image to the south. The exact time of this photograph is unknown.

Relatively small fires at the tops of windows, such as those in Figure 5–8, were a common feature when active burning was present near the outer walls and the aluminum façade was intact. Such fires were often the only flames visible in a given window. Figure 5–9 shows a frame taken from a video in which a number of such fires burning on the 96th and 98th floors of the west face of WTC 1 are visible. As discussed in Section 8.5, the fires on this floor appeared to burn with low intensity. Nevertheless, the material at the tops of the window was exposed and ignited.

In Section 4.2.2, it was noted that polyurethane was used to thermally insulate the areas above the aluminum head casings located just inside and above the windows. Polyurethane is a flammable polymeric material that is easily ignited. It is likely that the high-temperature gases generated by nearby fires either first ignited the polyurethane above the head casing, which, in turn, resulted in the head casing dropping down to expose the burning material, or first caused the head casing to drop down, exposing the polyurethane, which was then ignited. For either scenario the result is the same, a substantial area of flaming polyurethane becomes exposed near the top of the window. In Figure 5–9, a number of what appear to be thin lines are visible near the top of windows on the 96th and 98th floor. In some cases

flames are visible on top of these lines, while in others only the lines are apparent. A likely explanation for these observations is that the thin lines are the edges of aluminum head casings that have dropped down from above the windows and that the fires seen above the lines are burning on the polyurethane located above the head casing. The large number of isolated fires seen at the tops of windows suggests that the polymer burned for a period of time before falling and forming streamers.

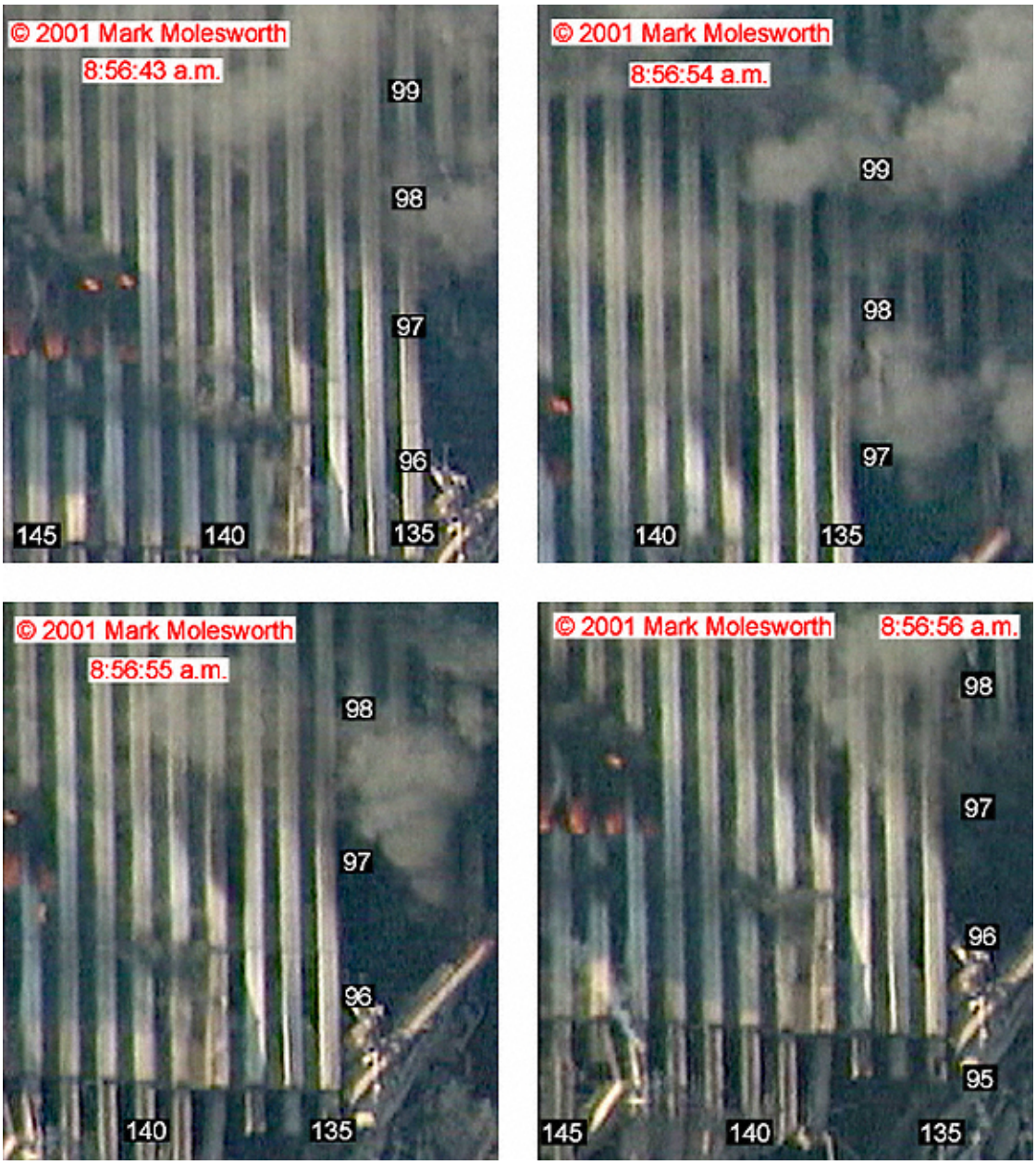


Figure 5-8. A series of four cropped frames from a video were recorded during the period when an isolated area of fire at the top of window 97-142 on the 97th floor dropped and formed a streamer. The intensity levels have been adjusted. Column and floor numbers have been added.

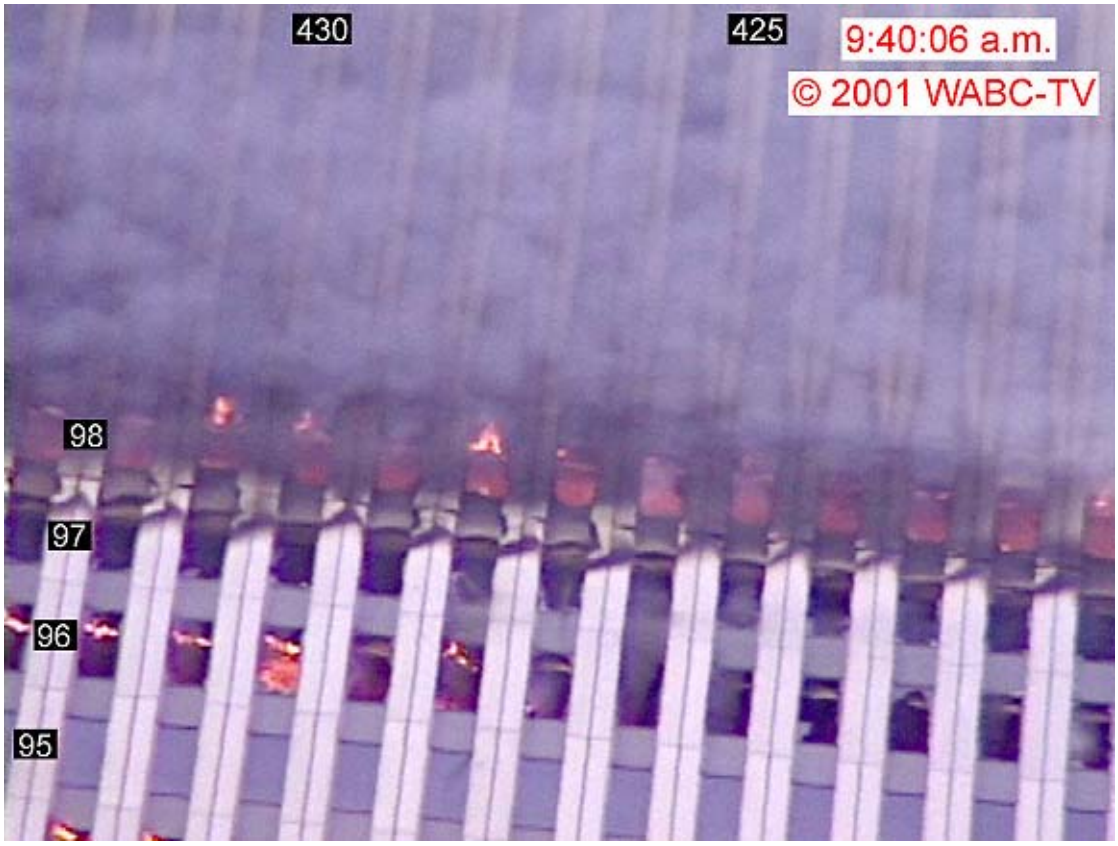


Figure 5-9. This close up view of the west face of WTC 1 was captured from a video recorded at 9:40:06 a.m. It has been enhanced by adjusting the intensity levels. Column and floors numbers have been added.

The second behavior was the formation of various types of distinctive marks on the aluminum that covered the external steel columns. These marks were created by flows of fire gases over the column covers as they exhausted from adjacent open windows. The type of mark created was found to depend on the nature of the nearby fire. At some locations of active fire, either no visible smoke exhaust or only light smoke was noted, even though the presence of fire and/or high temperatures was indicated by direct observation, the opening of windows, or other thermal effects (e.g., melted aluminum on the building façade). For this type of burning behavior either no marks or narrow black bands were observed on the aluminum column covers near the tops of the windows. Occasionally, it appeared as if smoke was escaping from expansion joints between the aluminum column covers adjacent to the tops of the windows. This type of fire-gas flow could also form smoke lines on the column covers.

At other locations on the fire floors, a deep layer of heavy smoke was released from a window, but no external flames were observed. For this type of smoke flow it was common to observe a series of striped lines across the column cover that reached down to where the bottom of the smoke layer had been located.

In contrast to the two types of smoke flow described above, there were extensive areas of the exterior façades over which local interior fires were accompanied by significant flame extension from open windows. The flaming gases exiting a window are naturally buoyant. Due to the thickness of the columns and their aluminum covers, the flames curved upward as they passed around the column upon

exiting a window. This flow pattern resulted in the formation of distinct patterns on the columns near the base of the burning flow that were easily identified. The marks resulted from deposited soot on the underside of the flames. Due to their shapes, this type of column pattern will be referred to as a "caret." Figure 5–10 show examples of carets observed on the 96th floor of the east face of WTC 1. Variations in the heights of the patterns are evident from window to window. The location of a caret on a column cover provides an indication for the distance between the top of the window and the lower region of the burning gases leaving the window. This, in turn, reflects the depth of the layer of rich combustion gases behind the window. Typically, a deeper layer corresponds to a local region of higher combustion gas formation and temperature and generally indicates a location of more intense burning.

Figure 5-10. This cropped photograph shows a portion of the east face of WTC 1 at 9:49:59 a.m. The image has been rotated and enhanced by adjusting the intensity levels. A number of carets are visible near the tops of windows on the 96th floor. These carets were created during periods of external flaming from adjacent open windows. Column and floor numbers have been added.

5.3 UNUSUAL BURNING AND SMOKE BEHAVIORS

During the review of the image databases, and particularly videos, a number of observations were made of behaviors that are not characteristic of "typical" building fires. Some of these observations involved the fire behavior. These included examples of extremely rapid apparent fire spread (based on fire appearance at windows on the outer façade). Generally, building fires go through a cycle of growth, intense burning, and decay which takes place on time scales on the order of tens of minutes. There were fires in the towers that burned for much longer periods than this, perhaps indicating the presence of unusually high fuel loads. There were also occasional flare ups of flames suggesting some change within the towers. Observations such as these are described in Chapter 8 and Chapter 9.

In both towers, there were occasions when large amounts of smoke and/or dust and sometimes flames were pushed simultaneously out of multiple open windows covering several floors and faces of the tower.

These events were typically short lived (on the order of a few seconds) and will be referred to as "puffs". The occurrence of puffs suggests the generation of pressure pulses within a given tower that are transmitted through open pathways to remote locations and drive smoke and other material from the tower. The pressure changes required to generate such puffs are not large and can be generated by events that result in relatively small volume changes, such as collapsing walls and ceilings, partial floor collapses, and sudden openings of ventilation pathways (e.g., an internal door). Some of the pressure pulses coincided with obvious events, such as an aircraft impact on or collapse of the other tower and are relatively easy to understand. Others occurred without outward indications of their sources. Since these puffs (pressure pulses) may be an indication of structurally important changes taking place within the towers, their occurrences have been documented.

5.4 HUMAN OBSERVATIONS AND BEHAVIORS

It was widely reported that numerous people either fell or jumped to their deaths on September 11, 2001. People also took actions, such as breaking out window glass, which had the potential to influence the fires and even modify the effects of the fires within the towers. These human behaviors provide unique, albeit imprecise, insights into the local conditions within the towers. Observations of human behavior are documented in this report in order to better understand the behavior of the fires. This documentation includes identifying upper-floor windows that were broken out by people and tabulating observations concerning falling human beings.

5.5 REFERENCES

Forney, G. P., and K. B. McGrattan. 2003. *User's Guide for Smokeview Version 3.1*: A Tool for Visualizing Fire Dynamics Simulation Data. NISTIR 6980. National Institute of Standards and Technology. Gaithersburg, MD.

Forney, G. P., D. Madrzykowski, K. B. McGrattan, and L. Sheppard. 2003. Understanding fire and smoke flow through modeling and visualization, *IEEE Computer Graphics and Applications*, vol. 23, p. 6-13.

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Chapter 6
OBSERVATIONS AND ANALYSIS RELATED TO THE AIRCRAFT IMPACT ON WORLD TRADE CENTER 1

6.1 INTRODUCTION

American Airlines Flight 11 struck the north face of World Trade Center (WTC) tower 1 at 8:46:30 a.m. By coincidence, at least two people were making video recordings nearby and videotaped the aircraft as it approached and struck the tower. National Institute of Standards and Technology (NIST) has received videotapes from three additional videographers who began recording within 35 s of the impact. Several photographers recorded images of the tower shortly after the impact. In addition, numerous close-up photographs of the different faces allowed an assessment of the exterior damage to the building caused by the collision. This chapter summarizes observations and analysis derived from this visual record. Topics addressed include a time line for events immediately following the impact, an estimate for the speed of the approaching aircraft, the immediate external damage (as evidenced by visual evidence from outside) to the tower, and the fire behavior in the immediate aftermath. The visual record has been used by other NIST Investigation Projects as the basis for independent or extended analyses. These analyses are discussed in other Investigation reports.

6.2 TIME LINE FOR THE IMPACT OF THE AIRCRAFT WITH WTC 1 AND SUBSEQUENT EVENTS

One of the videos showing the aircraft impact was recorded from the north and therefore observed the aircraft as it approached and entered the tower, as well as the immediate effects. This video has been used as the basis for the time line of events included in Table 6–1.

Table 6-1. Time Line for Events Immediately Following the Aircraft Impact on WTC 1.

Time (s)	Observation
0	Nose of aircraft strikes tower
0.03	Bright flash at front of aircraft
0.20	Aircraft tail disappears into building
0.43	Dust cloud begins to form on north face, appears to be ignited
0.67	Dust cloud apparent near the center of the east face
1.43	Dust cloud appears in vicinity of the upper mechanical equipment room floors (108th and 109th floors) near the center of the north face
1.77	Dust clouds appear at the upper mechanical equipment room floors (108th and 109th floors) at two locations on either side of center of the east face
3.43	Fire appears from behind southeast corner of tower
4.40	Area of fire evident on the east face
9.43	Fireballs appear to extinguish

Figure 6–1 shows a sequential series of frames taken from two videos that provides a visual record of the collision and subsequent events. Frame a) in the series was recorded just as the nose of the aircraft struck the tower at 8:46:30 a.m. The second, b), was recorded one frame later and shows a bright flash generated by the collision. This flash was short lived, being observed in only one field of the video (i.e., for 1/60 s).

Frame c) was recorded 3.5 s after the aircraft impact. It shows many of the features highlighted in Table 6–1. Dust clouds have formed on the north and east faces of the tower. These clouds appear to consist primarily of dust and other small debris at this time, since little flame is evident, and they do not have the dark color characteristic of smoke from burning aviation fuel. Some larger debris is evident falling below both dust clouds. Large flames can be seen at the southeast corner of the tower extending from behind the building (presumably emanating from the south face, see additional discussion of this point later in this section).

In Frame c) dust is visible exiting areas of the mechanical floor at the top of the tower on the 108th and 109th floors. On the north face the dust is coming from near the center. The diagram of ventilation louver locations for this face, shown in Figure A-1, in Appendix A indicates that this is close to a fresh air intake that provided air for the peripheral areas of the floors where the aircraft impacted. On the east face, the dust appears to be emanating from two areas, one near the center and one further to the south. The ventilation louver map for the east face in Figure A-2 shows that an exhaust louver was located on the upper mechanical floor near the center of this face, while both a large spill louver and an elevator supply intake were present further south.

Roughly 5 s later (frame d), the dust clouds on the north and east faces have grown substantially. The north-face dust cloud is considerably larger, and extensive flames can now be seen throughout the cloud, interspersed with the white dust. A large amount of debris can be seen falling below the aircraft impact location. The prevailing wind has begun to blow the external fireball and falling debris across the north face toward the east. Flames on the east face seem to be present only near the building, suggesting that much less aviation fuel has been expelled on this face. A small region of fire is still visible extending beyond the southern edge of the east face, i.e., apparently coming from the south face of the tower.

At 10.07 s following the aircraft impact (frame e), the fireball that formed on the north face appears to have dissipated, leaving a “thermal” that is continuing to rise. For this report, the word “thermal” is used to identify a mushroom-shaped buoyant plume generated by the rapid release of a large amount of heat. The dust cloud created by debris falling from this face has developed a tube-like appearance and has been blown to the east edge of the tower. A bright region of flame is present across much of the region where the aircraft entered. The dust cloud on the east face has continued to expand, and no flames are now evident within this cloud.

Figure 6-1. A series of frames from videos shows American Airlines Flight 11 striking WTC 1 and the immediate aftermath. Times relative to the aircraft impact time are shown in the upper left-hand corner.

Figure 6–1. A series of frames from videos shows American Airlines Flight 11 striking WTC 1 and the immediate aftermath. Times relative to the aircraft impact time are shown in the upper left-hand corner (continued).

The next frame, (f), was recorded roughly 8.5 s later. At this time the dust-filled cloud sinking below the impact area and the rising thermal created on the north face have been blown further by the wind and are now more than a building width to the east of the northeast corner of the tower. The tube-like cloud of debris extends downward many stories and has developed the appearance of a concentrated vortex. The wind has also blown the debris away from the east face, and this face can now be observed. Substantial fires are now evident on the north and east faces in areas where the dust plumes were initially observed. Even though frame (f) is more zoomed out than frame (e), it is evident that the fire on the north face is much smaller than it was just 8.5 s earlier, suggesting that fires due to the aviation fuel released by the aircraft impact are already beginning to burn out. A thermal can be seen rising behind WTC 1, which provides additional evidence that the south face was damaged by debris passing through the tower.

The following frame (g) was recorded 27.03 s after the aircraft impact by a second videographer located to the northwest of the tower. It provides a close-up view of the aircraft impact area on the north face. Substantial fire is evident in the large opening near the center of the face where the body of the aircraft struck. The horizontal extent of the flames is considerably reduced from that seen 17 s earlier in frame (e). At least three white streamers are falling from the vicinity of the aircraft impact. Such streamers were frequently observed over the course of the fire. A likely explanation for their formation is discussed in Section 5.2.

In the final frame, (h), shown in Figure 6–1, which was recorded 30.37 s after the aircraft impact, the videographer has zoomed out to show the north and west faces of the tower. On the north face flames are still evident in the area of the aircraft impact, and a distinct streamer can also be seen. Smoke is coming from the west face at several isolated positions, but the damage appears to be much less extensive than occurred on the east face, and no flames are evident. A dust plume can be seen near the center of the west face at the top of the building in the vicinity of the mechanical equipment room located on the 108th and 109th floors. Figure A-4 shows that there were several exhaust louvers in this area. A smoke plume is rising from the south face, and smoke seems to be flowing from the building from a location at the southwest corner.

None of the videos that recorded the aircraft impact or the immediate period afterward provided views of the south face of WTC 1. However, a photographer located to the southeast of the tower did take still images of the south face shortly after the aircraft impact. One of these images is reproduced in Figure 6–2. This image was recorded at 8:46:55 a.m., i.e. 25 s after the aircraft impact. A debris-filled vortex can be seen on the right side of the photo. This vortex was prominent in videos shot from northerly directions. It formed on the north face of WTC 1 and was then carried toward the southeast by the prevailing wind.

The photograph shows both WTC 1 and WTC 2, with the south face of WTC 1 partially hidden by WTC 2, which is in the foreground. An area of intense fire is apparent on the western side of the south face of WTC 1. This fire is in the vicinity of the 96th floor. An area of falling debris can be seen moving in front of the south face of WTC 2. This debris fell from the south face of WTC 1 and was blown to this location by the prevailing wind. Above the debris cloud a small thermal can be seen rising above the tower. This thermal must have resulted from a fireball that formed on the south face of WTC 2 following the aircraft impact. The occurrence of this fireball is consistent with the area of fire on the south face described above. The formation of a fireball on the south face indicates that a significant amount of aviation fuel from the aircraft passed all the way through the tower and burned on the other side.

Figure 6-2. View of the WTC towers shot at 8:46:55 a.m. from the southeast shortly after American Airlines Flight 11 struck WTC 1. A dust-filled vortex is visible on the right side. A second area of falling debris can be seen passing on the south side of WTC 2. Significant fires are present on the west side of the south face of WTC 1, which can be seen to the left and behind WTC 2.

The presence of significant burning on the south face of WTC 1 is also indicated by the photograph shown in Figure 6–3 that was taken 26 s (i.e., 8:46:56 a.m.) after the aircraft impact on the tower. The thermal formed by the fireball on the rear side can be seen behind the large thermal formed by the fireball on the north face. A large amount of smoke is rising from behind the tower, consistent with the heavy fire seen on the south face in Figure 6–2. This photograph also provides an excellent view of the vortex generated on the north face of WTC 1 by the aircraft impact. The vortex is large, extending all the way down to near the ground. It has been transported a large distance by the prevailing wind. Even at this distance, the large fire burning inside the impact cavity in the tower is evident. This is consistent with Figure 6–1 (g), which was recorded at nearly the same time.

Figure 6-3. A cropped photograph taken from the north shows the WTC towers at 8:46:56 a.m., i.e., 26 s after the aircraft impact on WTC 1. Colors have been adjusted.

6.3 ESTIMATED AIRCRAFT SPEED BASED ON SIMPLE ANALYSIS OF VIDEO OF THE AIRCRAFT IMPACT

By using a video shot from the north that shows the impact of the aircraft on WTC 2 (see frames a and b in Figure 6–1), it was possible to estimate the average speed of American Airlines Flight 11 as it entered the tower. This was done by determining the period between the time when the nose of the aircraft first struck the façade and the time when the rear edge of the vertical stabilizer at the rear of the aircraft entered the building. This period was determined from the number of video fields (1/60 s per field) required. The velocity can then be determined by dividing the known length of the aircraft by this time. The analysis assumes that the velocity vector is aligned along the aircraft. Based on the observed flight path, this is a good assumption.

A review of the video of the aircraft impact showed that the passage of the aircraft into the building required 14 video fields, or 0.233 s, with an uncertainty of ± 0.017 s based on a one field uncertainty in the determination. Dividing the known length of the aircraft, 159.2 ft (from the nose to the end of the

vertical stabilizer at the rear of the aircraft), by the passage time yields an average speed of 159.2 ft / 0.233 s = 683 ft/ s ± 50 ft/s or 466 mph ± 34 mph. The value can be compared with a value of 443 mph ± 30 mph reported in NIST NCSTAR 1-2B that was determined using a more sophisticated motion analysis of videos available in the data base. The two values agree within the reported uncertainties. These speeds are compared with other published estimates in NIST NCSTAR 1-2B.

6.4 ASSESSMENT OF DAMAGE DUE TO THE AIRCRAFT IMPACT AND SUBSEQUENT FIREBALLS BASED ON VISUAL EVIDENCE FOR WTC 1

6.4.1 Damage on the North Face Due to the Aircraft Impact

Frame (a) of Figure 6–1 shows American Airline Flight 11 at the moment it collided with WTC 1. It was not possible to estimate the initial damage to the tower using the video from which this frame was taken due to the distance, but numerous close-up videos and photos of the north face were taken during the time between the collision and the collapse of the tower at 10:28:22 a.m.

Figure 6–4 shows a relatively close view of the aircraft impact area on the north face of WTC 1 at 8:47:22 a.m., i.e., 52 s after the collision. This image was taken from a video, so the resolution is limited. Figure 6–5 shows another view of the same area taken around 9:30 a.m. Since Figure 6–5 was shot as a photograph on film, the resolution is much higher than in Figure 6–4. Damage to the steel façade and aluminum facing is apparent in both images. Comparison of the two images shows that the appearance of the damaged area is similar in both, which means that images recorded at different times can be used to assess the damage caused by the aircraft impact. By using several high-resolution images, a detailed façade map of the damage to the perimeter wall of the tower caused by the aircraft impact was prepared.

A drawing of the damage to the steel façade of WTC 1 was included in the FEMA World Trade Center Building Performance Study (McAllister 2002). The current map is in close agreement with this earlier assessment. Figure 6–6 shows a drawing that represents this damage. It is similar to that included in the FEMA report, but incorporates several minor changes that better reflect the geometry of the north face of WTC 1 in the vicinity of the aircraft impact.

By inspection of Figure 6–4 and similar images, it was observed that the wing tips and the top of the vertical stabilizer at the tail of the aircraft damaged the aluminum column covers on the steel façade without cutting through the steel below or completely removing the covers. Using these images, it was possible to map out locations on columns where the wingtips and the vertical stabilizer struck the tower. These locations were then transferred to the representation of the damaged steel façade shown in Figure 6–6 and are represented by dashed lines, with wings to the right and left and the vertical stabilizer in the center. The good agreement between the damage pattern and the wing-tip locations is evident. It was reported in the FEMA report (McAllister 2002) and widely in the media that American Airlines Flight 11 struck floors 94 to 98 of WTC 1. The dotted horizontal lines on the left side of Figure 6–6 indicate the locations of concrete floor slabs. It can be seen that while the tip of the left wing of the aircraft struck very close to the base of the 94th floor, the wing end marked column 153 at the very top of the 93rd floor. It is evident from the Figure that the right wing actually struck well up on the 99th floor on column 109. The impacted floors therefore range from the 93rd floor to the 99th floor.

Figure 6-4. This image of the north face of WTC 2 is a frame taken from a video recorded at 8:47:22 a.m. Column and floor numbers have been added.

Figure 6-5. A close-up image of the north face of WTC 1 recorded around 9:30 a.m. shows the area of WTC 1 where the aircraft impacted. Column and floor numbers have been added.

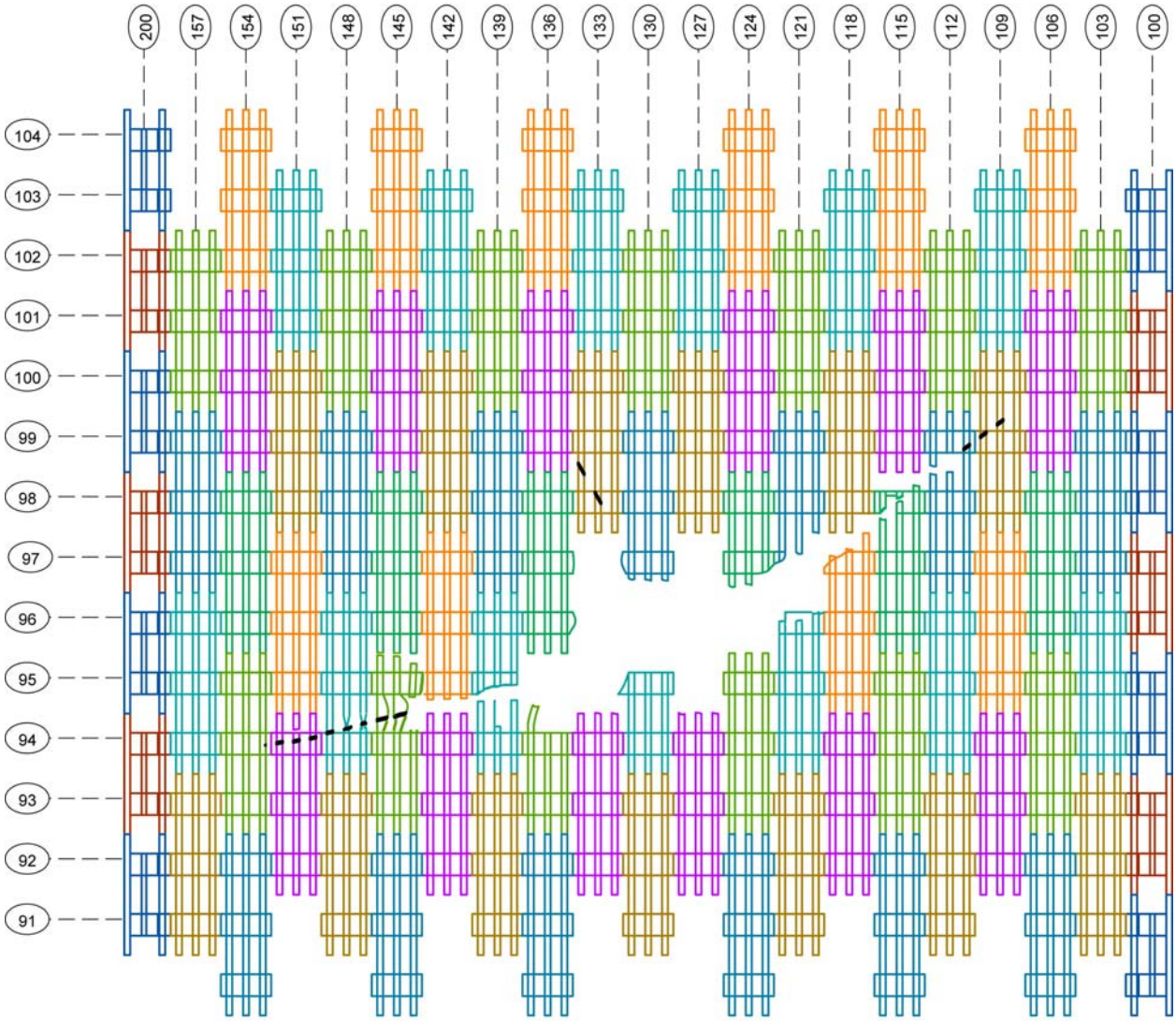

Figure 6-6. A drawing shows the aircraft impact damage to the steel façade of WTC 1. The dark dotted lines indicate locations where the wings and vertical stabilizer of the aircraft marked the aluminum cladding on columns.

In Figure 6–7 a scaled outline of a Boeing 767-200ER has been superimposed on the damage diagram for the north face. The inclination of the impact damage and aircraft overlay indicate that the aircraft was banking as it struck the tower. This is consistent with the appearance of the aircraft as it collided with the building (see Figure 6–1a).

The outline used in Figure 6–7 is for an aircraft located on the ground. During flight, the shape differs due to lift applied to the wings and other stresses placed on the aircraft by flight maneuvers. The position of the aircraft in the Figure has been adjusted to provide good agreement with the observed damage pattern and the wing and vertical stabilizer marks. The drawing indicates that the nose of the aircraft

struck close to the center of the face near columns 129 and 130 at a height that was near the concrete floor slab for the 96th floor.

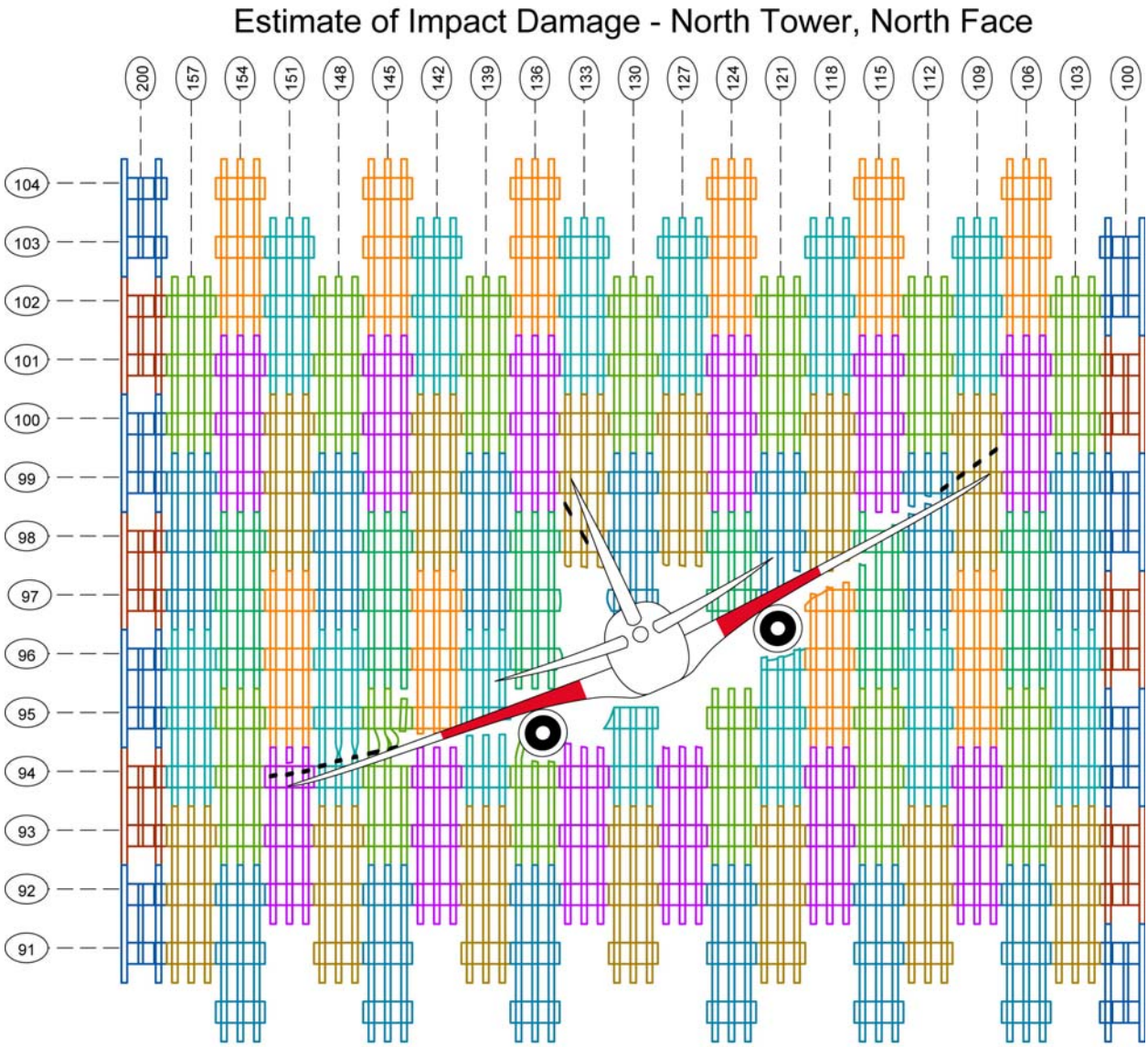

Figure 6-7. A scaled outline of a Boeing 767-200ER is superimposed on the damage diagram shown in Figure 6–6. The position of the aircraft has been adjusted to give the best match with the damage pattern and marks showing where the wing tips and vertical stabilizer struck. The red areas correspond to the approximate locations of fuel on the aircraft based on an analysis reported elsewhere (NIST NCSTAR 1-2B).

From Figure 6–5 and Figure 6–6 it can be seen that the passage of the aircraft through the north face façade broke out two complete steel panel sections (columns 126 to 128 and columns 132 to 134 extending from the middle of the 94th floor to the middle of the 97th floor) as well as portions of several other panel sections. Most likely these were pushed into the building, since there is no visual evidence that they landed on the ground. The end of one of these panel sections can be seen sticking out of the building at the bottom of the opening in the figures.

Similar drawings to Figure 6–6 and Figure 6–7, showing additional details of the damage to the perimeter steel structure on the north face and incorporating overlays of the aircraft outline, are included in NIST NCSTAR 1-3 and NIST NCSTAR 1-3C.

It is evident from Figure 6–4 and Figure 6–5 that substantial areas of the concrete floor slabs for the 95th through 97th floors were destroyed in the immediate vicinity of the aircraft impact location. There is a large open area in the impact region in which no floor slabs are visible. A substantial section of collapsed floor slab is apparent in the enlarged portion of Figure 6–5 shown in Figure 6–8. One of the trusses (indicated by an arrow) that supported the floor slab and the corrugated sheet metal on which the concrete was poured are visible. The floor slab section appears to have collapsed from above and is at least 17 ft wide. No visual material has been identified that allows the depth into the building of the floor removal and damage to be determined (it is apparently too dark to see inside), but it clearly extends many feet.

Figure 6-8. An enlarged and enhanced portion of Figure 6–5 shows a portion of one of WTC 1's floor slabs that has collapsed into the opening created by the aircraft impact. The corrugated steel on the bottom of the floor slab and a portion of one of the support trusses (indicated by an arrow) can be seen.

Floor slab removal at the outer edge of the building seems to have been isolated to regions in the immediate vicinity of the aircraft impact location. This conclusion is based on the appearance of the building in close-up images, as well as fire behaviors observed later in the event. Fires were seen burning and moving on several floors on either side of the aircraft impact area, which would not have been expected if the floor slabs were missing. Fires were eventually observed all the way across the 98th floor on the north face, suggesting that the floor slab was in place on this floor following the aircraft impact. The presence of debris and fires indicated that a significant fraction of the 94th floor slab was also intact in the area.

The glass in a number of windows on the north face was broken out by the aircraft impact. Figure 6–9 maps the condition of windows on the four faces of the tower immediately following the aircraft impact. Comparison of Figure 6–5 and Figure 6–9 shows that most of the open windows on the north face were in locations that were directly struck by the aircraft or had the aluminum façade, which held the windows in place, disturbed by the collision. Both the window glass and aluminum façade at more distant locations on this face appeared to be undisturbed.

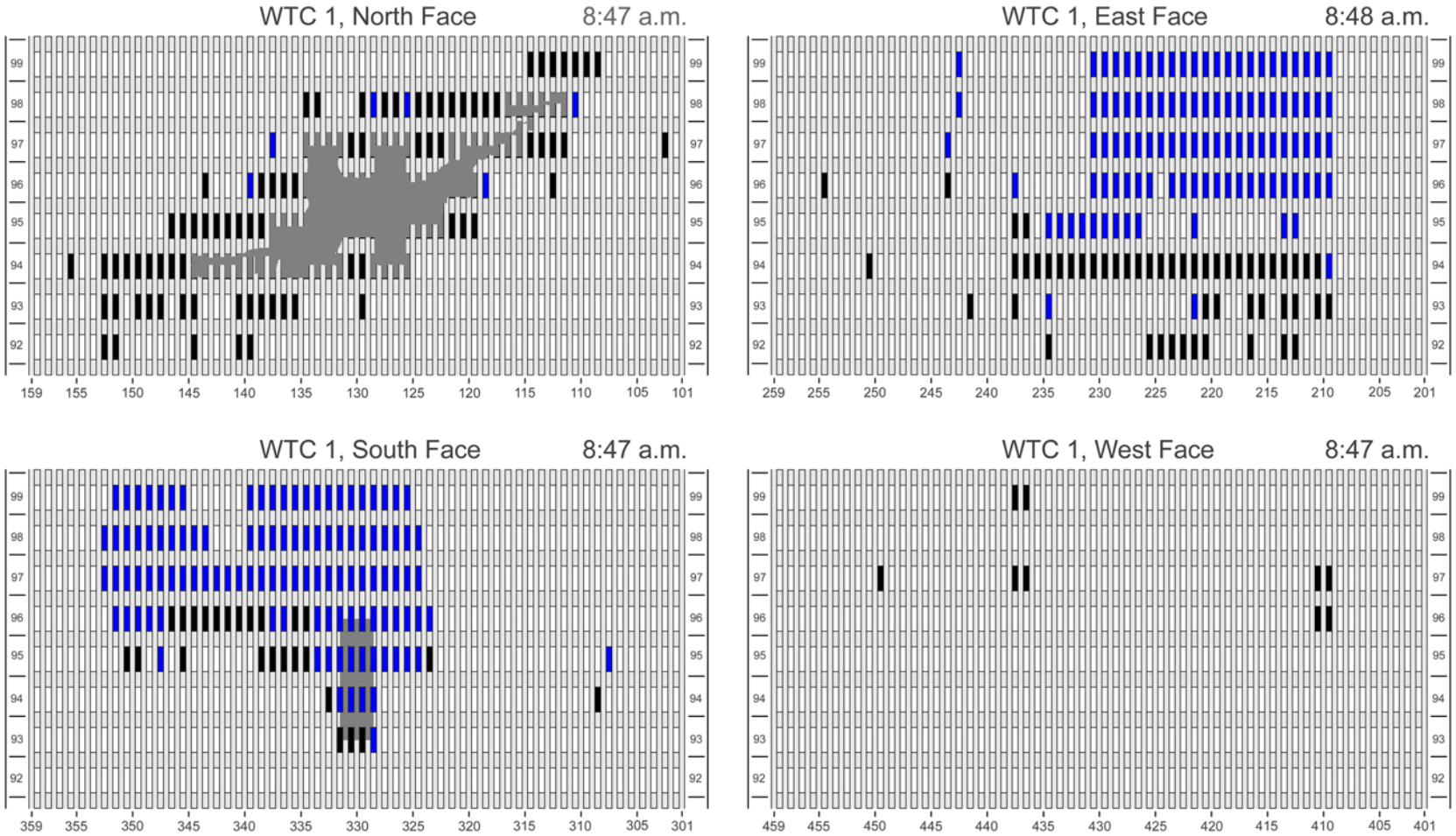

Figure 6-9. The condition of windows is shown for the four faces of WTC 1 around 8:47 a.m. shortly after it was struck by American Airlines Flight 11. The colors represent ▌- window broken open, ▯- glass in place, and ▌- not visible.

6.4.2 Damage on the East, South, and West Faces Due to the Aircraft Impact and Resulting Fireballs

Figure 6–10 shows a photograph of the east face of WTC 1 taken roughly four and a half minutes after the aircraft impact. It looks similar to more distant videos that were recorded very shortly after the event, suggesting that the appearance of this face has not changed significantly since the aircraft impact. Figure 6–11, which also looks similar, was taken just over a minute later and provides a closer view. Numbers indicating floors and columns have been added to both figures for reference.

Figure 6-10. Photograph showing the east face of WTC 1 recorded at 8:50:59 a.m. Column and floor numbers have been added.

The most prominent feature in Figure 6–11 is a long line of smoke on the 94th floor extending from roughly window 94-210 to window 94-237, or a distance of nearly 90 feet. Clearly, all of the glass in the windows over this length has been broken out. Closer inspection shows that several of the aluminum covers on these columns have been partially dislodged as well. Most are near the right edge of the region, but the cover for column 94-237 has been nearly removed. Two covers, for columns 94-213 and 94-216, are missing completely. The aluminum cover on the northeast corner for this floor has also been partially

displaced. This proved to be an easily recognized marker for the floor. Isolated windows at 94-241 and 94-250 are also missing.

Figure 6-11. Photograph of the east face of WTC 1 taken at 8:52:01 a.m. The photograph has been enhanced and cropped. Floor numbers are indicated along the left edge of the building and column numbers along the bottom of the photo.

Some damage and missing window glass are present on lower floors that were not directly impacted by the aircraft. Window glass has been broken out and some column covers have been displaced or removed completely on the 93rd floor from columns 93-209 to 93-216 as well as columns 93-219 and 93-220. The glass for window 93-237 is missing, and the aluminum cover for column 93-237 has been displaced. Damage is also apparent on the 92nd floor, where windows 92-212 and 92-213 have been broken out. A chair is stuck in window 92-212, and the aluminum cover on column 92-212 has been removed. Covers on columns 92-216 and 92-217 have been displaced, and the window glass between these two columns is missing. On the 91st floor, the covers on columns 91-213, 91-214, and 91-216 have been displaced, and windows 91-213 and 91-216 are open. There is no apparent damage lower than the 91st floor.

Portions of the east face above the 94th floor are hidden by the smoke rising from this floor. Only minimal damage is seen on these higher floors, including a displaced column cover and missing window glass at window 95-237 and three broken windows on the 96th floor at windows 96-243, 96-244, and 96-254. All window glass and column covers to the north of column 209 appear to be undisturbed.

A visual summary of the windows broken open on the east face as a result of the aircraft impact and resulting fireballs is included in Figure 6–9.

Visual evidence concerning the condition of the south face shortly after the aircraft impact is not as complete as that available for the east and north faces, but there is sufficient information to confirm that there was significant damage. Figure 6–12 is believed to be the earliest photograph in the NIST database that provides a good view of the south face. The exact time when it was recorded is not known, but the presence of a large amount of what appears to be dust on the south face, below the floors where damage is apparent, indicates that it was shot within a few minutes of the aircraft impact. The relatively small amount of fire on the south face, as well as the light smoke exiting open windows on the west face, suggests that the initial fires burning aviation fuel have died down substantially. A second view of the south face shot from south of the tower is shown in Figure 6–13. This photograph was taken at 8:55:37 a.m., slightly more than 9 min after the aircraft impact. Numbers have been added indicating column and floor numbers. The appearances of these two photos are similar, suggesting they both provide good indications of the initial damage to the south face of the tower.

A prominent feature in both photographs is the missing aluminum cover on the southwest corner of WTC 1 at the 96th floor. Heavy smoke is flowing from this opening. This missing cover is easily recognized and provides a quick reference for identifying the tower, face, and floors in visual material. In addition to the missing corner, some of the aluminum column covers on the face have been displaced. Using the corner marker as a guide, it is apparent that most of the smoke seen issuing from broken windows on the south face is coming from the 95th and 96th floors on the western side. Only a single window (94-308) to the east of column 322 appears to be broken open. There is an area of heavy smoke at the center of the face coming from lower down on the 93rd floor. Comparison of a number of photos and videos taken during the event showed that the smoke released from this point remained heavy until the tower collapsed. It was never possible to get a clear view of the damage in the immediate vicinity. As discussed further in Section 6.4.3, it is believed that the damage in this area was the result of the removal of a complete three story steel panel section from the face.

The condition of windows on the south face following the aircraft impact and resulting fireballs is indicated in Figure 6–9. Over 25 windows were missing, and additional ones may have been broken since much of the face on the left side was hidden by smoke. The asymmetry in the window damage is evident, with most of the observed broken windows extending from the center of the face toward the west edge.

In contrast to the relatively large number of windows missing on the east and south faces of the tower, the number of windows initially opened on the west face was considerably less. This can be seen in Figure 6–12 , which shows the west face shortly after the aircraft impact. The façade maps for window condition on the west face shown in Figure 6–9 is based on a number of photographs and videos and indicates that nine windows were broken open on this face by the aircraft impact and fireballs. The only obvious damage to the aluminum facing occurred on columns 410 and 411 at the 96th and 97th floors. The covers for column 410 were removed on both floors, while those on column 411 were partially dislodged.

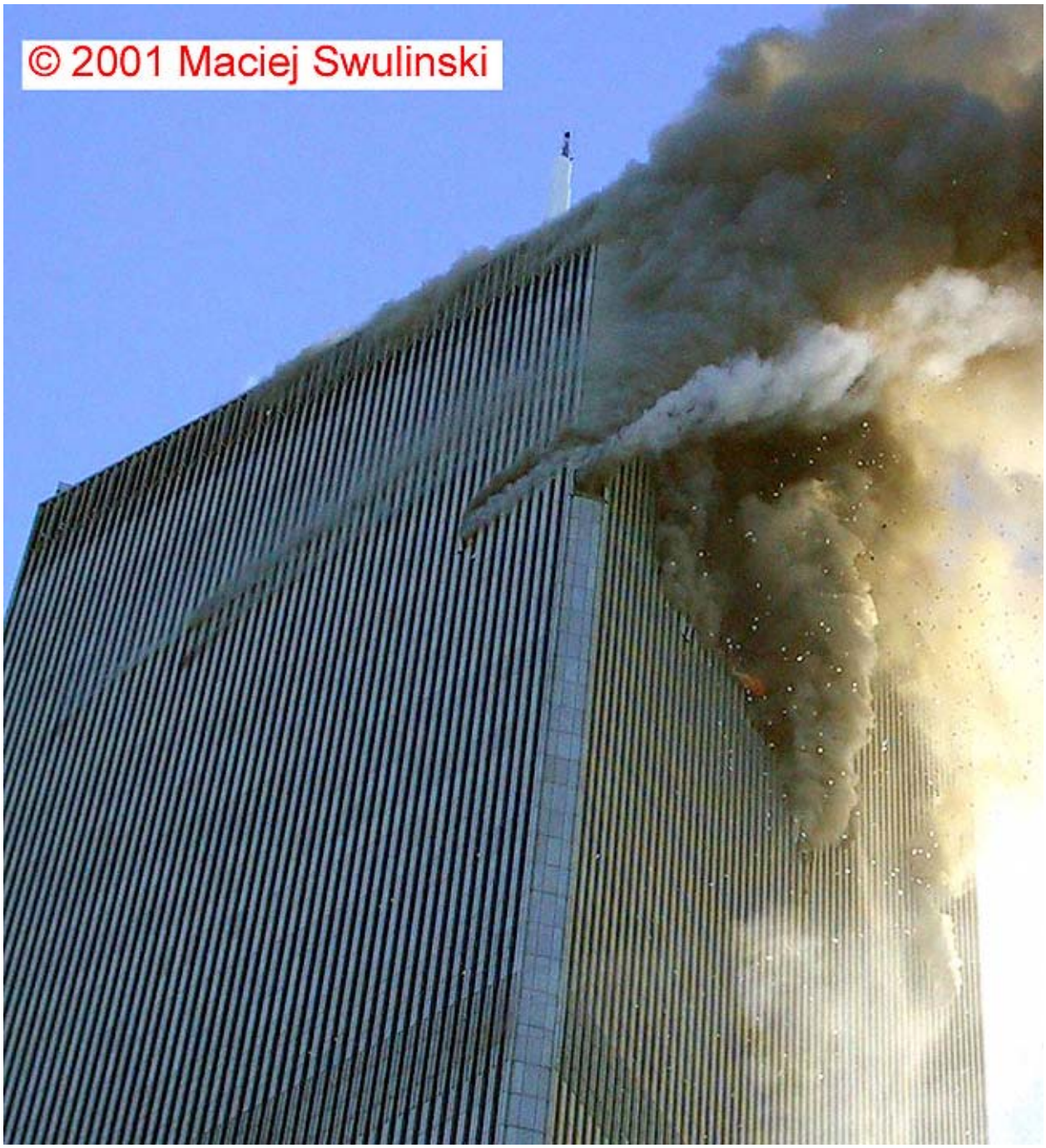

Figure 6-12. A cropped photograph shows the west and south faces of WTC 1 shortly after the aircraft impact. The image has been enhanced by adjusting the intensity levels. The exact time of the image is unknown, but the appearance suggests that it was taken within two minutes of the aircraft impact.

Figure 6-13. This enhanced and cropped photograph shows the south face of WTC 1 at 8:55:37 a.m. Column and floor numbers have been added.

6.4.3 Observations Concerning Debris Expelled from WTC 1 by the Aircraft Impact and Associated Fireballs

There was a significant amount of material expelled from WTC 1 following the aircraft impact and subsequent fireballs. The large dust clouds that formed on the north and south sides of the towers (see Figure 6–1 to Figure 6–3) have already been described. As noted, these clouds were transported large distances by the wind. A video shot from the east by Scott Myers (see Figure 7–16 for an example of frame taken from this video at a later time) showed that the vortex-like dust cloud from the north face of WTC 1 passed across both towers to the east and was still visible several blocks from the towers. This cloud appeared to consist of large amounts of fine dust and paper. Figure 6–14 shows that a layer of dust and other debris was deposited on Church Street, located to the north of the WTC complex, by the passage of the dust cloud. The depth of the tire tracks provides an indication for the thickness of the dust. Similar photographs showed that deposited debris ran along most of the length of Church Street between Liberty Street and Vesey Street, or a distance of four city blocks. Given the large area covered by the debris, it is evident that a substantial amount of material was expelled from the north face of WTC 1 by the aircraft impact and subsequent fireballs.

Figure 6-14. A photograph recorded around 8:51 a.m. shows debris present on Church Street, which ran along the east side of the WTC complex. WTC 5 is located on the left-hand side.

It is not possible to identify the source of the dust, but it seems likely that it consisted of pulverized concrete, since large areas of several floor slabs were missing in the vicinity of the aircraft impact, as well as other building materials, such as drywall. The large amount of pulverized debris generated provides additional evidence that the aircraft caused extensive damage to interior portions interior of the tower as it entered and passed through the tower.

Figure 6–15 shows another view of the streets around the WTC shortly after the aircraft struck WTC 1. This shot was taken from the corner of Liberty Street and Church Street looking west down Liberty Street. It was shot before WTC 2 was struck, so the debris has come from WTC 1. The bridge across Liberty Street connected the southwest corner of WTC 4 to the Bankers Trust Building. The building visible on the right side beyond WTC 4 is WTC 3 (Marriott Hotel), which was located on the corner of West Street. A deep layer of debris is seen strewn across much of the visible length of Liberty Street. Most of this debris is lying to the south of WTC 2. The only possible way for it to have reached this location is by being blown by the prevailing wind from the south face of WTC 1. It is likely that it was dropped from the dust cloud seen to the south of WTC 2 in Figure 6–2. This image, along with several others, shows that, in addition to a lot of paper, the debris in the street consisted of a number of aluminum column covers and what appeared to be small chunks of concrete. The amount and nature of the debris

indicates that the aircraft impact and fireballs must have caused significant damage close to and on the south face of WTC 1. There were also a number of small fires burning on Liberty Street immediately following the aircraft impact (not visible in Figure 6–15).

Figure 6-15. This photograph was taken from the corner of Liberty Street and Church Street looking west down Liberty Street after WTC 1 was struck by American Airlines Flight 11 but before WTC 2 was hit by United Airlines Flight 175. Some faces are blurred.

The extensive damage to the south face of WTC 1 suggests that some parts of the aircraft may have passed completely through WTC 1 following the aircraft impact on the north face. NIST has not obtained any images that show objects exiting the south face during the aircraft impact, but several photographs and videos in the collection show portions of a landing gear and aircraft tires at locations to the south of the tower that suggest they likely came from the south face of WTC 1.

Figure 6–16 shows a full three-story three-column-wide steel panel section (see the associated discussion and Figure 4-4 in Chapter 4) lying on the corner of Cedar Street near its intersection with West Street.

This spot is to the south of and roughly 690 ft from the south face of WTC 1. Close inspection shows that the panel section was released when the spandrel-to-spandrel connections failed by the bolts tearing through the edges of the spandrel plate. At the top and bottom of the panel section, the bolts used to connect the columns were sheared off. The photograph was taken prior to the collapse of either tower. There is an aircraft wheel embedded in one of the windows. The most likely source location for this panel section has been identified as the center of the south face of WTC 1 (i.e, columns 329 to 331) and extending from the middle of the 93rd floor to the middle of the 96th floor. This conclusion is based on the appearance of the damage in this area that can be seen in Figure 6–13 and the fact that building plans indicate that a full panel section occupied this location on the steel façade. Even though much of the

south face of WTC 1 was visible at various times in photographs or videos, there were no indications of such a large missing section elsewhere on the face. Even so, the location assignment should be considered tentative since, as discussed in Section 6.4.2, the area was obscured by smoke in all of the close-up images of the area that are available in the NIST database. Assuming the location is identified correctly, the wheel is embedded in a window (95-329) that was located on the 95th floor.

Figure 6-16. Photograph showing a full steel panel section lying in Cedar Street near its intersection with West Street. An aircraft wheel is embedded in one of the windows. The building behind the panel is Saint Nicholas Greek Orthodox Church and the lower section of WTC 2 can be seen across Liberty Street.

There are two types of retracTable landing gear on a Boeing 767-200ER, a single nose gear formed by a support strut holding two wheels near the front of the main body of the aircraft and two sets of main landing gear on the wings consisting of four wheels attached to carriages mounted to heavy support struts. The wheels used on the two types of landing gear have different appearances. By comparing the configuration of the wheel embedded in the steel panel section with photographs of landing gear for a

similar Boeing 767 provided to the Investigation (NIST NCSTAR 1-2B), it was determined that the wheel came from one of the main landing gear. This conclusion is based on the number and placement of the bolts in the wheel hub.

A curious aspect of Figure 6–16 is the large pipe that can be seen twisted about and rising above the panel section. A different view of the pipe is available in Figure 6–17, where it can be seen that it extends from well above the panel section across the pickup truck to the right and then up into the air. The force of the collision of the pipe with the pickup has crushed the pickup cargo bay. The pipe section length is considerably longer than the panel section, which is 36 ft. The pipe diameter has been estimated as 1.5 in., based on its size relative to the panel section.

Figure 6-17. This cropped and enhanced photograph shows another view of the three-story steel panel section included in Figure 6–16. A long pipe section attached to the steel rises above both the panel section and the pickup truck to the right. The building on the left is Saint Nicholas Greek Orthodox Church, and the building on the right is 90 West Street.

Review of building plans and consultation with The Port Authority of New York and New Jersey staff and consultants have provided a plausible explanation for the source of this pipe. Cooling at the perimeter of the towers was accomplished by means of cold-water induction units located along the outer wall at the base of the windows. These units were fed cooled water by a series of vertical risers (pipes) that extended either up or down from the mechanical equipment rooms. Water was returned by parallel risers. The pipe in the figures seems to be attached to the bottom of the steel panel section on the center column, i.e., column 130 at the 93rd floor. Induction units on the 92nd floor and higher were connected to the mechanical equipment room on the 106th floor. Building plans indicate that supply and return risers were located just to the inside of column 130. The supply riser was 1.5 in. pipe and the return riser was 2 in. pipe. The appearance and location of the pipe in the figures indicate that it is mostly likely part of a supply riser that fed the induction coolers at this location.

A second wheel from a landing gear, shown in Figure 6–18, was found much further south at the corner of Rector Street and West Street. This is a distance of roughly 1,385 ft from the base of the south face of WTC 1. The presence of a braking system indicates that this wheel also came from one of the two main landing gears.

Figure 6-18. The photograph shows a wheel from the aircraft that struck WTC 1 lying at the southeast corner of the intersection of Rector and West Streets.

The two wheels in Figure 6–16 and Figure 6–18 are the only large pieces of aircraft debris from WTC 1 that have been identified in the visual record. Numerous smaller pieces of aircraft debris are evident in close-ups of the street debris following the aircraft impact.

The aircraft wheel found embedded in the panel section at the corner of Cedar and West Street likely passed through the center of the building in order to hit the south face near the center. Based on where it landed, it is considered likely that the wheel that landed on the corner of Rector and West Streets also passed through the core, but this conclusion is not as well supported as for the other wheel.

6.5 FIRE BEHAVIOR IN THE PERIOD IMMEDIATELY FOLLOWING THE AIRCRAFT IMPACT

The fireballs that formed after the aircraft struck WTC 1 are described above. The timing and the appearance of the fireballs indicate that they resulted from aviation fuel fires ignited inside the tower, which then rapidly forced large amounts of unburned aviation fuel through openings either created by direct impact of the aircraft and/or debris or windows broken as a result of the overpressure generated inside the building by the fire itself. It is likely that most of the fuel leaving the building was atomized and burned when it mixed with air outside of the building. Fireballs formed on the north, east, and south faces, with the largest observed on the north face. This suggests that the largest amount of aviation fuel was blown backward through the opening created by the aircraft entry.

A simple analysis of the maximum amount of burning of jet fuel expected inside the building provides insight into why the fireballs formed and for the immediate fire behavior in the aftermath of the aircraft impact. The result of this analysis reveals that the maximum amount of burning that could have taken place within the building during the brief period following the aircraft impact was limited by the amount of available air on the floors involved and not by the amount of fuel. Start by assuming that the only air available for burning was already present when the aircraft struck. This is a plausible assumption given the short time period available. The analysis considers the amount of air present on an individual floor and the amount of jet fuel that can be burned by this air. The volume of air on a single floor is approximated as 200 ft × 200 ft × 12 ft = 480,000 ft^3. Using the density of air, this volume contains 36,500 lb of air or 8,450 lb of oxygen (23.14 % oxygen in air by mass). Each pound of oxygen can support the release of 5.95 MJ of energy due to combustion, so the maximum amount of energy that can be released on this floor by burning the available air is 8,450 lb O_2 × 5.95 MJ/lb O_2 = 50,300 MJ. Since the heat of combustion for Jet Fuel A is 20.2 MJ/lb, the maximum weight of aviation fuel that could be burned inside on a single floor is 50,300 MJ/20.2 MJ/lb = 2,490 lb fuel, or 365 gal, using a fuel density of 6.83 lb fuel/gal.

The amount of fuel on American Flight Airlines 11 when it struck WTC 1 has been reported as 10,000 gal (Barry 2003) distributed equally between tanks in the two wings. A fuel tank in the center of the aircraft is believed to have been empty. Based on the fuel locations indicated in Figure 6–7 and by assuming the fuel released from the fuel tanks moved over the floors directly in its path, it is expected that roughly 5,000 gal of jet fuel were dispersed over portions of the 96th and 97th floors from the starboard fuel tank and roughly 5,000 gal over the 94th and 95th floors from the port tank.

If the fuel was distributed evenly over four complete floors and ignited, the maximum amount that could have burned immediately within the building would have been on the order of 1,460 gal. Since the fuel is unlikely to have been evenly distributed, the actual amount burned was most likely less than this. Given that the maximum amount of aviation fuel that could have burned immediately is on the order of 15% of the total released from each tank, it is important to consider other possible dispositions for the remaining fuel.

Immediately after the aircraft impact, there was considerably more fuel on the floors where it had been released than there was air (oxygen) required to burn it. As already discussed, the formation of the fireballs demonstrates that a fraction of the remaining fuel was expelled from the building (mostly likely being forced out of openings as an atomized liquid due to the overpressures generated by internal burning). Based on the visual evidence for WTC 1, it has not proven possible to estimate the total fraction of fuel burned outside of the towers. The overpressures generated within the tower by the internal burning are also difficult to estimate since they depend in complicated ways on such parameters as the amount of fuel consumed and its burning rate, the time dependent vent area (the overpressure broke windows and removed portions of the curtain wall), fuel distribution, etc. Experimental measurements of overpressures in vented compartments subject to rapid burning of premixed fuel and air mixtures vary from less than 1 psi to as high as 5 psi. (Butlin and Tonkin 1974, Butlin 1975)

William Grosshandler of BFRL estimated the possible range of overpressures that could be developed in the towers using an approximate global analysis based on the maximum amount of heat release that would occur during oxygen-limited burning on a tower floor, the expected temperature rise and corresponding volume expansion, an estimate for the period of the induced flow, and estimates for the open area at the periphery of the tower available for gas flow to release the pressure increase. The analysis yielded values

falling between 0.5 psi and 3.0 psi for the average increase in pressure during the release period. Since the actual pressure is expected to increase rapidly to a value greater than the average and then fall off, the maximum pressure rise would be expected to be somewhat higher. This analysis therefore seems to predict a range of possible maximum overpressures that is consistent with the experimental measurements cited above.

Images show that immediately after the fireballs formed and the dust clouds and thermals had moved away from the building, large fires were still evident on the north, east, and south faces during the period from 10 s to 30 s following the aircraft impact. Figure 6–1e to Figure 6–1h and Figure 6–2 show examples. On the north face, a large fire was present in the opening created by the aircraft. On the east face, fires were seen near the center on the 94th floor, and on the south face fires were on the west side near the 96th floor. In Figure 6–1h, heavy black smoke can be seen coming from the windows broken on the west face during the aircraft impact. These observations indicate that combustion gases and fuel were still being pushed from the building by expanding gas generated by interior burning, but that the rate was already much reduced from that during the short period when the fireballs formed. These later fires tended to die down rapidly.

Videos of the tower show that between 40 s and 45 s after the aircraft impact, there was an abrupt decrease in the size of the flames burning within the impact cavity on the north face and the amount of smoke exiting the west face. This suggests that the pressure within the building was no longer increasing and expelling gases and/or fuel aerosol or, expressed another way, the burning rate within the building had become much lower than immediately following the aircraft impact. This “damping down” of the internal fires is expected due to oxygen depletion. In most interior spaces where fuel and air initially mixed, fuel was in excess, and burning would have depleted all available oxygen. Following thermal expansion, these volumes contained primarily heated fire gases and unburned fuel and could no longer support burning. This would remain true until fresh air was replenished within the volume. As a result, any jet fuel left behind in these volumes would not have been expected to burn for a substantial period of time.

It is also possible that fuel released on a particular floor could have been transported elsewhere within the building, where it would come in contact with additional fresh air and, if ignited, burn. There are numerous media reports of building occupants being burned in the ground-floor lobby of WTC 1 following the aircraft impact. Numerous eyewitness accounts describe a large flash fire on the concourse floor lobby at the time of aircraft impact, that came from one or more of the elevator shafts that ran from the concourse floor of the tower past the floors where the aircraft impact took place. This observation suggests that sufficient burning liquid aviation fuel entered at least one of these elevator shafts to continue burning, while it fell roughly 1,175 feet. Even after falling this distance, sufficient unburned fuel was available to create the overpressure that opened the elevator shaft at the concourse level and forced additional unburned fuel into the lobby area, creating the extensive flash fire observed. There were also reports of fires in the local elevators that serviced upper floors from the 78th floor sky lobby.

As discussed in later sections, there is visual evidence that extensive fires grew on the 92nd and 93rd floors within a short period (on the order of ten minutes) following the aircraft impact. This suggests that some fraction of the aviation fuel was also deposited on these lower floors, perhaps by passing through core shafts or courtesy stairwells installed in the perimeter areas around the core.

In the minutes immediately following the aircraft impact, relatively small fires were observed at a few isolated locations around the periphery of the building. This can be seen in Figure 6–19, which compares the observed fires on the four faces of WTC 1 for the first few minutes after the intense burning of aviation fuel initiated by the aircraft impact had subsided. These fires were likely burning small amounts of residual aviation fuel or building contents. They were not extinguished because they had direct access to outside air. During this period, light smoke was observed coming from numerous open windows where fire was not seen. These observations are consistent with the conclusion that internal fires were effectively damped down by oxygen depletion. The presence of significant smoke indicates some smaller fires were still burning in the interior of the building.

With time, fires began to appear over larger areas on the faces of WTC 1. The behaviors of fires subsequent to the initial period discussed here are the subject of Chapter 8.

6.6 SUMMARY OF OBSERVATIONS AND ADDITIONAL DISCUSSION

American Airlines Flight 11 struck WTC 1 on the north face at 8:46:30 a.m. at roughly 466 mph. The nose of the aircraft hit very near the center of the face at a location close to the base of the 96th floor. The collision severely damaged the steel façade as mapped out in Figure 6–6. Upon entering the building, the aircraft collapsed a large, but unknown area, of the floor slabs near the entry point. Visual evidence indicates a great deal of concrete and other building materials were pulverized during the collision.

The aircraft appeared to simply disappear into the building. Shortly afterwards, dust and aviation fuel were pushed out of openings on the north, east, and south sides of the building. It is most likely that this occurred due to an overpressure inside the building generated when aviation fuel released by the impact began to burn. When the unburned expelled aviation fuel mixed with the outside air, it formed fireballs. Dust was also seen coming out of locations on the 108th and 109th floors, where a mechanical equipment room was located. This observation indicates that some of the ductwork on the impact floors in the core area was compromised by the aircraft impact and that dust passed through the resulting pathways.

Even though the aircraft struck the north face of WTC 1 very near the center, damage patterns on the other faces as revealed by window and façade damage, generated debris, and initial fire distributions were asymmetric. On the east side there was significant damage near the center of the face on the 94th floor. A large fraction of the port wing of the aircraft struck this floor (see Figure 6–7) on the north face. With the exception of one localized area near the south side of the tower, on the opposite side of the building, damage to the west face was minimal. The one damaged area included the 96th floor, which is consistent with the location of the raised wing of the aircraft when it struck. (see Figure 6–7). The aluminum panel on the southwest corner of the 96th floor was removed, and there was considerable damage on the 96th

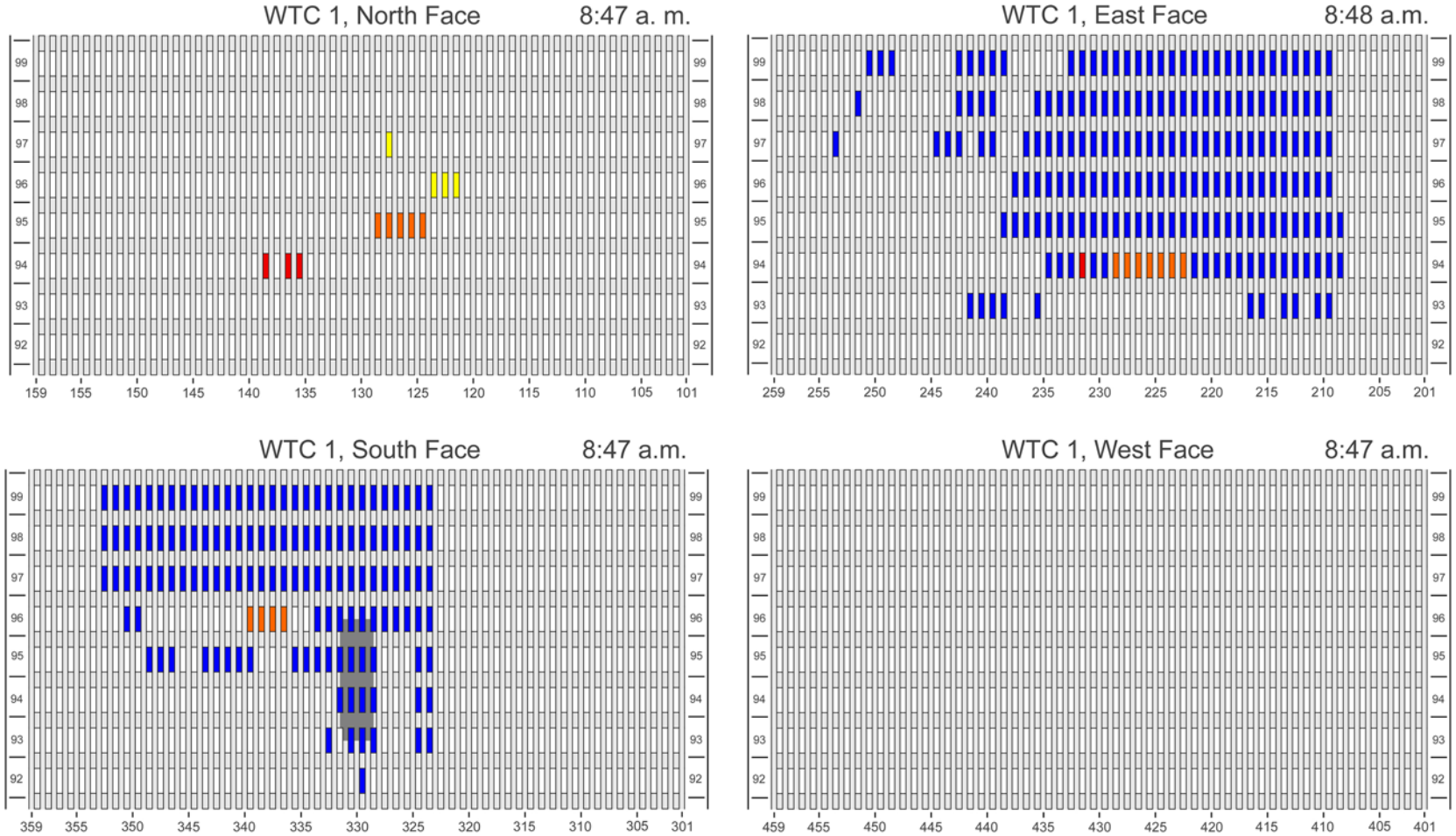

Figure 6-19. Maps of observed fires on the four faces of WTC 1 are shown for the period shortly after the rapid burn off of fuel released during the aircraft impact. The colors represent - no fire observed, - spot fire, - fire inside, - external flaming, and - not visible.

floor (and perhaps higher floors) on the western side of the south face. This damage extended to just beyond the center of the face, where an entire steel panel section had been removed and landed on the corner of West and Cedar Streets. A wheel from a wing landing gear was embedded in the panel section in a window from the 95th floor. This is consistent with the aircraft impact location on the north face (see Figure 6–7). A second aircraft wheel likely also passed through the building somewhere on the south face.

The picture that emerges is that the aircraft debris, which would have physically damaged the east face, and the aviation fuel released by the port fuel tank, which likely fueled the fireball on the east face, were somehow deflected away from the original trajectory of the aircraft and did most of their façade damage at the center of the east face. Only a couple of windows were broken to the south of this area. The opposite was true for debris and fuel from the starboard tank. In this case the debris and fuel seemed to pass all the way across the building, causing significant damage to the west side of the south face and generating a fireball from this location.

Very shortly after the aircraft impact, the fires ignited within the tower appeared to damp down to relatively low levels, with gently burning regions located near the periphery of the tower. This behavior is consistent with a simple analysis that indicated that the oxygen available for burning was likely completely consumed at locations where aviation fuel and air mixtures burned within the tower. A period of time was required to replenish the air at these locations and, hence, for the fires to begin to grow and spread.

6.7 REFERENCES

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Chapter 7
OBSERVATIONS AND ANALYSIS RELATED TO THE AIRCRAFT IMPACT ON WORLD TRADE CENTER 2

7.1 INTRODUCTION

By the time United Airline Flight 175 struck World Trade Center (WTC) 2 at 9:02:59 a.m., a large number of still and video cameras were trained on the WTC site. Many of these recorded the approach of the aircraft, its collision with the tower, and the events that immediately followed. The focus of this chapter is the use of this visual record to generate a time line for events immediately following the impact, to estimate the speed of the approaching aircraft, to characterize the response of the structure to being struck, to characterize the damage (as evidenced by visual evidence from the outside) to the tower, and to describe the fire behavior in the immediate aftermath. The visual record has been used by other National Institute of Standards and Technology (NIST) WTC Investigation projects as the basis for independent or extended analyses. These analyses are discussed in other Investigation reports.

7.2 TIME LINE FOR THE COLLISION OF THE AIRCRAFT WITH WTC 2 AND SUBSEQUENT EVENTS

More than 25 video clips of the aircraft impacting WTC 2 from all four sides are included in the visual database. Using visual cues, it was possible place all of these clips on a common time line accurate to one video frame, or 1/30 of a second. The synchronized clips were utilized to identify the specific events listed in Table 7–1 that took place during the 1.1 s following the collision. Times are relative to the initial impact of the nose of the aircraft on the south face. Window numbers are estimated based on observed locations relative to the width of a face and are generally accurate to ± 1 window.

Shortly following the aircraft impact, fireballs were observed to rapidly expand and grow outside of the tower. As discussed in Section 6.5, this behavior is expected when an extremely fuel-rich aerosol ignites within a building and is forced out of external openings by the overpressure resulting from the thermal expansion generated by burning within the building. The fuel-rich aerosol was formed when the fuel tanks on the aircraft ruptured due to the collision, releasing high velocity liquid aviation fuel that then formed the aerosol as it interacted with surrounding gas and solid structures inside the tower. Since much of the fuel was unburned when it exited the tower, most of the burning of the aerosol occurred outside when the expelled gases and aerosol mixed with the surrounding air.

The released fuel ultimately formed large fireballs outside of WTC 2, which hid the tower walls near the collision floors from view for many seconds. Figure 7–1 (shot from east northeast) shows the nascent fireballs and dust clouds as they appeared 1.2 s following the collision of the aircraft with the tower. The photo is relatively low resolution since it is a frame taken from a video clip. Even so, it reveals a number of details about the fireballs and dust clouds that resulted from the aircraft impact. Figure 7–2 shows a photograph of the east side of the tower taken at roughly the same time from the southeast.

Table 7-1. Time line for events immediately following the aircraft impact on WTC 2.

Time (s)	Observation
0	Nose of aircraft impacts WTC 2
0.03	Bright orange flash seen from the aircraft body in the vicinity of the tower wall, only apparent for one frame
0.17	Puff of dust appears on the south face near window 81-405
0.20	Aircraft disappears completely inside the tower
0.23	First appearance of damage and dust on east face near windows 82-340 and 82-341
0.26	Additional damage and dust appear on east face near windows 82-338 and 82-330
0.30	Damage and dust appear on the east face near window 81-316
0.40	Initial damage and dust appear on the northeast corner of the 81st floor
0.50	Large object exits north face near window 253 in vicinity of intersection of 81st and 82nd floors
0.50	Damage and dust appear on the east face near window 81-345
0.56	Fire appears on the east face in the dust plume in the vicinity of window 82-341 and spreads rapidly through the plume
0.56	Damage and dust appear on the north face near window 78-225
0.59	Fire appears on the south face in dust plumes located in vicinities of windows 79-433 and 81-416 on the 79th and 81st floors
0.59	Fires appear on the east face in other dust plumes on 81st and 82 floors and expand rapidly
0.59	Damage appears on the southern edge of the east face
0.63	Aluminum panel on the southeast corner of the 82nd floor is damaged
0.63	Flames appear in windows 83-322 to 83-335 on the 83rd floor of the east face
0.63	Line of fire covering windows 81-249 to 81-239 appears on the 81st floor of the north face
0.66	Fires expand on the north face covering windows 80-241 to 80-248, 81-234 to 81-248, and 82-243 to 82-249 for the 80th, 81st, and 82nd floors respectively
0.66	Fire appears outside of the north face as observed from the east
0.66	Fire appears in a dust plume on the south face near window 80-426 on the 80th floor
0.86	Damage appears at windows 78-236 to 78-240 on the 78th floor of the north face
0.89	Dust cloud appears on north face from upper level vents of the mechanical equipment room on the 75th and 76th floors from windows 76-243 to 76-257
0.92	Line of fire covering windows 79-233 to 79-240 appears on the 79th floor of the north face
0.99	Dust clouds appear on the east face from upper and lower level vents of the mechanical equipment room on the 75th and 76th floor from windows 76-325 to 76-332 and windows 75-335 to 75-337
1:02	Damage appears near window 80-229 on 80th floor of the north face
1:09	Line of fire appears in windows 80-229 and 80-228 on 80th floor of the north face

On the east face it can be seen that the several small fireballs that originally developed on the face (see Table 7–1) have coalesced into a single fireball that reaches nearly all the way across the face. At this point in time, the shape of the fireball was primarily determined by the flow of fuel from the building, as buoyancy has not had sufficient time to accelerate the heated gases upward.

Close inspection of Figure 7–1 shows that there are three distinct fireballs present on the north face. Videos shot from the north indicate that the largest of these grew from the area of fire that originally

appeared on the 80th, 81st, and 82nd floors in the vicinity of windows 239 to 249 (see Table 7–1). The second, somewhat smaller, of the fireballs is at roughly the same height and emanates from near the northeast corner. The third fireball is the smallest and is located below the other two. Northern views show that this fireball was formed from fire exiting from windows 79-233 to 79-240 on the 79th floor (see Table 7–1).

Figure 7-1. The nascent fireballs and dust clouds formed on WTC 2 1.2 s after the aircraft impact on the tower are shown. The image is a frame from a video.

A large cloud of dust is evident in Figure 7–1 on the south face that does not appear to be burning despite the fact that ignition was observed on this face (see Table 7–1). It appears as if there was much less fuel in the material that was expelled from this face than observed on the east and north faces. Other regions of dust can be seen below the fireball on the east face and in the vicinity of the mechanical equipment room on the 75th and 76th floors on the east and north faces.

The dust expelled during the aircraft impact from the mechanical equipment room on the north face appeared along a line roughly corresponding to the location of the spill louver placed at the eastern edge of the face (see Figure A-6). On the east side of the mechanical equipment room dust, appeared from two locations; one was near the center of the face, and the second was several windows to the south of the first. The more southern release also appeared to come from a lower position. The map of louver locations for this face, shown in Figure A-7, suggests that these dust releases may have come from peripheral and interior fresh air intakes that were present at these general locations.

No dust clouds or fireballs were observed on the west face.

As the fireballs continued to burn, buoyancy forces due to the heated gases began to dominate, and the fireballs were carried upward. Figure 7–3 shows the fireballs on the south and east faces of WTC 2 observed 4.3 s after the aircraft impact. Their appearances are very much changed from those in Figure 7–1 and Figure 7–2. Burning is now observed at heights well above where the aircraft impacted, and both fireballs have become more spherical in shape. Large amounts of dust and larger debris are seen falling downward below the fireballs. The fireball on the east face is considerably larger than that on the south.

Figure 7-2. This cropped photograph shows the fireball formed on the east face of WTC 2 following the aircraft impact that took place 1.1 s earlier. The east face of WTC 1 is visible in the background

Approval needed for image.

Figure 7-3. An image of WTC 2 recorded from the southeast is shown. The photograph was taken 4.3 s after the aircraft impact on the tower. The south face of WTC 1 can be seen burning in the background.

Burning on the south face seems to be concentrated more on the west side, with little flame evident in the dust cloud toward the east.

Figure 7–4 shows a photograph of the fireballs taken from just north of due east 4.6 s after the aircraft impact. The features of the fireballs are similar to those already described. The large extent of the fireball on the north face is apparent by noting that the width of each tower is 209 ft. The large amount of dust and larger debris (some flaming) generated by the collision and fireballs can be seen falling below the fireballs. Some isolated regions of fire are evident in the dust cloud on the south face.

Figure 7-4. An image of the fireball on WTC 2 recorded from just north of due east is shown. The photograph was taken 4.6 s after the aircraft impact on the tower.

Interestingly, in a photo by the same photographer taken 4.0 s after the collision, there is no fire evident in this dust plume.

A view of the fireballs shot from further north at roughly the same time (4.3 s after the aircraft impact) is shown in Figure 7–5. Intense fire covers nearly the entire plume on the north face. A large amount of dust and debris (some flaming) is seen falling below the fireball. The highlighted areas are two large pieces of aircraft debris that passed through the building. They will be discussed further below.

The fireballs continued to expand and rise for several more seconds. An image (Figure 7–6) shot 6.5 s after the aircraft impact shows the full extent of the fireballs from the east. The growth of the fireballs on each of the faces is apparent by comparison with the images recorded roughly two seconds earlier. The fireballs on the north and east faces are larger, and considerably more flame is visible in each than on the south face. Extensive areas on the surfaces of the north and east fireballs appear black, while the south fireball has a grayish appearance. These observations suggest that a larger amount of debris and dust and a relatively smaller amount of aviation fuel were expelled from the south face than from the north and east faces of the tower.

Figure 7-5. An image of the towers recorded from the north northeast is shown. The photograph was taken 4.3 s after the aircraft impact on WTC 2. Highlighted areas show two large pieces of aircraft debris that passed through the building and landed in the vicinity of the Church and Murray Streets intersection.

Figure 7–7 is an image recorded 7.9 s following the aircraft impact from the same perspective as Figure 7–4. The large fireball formed by the rapid expulsion of aviation fuel from the tower immediately following the aircraft impact has continued to rise and has begun to separate from the release point. Intense flaming is still seen in the vicinity of the building where the aircraft impact occurred. Even though significant façade damage is evident on the south side of the east face over three floors (80th, 81st, and 82nd), flames are emanating primarily from the 82nd floor windows. It is possible that flaming from higher windows is also occurring, but is hidden. Similar flaming is evident on the south and north faces.

Dark regions are beginning to show over large areas of the fireballs, particularly at lower locations. These dark regions are due to heavy smoke. As time passes the dark surface areas grow larger, while areas of orange flames become relatively smaller.

Figure 7-6. This cropped image of the towers recorded 6.5 s after the aircraft impact on WTC 2 was shot from the east on the opposite side of the East River in Brooklyn.

Figure 7-7. An image of WTC 2 recorded from just north of due east is shown. The photograph was taken 7.9 s after the aircraft impact on the tower. The locations of the 80th and 81st floors are identified

Large amounts of debris and dust are falling from the central region of the east face. Some of this debris is higher than the aircraft impact floors. This indicates that a portion of the debris that was expelled from the building was initially carried upward by the fireball. Since the debris is heavier than air, it eventually loses its upward momentum and drops from the bottom of the fireball.

Figure 7–8 shows a northern view of the fireball taken 8.7 s after the aircraft impact. The perspective is the same as in Figure 7–5. The appearance of the fireball is consistent with that described for Figure 7–7, but the amount of visible flame in the fireball appears to be significantly reduced, indicating that it is beginning to burn out. There appears to be a large amount of debris falling on the northeast corner of the tower and considerably less from regions of the north face more toward the center. The falling debris on the northeast corner is evident in Figure 7–7 as well. Similar to the east face photographs shown in Figure 7–6 and Figure 7–7, which were taken at roughly the same time, significant flaming from the tower is evident below the fireball in the vicinity of the aircraft impact location.

Videos indicate that the fireball created on the east face lasted slightly longer than that created on the north face (11 s versus 10 s). As already noted, the fireball on the south face appeared to be much smaller than the other two and to contain less flame. The last flames observed in the fireball on the south face were present roughly 8 s after the aircraft impact.

Figure 7-8. An image of the towers recorded from the north northeast is shown. The photograph was taken 8.7 s after the aircraft struck WTC 2.

Figure 7–9, taken 10 s after the second aircraft struck WTC 2, shows the debris and dust clouds on the south and east faces of WTC 2. The cloud on the south face is much larger than that on the east face. This is consistent with the conclusion that more debris was expelled from the south face than from either the east face or north face. The observation of a smaller, shorter-lived fireball on the south face suggests that less fuel was consumed by this fireball than those on the east face and north face.

Close-ups of the tower immediately following the fireball showed that, in addition to the dust and debris, the air surrounding the towers was filled with thousands of sheets of floating paper that were expelled from the tower along with the fuel and other debris.

Figure 7-9. This cropped black and white photograph was recorded from the southeast of WTC 2 10 s after the second aircraft impact.

After the flames in the rising fireball extinguished, the heated gases continued to rise, ultimately forming a distinct mushroom cloud. In this report the structure formed by these hot gases from a fireball is referred to as a "thermal" in order to distinguish it from the smoke plumes created by fires burning within the buildings and from the fireballs, which contain flame. Figure 7–10 shows the appearance of the thermal shot from the east from across the East River at 9:03:24 a.m. or 25 s after the aircraft impact. A view of the thermal from the west is shown in Figure 7–11. The exact time of this photograph has not been determined, but it was taken between three and four minutes after the aircraft impact. By simply using the known heights of the towers (roughly 1,365 feet), it is possible to estimate that the center of the head of the thermal had risen more than 1,400 feet in this period of time.

Figure 7-10. This cropped photograph recorded at 9:03:24 a.m., i.e., 25 s after the aircraft impact on WTC 2, shows the nascent thermal created by the fireballs on WTC 2. The intensity levels of the image have been adjusted.

7.3 QUANTITATIVE ANALYSES RELATED TO THE AIRCRAFT IMPACT AND BUILDING RESPONSE USING IMAGE ANALYSIS

One of the videographers on September 11, 2001, who was located just to the north of due east of WTC 2 and only a few blocks from the WTC site, placed a video camera on a sTable tripod, focused it on the top of the towers, and left it running unattended shortly after the first aircraft struck WTC 1. This camera captured the second aircraft hitting WTC 2. The sTable nature of the video has allowed a number of quantitative analyses to be performed. In the following section a calculation of the aircraft speed is discussed. Numerous eyewitnesses describe both towers swaying back and forth after the aircraft impact. The video clearly shows this oscillation and has allowed quantitative analyses of both its frequency (using two image-analysis approaches) and its amplitude as a function of time. A similar approach has also been used to analyze a separate short video shot from the north of WTC 2.

Figure 7-11. This cropped photograph shows the thermal created by the aircraft impact and subsequent fireballs on WTC 2. The picture was shot from across the Hudson River to the west southwest of the WTC complex.

7.3.1 Aircraft Speed

Figure 7–12 shows a series of cropped frames captured from the video shot from the east that shows the aircraft approaching WTC 2 and disappearing inside. These images have been used to determine the speed of the aircraft as it approached the tower. This was done by identifying the locations of the nose and tail of the aircraft relative to a fixed point defined to be the location on the frames where the aircraft passes out of sight behind the corner of the building. The aircraft was very nearly level relative to this point, so it is appropriate to simply count the number of picture elements, pixels, between this location and the two measurement points on the aircraft.

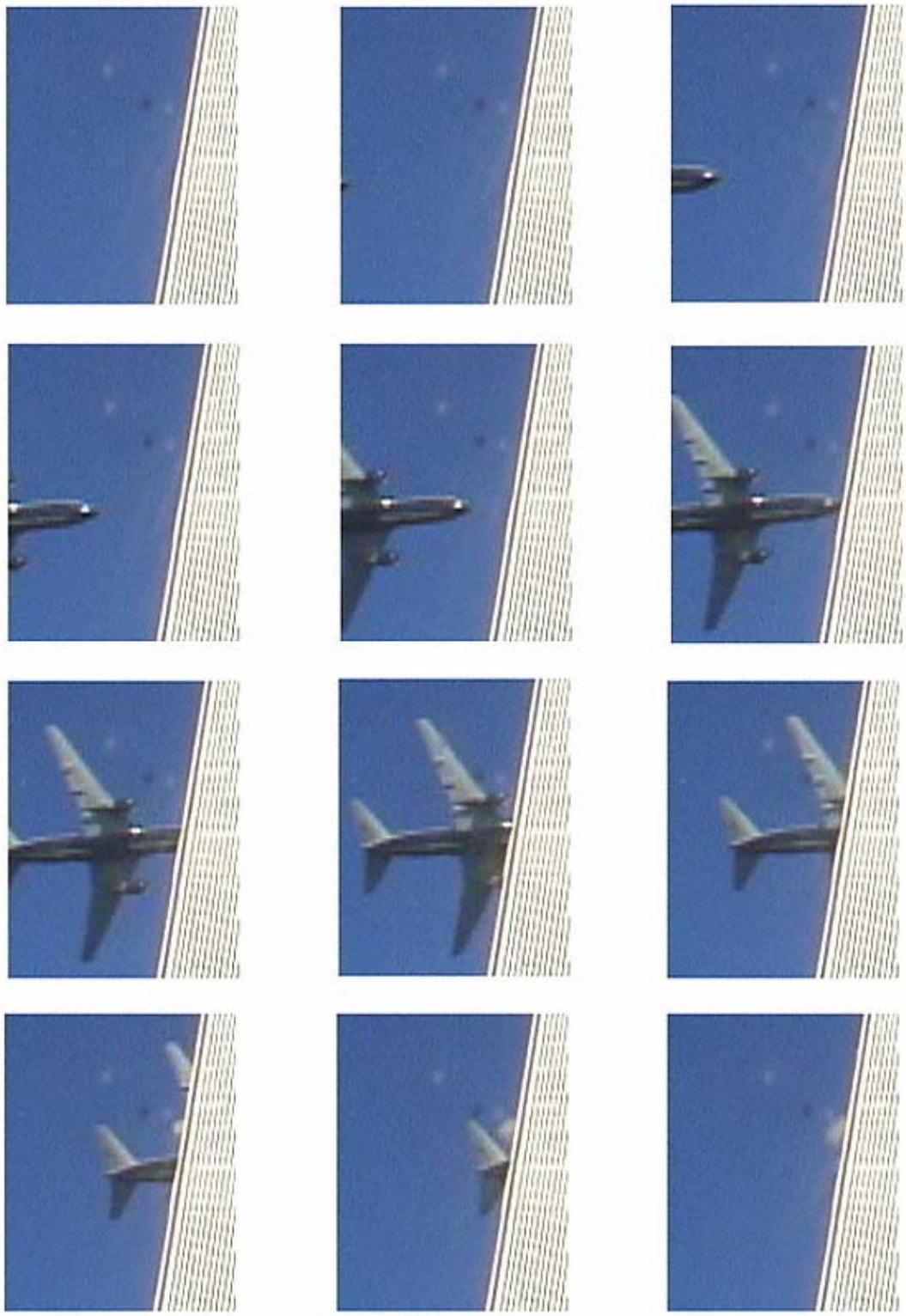

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Figure 7-12. Series of sequential cropped frames taken from a video shot on September 11th showing the aircraft approaching WTC 2. The frames, ordered from left to right and top to bottom, are separated by 33.3 ms.

Figure 7–13 shows the pixel locations of the two points as a function of time. Using linear least squares curve fits, it was possible to estimate the exact relative times when the nose and tail pass the reference location. The difference between these two times is the period required for the entire length of the aircraft to pass the reference location. The result is 0.1939 seconds. Since the distance between these two locations on the aircraft is known to be 155.0 ft, the average speed can be estimated by simply dividing this length by the passage time to give 155.0 ft/0.1939 s = 799 ft/s = 545 mph. An uncertainty estimate based solely on the uncertainty in the determined time difference yields a value of ± 18 mph, with 95 % confidence.

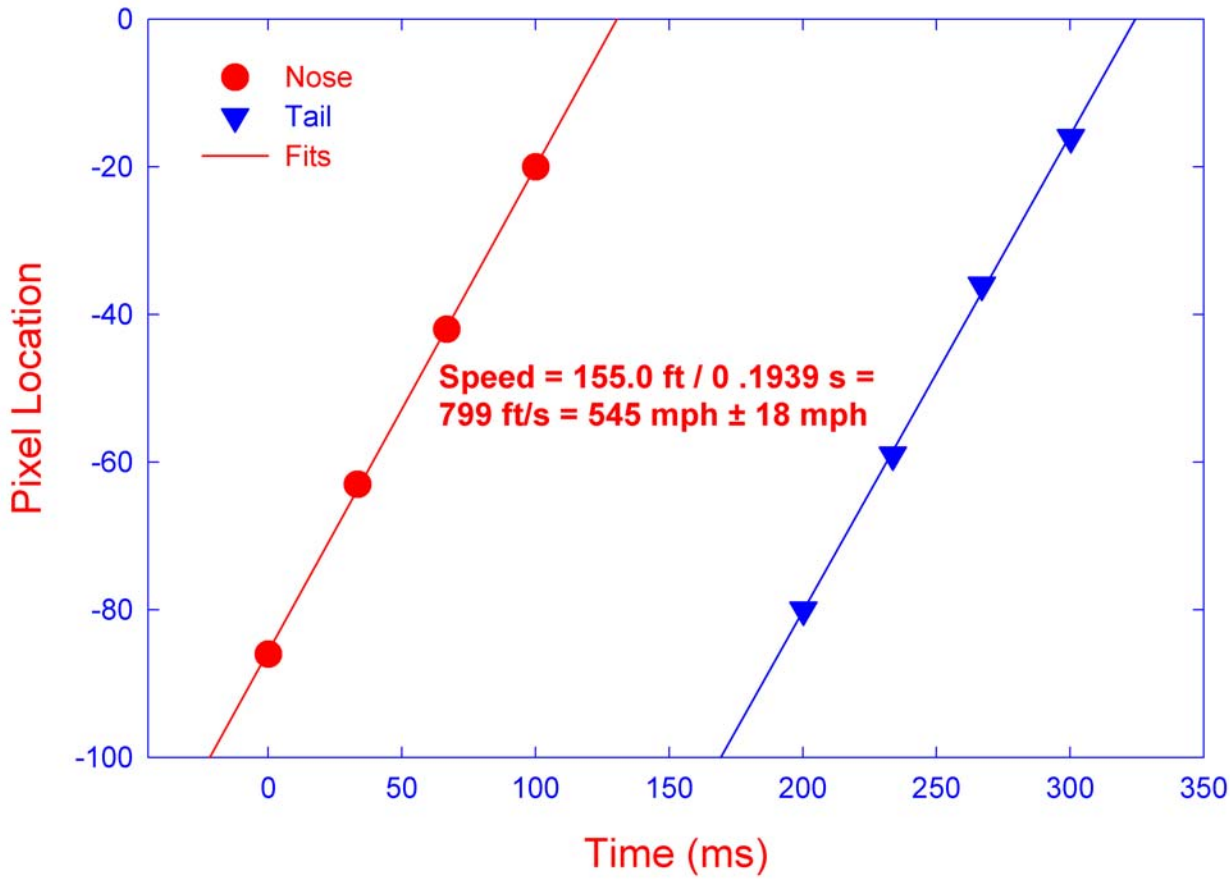

Figure 7-13. Plots of pixel locations for the nose and tail of the aircraft that struck WTC 2 as a function of time taken from the images shown in Figure 7–12. Straight lines are the results of linear least squares curve fits to the data. Extrapolation of the lines to pixel 0 allows the time for the passage of the aircraft to be calculated.

The speed estimated using this approach can be compared with a value of 542 mph ± 24 mph reported in NIST NCSTAR 1-2B, which was derived using a more sophisticated motion analysis of several videos available in the data base. The two values agree well, and the difference easily falls within the estimated uncertainties. These two estimates are compared with other published speeds in NIST NCSTAR 1-2B.

7.3.2 Determination of the Primary Oscillation Period of WTC 2 Using a Simple Image Analysis Approach

Close examination of the video, from which the frames shown in Figure 7–12 were extracted, revealed a perceptible movement of WTC 2 after it was struck by the aircraft. The building rocked back and forth, much as a pendulum, for many minutes. Image analysis was used to enhance this motion and estimate the period required for the building to sway through one complete cycle of the primary motion, i.e. a north-south sway. This was accomplished by creating a new video in which a single frame just prior to the aircraft impact was subtracted from subsequent frames. In this way small differences between images could be identified. If the image is unchanged from the initial frame, the result should be a black frame, but any changes in location or color appear in the difference video.

When this approach was applied to the video, a region of windows was observed on the building that seemed to appear and disappear. Figure 7–14 shows several frames of a composite video formed by overlaying half frames of the original video and the difference video. In the initial frame (time = 0.0 s) the aircraft has not yet appeared, and the difference frame is black. In the next frame (time = 10.7 s) the aircraft is approaching the building. The aircraft is evident in the difference frame since it represents a change in the frame. WTC 2 is still dark except near the top where changes due to smoke movement are apparent. In the third frame (time = 11.3 s) the aircraft has struck the building and dramatic changes in the appearance of the building façade in the difference frame are evident. Close inspection shows what appear to be curved lines running across the face of WTC 2. These curves result from an interaction between the straight lines formed by the windows and columns on the tower and the straight lines of picture elements (pixels) that make up the detector in the digital video camera. This well known behavior is called the moiré effect. As discussed in the following section, the moiré effect provides a sensitive approach for determining the displacement of the building as a function of time and allows a detailed analysis of the various oscillation frequencies of the tower following the aircraft impact.

Following the aircraft impact, areas of the tower face above the strike floors became hidden by smoke, and these areas do not provide useful information. However, the area of the tower below the strike floors to the left of the building in the foreground continues to show a distinct difference pattern since it is not obscured by smoke. This pattern is apparent in the fifth frame (time = 30.9 s). On the other hand, frames 4 and 6 (times = 28.0 s and 33.5 s, respectively) have been chosen for display because they are near null points, and the area appears dark in the difference frames since the location of the building is essentially unchanged from its position prior to the aircraft impact. When the video is played, the patterns in this area of the tower face alternately appear and disappear in the difference video.

Since the absence of color is easiest to identify, it is straight forward to determine times when the null points occur in the difference video. Figure 7–15 shows a plot of time versus null point number obtained from the difference video. The points fall on a straight line having a slope of 5.647 s ± 0.008 s (95 % confidence interval). Since the building passes through a null point twice during a single full oscillation, the period required is 11.3 s.

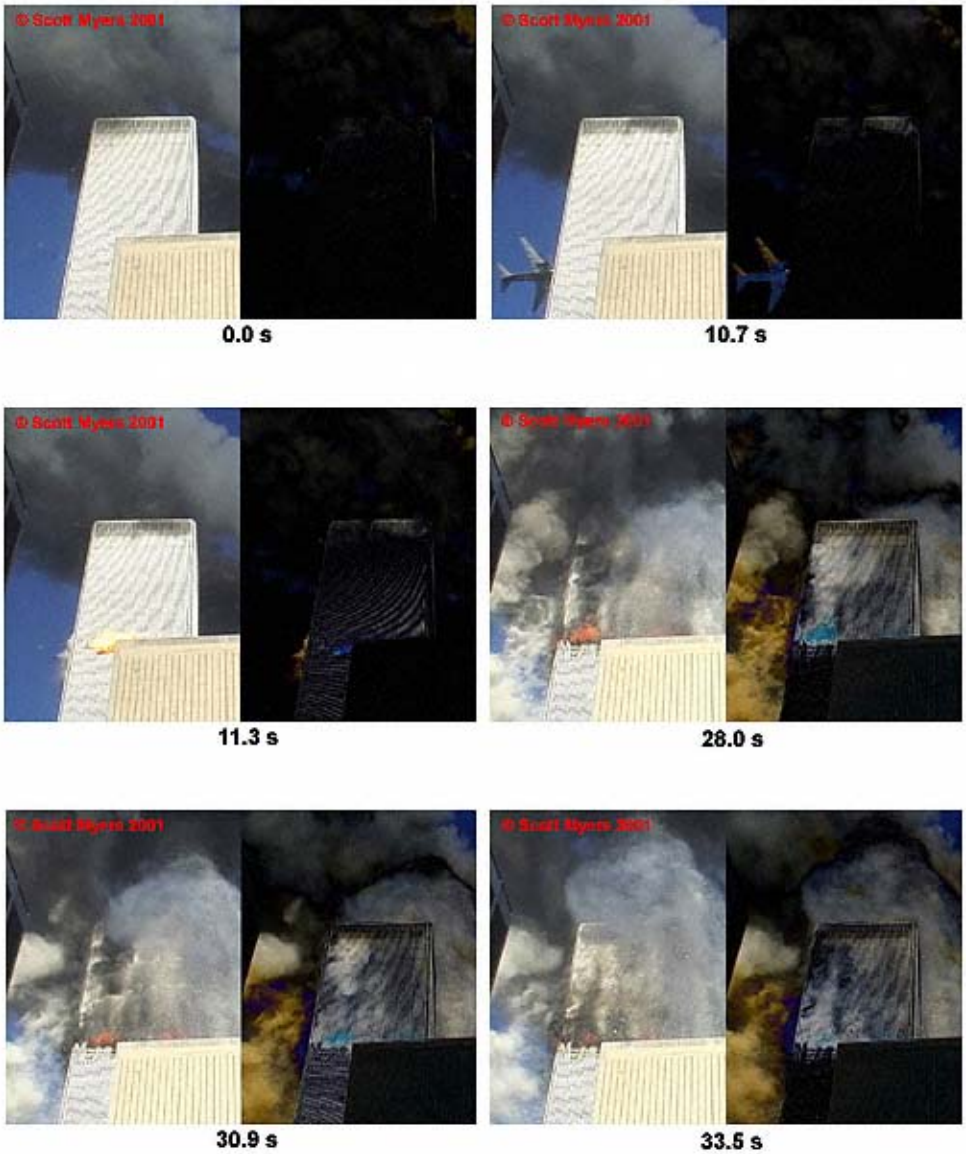

Figure 7-14. Frames from a composite video are shown. The half frames on the left are taken from a video showing the aircraft impact on WTC 2, while the half frames on the right are generated by subtracting a frame recorded prior to the aircraft impact from all subsequent frames in the original video. Times refer to the period since the start of the difference video.

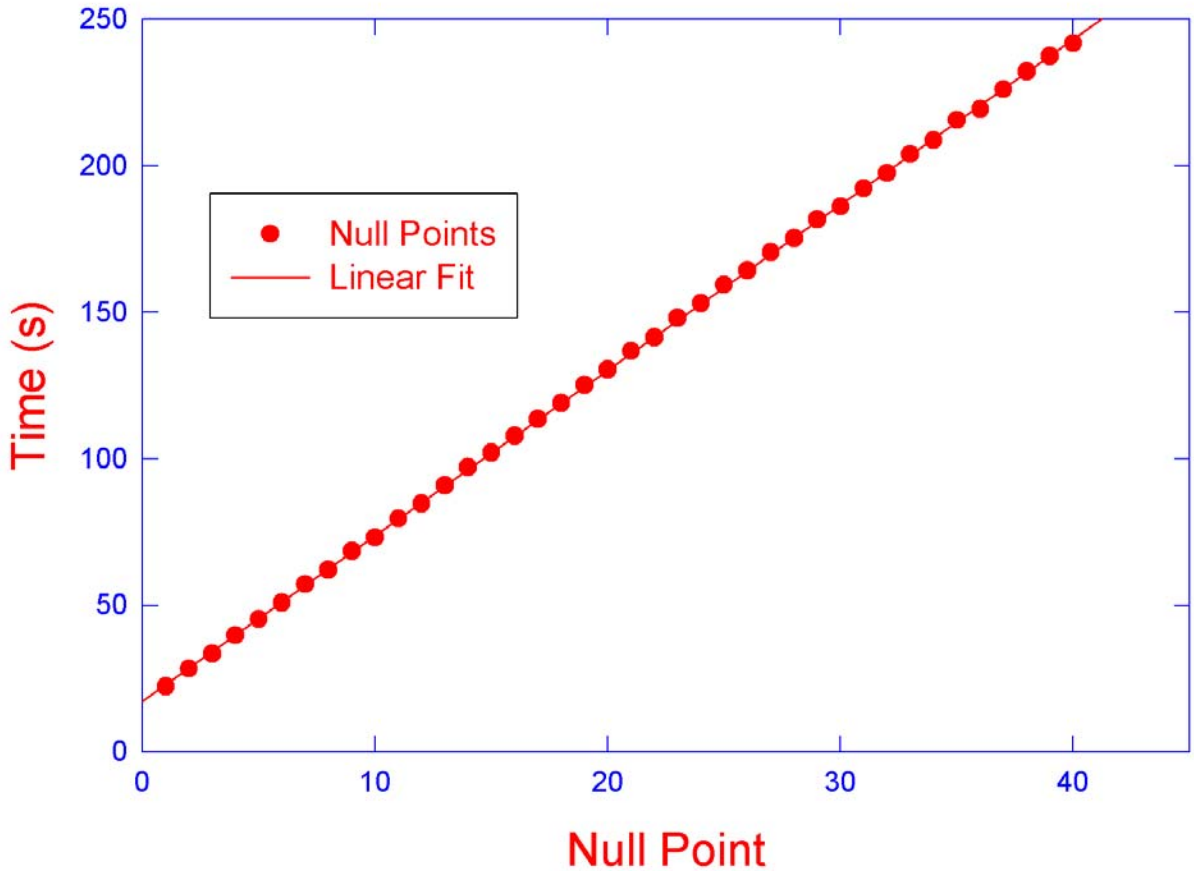

Figure 7-15. The time when null points are observed in the difference video of WTC 2 are plotted versus the null point number. The points fall on a straight line having a slope of 5.647 s ± 0.008 s.

The measured oscillation period is consistent with measurements that are available from WTC 1, accounting for the difference in orientation of the cores in the two buildings, which yielded average periods of 10.9 s in the east-west direction (averaged over a 9-year period that ended in 1993) and 11.6 s in the north-south direction (averaged over a 14-year period that also ended in 1993). (NIST NCSTAR 1-2) The value also agrees well with that determined for the primary period using the moiré analysis in the following section.

7.3.3 Moiré Analysis of Primary Frequencies and Time-Dependent Oscillation Amplitude Following the Aircraft Impact

The sTable nature of the video discussed in the last section allowed a more detailed analysis of the motion of WTC 2 to be performed using image analysis of the moiré patterns. The results include a measurement of the oscillation amplitudes of WTC 2 in the north-south direction along with the periods for translational and torsional movements of the tower. A similar analysis was applied to a second video shot from the north, providing a measurement of oscillation amplitudes in the east-west direction. In this section the analysis approach and major results are summarized. A detailed discussion of the method and additional results are presented in Appendix K.

Figure 7–16 shows a single frame from the video shot from the east as the aircraft impact on WTC 2 was taking place at 9:02:59 a.m. The video was filmed from a thirteenth-floor balcony located approximately 1,000 ft to the east and slightly north of WTC 2. WTC 2 appears to the left of the frame, WTC 1 to the right, and overlapping both towers in front is 22 Cortlandt Street, a 34-story office building located across from the WTC on the east side of Church Street. The lowest point of WTC 2 visible in the frame is the 70th floor. The camera was mounted on a tripod and was undisturbed for thirteen minutes prior to the aircraft impact on WTC 2 and for eleven minutes afterward. This period was sufficient to track the oscillations of WTC 2 induced by the impact until they had faded to background noise.

Figure 7-16. A single frame taken from a video shows the aircraft impact on WTC 2 at 9:02:59 a.m.

The moiré effect occurs when two images containing closely spaced lines are superimposed, generating interference patterns that attract the eye. Figure 7–17 demonstrates this effect for conditions chosen to mimic those present in the video. In the case of the video, the two line patterns are the set of lines on the WTC 2 façade formed by the alternating columns and windows, as indicated in (a) and the vertical columns of picture elements (pixels) that form the images recorded by digital video cameras, shown in (b). The superposition of the sets of lines results in the visual appearance of light curved lines shown in (c)—a moiré fringe pattern—that appears in the recorded image. The set of curves in (c) and (d) can be observed in Figure 7–14, especially in the difference frame at 11.3 s, and in Figure 7–16.

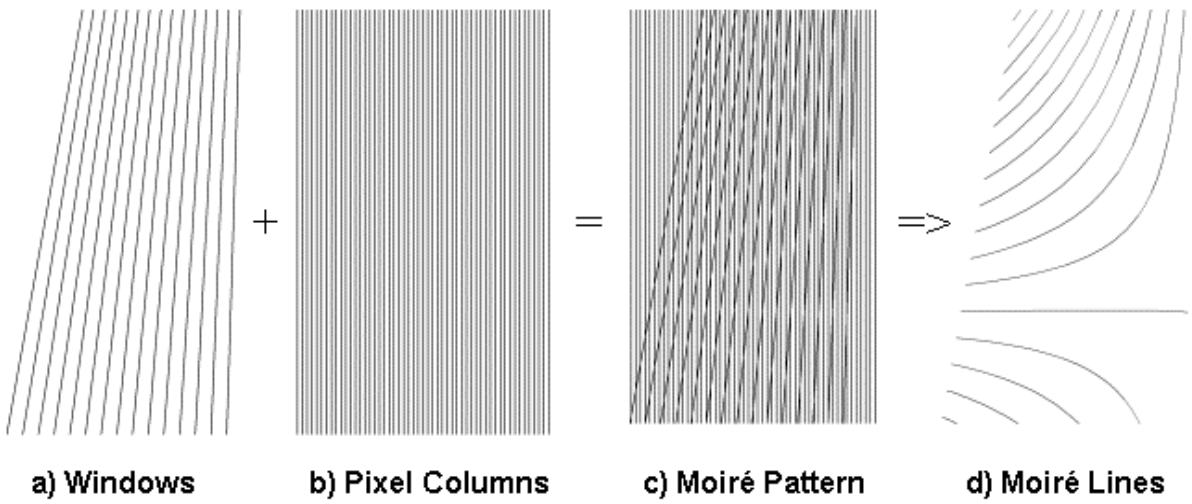

Figure 7-17. Drawings demonstrate the formation of a moiré fringe pattern (c and d) by the superposition of the lines on a tower façade (a) with the vertical columns of picture elements (pixels) of a digital camera.

Note that the lines generated by the moiré effect are much further apart than the window spacing on WTC 2. As the building swayed in response to the plane strike, the moiré pattern, in effect, amplified the motion. The motion was characterized through analysis of the points that make up the moiré fringes, which were located for each frame of the video using a computer-automated process. Similar analysis of the fixed 22 Cortlandt Street building allowed subtraction of small camera motions. By utilizing the known center-to-center column spacing of 40 in., it was possible to use the analysis to determine quantitative motions of the tower. Figure 7-18 plots the north-south displacement of the first line of windows on the 70th floor as a function of time, following correction for camera motion. The analysis also provides time-dependent data for the relative window spacing from the camera's perspective, the angle of the leftmost line of windows, and the change in angle from one line to the next.

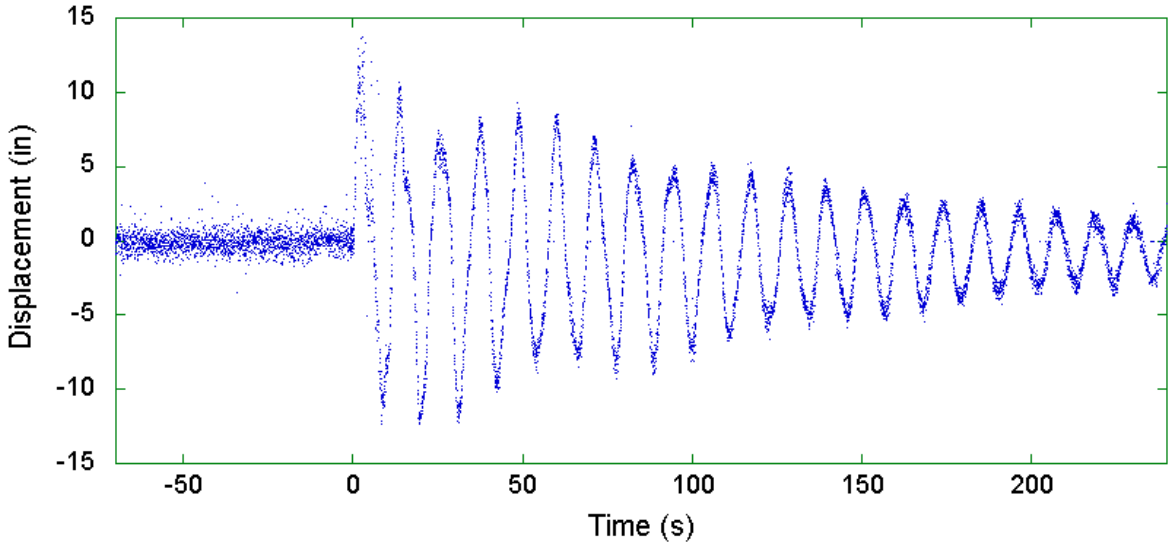

Figure 7-18. The displacement of the first (left-most) window line on the 70th floor of WTC 2 determined using moiré analysis is shown as a function of time.

Detailed frequency analysis of the displacement data shown in Figure 7–18 revealed the fundamental north-south mode with a period of 11.4 s, a torsional mode with a period of 5.3 s, and two higher frequency modes with periods of 3.9 s and 2.2 s. All periods are accurate to better than ± 0.1 s. The period of the fundamental mode is comparable to the computational value for WTC 2 and within normal expected variations as evidenced by measurements on WTC 1 (NIST NCSTAR 1-2). The torsional mode dominates the window spacing variation, as twisting of the building makes the camera's viewing angle of the east face alternatively more and less perpendicular. The highest frequency mode causes some jerkiness in the motion over the first few oscillations.

It is necessary to take into account the view angle of 15 degrees, relative to the east face normal, when determining the actual sway of the building at the 70th floor and when extrapolating the results to the roof of WTC 2. Following these corrections, the maximum excursion of the tower in the north direction upon impact was determined to be 12 in. ± 1 in. at the 70th floor and 22 in. ± 5 in. at the roof.

A second video, filmed from the north with the camera mounted on a tripod, provided an opportunity to determine the east-west motion of WTC 2 for a brief period following the aircraft impact. The four frames in Figure 7–19 illustrate the appearance of the video from this time. Frame (a) from just before impact shows the composition, with the top floors of WTC 1 and WTC 2 filling much of the frame. The base of the frame corresponds to the 94th floor of WTC 2. WTC 2 was observed to move for about seven seconds, first to the west then east, until the fireball covered the visible surface of WTC 2, as in frame (b). Frame (c) shows that the smoke gradually cleared from the west (right) side of the north face, allowing the building motion to once again be followed. Unfortunately, the camera zoomed back from the initial view about 19 s after the aircraft impact, as can be seen in frame (d), resulting in the loss of detail necessary for the moiré analysis.

Although the motion of WTC 2 in this video covers less than a pixel width horizontally, the moiré pattern for the nearly vertical lines of windows greatly amplifies this motion. Figure 7-20 shows the calculated east-west displacement of the 94th floor of WTC 2, with a total apparent sway of 12 in. ± 2 in. A frequency analysis of this brief set of data yielded a period of 5.3 s. This is consistent with the torsional mode found in the analysis of north-south motion and can be explained as follows. The aircraft struck WTC 2 on the south face off-center toward the east while moving toward the northeast relative to the tower. As a result, the tower was twisted in the counter-clockwise direction as seen from above, i.e., the aircraft impact imparted a brief angular momentum as seen from above. To an observer from the north, points on the north face appeared to suddenly move toward the west. The tower resisted this motion and tried to return to its original position. In doing so, it rotated clockwise, causing the apparent motion to the east evident in Figure 7-20. The torsional motion would have continued until it died down. It is uncertain why the estimated building motion is asymmetric relative to the original undisturbed position.

As indicated earlier, additional details concerning the moiré analysis procedure and the results may be found in Appendix K.

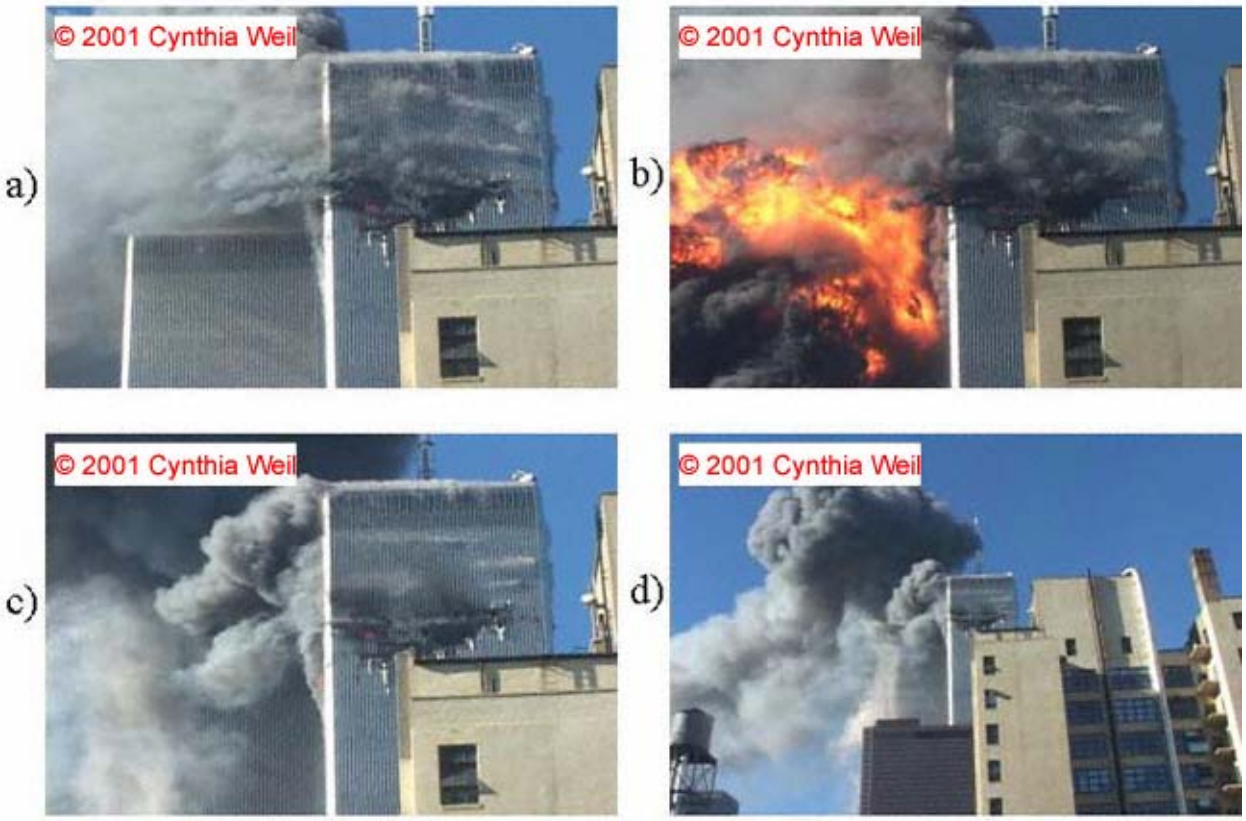

Figure 7-19. These four frames are taken from a video shot from the north around the time of aircraft impact, 9:02:59 a.m., on WTC 2.

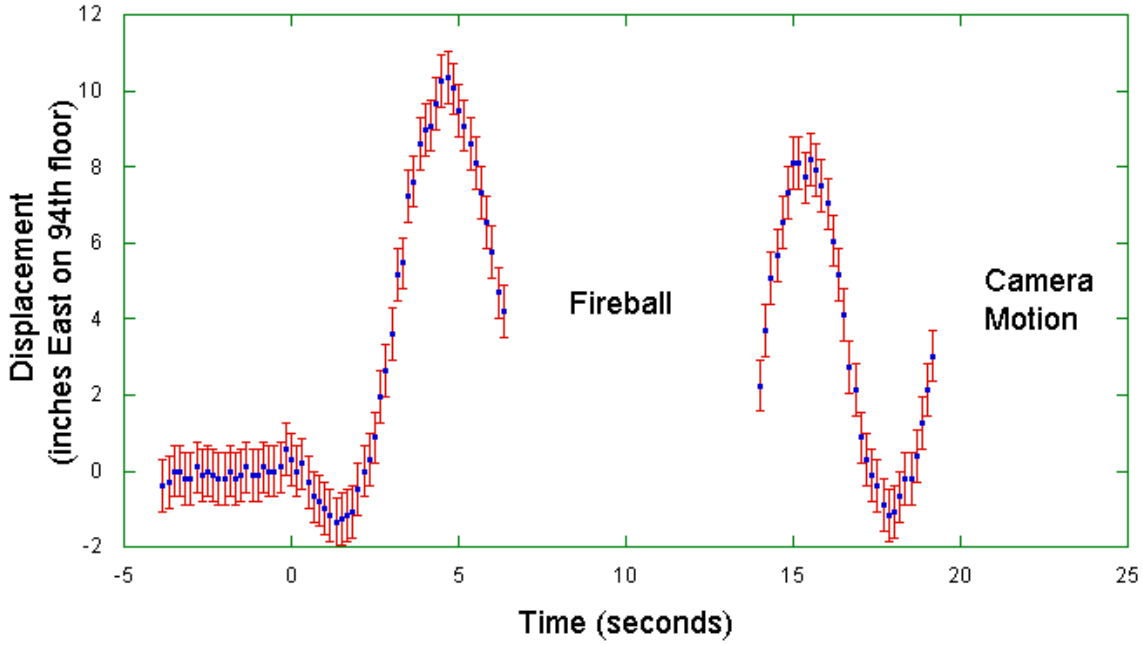

Figure 7-20. East-west motion of WTC 2 just before and after the aircraft impact. Error bars indicate measurement uncertainty.

7.4 DAMAGE ASSESSMENT DUE TO AIRCRAFT IMPACT AND SUBSEQUENT FIREBALLS BASED ON VISUAL EVIDENCE FOR WTC 2

7.4.1 Damage on the South Face Due to the Aircraft Impact

Figure 7–21 shows a photograph that was taken just prior to United Airlines Flight 175 striking WTC 2. The right wing of the aircraft is raised, as if the aircraft was turning to the left. Videos show that when the aircraft struck it appeared to disappear into the tower leaving a hole shaped like the aircraft. Very shortly after the aircraft impact, a large cloud of debris and burning aviation fuel exited the tower from the impact location, obscuring the region. Table 7–1 in Section 7.2 details some of the observations during the period immediately following the aircraft impact. As the fireball rose and the dust cloud cleared, the hole in the building became visible once again.

Figure 7-21. This photograph shows United Airlines Flight 175 just prior to its collision with the south face of WTC 2 at 9:02:59 a.m.

In the period between the aircraft impact and the tower collapse, a number of photographers and videographers recorded images of the aircraft impact location that have been used to characterize the external damage to the façade of the south face caused by the aircraft impact. Figure 7–22, Figure 7–23, and Figure 7–24 show examples of such images. These and other images were used to derive the damage diagram shown in Figure 7–25. The FEMA report (McAllister 2002) includes a similar Figure describing the damage to the steel façade inflicted by United Airlines Flight 175. The pattern in Figure 7–25 differs somewhat from that provided in this earlier study. Some inconsistencies in façade dimensions have also been corrected in Figure 7–25.

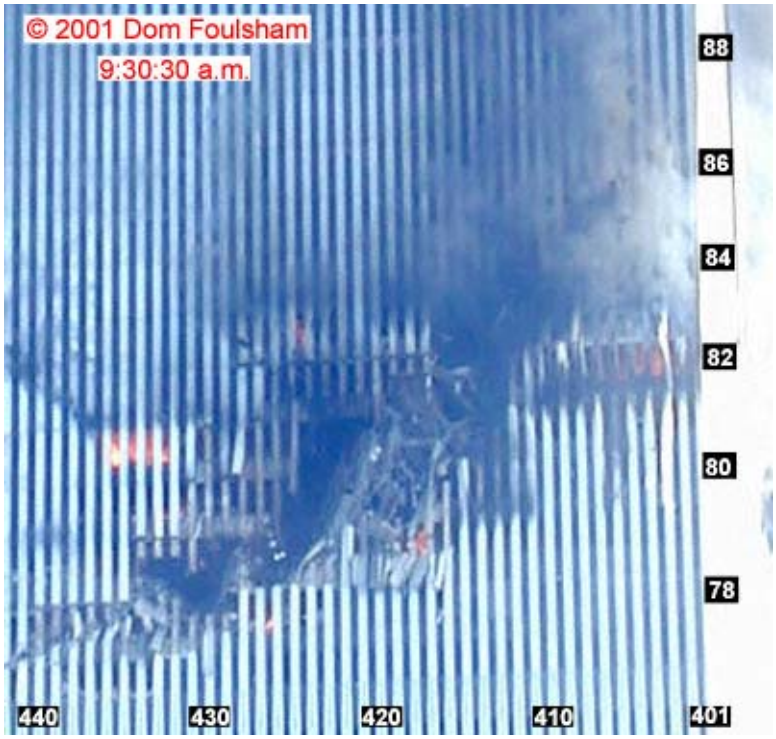

Figure 7-22. This cropped photograph shows the damage to the south face of WTC 2 caused by the aircraft impact. The image was enhanced by adjusting the intensity levels. Column and floor number have been added.

As was true for WTC 1, in areas of the façade struck by the wing tips and the upper portion of the vertical stabilizer, the aluminum covering was marked, but the aluminum covers were not removed and the steel was not cut through. Measurements for the location of the left wing tip were mapped out as shown in Figure 7–25. As already noted, the area at the end of the right wing was obscured by heavy smoke. However, there were brief periods when the location of the last column struck by the wing tip could be discerned. This location is indicated on column 85-404 of the 85th floor in Figure 7–25. The center of the aircraft impact location is clearly toward the east side of the face. The left wing marks extend to the bottom of the spandrel located below the 78th floor. The location of the concrete floor slab is above this point, which means the lowest point struck was on the 77th floor. Thus, the aircraft impact location on WTC 2 extends from the 77th floor to the 85th floor. This finding can be contrasted to the FEMA study (McAllister 2002) and most media sources, which reported that the impact floors extended from the 78th to the 84th floors.

In Figure 7–26, a scaled outline of a Boeing 767-200ER has been superimposed on the damage diagram for the south face. The inclination of the strike point is consistent with the aircraft banking as indicated by Figure 7–21.

Figure 7-23. A frame captured from a video recording of the aircraft impact location on the south face of WTC 2 is shown. The image has been enhanced by adjusting the intensity levels. Column numbers and floor numbers have been added.

The outline is for an aircraft located on the ground. During flight, the shape differs due to lift applied to the wings and other stresses placed on the aircraft by flight maneuvers. The position of the aircraft has been adjusted to provide good agreement with the observed damage pattern and the wing and vertical stabilizer marks. From the results, it can be seen that the nose of the aircraft struck near column 422 at a height that was just below the floor slab on the 81st floor. The port engine struck close to column 427 at a height just above the floor slab for the 79th floor, and the starboard engine struck near column 414 on the spandrel between the 81st and 82nd floors.

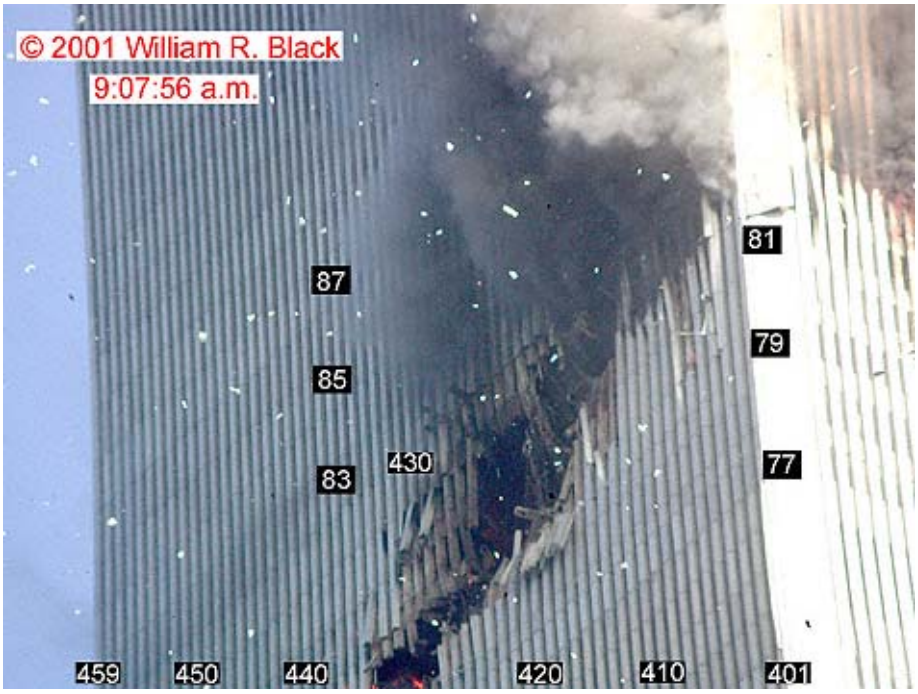

Figure 7-24. This cropped photograph shows the damage to the south face of WTC 2 caused by the aircraft impact. The original image has been enhanced by adjusting the intensity levels. Column and floor numbers have been added.

Close inspection of the photographs and videos reveals a great deal of debris piled on the right-hand side of the opening created by the aircraft impact. This debris, along with the depth of the opening, indicates that floor slabs in this area were partially collapsed by the collision. There is insufficient information to determine the exact areas over which the floor slab collapses occurred or the depth of the collapses inside the building. Visual evidence to be discussed in Section 7.4.3 suggests that at least some of the concrete in the floor slabs was pulverized during the collision.

Inspection of Figure 7–22, Figure 7–23, and Figure 7–24 shows that portions of the aluminum cladding that formed the curtain wall for the building were partially or completely removed at locations close to where the aircraft impact occurred. This includes areas on the 80th floor extending from column 80-426 to column 80-431, on the 81st floor extending from column 81-425 to column 81-430, and on the 82nd floor extending from column 82-420 to column 82-426. In Figure 7–24 it can be seen that the aluminum cladding covering the southeast corner on the 82nd floor was pushed outward during the event. It is likely that this occurred as a result of the overpressure within the building generated by burning of aviation fuel released from the tanks of the aircraft. This damage provided a convenient marker for identifying the 82nd floor.

In general, the glass in windows near the aircraft impact location was broken out, while those windows further away tended to remain intact, although some windows were blown open by the overpressure generated by the initial fireball formation within the building. Figure 7–27 is a color-coded representation showing the condition of the windows on the south face in the area immediately following the aircraft impact. Note that a portion of the face was hidden by smoke at this time.

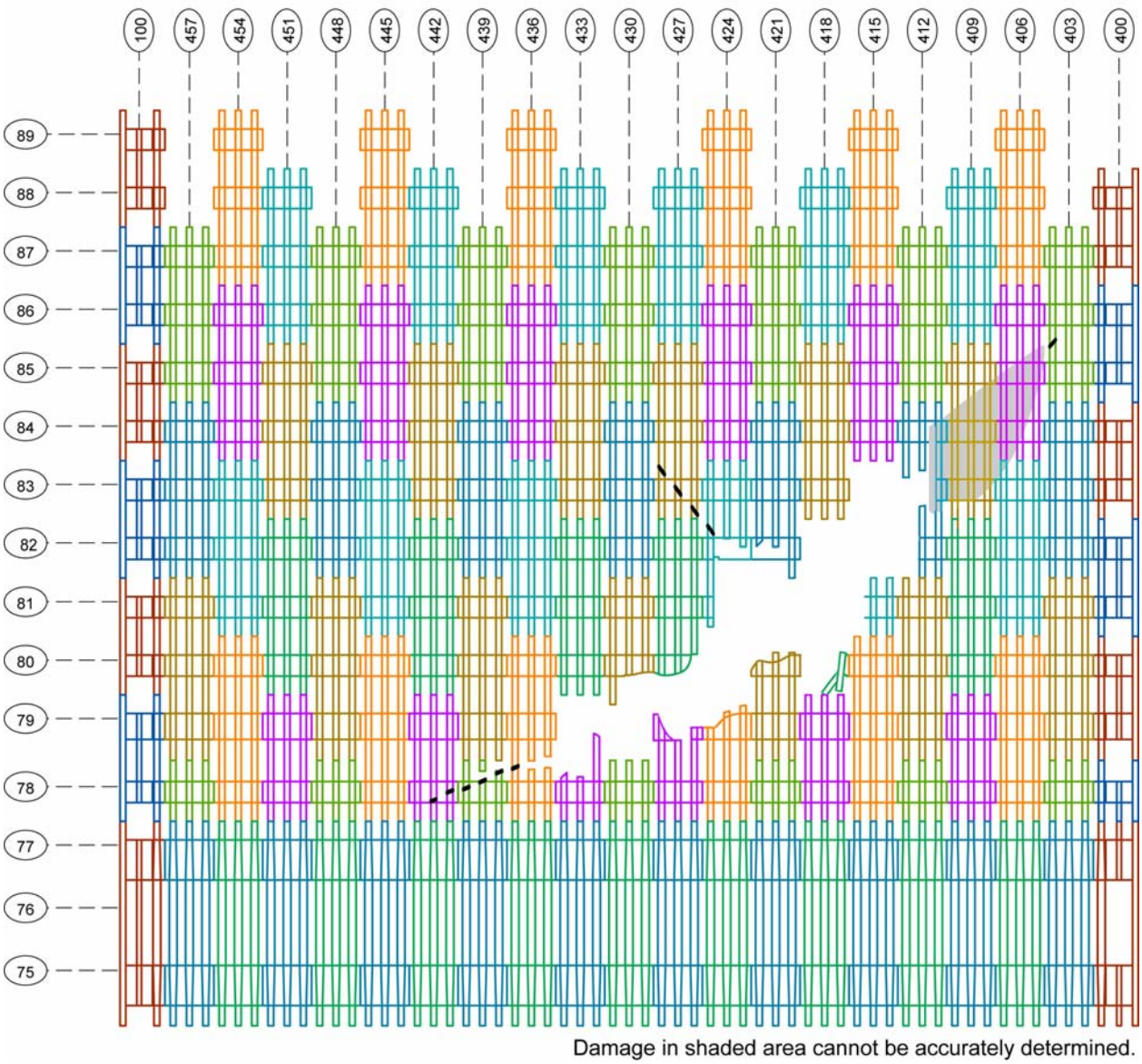

Figure 7-25. A diagram of the south-face steel façade of WTC 2 shows the damage inflicted by the aircraft impact. The dark dotted lines indicate locations where the wings and tail of the aircraft marked the aluminum cladding on columns. The area shaded in gray was hidden by smoke and could not be observed.

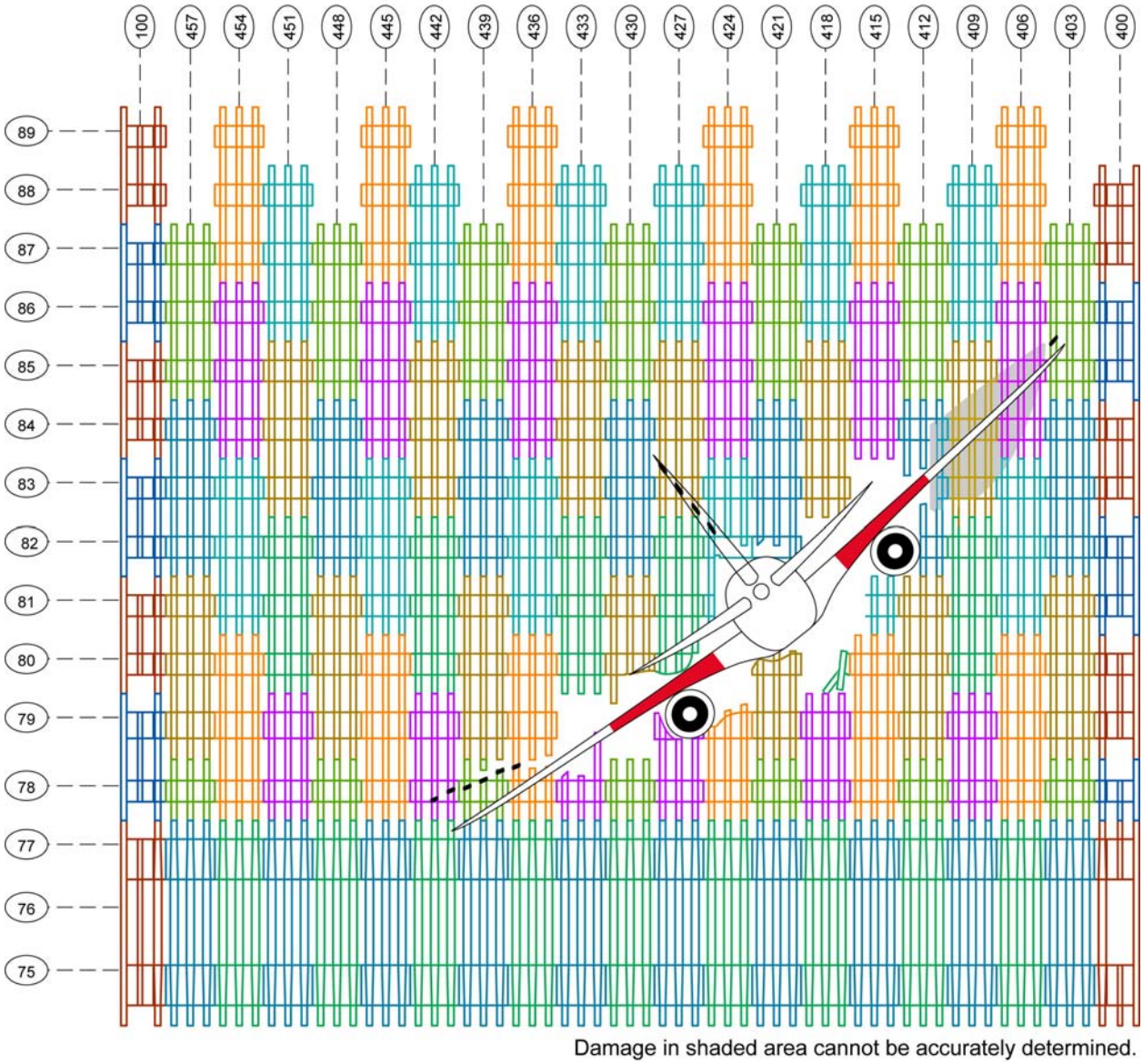

Figure 7-26. A scaled outline of a Boeing 767-200ER is superimposed on the damage diagram shown in Figure 7–25. The position of the aircraft has been adjusted to give the best match with the damage pattern and marks showing where the wing tips and vertical stabilizer struck. The match is not expected to be perfect since the drawing shows the aircraft as it appears when on the ground. The red areas correspond to the approximate locations of fuel on the aircraft based on an analysis reported elsewhere (NCSTAR 1-2B).

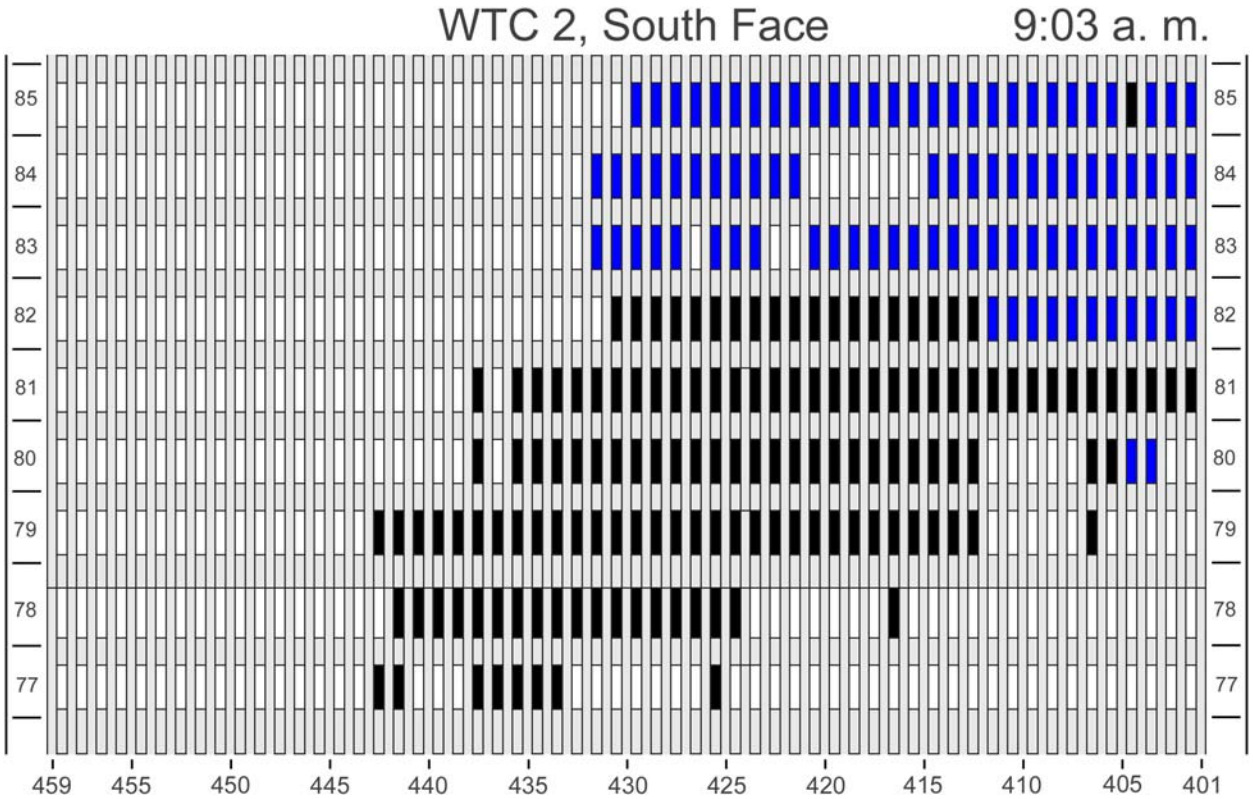

Figure 7-27. A schematic of observed window conditions on the south face of WTC 2 immediately following the aircraft impact is shown. Window and floor numbers are indicated. The colors represent ▌- window broken open, ▯- glass in place, and ▌- not visible.

7.4.2 Damage on the East, North, and West Faces of WTC 2 Due to the Aircraft Impact and Fireballs

Detailed observations derived from videos (see Table 7–1) show that debris (including a great deal of dust) as a result of the aircraft impact began to appear on the east face of WTC 2 0.23 s after the aircraft nose hit the tower and was followed very shortly thereafter by the appearance of large fireballs resulting from burning of the aviation fuel released from the aircraft. Figure 7–28 shows a photograph of the east face of WTC 2, recorded 23 min after the aircraft impact on the tower. The façade damage pattern (with the exception of some window breakage) is nearly unchanged from that immediately following the aircraft impact.

Substantial areas of the aluminum curtain wall have been removed over multiple floors. These areas appear dark due to the color of the underlying column and spandrel steel and fireproofing. In other areas the aluminum column and spandrel covers were disturbed, but remained in place. Video evidence and the wide extent of the damage indicate that much of this damage was due to the overpressures generated within the building by the sudden ignition of atomized aviation fuel and that these overpressures were sufficient to “blow off” numerous sections of the curtain wall. The potential magnitude of the overpressure generated within the tower was discussed in Section 6.5.

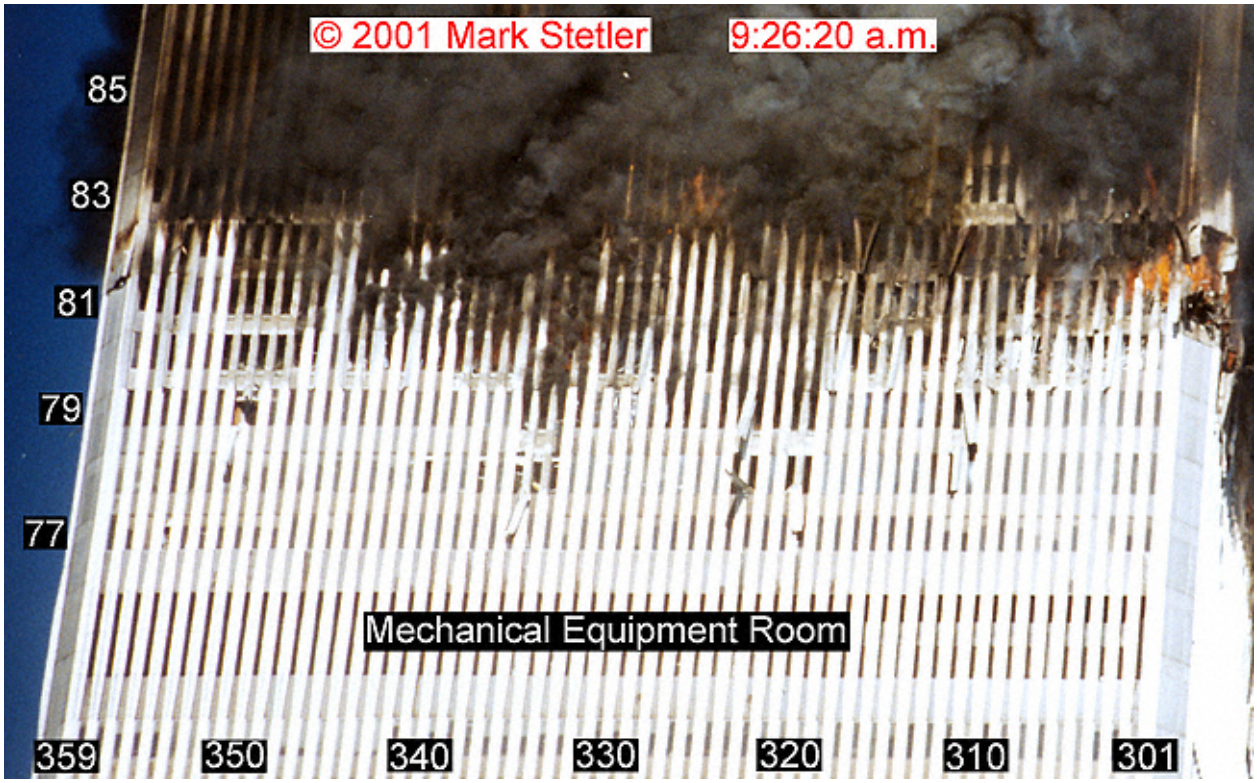

Figure 7-28. A cropped photograph shows the east face of WTC 2 at 9:26:20 a.m. The image has been rotated, and column and floor numbers have been added.

Figure 7–28, along with numerous other photographs and videos, was used as the basis for a detailed assessment of the initial damage to the curtain wall on the east face. Figure 7–29 shows the results. The information displayed includes details about the condition of the aluminum facing and whether or not window glass is missing or is still in place. It is apparent that the largest areas of damage were concentrated on the 80th, 81st, and 82nd floors. Based on Figure 7–26, these correspond to the two floors struck by the body of the aircraft (80th and 81st floors) and the floor where the majority of fuel from the starboard fuel tank was dumped (82nd floor). Interestingly, much less damage is apparent on the 79th floor, which is the floor where most of the fuel from the aircraft's port tank should have been released.

Figure 7–30 shows an enlarged region of the northeast corner of the tower taken from Figure 7–28. Large piles of debris can be seen through the windows near the corner on the 80th and 81st floors. It is likely that a large fraction of this debris was derived from the aircraft, since its body impacted on these two floors (see Figure 7–26). This suggests that either the debris was deflected from the core or that the aircraft was moving toward the east when it struck the tower, since the nose struck near column 422 on the south face.

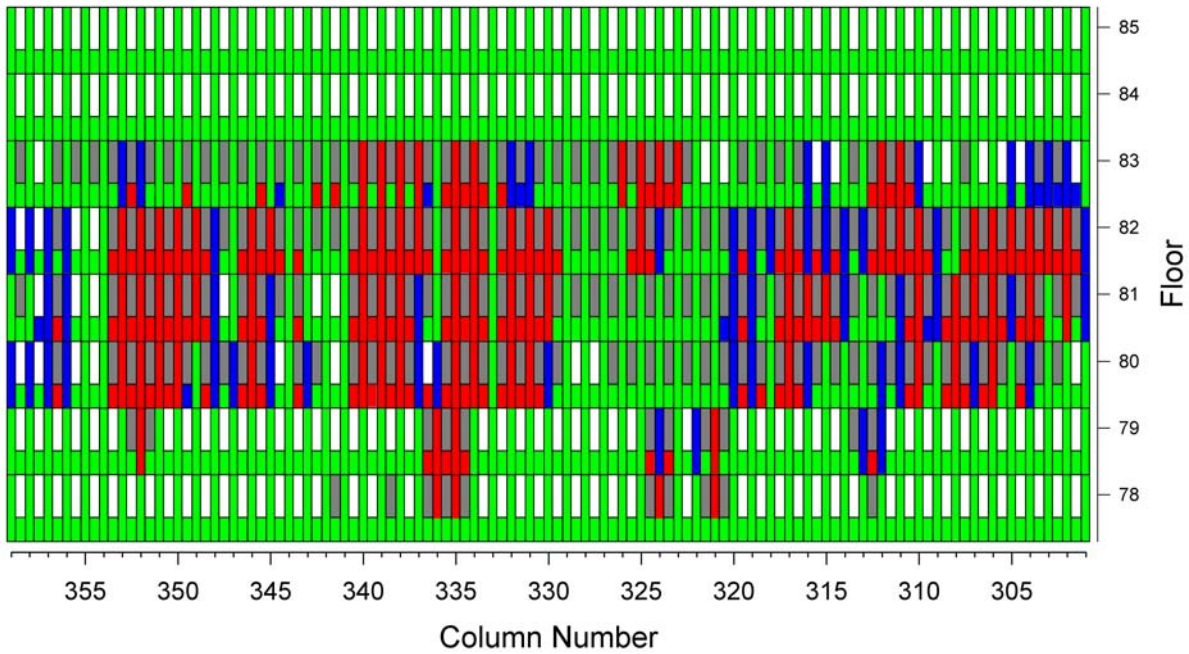

Figure 7-29. A color-coded map of the damage to the east face of WTC 2 as a result of the aircraft impact and fireball is shown. Details concerning damage to the aluminum curtain wall (- undisturbed, - disturbed but still in place, and - aluminum facing missing) and windows (- glass missing and - glass in place) are combined.

Figure 7–30 also shows that the aluminum panels on the 80th and 81st floors of the northeast corner have been pushed out and partially removed. This damage was present immediately following the aircraft impact. Observations included in Table 7–1 indicate that the initial damage in this area appeared 0.4 s after the aircraft impact. As discussed below, it is likely that one of the engines of the aircraft passed through this corner. A pile of debris can also be seen jutting from this corner on the 81st floor. The debris in the corner can be seen more clearly in Figure 7–31, which was shot from the northeast. Additional debris extends from windows on either side of the corner.

Large fires were ignited on the north face near the east side that made it difficult to observe conditions in this area immediately following the aircraft impact. Ultimately, these fires died down to a level where observations were possible. Figure 7–32 was taken just prior to the collapse at 9:58:37 a.m. and shows the eastern side of the north face. Some conclusions were drawn from this photograph concerning damage inflicted by the aircraft, even though the photograph was taken nearly an hour after the aircraft impact. Many of these conclusions were checked by reviewing videos and photographs taken at earlier times.

A casual inspection of Figure 7–32 reveals that significant areas of the aluminum curtain wall are missing. Reviews of early photographs and videos indicate the vast majority of this damage was present immediately after the fireball created by the aircraft impact dissipated. The most prominent region of missing curtain wall is a roughly rectangular area extending from column 238 to column 249 and covering the 80th, 81st, and 82nd floors. This area coincides with the locations (see Table 7–1) where the nascent fireball was first observed on this face 0.63 s following the aircraft impact. As will be discussed in more detail in Chapter 9, the observed fire behavior in this area following the fireball and before the

collapse of the tower was unusual in that very little fire was observed, and the area was close to the ambient temperature well after the aircraft impact. As a result, this area is referred to as the "cold spot".

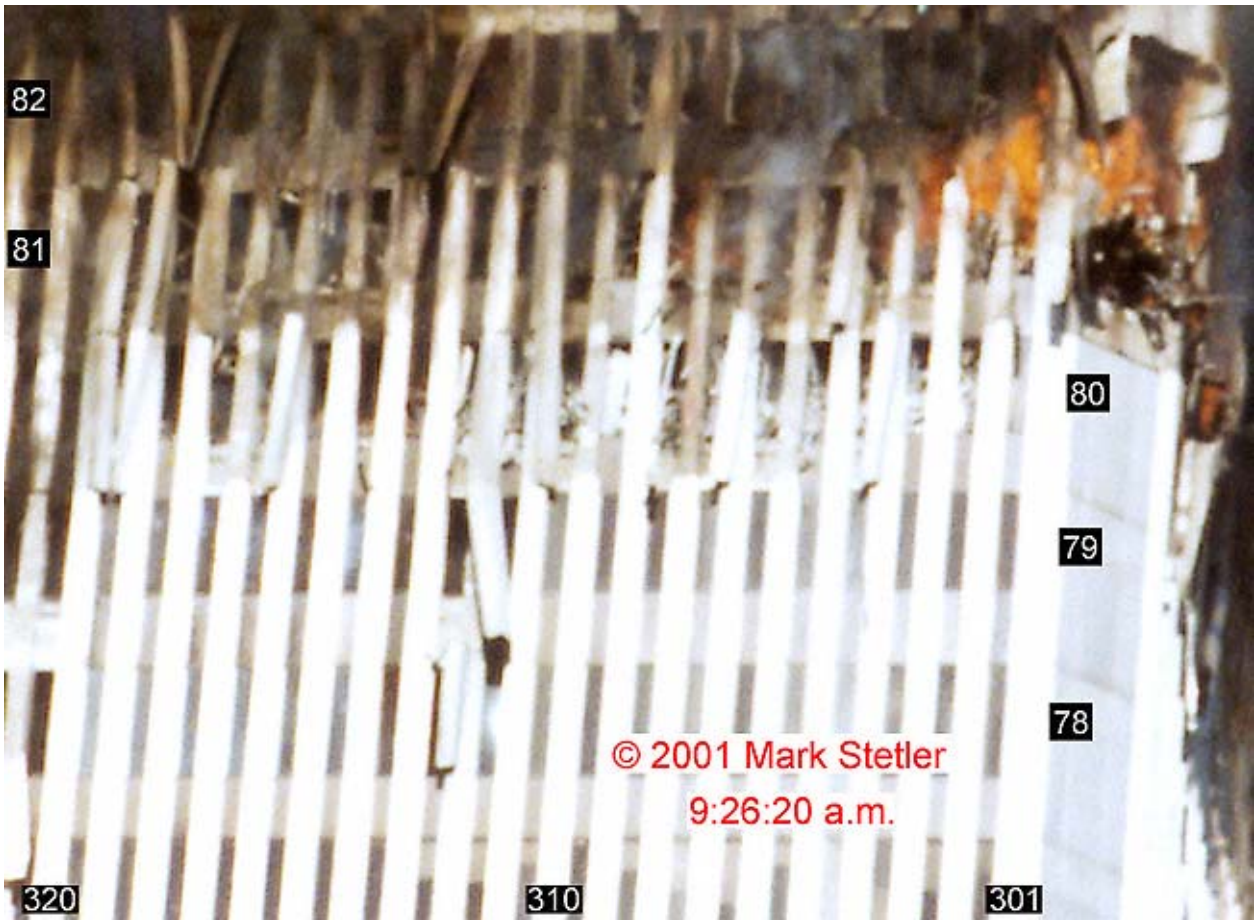

Figure 7-30. This photograph showing a portion of the east face of WTC 2 was cropped from the image shown in Figure 7–28. The image has been rotated, and column and floor numbers have been added. Note the large piles of debris on the 80th and 81st floors.

Three large piles of debris are evident through the windows on the north face. Two of these piles start at the northeast corner and extend out about eight windows toward the west on the 80th and 81st floors. These are the same floors where similar piles were observed on the east face at the north edge, suggesting that the debris essentially filled up the corners of the tower on these two floors. The third pile of debris can be seen on the 79th floor extending from roughly column 79-231 to column 79-240. As indicated in Table 7–1, these windows overlap an area where a distinct line of fire appeared 0.92 s after the aircraft impact.

Closer inspection of Figure 7–32 shows that column 253 has been severed just below the spandrel between the 81st and 82nd floors. The adjacent column, 81-254, is bent and split. This damage must be the result of a large part of the aircraft passing through the tower. As indicated in Table 7–1, such an object was observed breaking through the north face at this location 0.5 s after the aircraft impact on the tower.

Figure 7-31. This cropped photograph shows the northeast corner of WTC 2. This image was recorded between 9:05 a.m. and 9:19 a.m. Column and floor numbers have been added. The corner aluminum panels on the 81st and 82nd floors have been pushed outward. A large pile of debris is evident in the opening on the 81st floor, and a vertical steel column, numbered 82-300, can be seen on the 82nd floor.

Figure 7-32. A cropped and enhanced photograph of WTC 2 taken at 9:58:37 a.m. shows the east side of the north face. Piles of debris are evident on the 80th and 81st floors at the northeast corner and on the 79th floor to the right of column 241. The "cold" spot extends over the 80th to 82nd floors from column 238 to 249.

In the photograph the glass for four windows, 78-236 to 78-239, is missing. Again, this observation is consistent with the events listed in Table 7–1, which indicates that this damage first appeared on the north face 0.86 s after the aircraft impact. While not shown in Figure 7–32, the uncropped version of this photograph and numerous earlier photographs and videos indicate that the glass in windows 78-224 to 78-226 was broken out during the aircraft impact. The time line in Table 7–1 indicates that façade damage and dust appeared at this location 0.56 s after the aircraft impact. It is interesting that even though aircraft and/or parts of the building exited the north face on the 78th floor at two locations, no fire was observed emanating from windows on this floor.

The agreement between damage observed on the north face of WTC 2 and the events included in the time line provided in Table 7–1 is excellent. This agreement provides added confidence that locations identified on the faces of the tower from aircraft impact videos are accurate and that the various observations from Figure 7–32 are due to events that occurred during the aircraft impact.

Figure 7–32, along with other photographs and videos, was used to develop the map for exterior damage shown in Figure 7–33 for the north face of WTC 2 that combines damage to the aluminum facing and window glass that make up the curtain wall. Damage on this face is inclined at an angle which roughly matches that at which the aircraft struck the tower on the south face on the opposite side of the tower. This suggests that debris from the aircraft tended to pass straight through the tower, perhaps passing between and being guided by the floor slabs.

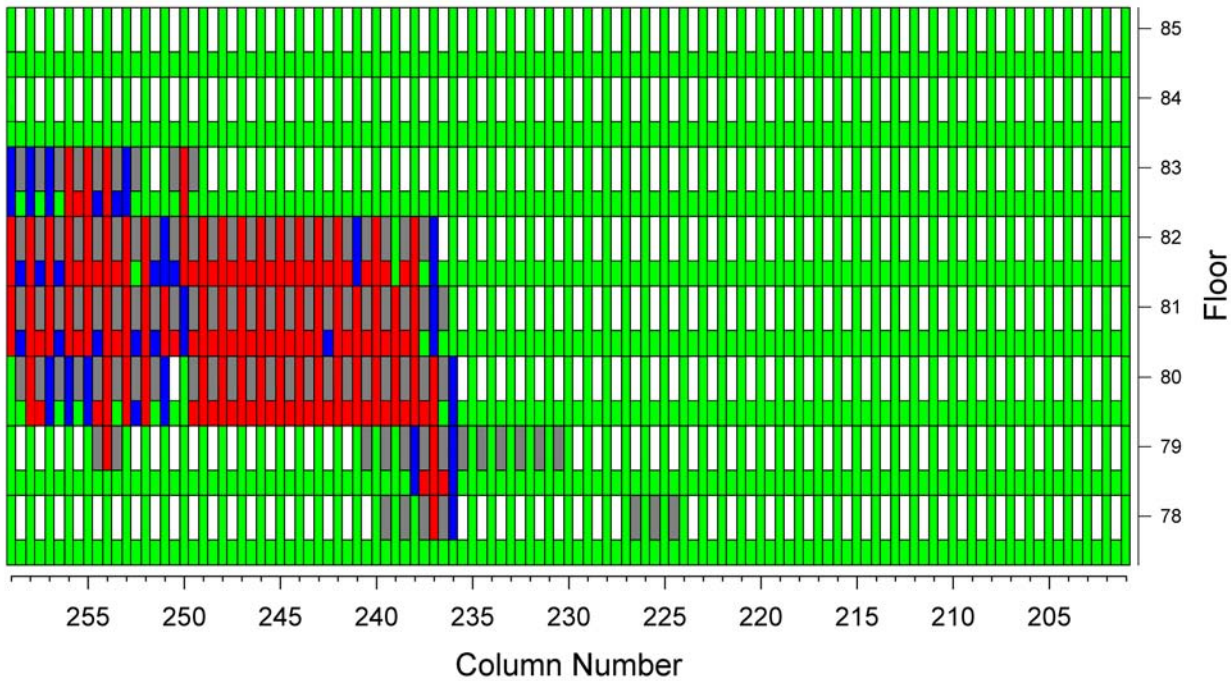

Figure 7-33. A color-coded visualization of initial damage to the north face of WTC 2 is shown. Information concerning damage to the aluminum on the curtain wall (- undisturbed, - disturbed but still in place, and - aluminum facing missing) and windows (- glass missing and - glass in place) are combined.

A large number of photographs and videos, some of which are reproduced below, show the west side of WTC 2 in the vicinity of the floors where the aircraft struck. There is no indication that the aircraft impact and resulting fireballs produced any damage on this face.

7.4.3 Observations Concerning Debris Expelled from WTC 2 by the Aircraft Impact and Associated Fireballs

In Section 7.2, the fireballs formed by the expulsion of aviation fuel from WTC 2 were described. There was also a great deal of aircraft and building debris that was expelled during the impact and subsequent fireballs. In this subsection some observations are discussed that provide clues for the break-up behavior of the aircraft as it entered and traveled through the tower and possible internal damage to the building caused by its passage.

Videos and photographs indicate that several pieces of the aircraft passed all the way through WTC 2 and exited at high speeds from the north side. Most of these were relatively small, but at least two were of substantial size. These two objects are highlighted in Figure 7–5. Both large pieces left smoke trails that formed parabolas as they fell to the ground. The object on the right was burning, and videos show that the flames suddenly grew dramatically and formed a long tail after the debris had passed by WTC 1. The object on the left, i.e., to the east, was spiraling as indicated by the smoke trail it left behind.

Videos and photographs available in the database lack sufficient resolution to allow direct identification of the objects that passed through the tower. However, it likely they correspond to two large aircraft parts that were subsequently found on the ground and on a building. Figure 7–34 is a photograph taken on September 11, 2001 that shows what appears to be a portion of one of the jet engines sitting very near the corner of Church and Murray Streets. This location is roughly 1,500 ft from the north side of WTC 2. Various photographs and videos indicate that this component hit the eastern edge of a building located on the west side of Church Street between Murray Street and Park Place (see the map in Figure 4-1) before falling the remaining distance and coming to rest at the northeast corner of the intersection. The impact on the building knocked a portion of the roof and other debris onto Church Street.

The FEMA report (McAlister 2002) describes damage to the roof of a building at 45 Park Place due to a landing gear that penetrated the roof. Park Place is the street that runs one block to the south of Murray Street, and the location lies roughly half way between Church Street and West Broadway to the west (see the map in Figure 4-1).

It is likely that the two large aircraft pieces visible in Figure 7–5 are the part of an engine and the landing gear subsequently identified. If correct, this means the two large aircraft pieces highlighted in Figure 7–5 landed at the corner of Church Street and Murray Street and 45 Park Place. The resting locations of the debris indicate the spiraling object was the engine (a plausible conclusion based on the shape of the component in Figure 7–34), and the flaming component was the landing gear.

Based on the video evidence summarized in Table 7–1, along with the observed damage pattern, the most likely exit location for the engine component was the northeast corner of the tower at the 81st floor, and for the landing gear it was in the vicinity of window 81-253 on the 81st floor. These locations are consistent with the aircraft impact location indicated in Figure 7–26 if both components came from the starboard side of the aircraft. If the exit locations are identified correctly, the engine component exited

the building moving toward the east at a horizontal angle of roughly 17 degrees to the normal for the north face, while the corresponding angle for the landing gear was approximately 12 degrees.

Approval needed for image.

Figure 7-34. This photograph shows what appears to be part of an aircraft engine lying near the northeast corner of the intersection of Church and Murray Streets. The photograph was taken prior to the collapse of WTC 2.

Several other smaller pieces of the aircraft were photographed or videotaped at various locations, including the Church and Vesey Streets intersection, in front of the Federal Building (Post Office) on Vesey Street, the roof of the Federal Building, and the roof of the Moody's Building on the northeast corner of Church Street and Barclay Street. The FEMA report (McAllister 2002) includes a photograph of a portion of the aircraft fuselage that was found on the roof of WTC 5 (corner of Church and Vesey Streets) following the collapses of both towers.

Photographs and videos of the plaza between the WTC buildings (see Figure 4-1) show a great deal of debris spread over the area. Most of this debris appeared to be relatively small, such as crushed pieces of concrete. There were no obvious large sections of the building or aircraft. Small fires were present on the plaza many minutes after the aircraft impact. This debris and flaming material most likely fell primarily from the north face of WTC 2, since this side overlooked the plaza.

Photographs and videos taken on Liberty Street and in the immediate vicinity show that a great deal of debris was also present on the south side of WTC 2. Some of this debris came from the first aircraft impact on WTC 1, as described in Section 6.4.3, but there was a much larger amount following the second aircraft impact. Figure 7–35 shows a photograph that was taken looking across Liberty Street toward WTC 2 following the second aircraft impact. The street is completely covered with debris.

Figure 7–36 shows an enlarged portion of Figure 7–35. This photograph is typical of other photographs of the debris taken in the vicinity. Various types of debris, including papers and cardboard boxes, are identifiable. There is also a great deal of what appears to be crushed concrete. A dimpled material is evident in the foreground. Similar material is seen elsewhere in the street debris. This material is likely a portion of a ceiling tile.

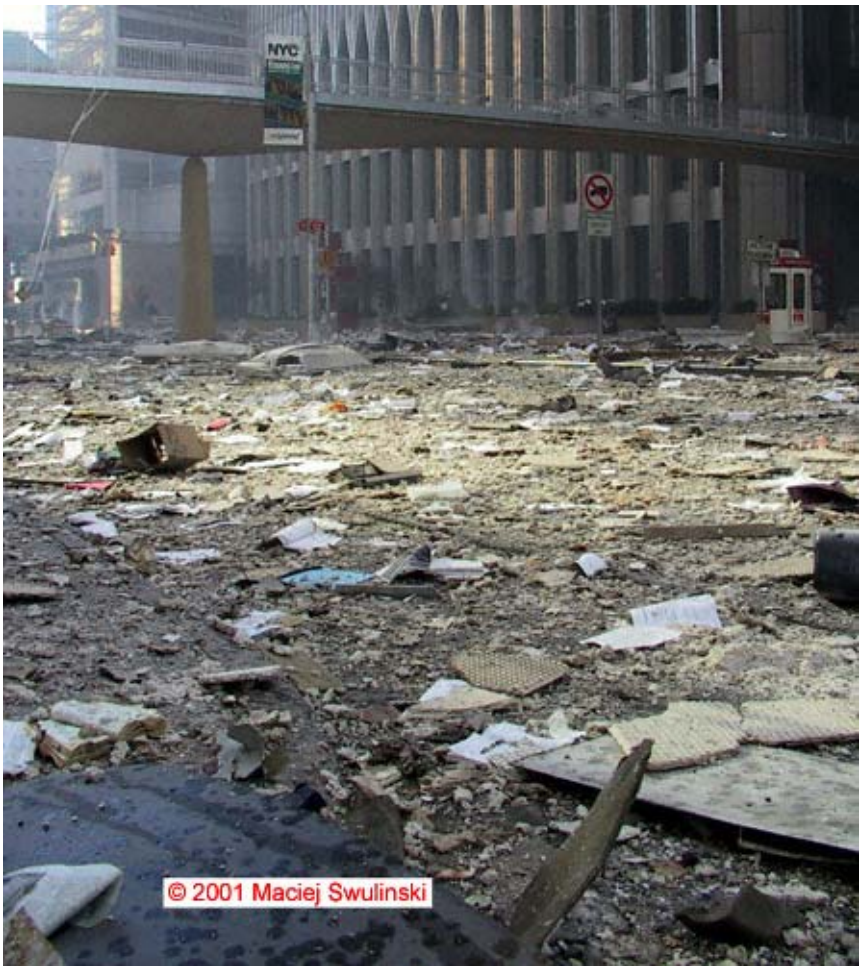

Figure 7-35. This cropped photograph taken from near the corner of Greenwich Street and Liberty Street shows debris on Liberty Street following the second aircraft impact on WTC 2. WTC 2 and WTC 3 are located in the background.

The debris in Figure 7–35 and Figure 7–36 most likely made up a portion of the dust cloud evident on the south face of WTC 2 in Figure 7–3 and Figure 7–9. This material was blown backward out of the tower by the overpressure generated by the initial fire inside the building that appeared shortly after the aircraft impact. The relatively large amount of what appears to be concrete, as well as its small size, suggests that the aircraft impact pulverized a significant amount of concrete floor slabs as it entered the tower. This is consistent with the large scooped-out cavity seen in the aircraft impact location (see Figure 7–22 to Figure 7–24). As noted previously, it has not been possible to visually observe the depth of such damage.

Figure 7-36. A close-up of the debris on Liberty Street created by the second aircraft impact is shown in an enlarged section from Figure 7–35.

7.5 FIRE BEHAVIOR IN THE PERIOD IMMEDIATELY FOLLOWING THE AIRCRAFT IMPACT

The appearances of the fireballs generated by the aircraft impact with WTC 2 have been described in earlier sections. The observations suggest that most of the aviation fuel that formed the fireballs was released from the starboard fuel tank of the aircraft. Much smaller fireballs appeared from the lower floors (primarily the 79th floor) struck by the port fuel tank.

A variety of photographs and videos indicate that, during the 5 s to 10 s period following the aircraft impact, intense flames extended from windows on the south face, east face, and north face of the tower. Examples of these flames can be seen in Figure 7–6 to Figure 7–8. The most intense flames were located on the south face and east face near the southeast corner of the 82nd floor, on the east face near the northeast corner, and on the north face near the northeast corner on the 81st floor. These flames increased in intensity after the formation of the fireball, with the largest flames observed roughly 8 s after impact.

Areas of smaller flames were seen at lower floors at roughly the same time. Their locations included the south face near the bottom of the opening in the tower created by the aircraft impact and near the center of the north face where the small fireball formed (see Table 7–1). An interesting observation is that no flames were obvious on the east face below the 80th floor during this period.

After the initial ten-second period following the aircraft impact, most of the large fires burning around WTC 2 began to decrease in size and to recede back into the building. In many locations fires were no longer visible after about 30 s. Figure 7–37 shows a photograph that was taken 44 s after the aircraft

impact. Comparison with Figure 7–6 to Figure 7–8 indicates to what a large extent the flames coming from open windows have died down. Only relatively small fires are now observed on the east face. Substantial flame extension is still present on the north face, with large flames evident on the 81st floor near the northeast corner, and somewhat smaller flames located near the center of the north face on the 79th floor. Both of these flaming regions are in areas where large piles of debris can be seen through the windows. The cold spot discussed earlier stands out between the two fire zones due to the absence of flame. Similar close-up photographs and videos from the south are not available in the database for this early time, but more distant images indicate only a few isolated small fires were present on this face at this time.

Figure 7-37. This cropped photograph showing WTC 2 from the northeast was taken from the corner of Vesey Street and Church Street at 9:03:43 a.m., i.e., 44 s after the aircraft impact. The intensity levels have been adjusted, and column and floor numbers have been added.

The lack of significant burning in interior regions in the immediate aftermath of the fireballs is also reflected in the absence of heavy smoke coming from the tower. Some smoke is evident in Figure 7–37, but it does not obscure the faces of the tower. Most of it seems to be emanating from the flaming areas visible near the outer edge of the tower. Figure 7–38 shows the east side of WTC 2 at roughly the same time. Only very light smoke is present, and most of the façade area above the floors with fires is visible.

Figure 7-38. This cropped photograph shows the east face of WTC 2 at 9:03:41 a.m. Column and floor numbers have been added.

The behaviors observed immediately following the aircraft impact allow a plausible description for the aviation fuel burning to be developed. As previously hypothesized, immediately after the aircraft struck the tower, the fuel tanks were ruptured, and much of the jet fuel was atomized. The total amount of fuel involved has been estimated as 9,120 gal (Midgett, 2003), divided equally between the starboard and port wing tanks (a center fuel tank is believed to have been empty). This means that roughly 4,560 gal of fuel was dispersed in the vicinity of the 81st and 82nd floors and 4,560 gal in the vicinity of the 79th floor.

In Section 6.5, an estimate based on the available air was provided for the maximum amount of jet fuel that could be burned on a single floor of a tower. If the fuel was distributed completely over two floors and ignition of the entire volume occurred, it would be expected that 730 gal of fuel would be consumed inside. In reality, it is unlikely that the fuel aerosol was distributed over two whole floors, so the total amount of fuel from one of the tanks burned inside was probably less than this amount. This analysis indicates that less than 15 % of the fuel released from a fuel tank would be expected to burn immediately within the building.

As already noted, the overpressure created by the combustion that does take place within the structure is expected to break windows and induce a flow of the gas and aviation fuel aerosol out of the building. It was the aviation fuel expelled from the building that generated the spectacular fireballs.

One interesting aspect of the observed fire behavior is that the fireballs on this tower formed predominantly from fuel dumped on the 82nd floor. The lack of a large fireball emanating from the 79th floor, along with the observation that there was very little fire visible on the floor in the immediate aftermath of the fireball, implies that most of the fuel from the port tank of the aircraft did not burn immediately following the impact. There are two likely explanations for this. One is that the fuel was transported elsewhere in the building, where it encountered fresh air and was then able to burn. There is no visual evidence that this took place. Another possibility is that the fuel was dumped in the vicinity of the 79th floor or into shafts within the core, and much of it failed to ignite. In this case, the fuel would be expected to form pools as the aerosol "rained out." The locations of these pools cannot be determined from the visual record.

Three estimates have previously been provided for the amount of jet fuel that burned outside WTC 2 in the fireballs. The FEMA report (McAllister 2002) used fireball correlations to derive a value between 1,000 gal and 3,000 gal. Baum and Rehm (2005) reported consistent results between two analytical and computational approaches of 10 % to 25 % (roughly 900 gal to 2,300 gal) of the total fuel being consumed. Note that one of the approaches is summarized in Rehm et al. (2003). The consistency of the three calculations is good. Since most of the fuel that formed the fireballs came from the starboard fuel tank, this suggests that 20 % to 50 % of this fuel burned externally, with another few percent consumed inside the building. The remainder of the fuel was presumably left behind in the tower following the initial fire. This is also likely the case for almost all of the fuel released by the aircraft's port fuel tank, primarily on the 78th and 79th floors.

As in WTC 1, once ignited, fires in the initial fuel aerosol/air mixture created by the aircraft impact would have been expected to spread and burn rapidly. Recall that visual analysis indicated that fire appeared on three sides of the tower in less than a second (see Table 6–1). Even though the thermal expansion and resulting overpressure of the mixture occurred rapidly, a finite time was still be required for the actual flow out of the tower to take place. Based on the intense fires observed, the aviation fuel aerosol was still being expelled after roughly 10 s. Once the flow induced by the overpressure generated by the internal

fire halted, it would be expected that burning within the tower would be damped due to oxygen depletion, as discussed in Section 6.5. A much longer time period would be required for the air necessary to support the fire to diffuse or flow back into these regions. This expectation is consistent with the fires retreating back into the building for most of the locations where it was initially expelled and with the lack of heavy smoke. This damping down required less than a minute.

As already noted above, unlike WTC 1, several extensive regions with large fires were present after the initial phase of the fire. The largest of these fires were in areas of the tower where large piles of debris had been formed and for which the windows and large sections of the aluminum facing had been removed. The short-lived jet fuel fires were apparently sufficient to widely ignite these debris piles. These fires were not efficiently damped down by the resulting oxygen depletion within the tower since they had ready access to oxygen from outside air at locations where the façade had been breached. The large flame extensions observed for these fires are consistent with this conclusion. Figure 7–39 provides maps for the fires observed during the period after the initial rapid burning had subsided.

7.6 SUMMARY OF OBSERVATIONS AND ADDITIONAL DISCUSSION

United Airlines Flight 175 struck WTC 2 on the south face at 9:03:59 a.m at roughly 545 mph. The nose of the aircraft hit very close to column 422 (toward the east side) of the face at a location near the base of the 81st floor. The collision severely damaged the steel façade as mapped out in Figure 7–25. Upon entering the building, the aircraft collapsed a large, but unknown area of the floor slabs near the entry point. Visual evidence indicates a great deal of concrete and other building materials were pulverized during the collision.

Numerous eyewitness accounts describe both towers swaying following the aircraft impacts. A stationary video recording of the aircraft impact on WTC 2 allowed this motion to be observed and analyzed. Review of the video indicates that the dominant motion was a north-south oscillation with a period of 11.3 s. The initial displacement of the building from its pre-collision position, as measured near the 73rd floor, was 12 in. ± 1 in. The building then began to sway back and forth. This displacement amplitude decayed exponentially with time. Movement was detectable for over 7 min following the aircraft impact.

The aircraft appeared to simply disappear into the tower after the collision. Shortly afterward, dust and fuel were pushed out of openings on the south, east, and north sides of the building. It is likely that this occurred due to an overpressure inside the building generated when aviation fuel released by the impact began to burn. Dust was also seen coming out of various locations of the mechanical equipment room on the 75th and 76th floors. This observation indicates that some of the ventilation ductwork in the core area was compromised by the aircraft impact and that dust passed through these pathways.

The entry of the aircraft caused significant damage to the south face of the tower as shown in Figure 7–25. Debris from the aircraft struck the east and north faces, and the overpressures generated by the internal fires caused additional damage. As a result, significant damage was done to the curtain wall (i.e., aluminum facing and windows) over multiple floors along the east face and on the eastern side of the north face.

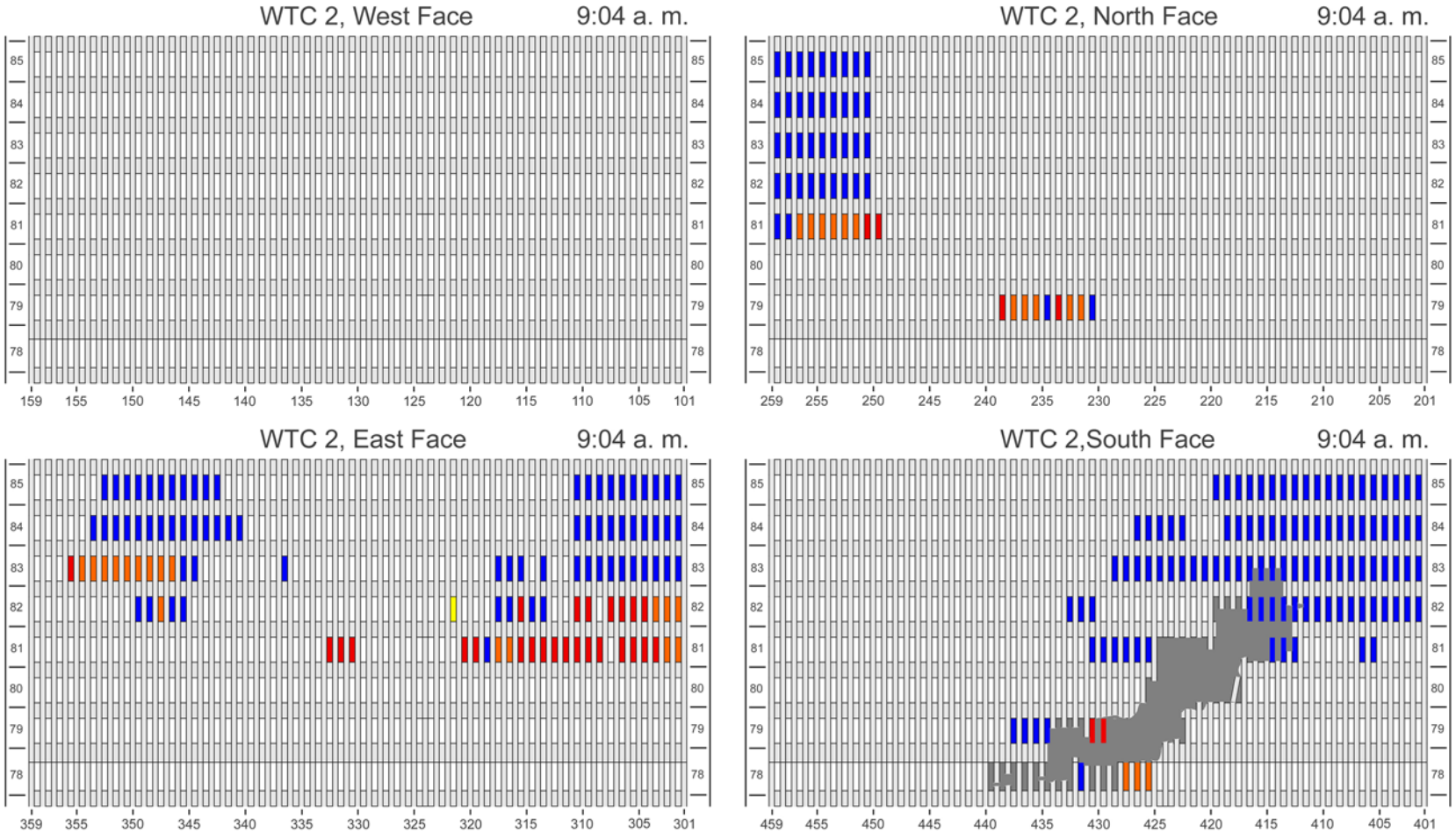

Figure 7-39. Maps of observed fires on the four faces of WTC 2 are shown for the period shortly after the rapid burn off of aviation fuel released during the aircraft impact. The colors represent - no fire observed, - spot fire, - fire inside, - external flaming, and - not visible.

A portion of a jet engine, a landing gear, and numerous smaller portions of the aircraft passed all the way through the building and out the other side on the north face. One column (81-253) was cut on the 81st floor face and a second was severely bent by debris, most likely a landing gear, exiting the north face. Otherwise, the steel panels on the east, north, and west faces were largely intact.

Large piles of interior debris were created against the outer walls on the east and north sides away from the aircraft impact location. On the 80th and 81st floor the debris piles were located around the northeast corner. These floors correspond to the floors where the main body of the aircraft entered the south face.

Therefore, it is likely that the debris consisted of portions of the aircraft, as well as building contents pushed in front of the aircraft debris as it moved all the way across the building. Apparently, most of the kinetic energy associated with the high speed aircraft impact was dissipated before reaching the far side, since the outer walls were intact once the debris came to a halt. The distribution of this debris suggests that the aircraft was moving toward the east when it struck the tower since much of it was observed along the east face.

Another large debris pile was located just to the right of the center of the east face on the 79th floor. If this debris came from the aircraft, it would have had to pass through the core of the building since the portion of the aircraft that struck the 79th floor was the port wing at a point close to the center of the south face. The location of the pile on the north face is consistent with the supposed trajectory of the aircraft toward the east.

Very shortly after the aircraft entered the building, fire appeared on the south, east, and north faces and quickly grew into large external fireballs, which rose and eventually formed a large thermal. These fireballs burned for roughly 10 s. The largest fireball was on the east side and appeared to be considerably larger than similar fireballs observed on WTC 1. The largest fireballs were formed from fuel ejected from the 82nd floor, suggesting the fuel came primarily from the starboard fuel tank of the aircraft.

The visual evidence indicates that the initial aviation fuel fires within the building rapidly depleted the available oxygen and damped down very shortly after ignition. Only a small fraction of the aviation fuel was consumed during this initial burning within the tower. Other sources have estimated the amount of fuel burned in the fireballs as between 10 % to 30 % of the total fuel. As noted, most of this fuel appears to have come from the starboard fuel tank of the aircraft. The remaining unburned fuel, on the order of 8,000 gallons, was apparently distributed initially unburned within the building.

In the immediate aftermath of the aircraft impact and fireballs, large fires were present at several locations on the periphery of the tower. The largest of these fires were burning on large debris piles created by the aircraft impact. The absence of heavy smoke indicated that large interior fires were not present at this time, consistent with oxygen having been depleted at interior locations.

7.7 REFERENCES

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Chapter 8
FIRE BEHAVIOR IN WORLD TRADE CENTER 1

8.1 8:47 A.M. TO 9:03 A.M.

As described in Section 6.5, intense fires fueled by released aviation fuel developed within World Trade Center (WTC) 1 immediately following the aircraft impact. The resulting thermal expansion forced additional atomized fuel from broken windows, which subsequently burned and formed exterior fireballs on the north, east, and south faces of the tower. The air in areas of the building where aviation fuel was ignited was apparently rapidly depleted, since the interior fires damped down within a few tens of seconds.

Appendices C to F provide summaries of visual observations for the north, east, south, and west faces of WTC 1, respectively, as a function of time until the collapse of the tower. Two maps are provided for each face and time analyzed. The first combines information concerning window condition (open or closed) and locations where fires (spot, internal, external flaming) are observed. Note that it was generally true that when fire was observed at a window, the glass was missing, i.e., it was very uncommon to observe fire through closed windows. The second map details locations where light or heavy smoke is seen flowing from open windows. This chapter provides a descriptive narrative of the fire behavior. The data sheets can be consulted for additional details concerning the fire behavior in WTC 1.

In the period immediately following the quenching of the initial internal fires, only relatively small fires were observed at locations with direct access to outside air at openings created by the aircraft impact and subsequent fireballs. Fire locations on the four faces at these early times have been compared in Figure 6-19. Visual images of the faces at these early times were included in Chapter 6 (see Figure 6-4, Figure 6-10, and Figure 6-12).

On the north face (Figure 6-19 and Figure 6-4), fires were only observed within the cavity created by the aircraft impact during this early period. On the east face (Figure 6-19 and Figure 6-10) a region of flame, with some extension out of windows, was present on the 94th floor, covering about ten windows centered near window 94-225. Recall that much of the aviation fuel from the aircraft's port tank was likely released on this floor and that a fireball was observed emanating from this area. Heavy smoke coming from the 94th floor hid much of the area immediately above this fire, while only a few isolated windows on lower floors were emitting smoke (see Figure 6-10). The aircraft impact and resulting overpressure due to the associated fires caused significant window breakage on the west side of the south face. Shortly after the impact, fires were observed extending from windows 96-336 to 96-339 on the 96th floor. As can be seen in the building map included in Figure 6-19 and the image in Figure 6-12, smoke from this floor and from isolated regions lower down obscured much of the west side of the south face above the 96th floor. The heavy smoke coming from the 93rd floor at the center of the face hides the location where a panel section is thought likely to have been dislodged by aircraft debris passing through the building (see Section 6.4.3). The area is hidden in all images of the south face in the visual database. During this early period no flames were seen on the west face, and smoke issuing from broken windows was relatively light (see Figure 6-12).

Even though only a few isolated fires were observed from the outside during this early period, it is likely that numerous small fires were present internally in regions where the jet fuel had been dispersed and ignited. These fires would be expected to grow as the oxygen depleted air (i.e., combustion gases) was replenished by fresh air from outside and elsewhere within the building. The first area where substantial fire spread and growth was observed was on the 97th floor just to the right of the aircraft impact point on the north face. As seen in Figure 8–1 an extensive fire was present at windows 97-110 to 97-116 around 8:50 a.m., i.e., roughly three and a half minutes after impact. Even though these windows were broken during the aircraft impact and subsequent fireballs, fire was not evident prior to this time. This fire would subsequently spread from this location toward the west face.

Figure 8-1. This image is extracted from a video recording that shows the north face of WTC 1 at 8:49:55 a.m. Column and floor numbers have been added.

During the first few minutes following the aircraft impact, similar extensive fire growth or spread was not evident on the east face. The location and intensity of the fires was little changed between 8:48 a.m. and 8:52 a.m. Figure 6-10 in Chapter 6 shows the appearance of this face around 8:51 a.m. In contrast, the original area of external flaming present on the 96th floor of the south face doubled in size between 8:47 a.m. and 8:52 a.m., and new regions of flame appeared to the west on both the 95th and 96th floors.

Very little change was noted on the west face of WTC 1 between 8:48 a.m. and just prior to 8:52 a.m. At this time a stream of smoke suddenly appeared from the south side of the 104th floor, i.e., well above the

floors impacted by the aircraft. Due to the distance from which the available images were shot, it is not possible to provide a definite explanation for why smoke suddenly appeared in this area. However, based on observations of the other faces described below, it is likely that smoke was released when people broke out windows. If correct, this means that significant smoke had traveled to higher floors within the tower and created inhospitable conditions during the roughly five minutes following the aircraft impact. It should be noted that this location is where a very intense fire was observed after 10:00 a.m. (see the later discussion.) There is no visual evidence to support a conclusion that the released smoke seen at this early time was the result of a significant fire on this floor.

At 8:50:55 a.m., light smoke began to come from window 97-144 on the 97th floor, which is located on the north face to the east of the cavity created by the aircraft impact. Fourteen seconds later the smoke suddenly became very dark and heavy. Shortly afterward flames appeared. As evident in Figure 8–1, prior to this time little or no smoke was seen in this region, and the windows in the area appeared to be intact. This developing fire grew rapidly and by 8:52 a.m. fire was visible in windows 97-142 to 97-146, with flames extending from windows 97-144 and 97-145.

Figure 8–2, showing the north face, was shot at 8:53:15 a.m. An enlarged portion of the image is reproduced as Figure 8–3. The fire to the east of the aircraft impact area has continued to spread, now extending from windows 97-142 to 97-148. In three of the windows (97-142, 97-143, and 97-144) isolated fires are burning at the tops of the open window frames. Videos show that pieces of solid burning fuel from these areas eventually fell and formed the white streamers described in Section 5.2 as the material floated downward. Appendix L summarizes observations of streamers on the four faces of WTC 1. The first streamer from the left of the impact cavity was observed at 8:54:52 a.m., falling from the top of window 97-145, and many additional streamers were observed during the next few minutes.

In Figure 8–2 and Figure 8–3 light smoke is coming from near window 96-150. This smoke is an early indication of a developing fire that will appear shortly and grow rapidly in this area.

Smoke is also flowing from the mechanical equipment rooms at the 108th and 109th floors in Figure 8–2. Smoke and/or dust were observed coming from these floors immediately following the aircraft impact, suggesting that ductwork within the core area had been compromised. Smoke was observed continuously coming from these floors after the impact. As described in Section 4.2.5, the smoke was actually flowing from louvers mounted in an interior wall located nearly 5 feet behind the exterior facade that is visible. The smoke appears to be coming from three distinct locations centered near windows 113, 122, and 132. Figure A-1 in Appendix A shows the locations of the various louvers on these floors and identifies which parts of the ventilation system were serviced by these louvers. On the north face of WTC 1 the louvers were part of the fresh air intake system that serviced the upper portion of the building extending from the 92nd floor to the top. The three locations are close to the three intakes that provided air to the core, interior, and peripheral areas of the lower floors in the northwest quadrant of the building. The ductwork for these ventilation systems extended downward through a shaft located on the northwest corner of the core. Smoke was clearly entering these three sets of ducts at some point. It should be noted that in order for the smoke to backflow through the intakes as observed, it had to pass through an extensive series of fans, preheating and cooling coils, and air filters.

Figure 8-2. A photograph of the north face of WTC 1 recorded at 8:53:15 a.m. is shown. The original has been cropped.

It is also important to note where smoke is not observed exiting from the upper mechanical equipment room floors on the north face. As shown in Figure A-1, there was a series of louvers at the western edge of the 108th floor (corresponding to windows 108-103 to 108-107) that provided fresh air to the air conditioning for the restaurant located on the 107th floor. No smoke was observed coming from this area. This is expected since this ductwork does not extend to the lower floors where the aircraft impacted. There were also three air intakes toward the east side of the north face that provided fresh air for the core, interior, and peripheral area systems in the northeast quadrant of the tower. The absence of smoke coming from these intakes may be an indication that this system was not as heavily damaged by the aircraft impact as that which serviced the northwest quadrant of the building.

At the time that the photograph in Figure 8–2 was taken, there was no indication that any windows on the north face above the 99th floor were missing. This situation changed abruptly 43 s later, i.e., at 8:53:58 a.m., when a light smoke plume appeared from the 104th floor at window 104-116. At the same time an object was seen falling from this location. This observation was the first indication on the north face that people trapped on floors above the aircraft impact area were breaking windows to provide access to outside air. Nine seconds later another object was observed falling from window 104-115, and shortly

thereafter a much heavier smoke plume began to exhaust from this window. Recall that a similar release of smoke from the same floor was observed on the south side of the west face roughly a minute earlier. The observations on the north face support the conclusion that much of the 104th floor had already filled with smoke under sufficient pressure to flow from broken windows within eight minutes following the aircraft impact.

Figure 8-3. An enlargement of a portion of the photograph reproduced in Figure 8–2 showing the north face of WTC 1 at 8:53:15 a.m. is shown. Labels showing floor and column numbers have been added.

Meanwhile, the fire burning near the center of the 94th floor on the east face of WTC 1 had continued to spread and grow. By 8:54 a.m. flames were coming out of many of the windows located between windows 94-215 and 94-231. Much of the upper region of the face was obscured by heavy smoke rising from this burning area as well as other windows.

It proved very difficult to determine whether smoke was flowing from louvers on the mechanical equipment rooms at the 108th and the 109th floors on the east face. This was not only due to smoke obscuration, but also to the expected smoke movement on the face induced as a result of the prevailing wind that was from the northwest (in tower coordinates) on September 11. Figure 8–4 shows a frame from a video shot from northeast of the World Trade Center complex at 8:54:34 a.m. The fire on the 94th floor of the east face is visible along with the heavy smoke from this floor and higher isolated windows.

Near the top of the tower in Figure 8–4 there appears to be a heavy flow of smoke from the area of the mechanical equipment room floors near the north edge of the east face. Smoke was present in this region continuously until the tower collapsed over an hour later. This area is close to the exhaust spill louver that served the northeast quadrant of the tower (see Figure A-2), and it is possible that the observed smoke was flowing from this system. However, there is another plausible explanation for these observations based on predictions of smoke movement obtained using the Fire Dynamics Simulator (FDS) (McGrattan, 2004). For the simulations, smoke was assumed to come from the 94th floor across

the entire east and south faces, and a wind of 11 mph from the northwest was imposed. The results of the simulation show that low pressure regions created by the wind flowing over and around the building tended to draw buoyant smoke rising upwards due to buoyancy across the east and south faces toward the upper northeast and southwest corners, respectively. This smoke was then swept into the wind streamlines passing over the north face and west face, resulting in, what appeared to be, two distinct smoke plumes flowing from these corners. Based on the FDS results and review of a large number of photographs and videos, NIST has concluded that it is unlikely that large amounts of fire gases were exhausted from the upper mechanical equipment room floors on the east side of WTC 1.

Even though a large amount of smoke hides much of the east face in Figure 8–4, it is still possible to see portions of the façade for floors above the 94th floor where fire is present. This is true for a small region on the lower northern edge and a larger area on the southern side of the face. In these areas smoke was observed coming from windows higher on the face, which indicates that people were also breaking windows on this face at roughly the same time as on the west and north faces. At 8:53:24 a.m. dense smoke plumes appeared at windows 105-245 and 105-246 on the 105th floor. Several additional windows on this floor were broken around this time. The nearly simultaneous decisions by people to break windows on three sides of the tower suggest that smoke had already spread over extensive volumes of the upper floors. Two windows, 99-201 and 99-202, were also broken out on the 99th floor around 8:53 a.m. Light smoke was observed flowing from these windows. Earlier, the windows appeared to be intact.

Figure 8-4. A frame captured from a video shot from the northeast shows the north and east faces of WTC 1 at 8:54:34 a.m. The undamaged WTC 2 is to the left.

In Figure 8–4, heavy smoke can be seen on the east face, coming from a few windows on the 93rd floor, located immediately below the 94th floor where significant fires and smoke flow are evident. An area of light smoke is also coming from a section of the open windows on the 92nd floor. Review of visual material around this time indicates that both the number of windows where smoke was observed and the smoke density appeared to be increasing on these floors. These observations suggest that fires, which were not yet visible from the outside, were growing on these two floors.

During the period around 8:54 a.m., the amount of visual material showing the south face of WTC 1 is limited. There was a great deal of smoke coming from the south face that tended to hide large sections of the face above the 96th floor. This was particularly true high on the west side of the face, which was located above the burning area on the 96th floor and which also tended to be obscured by the smoke from the south face that was concentrated at the upper southwest corner, as revealed by the FDS calculations. Smoke coming around the corners from both the east and west faces also hid parts of the south face. It is particularly difficult to view the mechanical equipment rooms on the 108th and 109th floors, and it has not been possible to determine whether or not smoke was coming from the intake louvers located on these floors.

Several windows were opened on the 101st floor on the east side of the south face (presumably by people), and smoke was flowing from these locations (see Figure 6-12). Images suggest that additional windows may have been open higher up on the east side, but the quality of the images and the amount of smoke coming from other locations did not allow this to be confirmed.

The fires seen on the 96th floor of the south face continued to grow during this time, and by 8:56 a.m. covered at least ten windows from windows 96-334 to 96-343, with significant flame extension. These fires can be seen in Figure 6-13, which was taken at roughly this time. There is little evidence for fires on other floors of this face.

With the exception of the appearance of smoke on the 104th floor of the west face around 8:52 a.m., prior to 8:55 a.m. the appearance of this face was little changed from that immediately after the aircraft impact. Many of the images available for this face were taken from long distances, and it is difficult to discern fine details. For instance, analysis of images recorded near 8:47 a.m. and 8:48 a.m. indicated that smoke was coming from windows on the 108th and 109th mechanical equipment room floors. This smoke could not be seen in many of the longer distant images recorded during the next six minutes or so. Figure 8–5 shows a photograph taken from the north northwest that provides a partial view of the west face of WTC 1 at 8:55:15 a.m. While it is difficult to determine exact locations from this angle, it is evident that smoke was indeed coming from the mechanical equipment room floors near the center of the face. This observation suggests that smoke had been flowing from these mechanical equipment room floor windows since the aircraft impact. Smoke coming from windows on the 104th floor can also be seen in the photograph. Based on the locations for observed smoke and using the locations of exhaust louvers shown in Figure A-4, the visual evidence indicates that exhaust ducts in the core have been compromised.

Figure 8–5 was taken just after the beginning of a dramatic change in the fire behavior on the west face of the tower. Videos show that at 8:55:09 a.m. there was a sudden increase in the volume of smoke coming from near window 97-435 on the 97th floor. Almost immediately, smoke began to appear at additional windows, and flames were observed shortly afterwards. The initial stages of this rapid change are indicated by the appearance of smoke at multiple windows on the 97th floor in Figure 8–5. Within a minute following the initial increase in smoke, external flaming was observed from roughly window

97-430 to window 97-444. The number of windows where heavy smoke was observed was greater, reaching from window 97-425 to window 97-445. In the span of roughly one minute, this fire on the west side of the 97th floor opened windows over a distance of nearly 97 feet.

Figure 8-5. A photograph of WTC 1 recorded at 8:55:15 a.m. shows the north and west faces. The original image has been rotated and cropped. Numbers indicating column numbers for the north face and floors have been added.

The west face of WTC 1 was filmed from a helicopter around this time. Figure 8–6 shows a frame taken from this video that was recorded at 8:58:06 a.m. Intense fire and heavy smoke are present over the same range of windows observed roughly two minutes earlier. Following the extremely rapid fire spread during the minute that started around 8:55 a.m., the fire appears to have stabilized for a period of time. It

is not clear why the initial fire spread was so fast or why it abruptly slowed since the floor plan layout for the 97th floor (see Figure B-6 in Appendix B) indicates there were no partitions present in the immediate vicinity of the fire.

Another feature of the west face around 8:58 a.m. can be seen in Figure 8–6. Numerous plumes of heavy dark smoke are flowing from windows high above the 97th floor on the north side of the face. These plumes are present on the 102nd, 104th, 105th, and 107th floors. People in these areas have broken out the window glass. It is difficult to determine exactly when these windows were opened due to the quality of the imagery during this period, but smoke first appears from the upper regions of the northern side around 8:55:30 a.m. Multiple windows over several floors had been broken by 8:56 a.m., and the number continued to increase during the next two minutes.

Figure 8-6. This image shows the west face of WTC 1 at 8:58:06 a.m. It is a frame taken from a video shot from a helicopter. Floor and column numbers have been added for WTC1. WTC 2 is in the background on the right side. Smoke is flowing from the damaged area on the corner of the 96th floor.

Meanwhile, between 8:54 a.m. and 9:00 a.m. fires observed on the north face of WTC 1 continued to grow and spread. Figure 8–4 shows the appearance of the face at 8:54:34 a.m. The fires on the 97th floor on either side of the aircraft impact cavity are the dominant features. Figure 8–5 provides a closer view of the face at 8:55:15 a.m. Heavy flames were now coming from window 97-148, which is two windows to the east of window 97-146, where the heaviest flames were present three minutes earlier in Figure 8–3, but have now receded back into the window. The heavy smoke coming from windows 96-137, 96-147,

and 96-150 in Figure 8–4 indicates that an unseen fire was continuing to grow on the 96th floor on this side of the north face.

On the morning of September 11, 2001, a specialist in the use of infrared thermography for assessing the operation of building systems was performing an inspection in a building near the WTC site. Shortly after the first aircraft struck WTC 1, the operator went outside and trained the infrared camera on WTC 1 and took two images of the burning tower. The operator also videotaped the tower using a standard video camera, which allows the thermal images to be compared with standard video images taken from the same location.

Infrared cameras record images at wavelengths where objects near room-temperature radiate heat. Since the radiated heat from an object increases with temperature, the apparent "brightness" of an object in an infrared image is related to its surface temperature. It is possible to make quantitative measurements of surface temperature when certain parameters of the camera and object are well characterized. However, it is important to recognize that this is not possible for the infrared images of the towers discussed in this report. There are several reasons why the infrared images reproduced here provide only a qualitative indication of relative temperature. The most important is the temperature range setting of the camera used to take the images. Prior to the aircraft impact it was being used to monitor objects near room temperature and had been adjusted to saturate at a maximum surface temperatures of 120 °C. The temperature range was not adjusted before taking the WTC images. Since flame temperatures are much higher, the camera output was easily saturated by the heat coming from the fires. There are additional factors, such as the unknown surface properties of the tower materials and the camera resolution, that preclude quantitative measurements from the images.

Nonetheless, the infrared images provide unique insights into the heat distribution inside the towers. One of the infrared images showing the north face of WTC 1 around 8:55:55 a.m. (the time uncertainty is estimated to be 15 s) is shown in Figure 8–7. The dimensions of the infrared image are 255 pixels × 240 pixels. It is compared with a frame from a video that was shot from the same location roughly two minutes earlier. The video frame has been rotated and scaled to match the infrared image.

It is immediately clear that large areas of the infrared image are saturated, indicating the presence of strong heating. Even so, there are some interesting features resolved in the image. By comparing the standard and infrared images it is seen that the smoke plumes leaving the aircraft impact cavity and the area of fire on the 97th floor to the east are hot and radiating as they exit the building, but cool rapidly as they move away. There is an isolated bright area near the western edge of the north face, indicating a high temperature region. In Figure 8–5, it can be seen that there is a smoke plume exiting from window 97-102 on the 97th floor. This plume is the source of the high temperature spot. A distinct line connects to the bright spot. This line shows that heat is being radiated from the 97th floor even though, as can be seen in Figure 8–5, the windows are still in place and no smoke and fire are visible in these windows.

The fire on the 97th floor to the immediate right of the aircraft impact cavity has saturated the camera output. Much of the area inside the aircraft impact cavity is also saturated, showing that the smoke flowing from this area was hot. The heat distribution on the east side of the cavity is consistent with the visible fire distribution. There is an extensive length across the face that is saturated. This corresponds to the large fire on the 97th floor that is visible in the video frame and Figure 8–5. This area does not extend all the way to the east edge of the face, and the northern edge of the east face is still relatively unheated. There is a shorter heated length on the floor below that is separated from the aircraft cavity by a cooler

region. This heating is due to the fire that was growing on the 96th floor and had not yet appeared on the face. There is evidence of an isolated fire burning in the eastern half of the 94th floor on the north side.

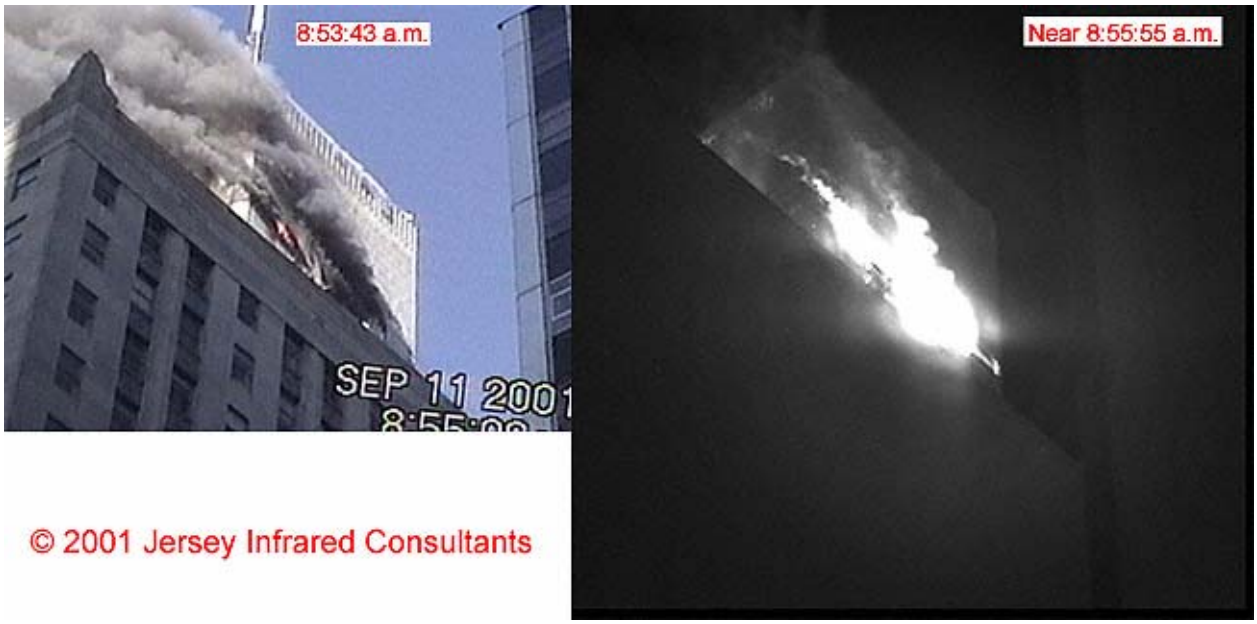

Figure 8-7. Images of the north face of WTC 1 recorded using a standard video camera (left) and an infrared camera (right) are shown. The frame from the video camera was recorded at 8:53:43 a.m., and the infrared image was shot around 8:55:55 a.m. (the uncertainty is estimated as 15 s) from roughly the same location. The infrared image intensity levels were adjusted. The video frame has been cropped, rotated and sized to match the infrared image. The building in the foreground is the post office on the corner of Church and Vesey Streets.

Standard images show that the amount of smoke coming from the windows on the eastern side of the aircraft impact cavity on the 96th floor continued to increase until flames were first observed inside windows 96-145, 96-146 and 96-147 around 8:57 a.m. After this time, fire growth at this location was rapid, and flames extended from window 96-148 at 8:57:18 a.m. Figure 8–8 shows a photograph of the north face that was shot at 8:59:59 a.m. At this time, the fire on the 97th floor to the west of the aircraft impact cavity was still burning, but at a reduced intensity. On the east side of the impact area flames extended from windows 97-151 and 97-152 on the 97th floor, but the fire that was present immediately to the right of this location earlier (compare Figure 8–8 with Figure 8–3 and Figure 8–5) is no longer evident. On the 96th floor, flames are visible in window 96-143 to window 96-149, with external flames coming from window 96-149. At earlier times a small fire was present on the 93rd floor in the vicinity of window 93-143 (see Figure 8–3 and Figure 8–5). This fire is no longer evident in the photograph shown in Figure 8–8, which was taken around 9:00 a.m.

In Figure 8–8, numerous plumes of smoke are seen exiting from windows well above the fire floors on the north façade. There are also many additional windows that have been broken by people at these locations, but they do not have dense smoke flowing from them. The smoke coming from the mechanical equipment room on the 108th and 109th floors can also be seen in this photograph.

Figure 8-8. This photograph of the north face of WTC 1 was recorded at 8:59:59 a.m. The image has been cropped and floor and column numbers have been added.

During this period when both the 96th and 97th floors were actively burning on the east side of the aircraft impact cavity on the north face, numerous streamers were recorded falling from the area. A summary of the observations included in Appendix L shows that between 8:54:52 a.m. and 9:02:14 a.m. 17 streamers were observed falling from these two floors. Streamers fell from windows extending over a range from window 97-142 to window 97-154 on the 97th floor and window 96-148 to window 96-153 on the 96th floor. The release of streamers is obviously correlated with the presence of an active fire in the immediate vicinity.

Figure 8–9 shows the east face of WTC 1 at 8:59:13 a.m. As observed earlier, a significant fire continues to burn over a large extent of the 94th floor. Intense burning was particularly evident at windows 94-226 and 94-227. Closer inspection of the photograph shows that distinct “carets” are present on the column covers next to these windows as well as on the covers for columns 94-229 to 94-232. As discussed in Section 5.2, these carets indicate that sometime earlier flames were extended out of windows 94-229 to 94-231 and subsequently withdrew back into the windows. These carets are an additional indicator of the intensity of the fires burning on this floor.

A major change in the east façade fire behavior is also apparent in Figure 8–9. Flames can now be seen at windows 97-208 to 97-210 on the 97th floor. It is difficult to determine exactly when fire growth started at this location due to obscuration by smoke coming from below. However, at least two videos showed flames erupting from these windows at 8:56:45 a.m., while another video showed an intense flame near window 97-211 at 8:58:19 a.m. A close-up photograph showed fire in window 97-114 at 8:57:38 a.m. It seems likely that fire first broke out on the 97th floor on this face around 8:56:45 a.m. and rapidly spread over at least seven windows.

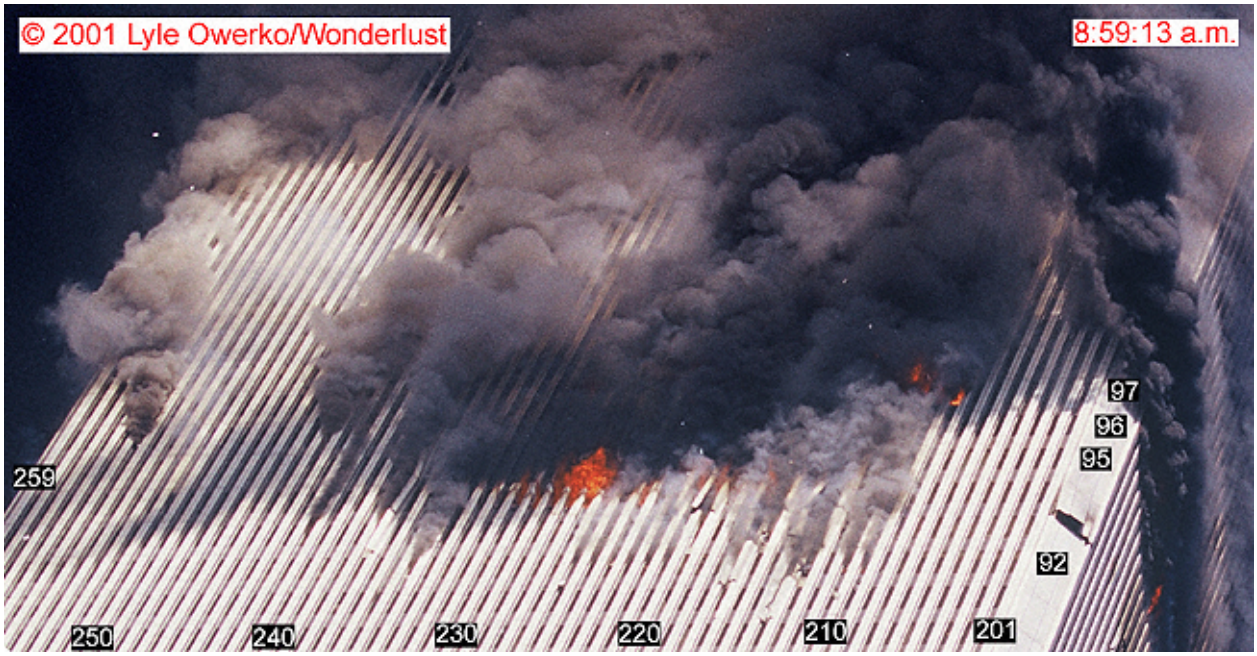

Figure 8-9. This view of the east face of WTC 1 was recorded at 8:59:13 a.m. The original image has been rotated and cropped. Column and floor numbers have been added.

In two videos recorded just after 9:00 a.m., the fires on the 97th floor are seen through the smoke extending out of multiple windows, covering a range of windows from 97-208 to at least 97-225. These videos show that very rapid fire spread and growth has occurred along the eastern periphery of the 97th floor in a manner similar to that observed somewhat earlier on the west face.

As detailed in Appendix L, streamers were frequently seen falling from the east face starting just after 8:58 a.m. Due to the direct lighting of the east façade by the morning sun, it was difficult to detect these streamers in imagery taken from the east, and most of them were seen falling along the face in views from the north. As a result, in most cases it is not possible to identify where they formed. Since the formation of streamers is strongly associated with active fires, it is likely they were coming from the active fire areas on the 94th and 97th floors toward the center of the face.

The amount of smoke coming from windows on the 92nd and 93rd floors in Figure 8–9 has increased further from earlier times, suggesting that internal fires are continuing to grow on these floors in the vicinity of the windows where smoke is observed (see Figure 8–9). Observations of people falling from the tower support this conclusion. Appendix M summarizes times when and locations where people were observed falling from WTC 1. Very shortly following the aircraft impact (8:51:01 a.m.), a single person was observed falling from window 93-149 on the 93rd floor. Images of the north face indicate that a fire

was burning in this immediate vicinity around this time. No additional people were observed falling until 8:58:04 a.m., when one fell from window 93-215 on the east side of the 93rd floor. In the next 20 s, three more people fell from or near window 93-215 and a fourth from window 93-223. This sudden increase in the number of falling people may indicate that conditions were becoming intolerable and that escape to other locations was not possible.

Starting at 8:58:23 a.m., eight people fell from several locations on the east side of the 92nd floor in less than two minutes. They fell from two separate locations centered near window 92-210 and window 92-220. In Figure 8–9, smoke can be seen flowing from windows at both of these locations. These human behaviors suggest that significant fires were ignited on the east sides of the 92nd and 93rd floors following the aircraft impact. Initially, these fires did not seem to create intolerable conditions at interior locations near the east face. However, the observations suggest that with time they grew until it was no longer possible for the people to stay at these locations or to move away from the fires.

Between 8:56 a.m. and 9:02 a.m., the fires on the 96th floor of the south face continued to grow and spread. Videos show that at 9:01:11 a.m. intense flames suddenly burst from window 96-355. Figure 8–10 shows the south face shortly after this event in a frame taken from a video. It has not been possible to time the video clip exactly, but the image was recorded within a minute of 9:02 a.m., based on the known times when fire appeared at window 96-335 and when the second plane struck WTC 2. The image shows flames extending from multiple windows on the 96th floor, including windows 96-355 and 96-356. Flames can also be seen coming from the northwest corner where the aluminum facing was dislodged during the aircraft impact. Note that some of the available imagery indicated that some fire was present on the 97th floor around this time.

As seen in Figure 8–10, there is a large amount of smoke coming from broken windows on the 95th floor, even though no flames are apparent. This may be an indication that a substantial fire was present somewhere on this floor. The heavy smoke coming from the center of the face at the 93rd floor continues to hide the location where the steel panel section is believed to have been dislodged during the aircraft impact. Lighter smoke is flowing from several other windows on the 93rd floor.

Around this time a few streamers were observed on the south face as detailed in Appendix L. It is likely that there were additional streamers formed that were not observed due to the limited imagery from this direction and the direction of the sun, which did not illuminate the trailing smoke from the streamers until they were blown well away from the tower.

As already described, following a period of very rapid fire spread on the west side of the 97th floor starting around 8:55 a.m., the fire seemed to stabilize for several minutes, and additional spread was limited. This period ended at 9:01:09 a.m., when heavy smoke erupted from a number of windows to the south of the original fire area. In less than five seconds heavy smoke appeared at windows 97-422 to 97-415 moving from north to south. At this time, flames still extended from window 97-425 and other windows towards the north, and smoke did not appear to be coming from windows 97-423 and 97-424.

Figure 8–11 is a photograph of the west face of WTC 1 taken shortly after the second rapid fire spread episode. It has not been possible to time this image exactly, but based on observed fire behaviors on this face, it was taken between 9:01:09 a.m. and 9:02:17 a.m., or roughly around 9:01:40 a.m. Intense fires are present in the windows where the initial rapid fire spread took place, and heavy smoke is coming from

windows where the second took place. In the area with flames, carets are present at the tops of the columns, indicating the past presence of flames coming out of these windows.

Figure 8-10. This image showing the south face was captured from a video. It was not possible to time this image exactly, but it was recorded within a minute of 9:02 a.m. Column and floor numbers have been added.

The figure shows large amounts of smoke continuing to pour from windows well above the 97th floor on the north side of the face. The smoke is particularly heavy from window 107-458. A row of open windows is also present on the 95th floor extending from window 95-441 to window 95-447, with window 95-442 still in place. It is not known exactly when these windows were broken since they were not observed until around 9:00 a.m. They may have been broken during the aircraft impact or by people, who were observed in the open windows. The absence of any smoke or dust coming from the area may indicate that the latter explanation is more likely. The same is true for two windows (windows 92-424 and 92-434) on the 92nd floor that appear to be open in the uncropped version of Figure 8–11.

Based on the extensive flame evident on the west face and observations on the other faces, it is likely that numerous streamers were formed during this period. The table in Appendix L does indicate the observation of a number of streamers on the west face during this period of intense burning. However, it is likely that many were missed because of the limited close-up imagery around this time and the fact that this face was shaded from the sunlight that made the streamers highly visible. In videos, the streamers often seemed to suddenly appear as they were blown south from behind the tower into the sunlight, streaming past the south side of the building.

Figure 8-11. Image of the west face of WTC 1 recorded between 9:01:09 a.m. and 9:02:17 a.m. The image has been cropped and rotated, and column and floor numbers have been added.

Several videos show that heavy smoke was released suddenly from window 97-458 on the north edge of the west face at 9:02:17 a.m. Shortly thereafter fire was observed in this area. Interestingly, there is no indication of a fire at this location in Figure 8–11, which was taken less than a minute earlier. Figure 8–12 shows a photograph of the north face and an oblique view of the west face shot at 9:02:31 a.m., or 14 s after the initial release of smoke at the corner. Flames appear to extend from windows 97-458 to 97-453, and smoke is coming from locations near windows 97-453 and 97-449, as well numerous windows starting near window 97- 445 and going toward the south.

In Figure 8–12, fire is present in windows 97-101 to 97-113 on the north face. Window 97-101 still appears to be in place. If so, this observation represents one of the few examples where flames were visible through an intact window. Even though heavy flames are present along the north side of the 97th floor, there is no flame extension, and very little smoke is coming from the windows. It is possible to estimate when flame spread occurred over the final western portion of the north side of the 97th floor. A close-up photograph taken at 8:59:59 a.m. showed that flames were present in windows 97-111 to 97-115, window 97-109 was in place, smoke was coming from window 97-108, and the remaining windows towards the west were intact, except for window 97-102, which had been broken immediately after the aircraft struck the tower. At 9:00:19 a.m. a video shows that heavier smoke started coming from window 97-104 and, shortly thereafter, from window 97-102. Even though the video was shot from a distance, a short burst of flame from window 97-106 was observed at 9:00:20 a.m.

The fire behavior described above suggests that the fire that erupted from window 97-458 at 9:02:17 a.m. was a continuation of the fire spread observed on the north face. It is interesting to consider why the intense fire that grew rapidly over windows 97-110 to 97-116 around 8:50 a.m. did not spread westward for the next ten minutes. A review of the floor plan layouts for the 97th floor (see Figure B-6) shows that

there was a group of three rooms located at the northwest corner of the floor. One of these rooms had a rectangular shape, with one interior wall that abutted column 97-108 and a second that terminated at column 97-456, with the remaining two walls formed by the exterior walls. Based on visual observations, it can be concluded that these walls were able to appreciably slow the fire spread into these rooms. This conclusion requires that these walls remained essentially intact despite the aircraft impact only a short distance away. The sudden appearance of flame and smoke on the west face suggests that flashover occurred in the enclosed space at this time, even though fire seems to have entered the space somewhat earlier.

Figure 8-12. This photograph was shot from the northwest and shows the north and west faces of WTC 1 at 9:02 31 a.m. The image has been cropped and the intensity levels have been adjusted. Column and floor numbers have been added.

By the time United Airline Flight 175 impacted WTC 2 at 9:02:59 a.m., WTC 1 had been burning for sixteen and a half minutes. During this period, the fires observed within the building had spread and

grown rapidly as compared to the situation immediately following the aircraft impact. Since the spread of observed fire to new locations was generally accompanied by the removal of windows, one way to gauge this growth is to compare the changes in open windows between the two times. In Figure 8–13, the spread sheets describing the condition of windows have been used to generate sets of window maps for the two times, which provide a direct visual comparison of open window locations. Even though the evidence suggests that fires were present on the 92nd to the 97th floors by 9:03 a.m., the maps show only the 94th to 97th floors, which were the floors where most of the early fire growth was seen.

A quick glance at the maps shows that the most extensive fire growth took place on the 97th floor. This growth can be quantified by counting the various window conditions on the four faces of WTC 1 shortly after it was impacted by the aircraft and around 9:03 a.m., when WTC 2 was struck. Table 8–1 is a summary of the results of such an analysis for the 94th though 97th floors. One simple approach, which is approximate due to the presence of hidden windows, but revealing, is to determine the increase in the number of open windows on each face and to sum the results for each floor. The results are 8, 18, 22, and 85 for the 94th, 95th, 96th, and 97th floors, respectively. Based on the visual observations discussed above, the increases in observed open windows on the 94th and 95th floors were not likely due to spreading fires, but were mostly due to either people breaking windows or to windows that were hidden at the earlier time becoming visible later. On the other hand, the changes for the 96th and 97th floors were primarily due to fire spread. By far, the largest fire growth during the period occurred on the 97th floor, with the number of observed open windows increasing from 30 to 115. On the 96th floor, the initial number was 35, which increased to 57.

Closer scrutiny of the numbers in Table 8–1 reveals trends that were evident from the qualitative descriptions given earlier. The changes in open windows during this period for the 97th floor are distributed over the east, north, and west sides of the floor, while those for the 96th are concentrated primarily on the north and south faces.

The approximate total number of windows that were opened during the first fifteen minutes of the fires in WTC 1 is 133, which can be compared with an approximate total number open immediately following the aircraft impact of 166. This roughly 80 % increase in open window area, as well as the spatial distribution of the open windows, has significant implications for subsequent fire growth and spread. This is particularly true because, in some areas of the building, burning may have been ventilation limited. For these areas, the total area of vents for outside air and their spatial distribution would be expected to be a major factor in determining the maximum possible heat release rate within the tower at a given time, as well as influencing where burning could take place and where additional fire spread would occur.

In Figure 8–14, a different type of mapping is used to provide additional insights into the fire behavior during the period. For this mapping, the fire data sheets have been used to generate a description of the integrated fire behavior for each face. The maps are based on new data sheets generated for the four faces in which each window is assigned the highest fire value reported in the fire data sheets for that window during the period. The result shows windows where fire was observed during the period along with an indication for the maximum intensity of a fire in a given window.

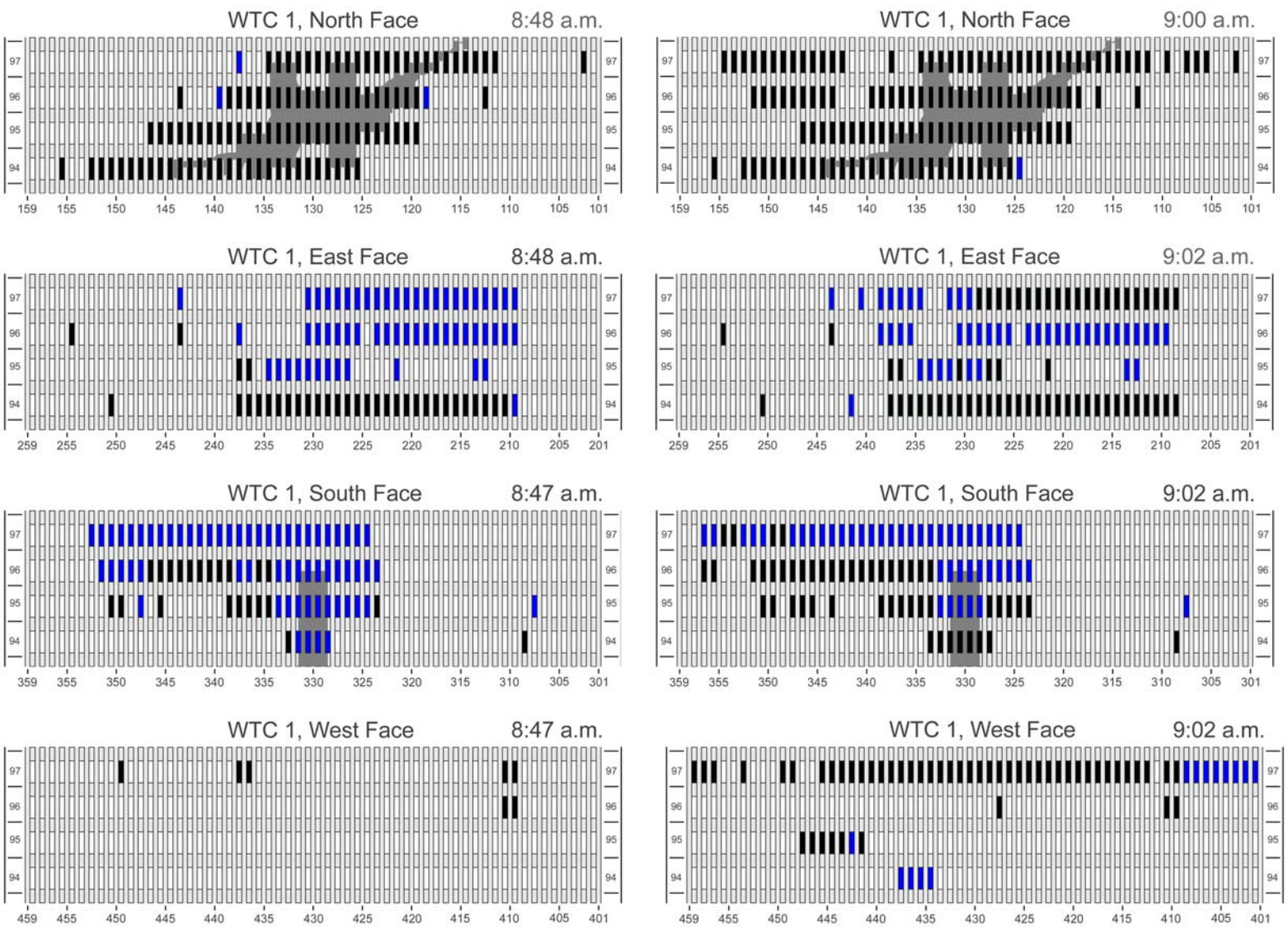

Figure 8-13. Maps for the 94th through the 97th floors compare missing windows for the four faces of WTC 1 at two times, shortly after the aircraft impact and roughly 15 minutes later. The color coding used for the maps is indicated in Figure 5-1.

Table 8-1. Comparison of Window Conditions on the Four Faces of WTC 1 Close to the Times of Aircraft Impacts on WTC 1 and WTC 2

	Around 8:47 a.m.				**Around 9:03 a.m.**		
	Open Window	**Glass in Place**	**"Can't See"**		**Open Window**	**Glass in Place**	**"Can't See"**
Floor	North Face 8:47 a.m.				North Face 9:04 a.m.		
97	25	32	1		48	7	3
96	22	34	2		33	24	1
95	28	30	0		28	30	0
94	29	29	0		29	28	1
Floor	East Face 8:48 a.m.				East Face 9:02 a.m.		
97	0	35	23		21	27	10
96	2	34	22		2	31	25
95	2	44	12		6	44	8
94	29	28	1		31	26	1
Floor	South Face 8:48 a.m.				South Face 9:02 a.m.		
97	0	29	29		4	25	29
96	11	29	18		21	27	10
95	9	37	12		17	35	6
94	2	52	4		8	50	0
Floor	West Face 8:47 a.m.				West Face 9:02 a.m.		
97	5	53	0		42	8	8
96	2	56	0		3	55	0
95	0	58	0		6	51	1
94	0	58	0		0	54	4

Comparison of these maps with similar maps in Figure 6-19 showing the fire distribution shortly after the aircraft impact provides a clear indication of the fire growth and spread during the period. The extensive fire growth on the 97th floor on the north, east, and west faces stands out. The fire growth on the 94th and 96th floors is also easily identified. The relatively high number of windows which had flames extending from the windows (orange) suggests that the fires that grew during the period were, in general, quite intense.

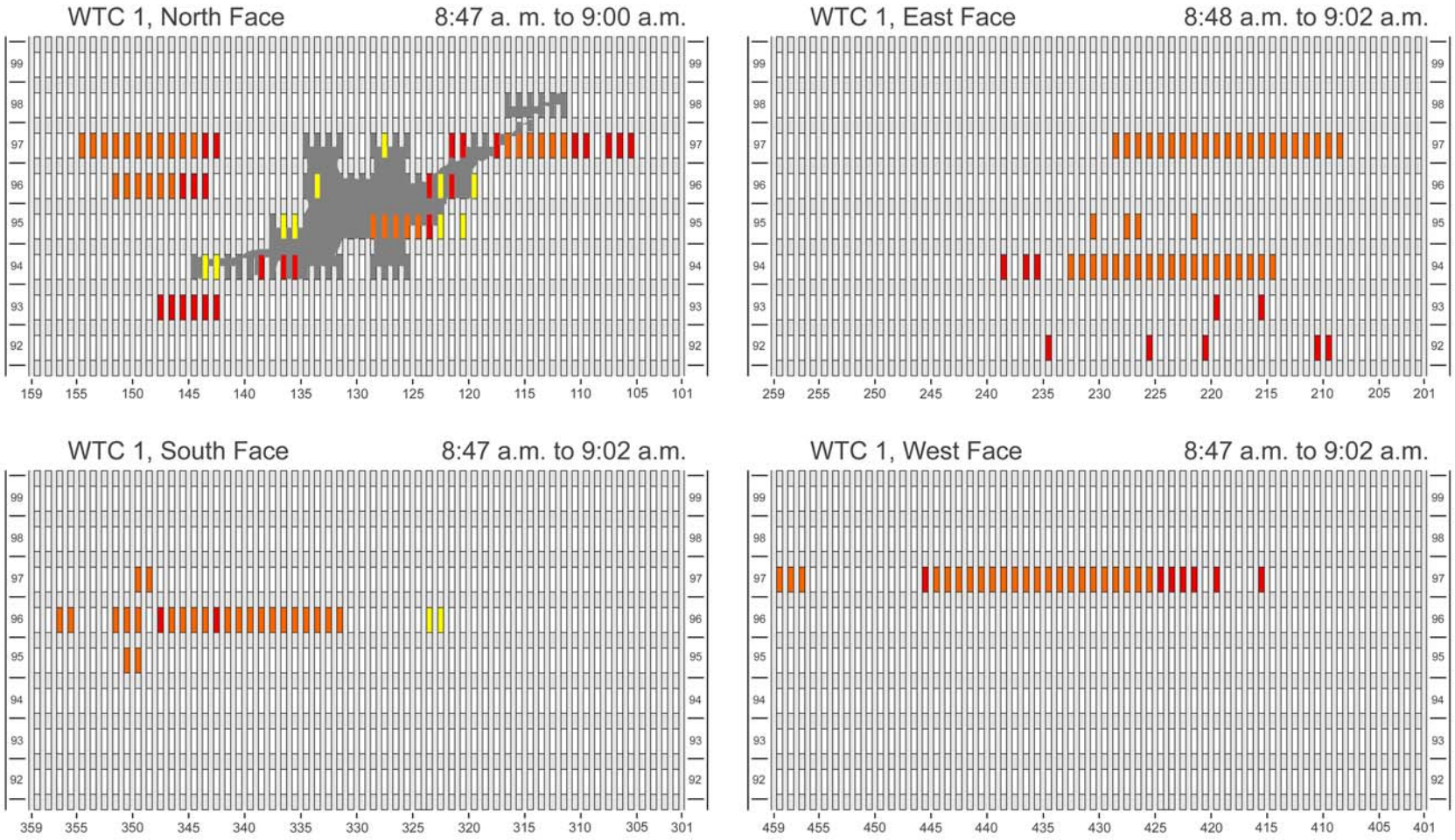

Figure 8-14. Maps of integrated fire observations between 8:47 a.m. and 9:03 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

The extraordinarily rapid fire spread and intense flames observed on the 97th floor are likely associated with the presence of unburned aviation fuel distributed in these areas. As discussed in Section 6.5, a significant amount of fuel was likely dumped on this floor from the starboard fuel tank of the aircraft. The absence of extensive window breakage immediately after impact in locations away from the impact zone implies the absence of significant overpressures, which suggests, in turn, that a large area of the distributed aviation fuel on the 97th floor did not ignite immediately following aircraft impact. This unburned fuel was presumably distributed over areas extending along the intact north exterior wall and the central sections of the east and west walls, since subsequent rapid fire growth occurred in these areas.

As described in Section 6.5, it is likely that significant aviation fuel was also distributed on the 94th and 96th floors during the aircraft impact. On the 96th floor, the observed rapid fire growth to the east of the aircraft impact cavity on the north face could be the result of this distributed fuel. Subsequent rapid fire spread along the east face (see the following section) is also consistent with the presence of liquid fuel. However, up to the current time, no substantial fire growth has been observed on the west side of this floor. Later fire growth on this side will prove to be much less vigorous than on the 97th floor and will move from south to north. On the other hand, fires were observed on the west side of the south facade of the 96th floor shortly after the aircraft impact, and these fires did spread and become more intense during this early period. Recall also that a fireball was observed on the south face, most likely, indicating that ignition occurred somewhere on the west side of the tower, based on the south face damage pattern. These observations are consistent with the hypothesis that a significant volume of atomized aviation fuel on the west side of the 96th floor was ignited during the aircraft impact and that the subsequent fire and overpressure removed a significant portion of the fuel initially distributed in the area.

Similar arguments apply for the 94th floor. During this early period, fire growth on this floor had been modest with the exception of the fire near the center of the east face, which was present immediately following aircraft impact. The formation of a fireball on the east side of the tower indicates that ignition occurred in the area and that significant amounts of aviation fuel were expelled from the floor. Subsequent fire behaviors on this floor, described below, are not consistent with the presence of large amounts of liquid fuel at other locations on the floor. The fires growing on the east sides of the 92nd and 93rd floors may be an indication that some fraction of fuel from the aircraft's port tank reached these floors and was ignited.

Little fire growth has been observed on the 95th floor up to this time. This suggests that significant amounts of aviation fuel were not distributed on this floor. This conclusion is consistent with the expected initial distribution of the fuel on the aircraft (see the discussion in Section 6.5).

8.2 RESPONSE OF WTC 1 TO THE IMPACT OF UNITED AIRLINES FLIGHT 175 ON WTC 2

The impact of United Airlines Flight 175 on WTC 2 resulted in some interesting short-term effects in WTC 1. Almost exactly one second after the nose of the aircraft entered WTC 2, a pressure pulse passed through WTC 1 that pushed smoke, and in a few cases fire, from windows located throughout the upper portion of the tower. Figure 8–15 shows the results of this pressure pulse on the east face of WTC 1. The two images are separated by 0.4 s and were recorded roughly one second after the aircraft struck. In the image on the right, puffs of smoke have been pushed out of several windows on the south side of the 96th floor (the floor with smoke coming from a window near the south edge) as well as windows on the 92nd

through 95th floors. Other videos show that almost simultaneously similar puffs of smoke appeared from broken windows on the 92nd, 93rd, 94th, 96th, 97th, 101st, 103rd, 104th, 105th, and 107th floors, as well as from the mechanical equipment room on the 108th and 109th floors. A large burst of flame was ejected by the fire burning on the 97th floor at the north edge of the west face. These observations suggest that a pressure pulse created either by the entry of the aircraft into WTC 2 or the resulting ignition of aviation fuel within the tower was transmitted to WTC 1. The widespread observation of ejected gases suggests that low resistance pathways existed that allowed pressure pulses to be transmitted throughout the upper regions of WTC 1.

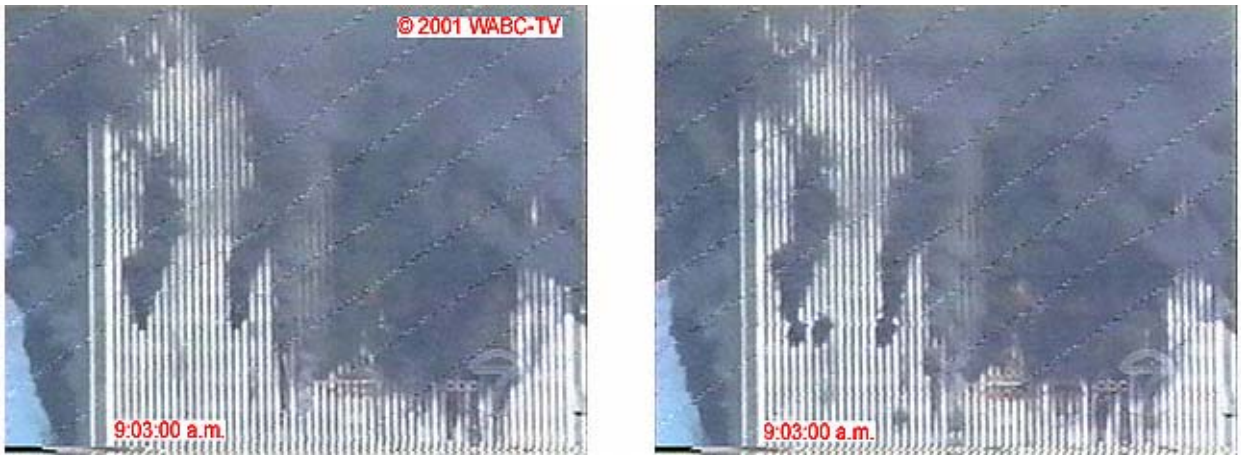

Figure 8-15. This figure shows two frames taken from a video that were recorded 12 frames apart, i.e., 0.4 s. The images show the east face of WTC 1 at 9:03:00 a.m.

The fireballs generated on the north face of WTC 2 following the aircraft impact caused major modifications in the observed fire and smoke behaviors of WTC 1. As the fireball initially developed, it affected the flows coming from the east face of WTC 1 by pushing smoke away from windows. Areas of the face hidden by smoke up until this time became viewable for a brief period. As the fireball continued to grow, it began to entrain a large amount of air that was drawn inward at the base. This, in turn, created a low pressure region at the east face of WTC 1 that appears to have been strong enough to draw large volumes of gas from within the building out through the broken windows.

Figure 8–16 shows six frames taken from a video of the east face of WTC 1 during the period when the fireball was forming and rising away from the north face of WTC 2. The fireball itself is visible at the sides of the two earliest images and at the top of the third. In the image at 9:03:05 a.m., much of the smoke has been drawn away from the face of the tower, and it is possible to see the area near the right center of the face where fires have been burning. It is interesting that there are no external flames present at this time. While it still difficult to determine with certainty, it appears as if windows are open on the 94th floor from windows 94-212 to 94-233, on the 95th floor from windows 95-222 to 95-227, on the 96th floor at window 96-224, and on the 97th floor from windows 97-212 to 97-227.

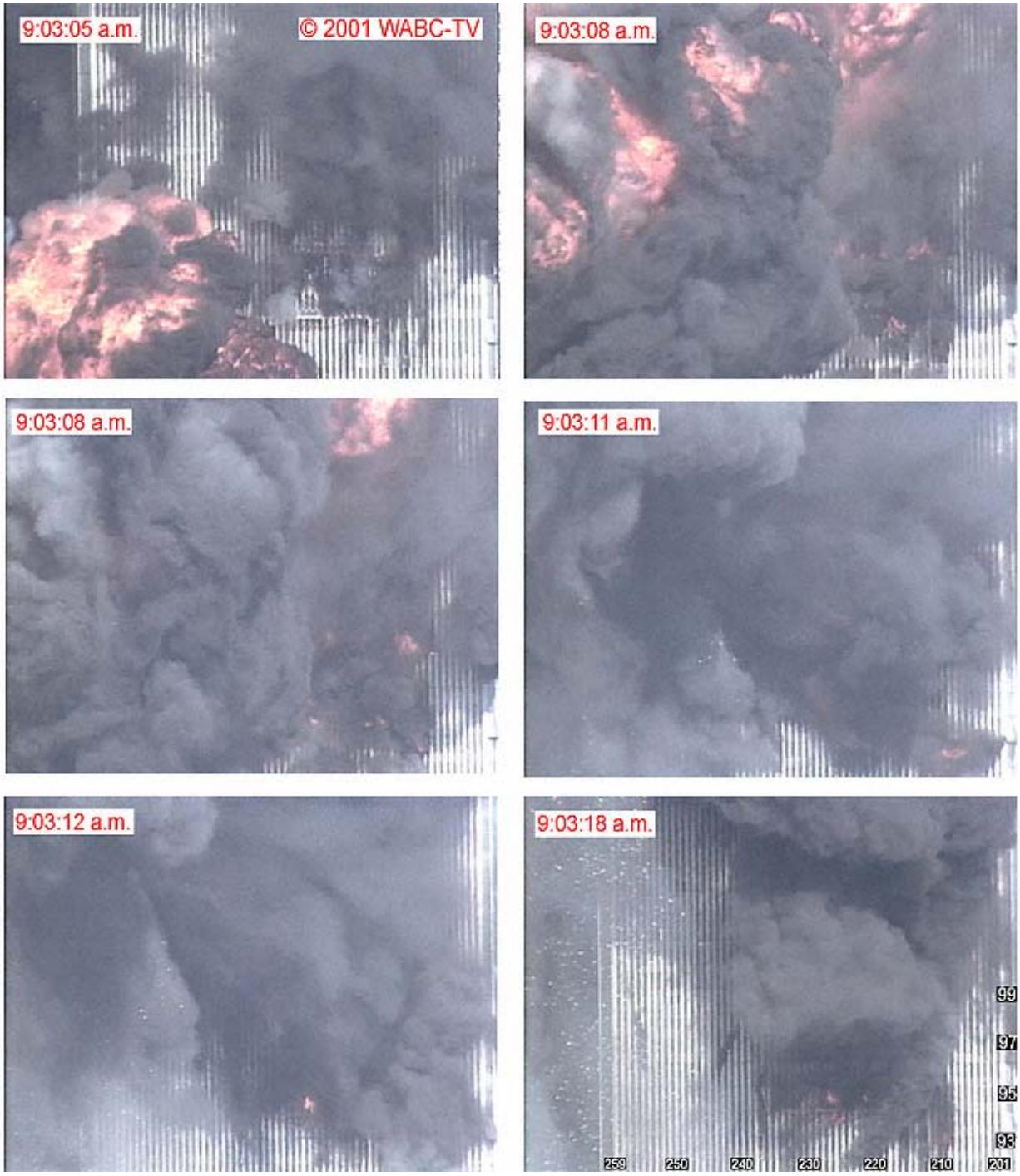

Figure 8-16. Six frames taken from a video of the east face of WTC 1 are shown. These images were recorded during and just after a fireball formed on the north face of WTC 2 following the aircraft impact. Column and floor numbers have been added to the lower right-hand image.

The appearance of the face changed dramatically during the next three seconds. At 9:03:08 a.m. more of the face is hidden by the fireball, but most significantly, flames now appear to have been drawn out of windows 94-216 to 94-218 on the 94th floor, window 95-221 on the 95th floor, and a range of windows on the 97th floor extending from window 97-208 to window 97-227. This is the first image that shows a fire burning on the 95th floor. The next image was recorded 0.6 s later. Flames can now be seen coming from window 93-210 as well as from windows 94-225 and 95-226. At 9:03:11 a.m. the flame extending from around window 93-210 was particularly evident, and at 9:03:12 a.m. the same was true for the flames near windows 95-226 and 95-227. At 9:03:18 a.m. a small flame was observed burning at the top of window 92-212. In this photo the flames extending from window 93-209 on the 93rd floor are distinct. Flames are also present on the 94th floor at windows 94-225 and 94-226 and on the 95th floor at two locations around windows 95-220 and 95-226. Even though not easily seen in the captured images, there appeared to be a small fire on the 96th floor near window 96-216 during the sequence.

Shortly after the fireball began to rise, smoke flow from windows across the remaining three faces was disrupted, nearly ceasing for a few seconds on the north face. This observation provides further evidence that pressure variations could pass through the upper regions of the tower.

8.3 9:03 A.M. TO 9:18 A.M.

Compared to the rapid fire growth on the north face of WTC 1 during the first fifteen minutes of the event, fire spread during the following fifteen minutes was much reduced. The intense fires that grew on the 96th and 97th floors retreated into the building and began to die down. Figure 8–17 shows a photograph of the north face that was shot at 9:06:36 a.m. Even though the fire on the west side of the 97th floor had spread all the way to the west wall somewhat earlier, the two fires burning eastward on the 96th and 97th floors appear to have stopped spreading. The last window with fire present on the 97th floor is window 97-154. Flames are also evident at the other end of the area, starting at window 97-141. On the 96th floor fire is present at window 96-151, and from window 96-152 on to the east end of the floor, windows appear to be intact. This is clearer in Figure 8–18, which shows a blowup of the area taken from Figure 8–17.

Another prominent feature in Figure 8–18 is the row of carets running across the tops of the column covers. These provide a clear visual indication of how intense the earlier fires in these windows were. It is interesting to compare the appearance of the column covers in this area with those on the 97th floor to the west of the aircraft impact cavity. A blowup of this area is also included in Figure 8–18. The columns are barely marked despite the presence of an active fire in the area for many minutes. This suggests that this fire must be venting somewhere other than through the open windows on the north face. As already discussed, and can be seen in the figure, flames and smoke were coming from this area on the west face of the tower. The smoke issuing from the right side of the aircraft impact cavity may also be due to effluent from this fire. Comparison of Figure 8–17 with earlier images of the north face shows that the flow of smoke from the cavity had also decreased with time. The pathways of venting are expected to influence the local heating of the exterior columns since the imposed heat flux will vary with changes in the flow direction through the opening. Exhausting fire gases will tend to heat the columns, while in-flowing outside air will cool the columns.

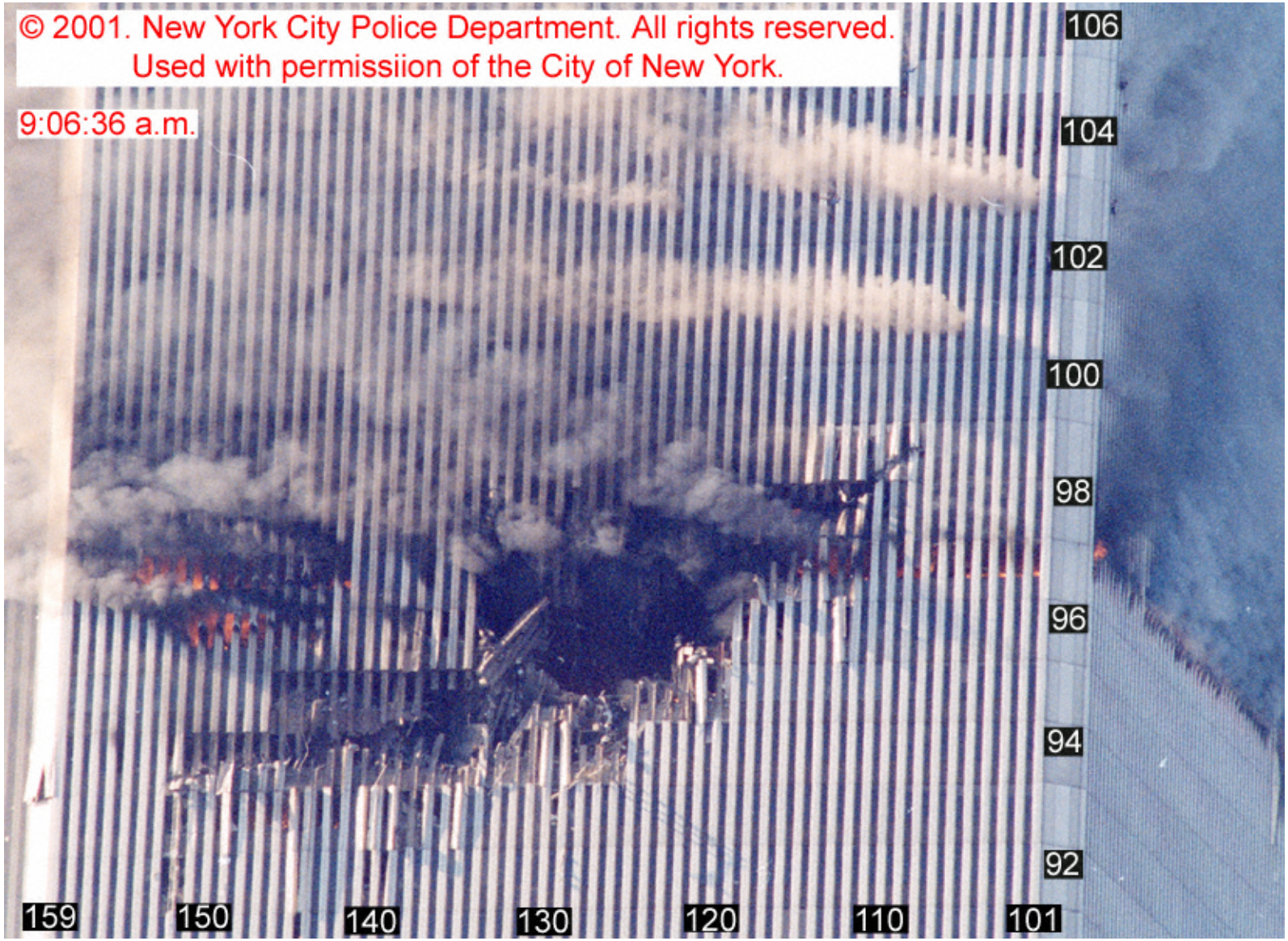

Figure 8-17. A photograph of the north face of WTC 1 recorded at 9:06:36 a.m. is shown. The image has been cropped, rotated, and enhanced. Column and floor numbers have been added.

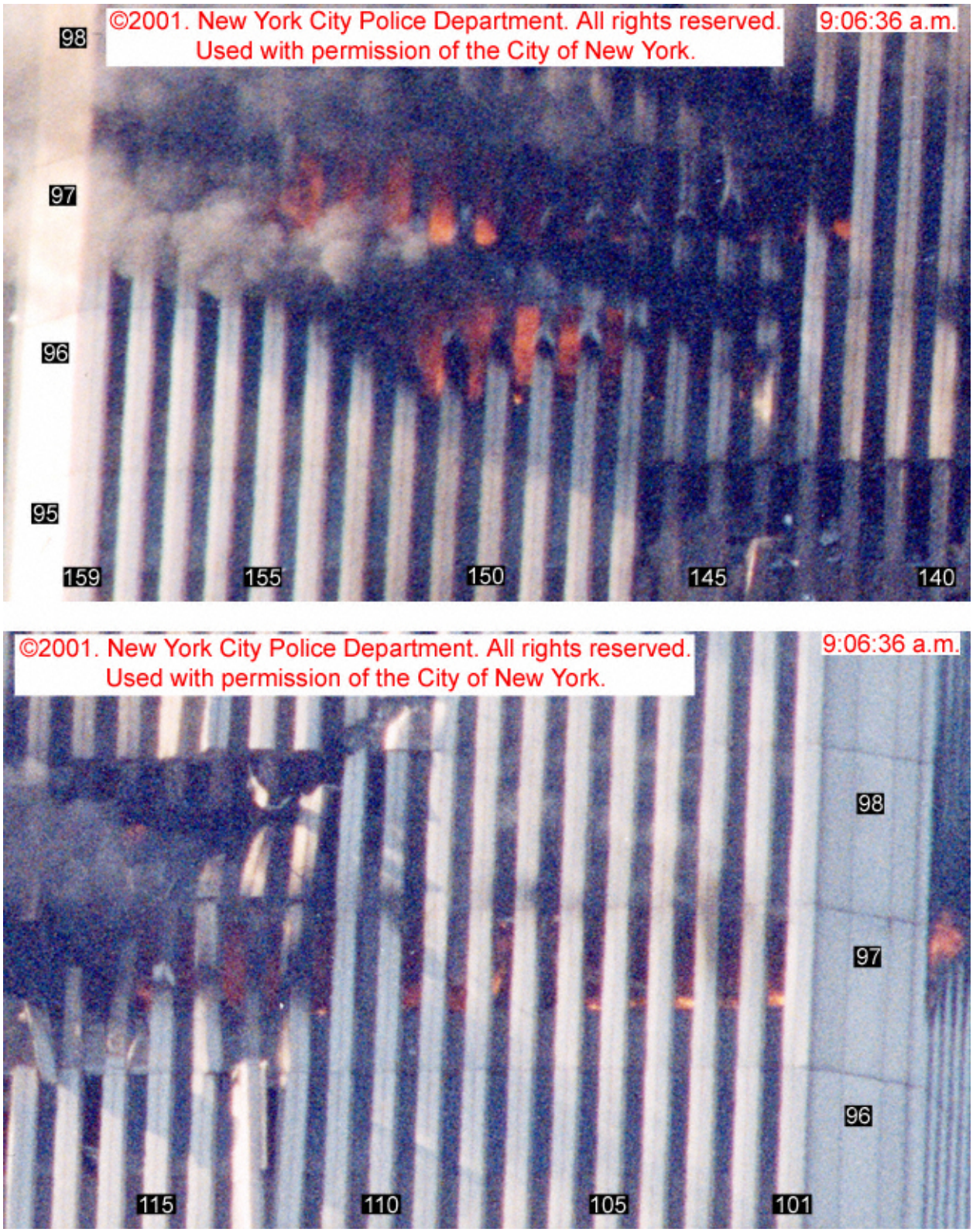

Figure 8-18. Two close-ups of the north face of WTC 1 taken from the photograph in Figure 8–17 show the east and west sides of the face around the 97th floor. The photos have been rotated, enhanced, and column and floor number have been added.

A small fire continues to burn on the 93rd floor around window 93-145. There is also a small spot fire present in window 98-115 on the 98th floor. This window is immediately above the location where an intense fire initially fire grew on the 97th floor. Since the windows immediately above on the 98th floor were broken out by the aircraft impact, it is reasonable to assume that flames from below ignited this fire.

In-place windows can be seen in Figure 8–18. On the east side of the building window panes are in their frames on the 95th floor as well as on either side of the fire areas on the 96th and 97th floors. On the west side most windows are still in place on the 96th floor and on the 98th and 99th floors at locations removed from the immediate vicinity of the plane strike. These observations suggest that windows are only removed when active burning is present in the immediate area of the window.

The abrupt halt of flame spread on the east sides of the 96th and 97th floors suggests that there may have been walls acting as fire breaks in these areas. Figure B-5 and Figure B-6 in Appendix B show floor plan layouts for these two levels. On the 96th floor there were three small rooms in the northeast corner. One of these rooms was rectangular and extended from an interior wall located along column 96-152 to the northeast corner and terminated at a back wall that extended to column 96-204 on the east face. The wall at column 96-152 appears to have acted as a fire block since flames were observed coming from window 96-151, while window 96-152 remained intact. There were also three rooms in the northeast corner of the 97th floor. However, as seen in Figure B-6, the open area that spanned most of the north face didn't end until it reached a wall located at column 97-155. This is exactly where the fire has stopped, since the last window with observed fire is window 97-154.

The 12 min after 9:06 a.m. were relatively quiet on the north face with regard to fire behavior. The large fires that grew on the 96th and 97th floor between 8:47 a.m. and 9:03 a.m. continued to die down. This is evident in Figure 8–19, which shows the appearance of the north face at 9:15:54 a.m. In the photograph it does not appear as if the fires have passed through the walls for rooms located on the northeast corners of these floors. Videos do show that light smoke appeared from windows 96-157 and 96-158 at 9:17:56 a.m. Closer inspection of the photo shows that a relatively small fire has appeared on the 94th floor in windows 94-114 and 94-115. This is an early indication that fire has begun to grow on the west side of the aircraft strike point on this floor. Earlier photographs showed that these windows were intact at 9:14:44 a.m. By 9:18 a.m. fire was visible in four windows at this location.

In Appendix L, it can be seen that the number of streamers observed on the north face during the period from 9:03 a.m. to 9:18 a.m. was much decreased from that seen during the preceding fifteen minutes. The streamers that were observed were on the west side of the tower shortly after the fire spread into this area. These observations provide further evidence that streamers typically formed shortly after active fire had broken windows in a given area.

In contrast to the north face of WTC 1, the fires burning on the periphery of the east side of the tower continued to spread during this time period, initiating new areas of intense burning, while areas ignited somewhat earlier were dying down. Figure 8–20 shows the east face at 9:07:09 a.m. The appearance has changed considerably in the four minutes since 9:03 a.m. (see Figure 8–15 and Figure 8–16) and even more so from earlier times. Two important changes are the appearance of extensive areas of flame on the 92nd floor (extending roughly from window 92-216 to window 92-225) and on the 96th floor (visible over at least windows 96-217 to 96-227). Several distinct carets can already be seen on column covers on the 96th floor, indicating that strong external flaming had already taken place from windows adjacent to these columns. At the earlier time there had only been indications of small fires on both of these floors.

Figure 8-19. An image recorded at 9:15:54 a.m. shows the north face of WTC 1. The original has been cropped, rotated, and enhanced. Column and floor numbers have been added.

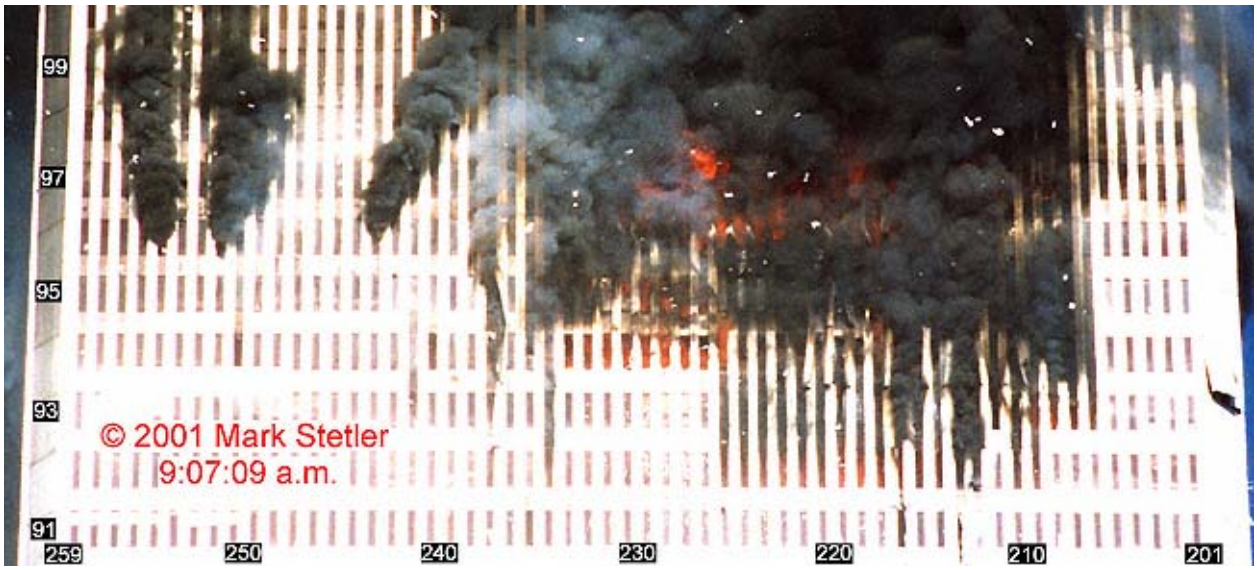

Figure 8-20. This cropped photograph shows the east face of WTC 1 at 9:07:09 a.m. It has been rotated slightly and enhanced to emphasize the presence of fire. Column and floor numbers have been added.

The intense fires on the 94th and 97th floors, which developed earliest on this face, have died down considerably in the windows where they were first observed. For an example of the earlier fire distribution, see Figure 8–9, which shows fire locations around 8:59 a.m. At this earlier time, intense burning with flame extension was seen over windows 94-214 to 94-228 on the 94th floor and windows 97-208 to 97-228 on the 97th floor. In Figure 8–20, a region of intense flaming is evident on the 94th floor, extending from window 94-225 to at least window 94-233, with some flame extension in the area, while windows further to the north appear to have little fire present. This shows that the fires on this

floor were spreading to the south at the same time they were dying down in areas that were ignited earlier. The same was true for the 97th floor. At 9:07 a.m., the most intense burning was located near windows 97-218 to 97-229. The largest flame extension was from window 97-226 at this time. At the time the photograph in Figure 8–9 was taken, flames were coming from window 97-208.

Around 9:03 a.m. there was a fire near column 95-225 on the 95th floor. In Figure 8–20, the fire on this floor now extends to window 95-231. The extended flames observed on the 93rd floor near column 93-210 around 9:03 a.m. have receded back into the building and are not obvious in the photograph. In their wake they left a dark caret at the top of the aluminum cover for column 93-210.

Figure 8–21 shows a close-up frame from a video of a portion of the east face recorded at 9:16:08 a.m. Intense flames are coming from windows 96-208 and 96-209. In the video it is clear that flames are exiting from across the entire burning region that is visible on this floor. A series of carets are seen at the tops of the column covers. The carets appear to be glowing near the center. The physical mechanism responsible for this glow is not known, but it does suggest that significant heating was taking place at this time. Recall that flames were observed on the 97th floor immediately above this location around 8:59 a.m. (see Figure 8–9). These flames are no longer visible, providing additional evidence that flames are growing and then decaying in relatively short period of times.

Figure 8-21. A close up of a portion of the east face of WTC 1 is shown. The image is a frame taken from a video recorded at 9:16:08 a.m. Column and floor numbers have been added. The area to the left with the scaffolding is another building in the foreground.

Even though flames have been observed extending from windows 96-208 and 97-208 on the 96th and 97th floors, the adjacent windows to the north, window 96-207 and window 97-207, are still intact. In fact, the entire area to the east of column 208 on floors 94 through 98 appears to be unaffected by the fires, except for soot deposited on the left side of the area. The sharp demarcation line for the fires on the 96th and 97th floors suggests that fire spread is being inhibited in a manner similar to that already described for the north face. The plan layouts for these floors shown in Appendix B (Figure B-5 and Figure B-6) indicate that both floors had rooms in the northeast corners, with walls that terminated at column 208.

These general trends in the observed fire behavior for the east face continued over the next several minutes. Figure 8–22 shows a photograph that was taken at 9:15:54 a.m. There are regions of extensive fire. Flames can be seen on the 92nd floor from window 92-209 to window 92-235. One curious aspect of these flames is that there is little, if any, flame extension, and there is only heavy smoke coming from windows on the right side of the area. As a result of these characteristics, in many images of the east face recorded around this time, the fire on the 92nd floor is not readily apparent, and the smoke flow from these windows appears to be light. Fire is only observed in images taken nearly perpendicular to the face from relatively long distances. As discussed in Section 4.2.7, such observations are due to the geometry of the building and either suggest the fires are located near the floor or are set back from the windows.

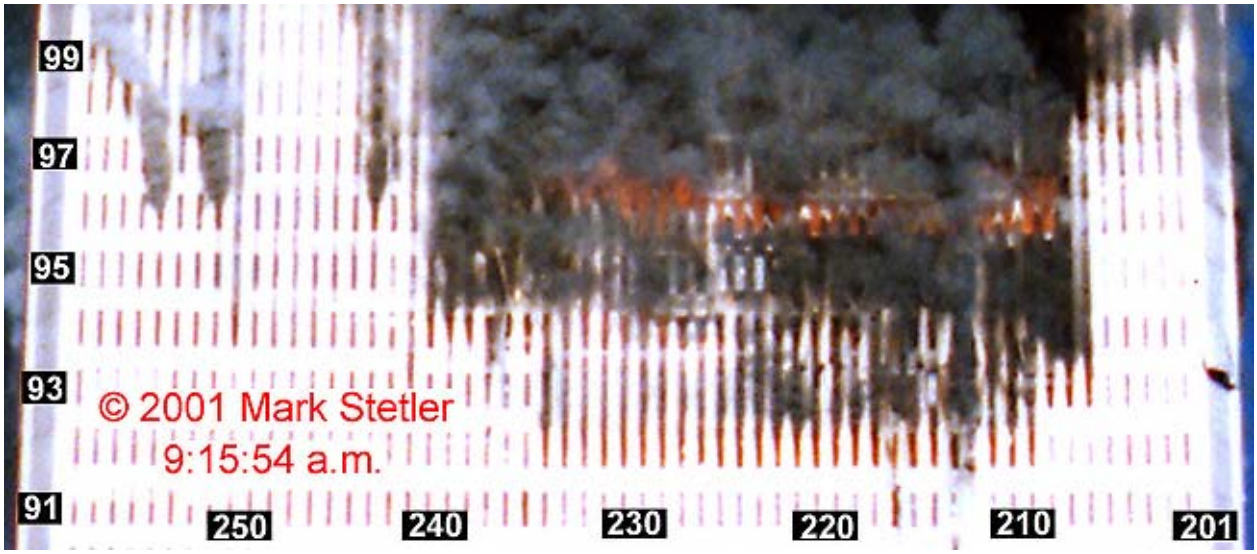

Figure 8-22. This cropped photograph shows the east face of WTC 1 at 9:15:54 a.m. The image has been rotated and enhanced to improve the dynamic range. Column and floor numbers have been added.

On the 93rd floor, there appears to a small fire covering several windows starting at window 93-206. There is some smoke coming from the area.

Unlike earlier, at this moment, only limited flame extension is observed from windows on the 94th floor. Flames can be seen inside the windows starting near window 94-224, and they have now spread as far south as window 94-240. Even though smoke is still coming from some windows, there is little flame evident in windows to the north of window 94-223.

The fire observed earlier on the 95th floor in windows 95-225 to 95-231 has died down. Interestingly, intact windows can be seen to the immediate right of this area. Images recorded much later show that many windows to the north remained intact.

The fire on the 96th floor continues to burn fiercely. A continuous region of flames extends from windows 96-208 to 96-234. There is significant flame extension from around windows 96-208 and 96-209 and from windows 96-227 to 96-234. A distinct row of carets at the tops of the column covers is visible over much of the fire length, providing an indication of the maximum depths of the layer of flaming gases that flowed earlier from the adjacent windows. The layer depth is related to the local intensity of burning, with a deeper depth indicating a more intense fire.

Some of the 97th floor is hidden by smoke. This is especially true near the center of the face, where a substantial fire may still be present. Many open windows can be seen to the north of this area in which there does not appear to be fire present. In other places, e.g., near window 97-211, relatively low-level burning is taking place. Similar to part of the 94th floor, the fires on the 97th floor that grew the earliest on this face now appear to have died down.

An infrared image showing the north and east faces of WTC 1 that was taken around 9:14:50 a.m. is compared in Figure 8–23 with a standard video frame recorded shortly afterward from the same location. These images were recorded at roughly the same times as Figure 8–19 (9:18:17 a.m.) and Figure 8–22 (9:15:54 a.m.), which show the north and east faces of WTC 1, respectively. Recall from the earlier discussion that the infrared photographs provide only a qualitative indication of where heating of the building façade is taking place.

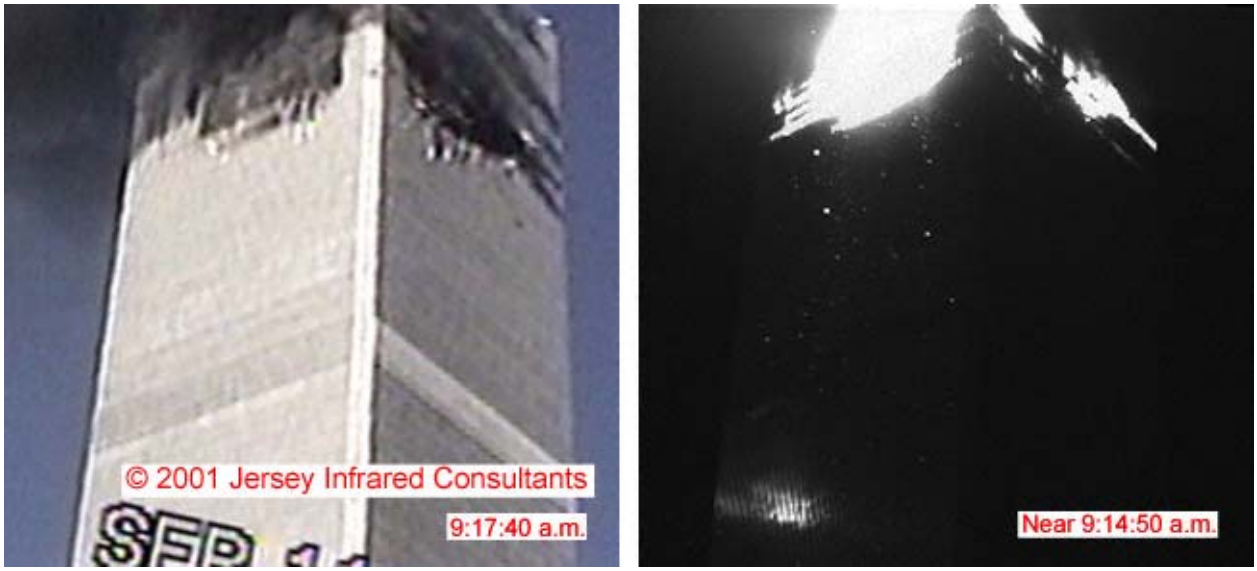

Figure 8-23. A frame from a standard video camera (left) and an image from an infrared camera (right) showing the north and east faces of WTC 1 are compared. The video frame was shot at 9:17:40 a.m., and the infrared image was taken around 9:14:50 a.m. (an uncertainty of 15 s has been assigned). The infrared image intensity levels were adjusted. The video frame has been rotated and sized to match the infrared image.

The appearance of the north face in the current infrared image differs considerably from that observed around 8:55:55 a.m. in Figure 8–7. The primary reason for this is that the amount of smoke flow from the

face has decreased, and, as a result, individual floors are more easily identified. The bright line on the west side of the face is the result of the fire that has spread in this direction on the 97th floor. Despite the presence of this fire, the areas immediately below on the 95th and 96th floors have temperatures that are close to ambient. There is evidence for mild heating along the 94th floor on the right side of the aircraft impact cavity, even though it does not appear to reach all the way to the west edge. Fire will appear in this area shortly (see ahead).

There is considerable heating in the immediate vicinity of the aircraft impact cavity. This is most likely associated with the heavy smoke (presumably heated) that is still flowing from the area. The two bright lines on the east side of the north face are due to heating by the fires that have been burning on the 96th and 97th floors. It is interesting that there is a region between the aircraft impact cavity and these heated regions that has remained relatively cool. This means that this area had neither burned nor been heated by fire gases from nearby fires.

In Figure 8–23, the area where the 96th and 97th floors intersect with the northeast corner of the tower is not visible. At one point on September 11, the camera operator connected the infrared camera output to their standard video recorder and made a recording of the infrared camera display. A frame from this recording showing more of WTC 1 is reproduced in Figure 8–24. It was recorded around 9:16:45 a.m. The camera was using a false-color scale to display intensity, where blue represents the lowest intensities and red the highest. The thermal features on the north face already described are apparent in Figure 8–24. It is also clear that there were cool regions on the northeast corners of the 96th and 97th floors at this time despite the presence of nearby intense fires on these floors on both the north and east faces. The existence of these relatively cool areas is consistent with other observations that fire spread on these floors was inhibited as the flames approached the northeast corner.

Two small areas of strong heating are visible on the north face at the eastern side of the 94th floor in Figure 8–23 and Figure 8–24. A similar locally heated spot can be seen immediately below on the 93rd floor. The fires present on the 93rd floor have already been described based on visual imagery.

In Figure 8–23 there appears to be a heated area on the east face many floors below the fire floors. There are no other indications of a fire burning in this area, and it is believed that this apparent heating results from a reflection of the fires burning in WTC 2.

The difference in the amount of heating on the north and east faces in Figure 8–23 and Figure 8–24 is striking. Much of the area above the fires on the 92nd floor at the center of the east face is saturated, i.e., strongly heated. This is likely due to the large amounts of smoke and heat flowing from open windows near the intense fires burning on multiple floors of this face.

Despite this strong heating, there are parts of the east face in Figure 8–23 where individual floors and windows can be identified. On the south side of the face heat has migrated along the 94th through 97th floors, resulting in the bright lines that are visible in the infrared image. Individual windows are barely resolved. Figure 8–22 shows that smoke was flowing from only a few of the windows in this area and that most of the windows were still closed around this time. Heavy smoke can be seen coming from two windows (96-251 and 96-254) on the southern side of the 96th floor in Figure 8–22. In Figure 8–23 these two windows stand out as two larger bright spots near the southern edge of the tower. Using these windows for reference, it can be seen that the heated sections of the 95th, 96th, and 97th floors do not extend beyond column 250, while the heating on the 94th floor seems to have reached the south end of the

floor. The southern portion of the east side of the 92nd floor appears unheated despite the presence of a substantial fire near the center of this floor.

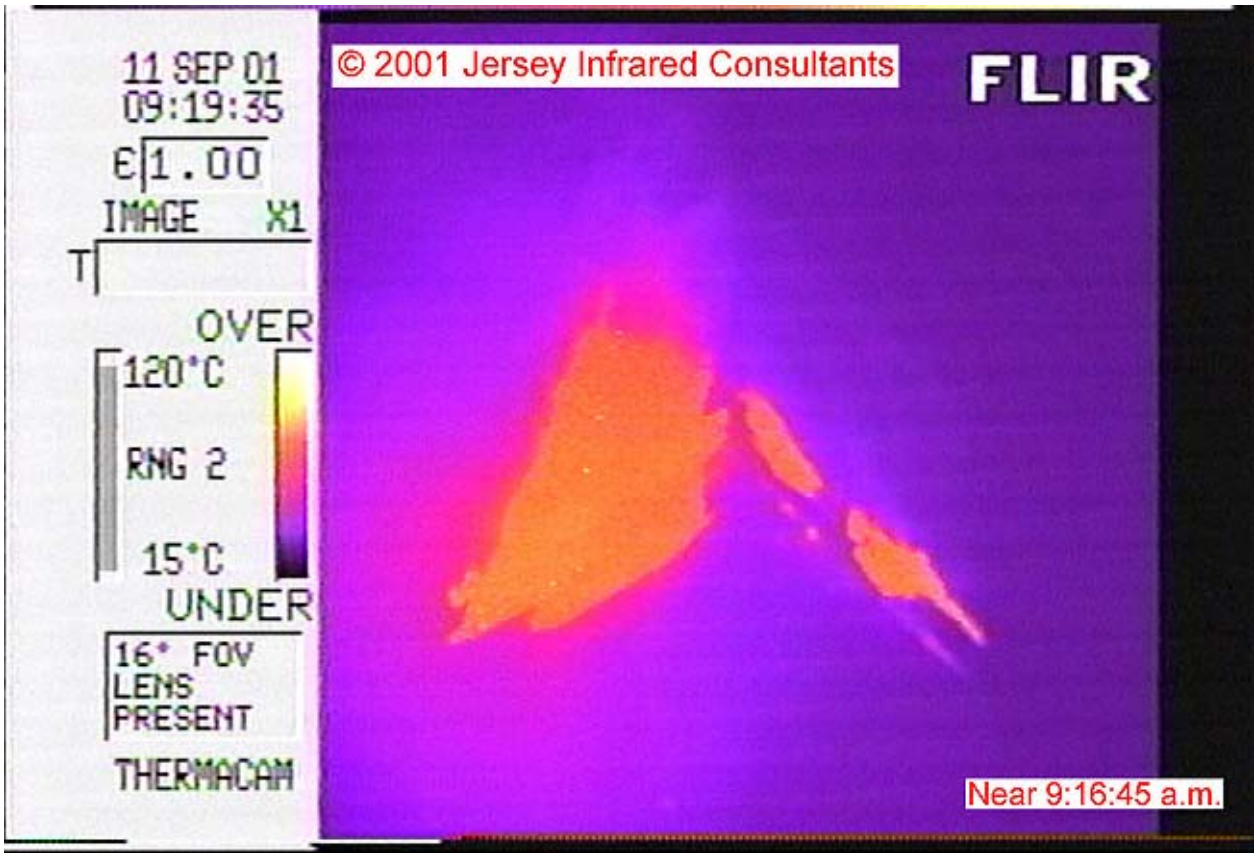

Figure 8-24. This frame from a standard video recording of the display from an infrared camera shows the north and east faces of WTC 1. It was shot around 9:16:45 a.m. (an uncertainty of 15 s is assigned) using a false-color scale for intensity. The output is strongly saturated.

On the northern side of the east face there are heated areas that reach as far as the northeast corner on the 96th and 97th floors. This is clearer in Figure 8–24, which shows more of the tower. Recall that at the times these images were taken the glass for all of the windows inside the northeast corner rooms was still in place on these floors despite the presence of nearby intense fires. On the lower floors there appears to be mild heating at the northern edges of the 92nd and 94th floors, while the 93rd and 95th floors are close to the ambient temperature.

The table of streamer observation included in Appendix L indicates that relatively few streamers were observed on the east face during this period. The streamers came from the 96th and 97th floors for the two cases for which source windows were identified. Since active flaming and flame spread is occurring during this time, it is likely that many other streamers were formed, but not observed.

During the initial part of this time period, the fires on the west side of the 96th floor on the south face continued to spread and grow. Distant images indicate that fire fully covered the area near the west wall shortly after 9:03 a.m. Figure 8–25 shows the west side of the south face as it appeared at 9:08:54 a.m. The image was captured from a video recording. On the 96th floor, flames now extended from at least

window 96-335 all the way west to window 96-358. The flames were particularly heavy on the west edge from windows 96-350 to 96-358. At this time, flames are not visible on other floors.

Figure 8-25. This image showing the south face of WTC 1 at 9:08:54 a.m. is a frame taken from a video. Column and floor numbers have been added.

During the next five minutes, the appearance of the south face changed dramatically as can be seen by comparing Figure 8–25 with another captured video frame shown in Figure 8–26. While the fires on the 96th floor were beginning to die down and recede back into the tower, extensive areas of flame were now apparent on both the 95th and 97th floors. The fire on the 95th floor can be seen in windows 95-340 to 95-346, while flames are visible extending from windows 97-336 to 97-354 on the 97th floor. The fire on the 97th floor may actually extend to the west face, but this cannot be confirmed since the area was hidden by heavy smoke coming from below.

Even though the west side of the south face is heavily involved in flames, there has been no apparent fire spread toward the east beyond the initially damaged area near the center of the face.

The fire intensity on the south face appears to have gone through several cycles, alternating between periods during which flames extended large distances from multiple windows and those where the flames receded back into the building. Figure 8–27, a photograph shot at around 9:16:40 a.m., i.e., roughly two minutes later than Figure 8–26, shows an example of one of the intense burning periods. The fire on the 95th floor has spread to the east and now extends to at least window 95-333. Flames are coming from several windows to the left of window 95-340. Heavy smoke, which partially obscures the areas above, is pouring from the openings. Bright yellow flames, which appear to reach down to the bases of the

windows, are now jetting from multiple windows on the 96th floor. It appears as if a portion of the exterior wall is covered by a continuous sheet of flame several stories tall. Fire is evident on the 97th floor, but it is not possible to judge whether flames are coming out of the windows on this floor due to the heavy smoke and flames rising from the 95th and 96th floors.

Figure 8-26. This image showing the south face of WTC 1 at 9:14:47 a.m. is a frame taken from a video. Column and floor numbers have been added.

A row of carets is already visible at the tops of the covers for columns 96-352 to 96-359. Despite the intense flames, few streamers were observed falling from the south face as shown in Appendix L. This is not unexpected since imagery from this direction is more limited than for the north and east faces, and many of the available shots are from such distances that streamers are difficult to identify. During this time period, the south face was in shadow, and streamers were not illuminated by sunlight until they had traveled a considerable distance from the building.

Figure 8-27. This image of the south face has been cropped from a high-resolution photograph. There is a 35 s uncertainty in the assigned time of 9:16:40 a.m. The image has been enhanced and rotated. Column and floor numbers have been added.

The fires on the west face during this time period continued to undergo unusual and dramatic changes in behavior. But first, following the two periods of rapid fire spread prior to 9:03 a.m., the fires again underwent another pause during which further fire spread was not evident. Figure 8–28 shows the west face as it appeared at 9:04:41 a.m. Flames, with a couple of breaks, can be seen in or extending from window 97-412 to window 97-458. This is roughly the same area that was burning just prior to 9:03 a.m., although the flames in the southern part of the area are more evident than earlier. Heavy smoke is pouring from multiple windows on this floor. Other features present in Figure 8–28 include heavy smoke flow from windows 96-409, 96-410, 97-409, and 97-410 on the 96th and 97th floors, the heavy smoke coming from broken windows in the upper northern portion of the face, and the fire coming from the southwest corner of the 96th floor where the aluminum panel was dislodged during the aircraft impact and subsequent fireball. A streamer can be seen near column 414 at the bottom of the photograph.

The open windows on the 95th floor, visible in Figure 8–11, can also be seen in Figure 8–28. There are also four windows, 94-434 to 94-437, on the 94th floor that are now open, but were in place in the earlier photograph taken at 9:01:40 a.m. These windows are believed to have been broken out by people. Atthis time there is no smoke coming from either set of open windows despite the presence of fires elsewhere on both floors.

Figure 8-28. A cropped photograph of the west face of WTC 1 taken at 9:04:41 a.m. is shown. The image has been enhanced and rotated. Window and floor numbers have been added. A streamer can be seen falling near the bottom of the image at column 414.

Mostly long-distance photographs and videos show that the conditions present in Figure 8–28 did not change appreciably until 9:06:27 a.m. At this time a short-lived, but intense, burst of flame appeared near the top of window 97-408, as can be seen in Figure 8–29. Very shortly after this flame appeared, the amount of smoke coming from open windows on the 97th floor decreased dramatically, and it was possible to see parts of the west façade that had been hidden just before. The heavy smoke is still evident in Figure 8–29.

Figure 8-29. This image of the north and west faces of WTC 1 is a frame from a video recorded by a news helicopter at 9:06:28 a.m. WTC 2 can be seen behind WTC 1. Note the burst of flame from near window 97-408 at the southwest corner of WTC 1.

Another frame taken from a video shot by a news helicopter is shown in Figure 8–30. This image was taken four and a half minutes later than Figure 8–29. An extensive area of flame is still present on the 97th floor, but the flames toward the center of the face appear to have receded deep inside the building. There is very little smoke coming from the region. Most of the west face is now visible. In particular, the smoke coming from two areas on the south side of the face at the 104th floor can now be seen clearly. On the north side of the face the heaviest smoke flow from the upper floors is coming from the 107th floor, with strong smoke plumes also issuing from open windows on the 104th and 105th floors.

There appears to be a small fire on the 96th floor at window 96-406. Small fires such as this one were not observed on the west face of the 96th floor until around 9:08 a.m. This was the case despite the fact that an intense fire had been burning just around the southwest corner on this floor for over 20 minutes. Several windows did open near the corner during this time period, suggesting that heating was taking place in the area. There is a remarkable difference in the fire growth and spread on the western

peripheries of the 96th and 97th floors. This is especially true when it is recalled that substantial amounts of aviation fuel were likely spread across the western sides of both of these floors (see the discussion in Section 6.5).

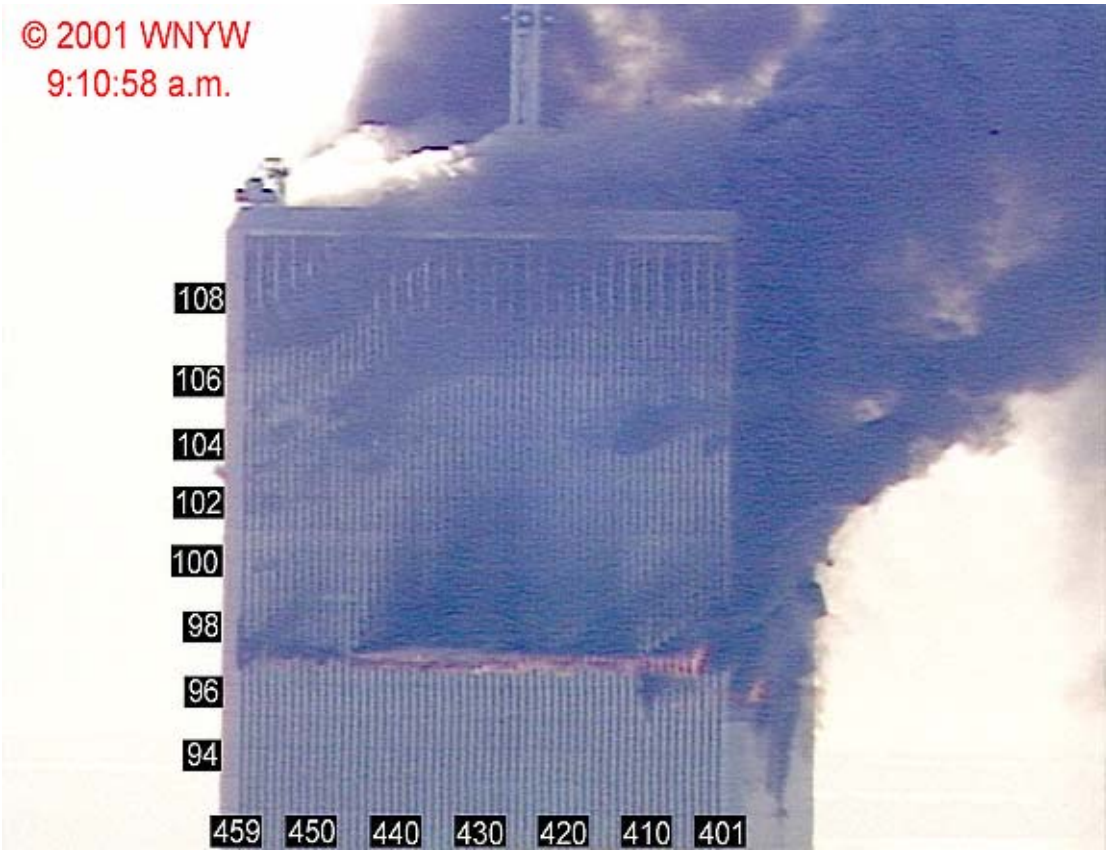

Figure 8-30. This image of the west face of WTC 1 and an oblique view of the south face is a frame from a video recorded by a news helicopter at 9:10:58 a.m. Column and floor numbers have been added.

A higher resolution photograph of the west face taken at 9:14:46 a.m. is shown in Figure 8–31. The photographer was located just to the west of the WTC site and was, therefore, shooting up at the building from a steep angle. The only area in which fire is evident in this photograph is on the 97th floor at the south edge in windows 97-401 to 97-406. While the flame lengths are fairly short, there does appear to be some flame extension from these windows. The smoke plumes from higher floors described above are also visible, and a spot fire is present in window 96-404. There are still no indications of smoke or fire on floors below the 96th.

During the time period from 9:03 a.m. to 9:18 a.m., only a few streamers were observed on the west face, as shown in Appendix L. One of these streamers is visible in Figure 8–28. It is difficult to see this streamer, even though the photograph is fairly close up. This is due to the fact that the streamer is not illuminated by sunlight. There are relatively few photographs of the west face showing the detail of Figure 8–28 during this time period. Given the intensity of the fires on the west face, it is likely that numerous streamers were formed, but that they simply were not observed.

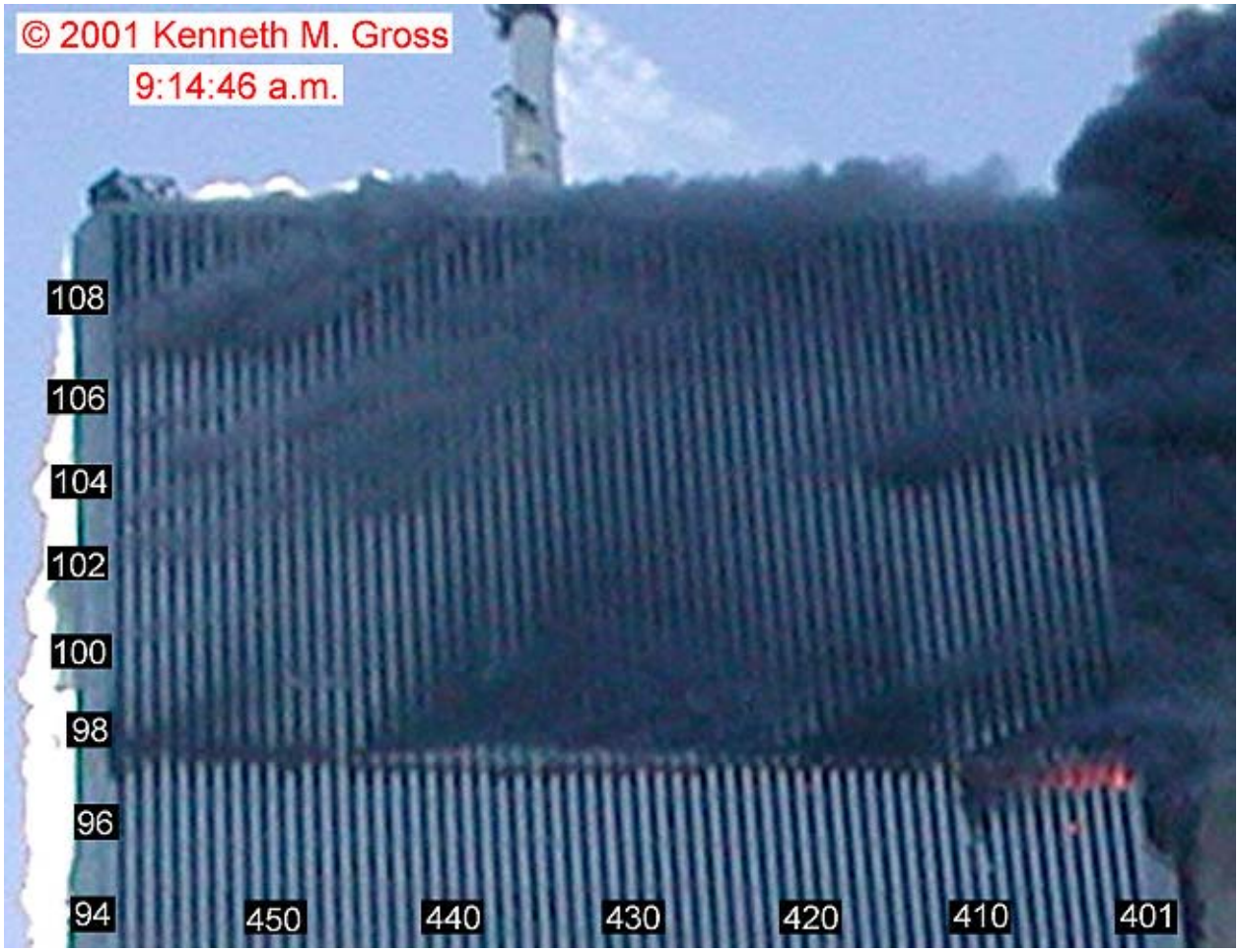

Figure 8-31. This cropped photograph shows the west face of WTC 1 at 9:14:46 a.m. It was shot from the ground a short distance from the WTC site. Column and floor numbers have been added.

During this time period, fourteen people were observed falling from WTC 1. Unlike during the first time period when a large number of people fell from windows at or below the aircraft impact floors, all of the people for which the origins of the falls are identified came from above the aircraft impact floors. The largest number fell near the southwest corner along the west face. While it is not possible to say with certainty, it seems likely these people came from the 104th floor. There are a number of open windows in this area with heavy smoke flowing out. A number of people were also observed falling on the south face. It is likely that many more fell on this face than were observed since close-up visual coverage from the south is less complete than for the other three faces.

In Figure 8–32, window breakage is used as a surrogate for fire spread to provide a visual indication for fire growth during the period covering roughly 9:03 a.m. to 9:18 a.m. It should be kept in mind that open windows do not provide a perfect history of fire locations since many windows were broken during the aircraft impact and accompanying fireballs. It is also likely that some of the windows that were open at this time were broken by people. This is particularly the case on the 94th and 95th floors on the west face.

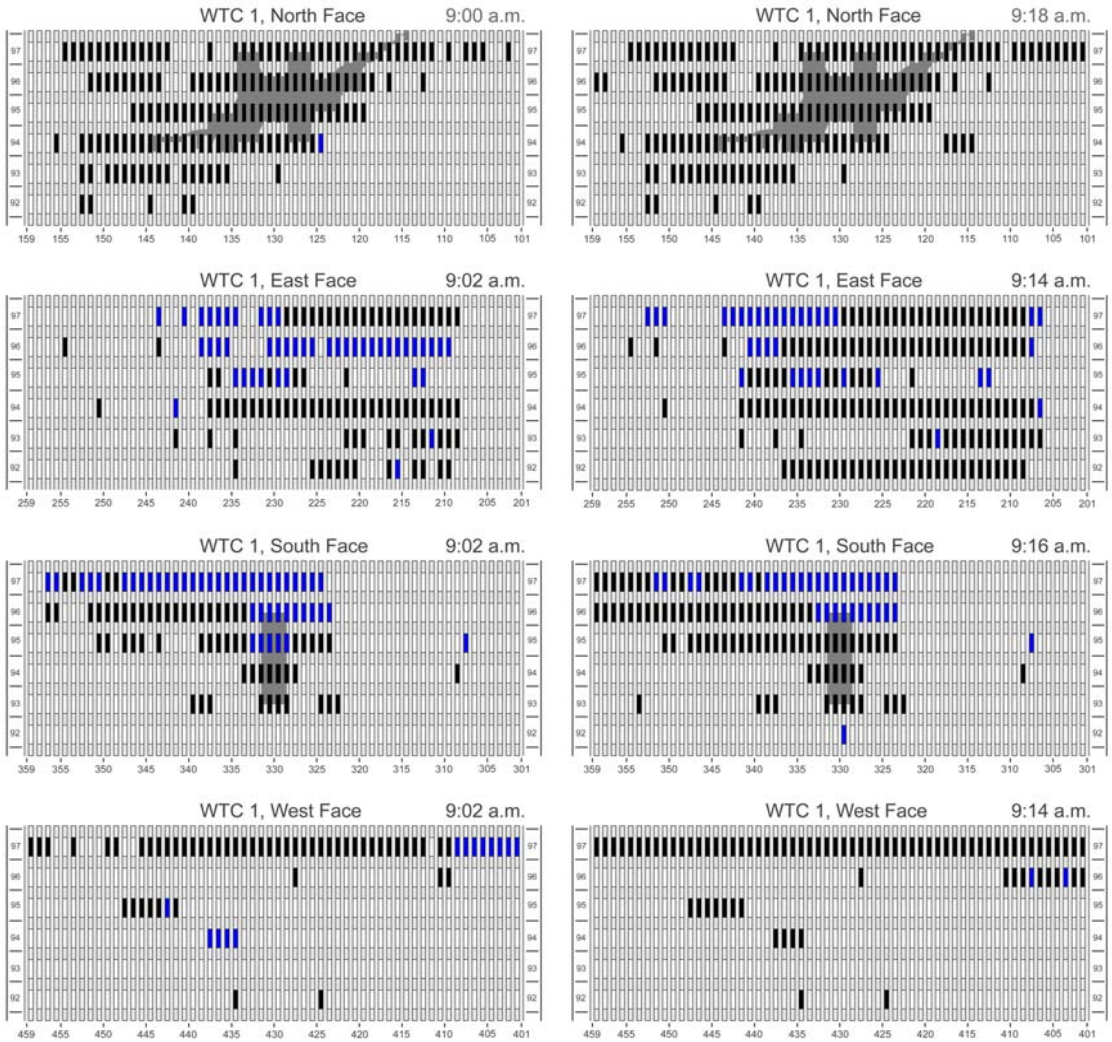

Figure 8-32. Maps for the 92nd through the 97th floors compare missing window glass for the four faces of WTC 1 at two times, around 9:02 a.m. and roughly 15 minutes later. The color coding used for the maps is indicated in Figure 5-1.

As described in detail above, the primary areas of fire growth during this period were on the east and south faces of the tower. On the east face, the major fire expansion was on the 92nd and 96th floors, with smaller areas of growth on the 94th and 95th floors. On the south face, fire spread continued on the western side of the 96th floor and wide-spread fires appeared on the same side of the face on the 95th and 96th floors.

The window records also provide a means to visualize some of the major characteristics of the fire development thus far. It is also helpful to refer to Figure 8–13, which is a similar drawing comparing window condition at around 8:48 a.m. and 9:03 a.m. In Figure 8–32 it can be seen that by 9:18 a.m. broken windows on the 97th floor extended in a nearly continuous band from window 97-340 on the south face, along the western and northern faces, and reached at least as far as window 97-229 on the east face. The only breaks in the band are a small region on the north face just to the left of the aircraft impact point and a series of windows on the northeast corner that were located within a corner office. The large extent of the fires on this floor is even more remarkable when the relatively few windows that were missing immediately following the aircraft impact (see Figure 8–13) are considered.

Integrated maps for fire intensity for the period, similar to those shown in Figure 8–14, are included in Figure 8–33. Comparison of these two figures confirms the general trends in fire spread described above. Such a comparison also shows that some of the fires observed during the initial period have died down and are not apparent during the second time period. Examples include fires on the 97th floor on the north face and areas on the 94th and 97th floors on the east face.

From Figure 8–33 it appears as if the most intense and widespread fires during the period from 9:03 a.m. to 9:18 a.m. were on the 96th and 97th floors. The east side of the tower had the most widespread fires,

with flames visible from the 92nd floor to the 97th floor. The absence of burning in the southwest quadrant of the tower is evident from the maps.

In Section 6.4.2 it was pointed out that the aircraft and fireball damage to the tower was asymmetrical and that the southeast quadrant appeared to be relatively undamaged. Figure 8–32 and Figure 8–33 show quite distinctly that major fire development has not yet occurred at the periphery of this quadrant. This is further evidence that aircraft debris and/or fuel did not reach the periphery of this quadrant to any great extent.

On the other hand, the extremely rapid fire spread on the 97th floor suggests that aviation fuel was distributed widely over this floor, with the exception of the southeast quadrant. Similarly, the rapid fire spread on the east side of the 92nd floor suggests a significant amount of aviation fuel reached this floor. Presumably this fuel came from the 94th floor, where the aircraft's port fuel tank is likely to have spilled most of its contents.

Despite the presence of fires near the center of the east face on floors 92 to 97 and nearby intense fires on the 96th and 97th floors of the north face, most window glass in the northeast corner of the tower is still in place at 9:18 a.m. This suggests that walls for rooms located in the corners of these floors had been effective in slowing the spread of the fires.

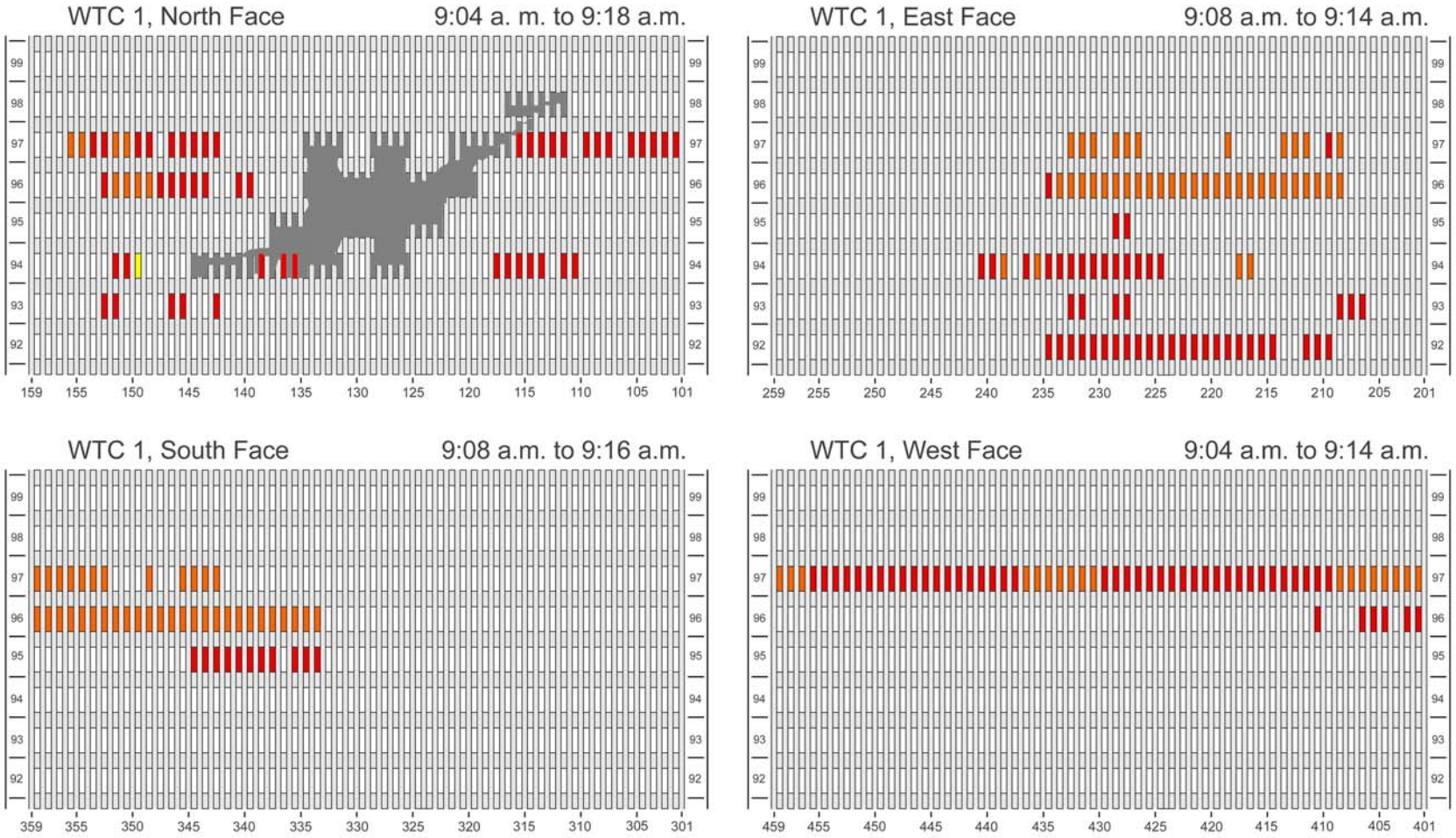

Figure 8-33. Maps of integrated fire observations between 9:03 a.m. and 9:18 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

8.4 9:18 A.M. TO 9:35 A.M.

Figure 8–19, which was shot at 9:18:17 a.m., shows evidence on the north face of initial fire spread into a room in the northeast corner of the 96th floor and into an area on the 94th floor to the west of the aircraft impact area, locations where fire had not been observed earlier. In videos of the area, fire first became visible in windows 96-152 and 96-153 at 9:19:00 a.m. At the same time, an object (perhaps a window) was observed falling just below this spot. Two seconds later heavy flames burst from these windows. The photograph in Figure 8–34 was taken one second later. Heavy flames are coming from windows 96-153, 96-154, and 96-155. The fire progressed quickly across the remaining distance to the east wall, and flames erupted from window 96-158 at 9:19:33 a.m. This rapid fire spread with flames out of the windows is consistent with the occurrence of flashover in the rectangular room having walls located at columns 96-152 and 96-204 (see Figure B-5).

As the table in Appendix L indicates, the first streamer from this area was observed falling from around window 96-153 at 9:19:19 a.m. During the next few minutes, several additional streamers were generated from this vicinity.

At 9:18:32 a.m. a bright flame appeared in window 94-111, well to the west of the flame present on this floor in Figure 8–19. Fire filled in the length between the two locations during the next 20 s or so. By 9:19:03 a.m. windows from 94-110 to 94-117 were open with flames visible, as seen in Figure 8–34. Note the large number of windows where isolated flames are evident at the tops of the frames in Figure 8–34. Not surprisingly, streamers were observed falling from this region starting at 9:19:42 a.m. Given the amount of fire, there is remarkably little smoke exhausting from the open windows. It is difficult to determine if smoke is flowing elsewhere, but there is no indication of smoke at the 94th floor level from the aircraft impact cavity.

Small fires are present inside the building at window 94-150 on the 94th floor and windows 93-145, 93-151, and 93-152 on the 93rd floor. Many window panes remain in place close to the fires on both floors.

The smoke and flame from the fire on the 96th floor made it difficult to identify what was happening in the windows immediately above on the 97th floor in images taken from a distance. In a close-up photograph taken at 9:19:44 a.m., flames are observed on the 97th floor in windows 97-155 to 97-158. Sometime from just before 9:19 a.m. to 9:19:44 a.m., this fire penetrated the wall located at column 97-155 and broke out the four north face windows inside the room.

A close-up photograph taken at 9:20:51 a.m. shows that the appearance of the fires on the 96th and 97th floors was somewhat changed from that seen in Figure 8–34. Heavy flames were present in all of the north side windows that were originally within the corner rooms. Flames were extended primarily from the two windows nearest the east face on both floors. The fire on the 94th floor had a similar appearance to that in Figure 8–34, with extensive flames present inside the building, numerous areas burning at the tops of window openings, and only light smoke coming from the windows. This fire had continued to spread to the east and now extended from windows 94-106 to 94-117.

Figure 8-34. An image recorded at 9:19:03 a.m. shows the north face of WTC 1. The original has been cropped, rotated, and enhanced. Column and floor numbers have been added.

Around 9:23 a.m. the flames extending out of windows on the 96th floor receded back into the building. At roughly the same time, the smoke issuing from the aircraft impact cavity became extremely light. A light puff of smoke appeared from the window (94-158) at the eastern edge of the 94th floor at 9:23:52 a.m. This window had been intact at 9:23:41 a.m.

Figure 8–35 shows the north face of WTC 1 as it appeared at 9:25:28 a.m. The amount of smoke coming from the north face, particularly the aircraft impact cavity, has decreased markedly as compared to images taken earlier. There are fires visible on multiple floors, but the amount of smoke coming from these floors is very low. In fact, the densest smoke appears to be coming from open windows that are well above the fire floors. This observation indicates that smoke is still moving upward inside the building and following flow pathways to windows opened by people trapped above the aircraft impact floors. Smoke is still flowing from the air intakes on the 108th and 109th floors.

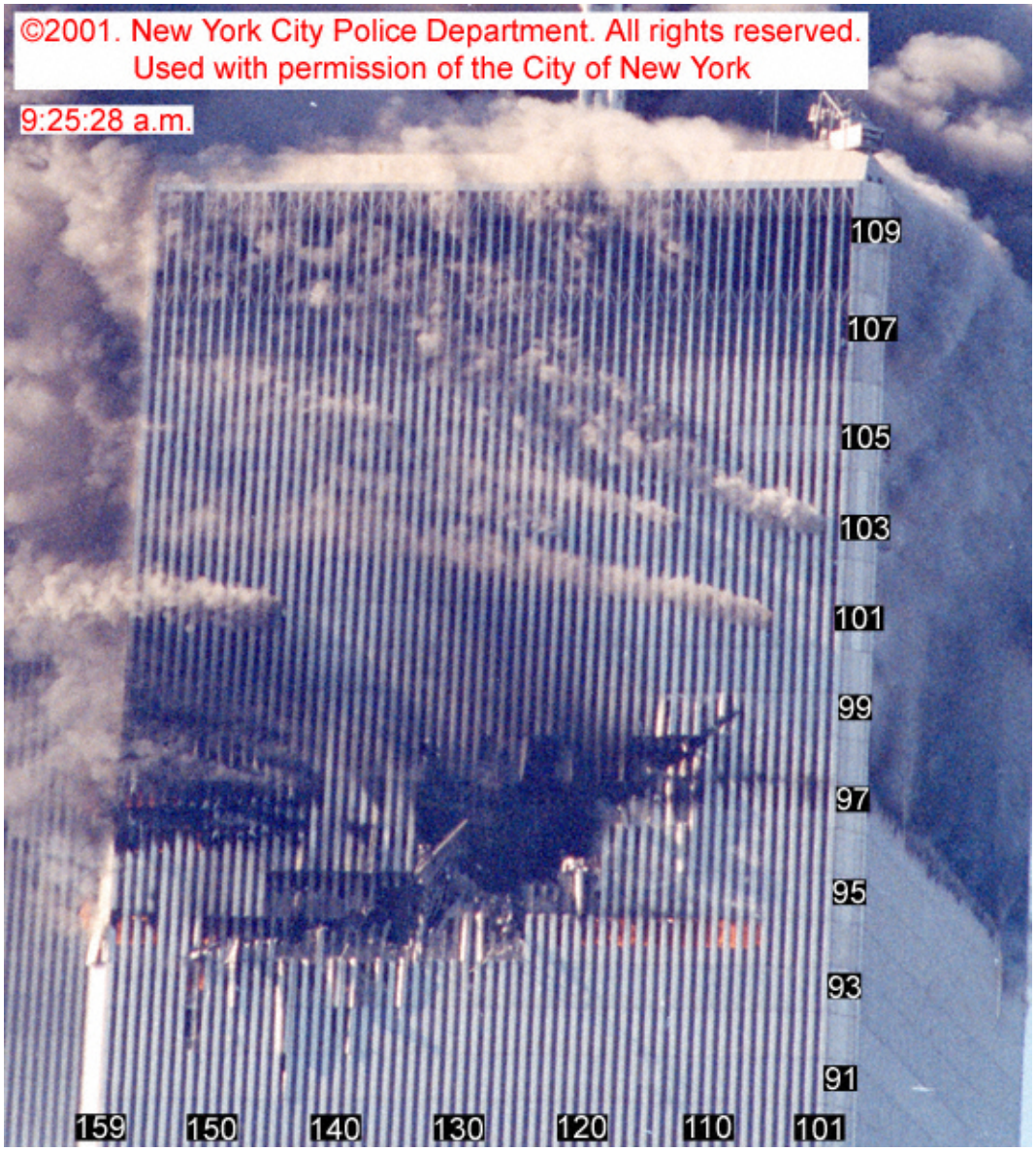

Figure 8-35. An image recorded at 9:25:28 a.m. shows the north face and an oblique view of the west face of WTC 1. The original has been cropped, rotated, and enhanced. Column and floor numbers have been added.

In Figure 8–36 two areas on either side of the aircraft impact cavity in Figure 8–35 have been blown up in order to provide a better view of the active fires. On the east side, fires can be seen on the 93rd, 94th, 96th, and 97th floors. Fires that appear to be relatively small and isolated are present at two locations centered near windows 93-139 and 93-151 on the 93rd floor. On the 94th floor an isolated fire is also present near window 94-151, but the major change from earlier times is that the glass in windows 94-155 to 94-158 is now missing, and an intense fire is evident burning within the building behind the four open windows. Isolated fires are present at the tops of the two windows in the center of the group. Note that that the two adjacent windows, 94-153 and 94-154, are still in place. Flames can be seen through multiple open windows on the 96th and 97th floors. There is now no flame extension from the north face windows, and the fires have died down considerably from their levels of a few minutes earlier (e.g., compare with Figure 8–34 recorded at 9:19:03 a.m.).

On the west side of the north face, fire is only visible on the 94th floor. The apparent intensity of this fire has also died down somewhat from a few minutes earlier. The fire has broken into two sections on either side of a central region running from roughly windows 94-109 to 94-113, where only small fires near the bases or tops of the windows are evident. The fire spread to the west has paused at window 94-106, and the five windows to the west have glass in place. This suggests that the fire spread to the west had been slowed down by an internal wall located at column 94-106. The floor plan layout in Figure B-3 indicates that there was indeed an internal wall that terminated on this column.

The areas of the north face of WTC 1 included in Figure 8–36 provide good examples of the correlation of local fire behavior with the column cover marks observed next to windows where fire is present. On the 96th and 97th floors the fires created conditions in which flames extended from the windows. A series of carets are present at the tops of the windows running across these two floors. The heights of the carets vary over the region providing an indication of the local maximum burning intensity. In contrast, fires on the 93rd and 94th floors did not generally extend from windows and did not generate a great deal of smoke flow from the windows. For these windows there were sometimes narrow, dark lines at the tops of the adjacent aluminum column covers, and for others very little marking of the column covers occurred.

An enlarged image of the fires on the west side of the north face is also included in Figure 8–36. The marks on the column covers on the 97th floor show evidence for both types of fires. Those nearest the airplane strike point are marked with carets. Flame extension was observed in this area shortly following the aircraft impact. Further to the west there are black marks above the windows, except for the column covers on either side of window 97-102, which are marked with carets. As discussed earlier, fires on this part of the 97th floor did not extend from these windows for any significant period of time. The same types of narrow black bands are observed at the tops of the columns above the burning region on the 94th floor. Recall that this was a region of heavy burning, but without flame extension.

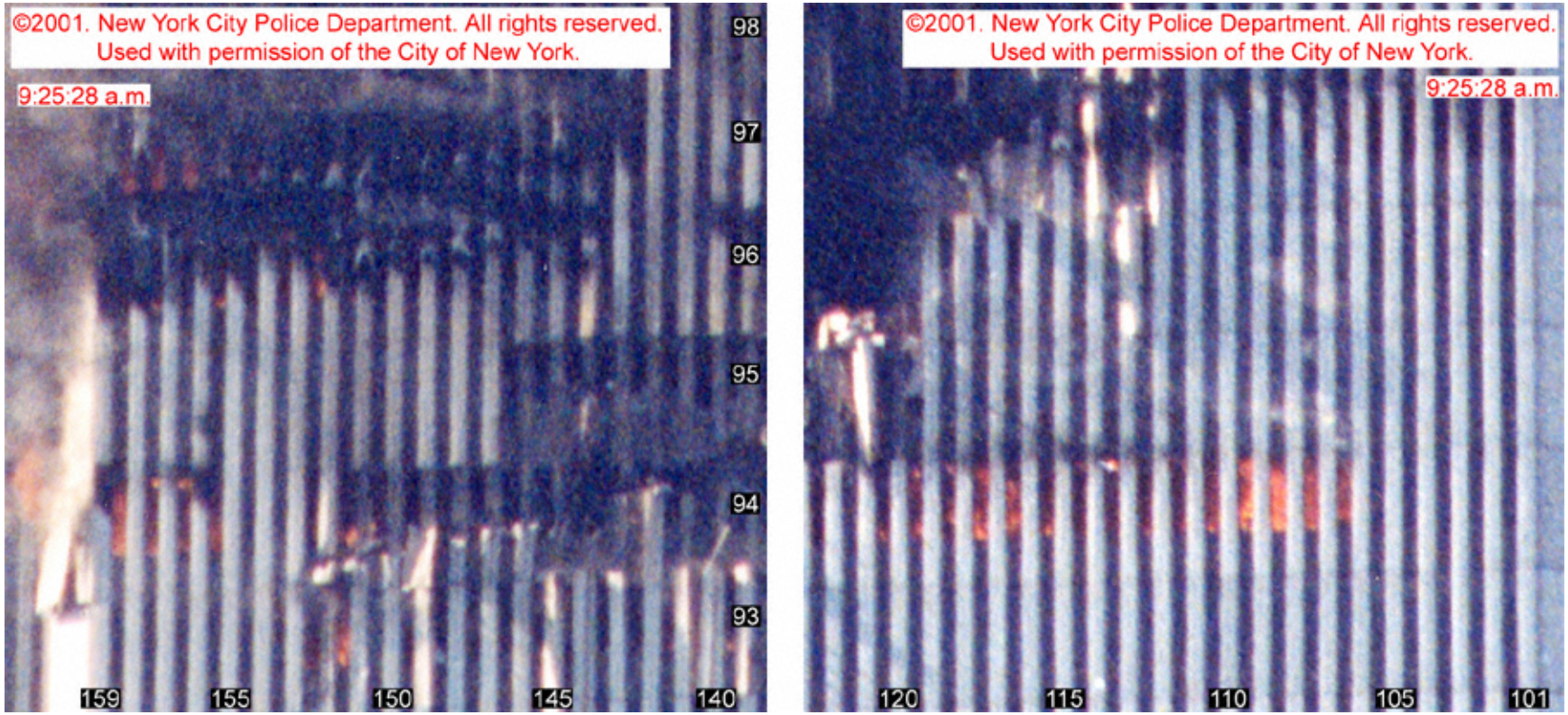

Figure 8-36. Two blowups from Figure 8–35 of areas on the north face of WTC1 are shown. The photograph was taken at 9:25:28 a.m. The images have been enhanced, and column and floor numbers have been added.

Figure 8-37. This cropped photograph shows the north face of WTC 1 at 9:28:21 a.m. The image has been rotated and enhanced. Column and floor numbers have been added.

Figure 8–37 shows a photograph of the fire floors on the north face taken at 9:28:21 a.m. The fires which grew rapidly at the start of the period are continuing to die down. In particular, the large fires that appeared within the rooms on the northeast corners of the 96th and 97th floors are now barely visible. The fires on either side of the aircraft impact cavity on the 94th floor are also decreasing in size. On the east side there are still fires burning at the window head casings of windows 94-156 to 94-158. An isolated fire can still be seen on the 93rd floor through open windows 93-152 and 93-153.

While it is difficult to make out in Figure 8–37, close inspection shows that there is a small spot fire visible in window 98-123 on the 98th floor. Recall that a similar fire was observed on this floor in window 98-115 around 9:06 a.m. Most windows were still in place on this floor around the time Figure 8–37 was taken.

During the next several minutes, the older fires on the north face of WTC 1 continued to die down, but on the 98th floor the fires were growing and appearing at new locations. Around 9:29:10 a.m. a video shows a sudden increase in the brightness of the flame at window 98-124. Near 9:31:40 a.m. the amount of smoke coming from the aircraft impact cavity increased dramatically. Figure 8–38 is an image of the face captured from a video recording shortly after 9:35 a.m. Flames are visible in many windows, ranging from at least window 98-122 to window 98-139. There is a bright flame at the head casing of window 98-138. Most of the imagery of the north face during the period from around 9:29 a.m. to 9:35 a.m. was shot at a longer distance than Figure 8–38, and it has not been possible to follow the growth of the fires seen in this image in detail. It does appear that much of this fire growth occurred around 9:35 a.m. At this time very little north face flame is visible on other floors.

The close-up photograph in Figure 8–39 shows the northeast corner of WTC 1 at 9:19:03 a.m. On the north face, the flames that first emerged from windows on the 96th floor at 9:19:00 a.m. are evident. At the time of Figure 8–39, the largest flame jet was coming from window 96-154. On the east face heavy flames were present in windows 96-208 to 96-211. The distinct carets on the column covers attest to the intensity of the fires that have been burning in the area. The window glass on the inside of the internal wall at column 96-208 is still in place. This is not the case on the 97th floor. Flames are evident through a partially opened window 97-207, indicating that fire had penetrated the wall at column 97-208 by this

time. Recall that fire appeared in windows on the north face at the northeast corner of the 97th floor around this time, but that it was not possible to determine exactly when the windows opened.

Figure 8-38. A frame taken from a video shows the north face of WTC 1 at 9:35:51 a.m. The image has been enhanced. Column and floor number have been added.

On the 95th floor, windows from the north edge out to window 95-207 appear intact. It looks as if there was a small fire in window 94-207, and the window may be partially broken out. This is not clear. Carets on the covers of columns 93-206 to 93-208 are telltale signs of the extended flames that came from windows 93-206 to 93-208 at an earlier time. Glass for windows to the north of column 93-205 is still intact. These observations suggest that a wall at column 93-205 may have slowed the spread of this fire. However, it is not possible to confirm this since the plan layout for this floor shown in Figure B-2 does not cover this section of the floor. For the 92nd floor, glass is intact in windows extending from the north edge to at least window 92-207. The floor plan layout in Figure B-1 indicates that there was a room in the northeast corner of this floor with walls that extended to columns 92-155 and 92-204. The interior wall on the south side of this room was glass.

The image in Figure 8–40 was taken from a close-up video showing the central portion of the east face. It was recorded at 9:19:48 a.m. A fire on the 96th floor extends from at least window 96-214 to window 96-233. The fires in the northern part of the photograph on the 96th floor are less intense than those further to the south. When combined with Figure 8–39, this suggests that the fires on the 96th floor are still most intense at either end of the burning area, with an area of dying fire in the center.

Figure 8-39. This cropped close-up photograph showing the northeast corner of WTC 1 was taken at 9:19:03 a.m. It has been enhanced, and column and floor numbers have been added.

Extended flames are coming from window 96-231 in Figure 8–40. The presence of carets indicates that flames had earlier been present at least as far south as window 96-238, but at this time these flames were not visible. The floor plan layout for this floor (see Figure B-5 in Appendix B) does not provide an explanation for this fire distribution, since there are no walls or rooms indicated in this area of the floor.

A region of flame is also evident on the 97th floor, starting near window 97-225 and going west. The full extent of this flaming region is not known, since fire and smoke from the 96th floor hid a portion of these windows. The flames visible on the 97th floor do not extend from windows and appear to be dying down.

There are no extensive flame regions evident on the 93rd or 94th floors. A review of videos recorded around this time indicates that the fires on these floors had indeed died down. Smoke is visible coming from below in Figure 8–40. This smoke is coming from the 92nd floor.

Figure 8-40. A frame taken from a video shows a portion of the east face of WTC 1 at 9:19:48 a.m. The image has been enhanced, column and floor numbers added.

There are some interesting variations in the column smoke markings in Figure 8–40. In particular, consider the 94th floor. Many of the column covers have distinct carets that are characteristic of locations next to windows that have experienced extended flames. Clear examples of carets can be seen on the covers for columns 94-226 to 94-230. On other column covers the smoke marks take the form of alternating horizontal bands of light and dark areas. The marks on the covers for columns 94-231 to 94-234 show good examples of this type. By comparing the markings with the local fire behavior, it has been possible to correlate the formation of this type of smoke mark with windows from which there had been a heavy smoke flow, but for which external flaming was not observed. In contrast to the mixed fire behavior seen on the 94th floor, carets are present on nearly all of the columns on the 96th floor visible in Figure 8–40.

At 9:20:45 a.m., window 96-203 at the northeast corner of the 96th floor opened, and heavy smoke began to pour out. This was followed almost immediately by external flaming. Figure 8–41 is a frame taken from a video showing the appearance of this flame one second later, at 9:20:46 a.m. It has been nearly 75 s since the last window on the north side of the rectangular room in the northeast corner of this floor opened. The wall for this room on the east face is located at column 96-204 (see Figure B-5), i.e., next to the window on the east side of the room that first opened.

Six seconds after window 96-203 opened, smoke and fire began to come from window 96-202, and another 4 s later the same occurred at window 96-201. At this point all ten of the windows in the outer walls of the rectangular room at the northeast corner had been opened by the fire. The entire process took

approximately one and a half minutes. As seen by referring to Figure B-5 in Appendix B, there was a second room on the east outer wall just to the south of the rectangular corner room. This room had four windows on the east wall. By 9:20:46 a.m., this room was already on fire since flames can be seen in window 96-207. Fire is visible in the image extending from at least window 96-207 to window 96-231. At 9:21:01 a.m. flames appeared abruptly at window 96-207. Interestingly, this was the same time when the external flames on the north face of the building receded back into the tower.

Figure 8-41. A frame taken from a video shows a portion of the east face of WTC 1 at 9:20:46 a.m. The image has been enhanced. Column and floor numbers have been added.

In Figure 8–41 heavy smoke is flowing from a number of windows on the 92nd floor, starting at window 92-208 and running to the last visible window, 92-230. A dull orange glow is evident in the vicinity of windows 92-214 to 92-218, but the remaining open windows appear to be dark. Shortly after Figure 8–41 was shot, the video zoomed out, revealing that internal fires were present inside the tower at least as far south as window 92-234, with open windows as far as window 92-237. Figure 8–22, which was taken at 9:15:54 a.m., showed internal fires in this same area. During the intervening period, the fire had moved north one window, having opened window 92-208. There is no obvious reason for the fire spread to slow down at this location, since the floor plan layout in Figure B-2 in Appendix B indicates there was not a wall at column 92-208. At 9:15:54 a.m. the fire had already moved as far south as window 92-234. During the next five minutes, three additional windows were opened. Fire spread in this direction also appears to have been retarded. The floor plan layout for this floor does indicate that there was a wall located at column 92-238, i.e., right next to open window 92-237. Detailed drawings for this floor show

that there was a large open area running along the east side of the 92nd floor from column 204 to column 238 in which a number of office modules were spaced closely together.

At 9:22:49 a.m. a smoke stream appeared from window 94-205 at the northeast corner of the 94th floor. The windows to the north of this location then opened sequentially until smoke appeared at 94-201 at 9:23:54 a.m. Very shortly after the last window opened, flames came from these windows. Recall that a light puff of smoke came from window 94-158 on the north face at 9:23:52 a.m. These observations suggest that fire entered the room at the northeast corner of the 94th floor by passing through the south wall and then spread along the east wall and finally onto the north wall. The appearance of dark smoke and intense flames from the windows indicates that flashover occurred in the space.

Figure 8–42 is a photograph of the east face taken at 9:25:57 a.m. The flames which had earlier spread into rooms located on the northeast corners of the 94th and 96th floors are still burning intensely. There is also now a large fire burning in the northeast corner room on the 97th floor. It has not been possible to identify exactly when this fire appeared because smoke and fire from the 96th floor hid its development from view. However, a video taken near 9:23:30 a.m. shows that flames were coming from window 97-203 at that time, so it must have appeared between 9:20:45 a.m., when fire was first visible in the area on the 96th floor, and this time.

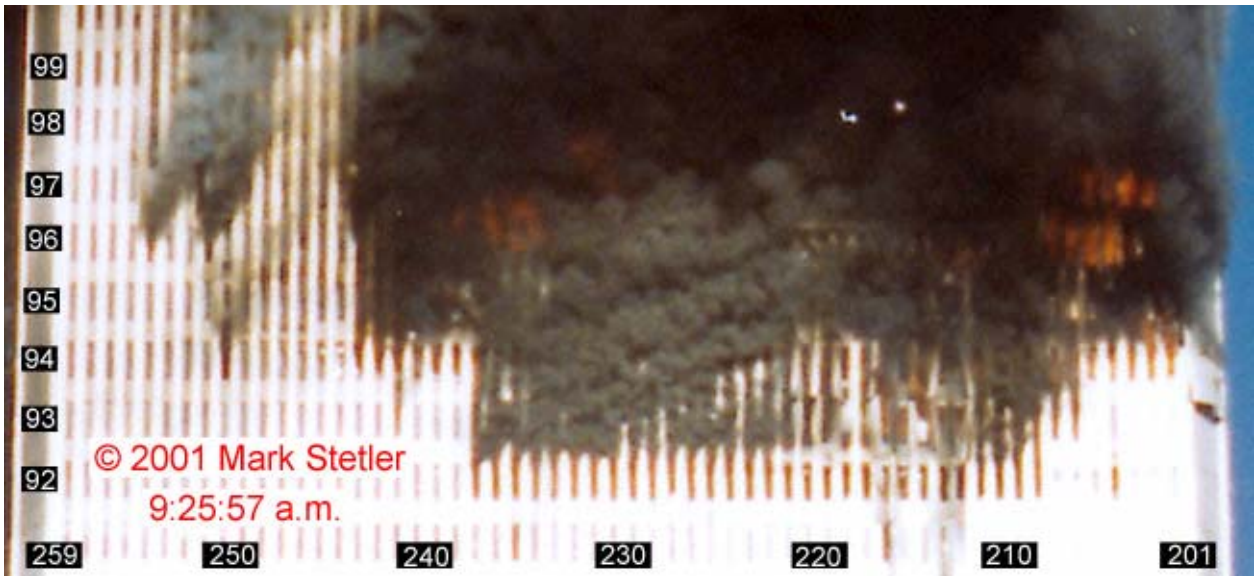

Figure 8-42. This cropped photograph shows the east face of WTC 1 at 9:25:57 a.m. The image has been rotated slightly and column and floor numbers have been added.

Fire is evident at a couple of locations on the 93rd floor. It appears as if flames are present inside window 93-206, while adjacent windows to the north still have glass in place. Recall that window 93-206 was already open at 9:19:03 a.m. (see Figure 8–39) and that fire spread to the north had seemed to pause at this location prior to this. The observations continue to suggest the presence of a room in the northeast corner of this floor with a wall at column 93-206, even though the incomplete floor plan layout in Figure B-2 does not allow this to be confirmed.

On the 92nd floor, fire appears to be present at an isolated window 92-204. According to the floor plan layout, Figure B-1 in Appendix B, there was a wall for a corner office at column 92-204. Apparently, the

fire on this floor has now reached the outside of this wall. Flames on the 92nd floor extend as far south as window 92-237. There is no indication that the fire has passed through the wall that terminates at column 92-238 at this time.

The exhausting smoke and flames visible in Figure 8–42 indicate the presence of an active fire on the 94th floor at windows 94-238 to 94-244. Fire in this region was not evident roughly six minutes earlier when the image in Figure 8–40 was recorded. The pause in fire spread on the 94th floor suggests that the fire had been temporarily blocked by a wall. It is not clear that this was the case since, even though there was a wall connecting column 94-238 to the core (see Figure B-3 in Appendix B), this is not the exact location where the fire paused. As early as 9:15:54 a.m. (see Figure 8–22) there was evidence that the fire had spread as far as window 92-240 on the east face. This is one of the few examples identified thus far where a spreading fire did not appear to pause immediately outside of a known existing wall. It is possible that this wall was breeched during the aircraft impact, since there was minor façade damage on the 94th floor in this quadrant on both the east and south faces. However, this does not provide an explanation for the reduced rate of fire spread after the fire had passed through the wall.

In Figure 8–42 fires are visible between windows 96-230 and 96-240 on the 96th floor and windows 97-230 and 97-240 on the 96th and 97th floors. This indicates that the fires on these floors are continuing to spread toward the south.

A short video clip recorded around 9:32:45 a.m. provided a similar, but more distant, view of the east face as the frame shown in Figure 8–40. This clip shows that the fires in much of the area burning earlier on the east face had died down. This includes the areas near the north edge on the 94th, 95th, and 97th floors, which were heavily involved in flames at 9:25:57 a.m. (see Figure 8–42). Fires that appeared to be relatively isolated were burning on the 94th, 96th, and 97th floors. On the 94th floor, flames were coming from window 94-245. On the 96th floor, a narrow region of flame was visible, covering windows 96-232 to 96-237, with long extended flames coming from windows 96-236 and 96-237. The fire on the 97th floor appeared to be more localized around window 97-229 and less intense than the fire on the 96th floor. The extent of the fire burning internally on the 92nd floor was reduced from that seen earlier. Flames were visible from roughly window 92-222 to window 92-232.

At 9:32:58 a.m., smoke emerged from the northeast corner of the 93rd floor at window 93-205. During the next 31s, the successive windows toward the north opened, reaching window 93-201. At this time, 9:33:29 a.m., flames appeared in the area. Figure 8–43 shows a photograph of the east face recorded at 9:34:20 a.m. From this angle and distance, only flames extending from windows are apparent. Flames are coming out of windows 93-201 to 93-205. The sudden fire development and flame extension from windows is a strong indication that flashover has occurred within an enclosed space located around windows 93-201 to 93-205. The evidence for an enclosed space with walls that hindered fire spread into the northeast corner of the 93rd floor is quite strong even though the presence of such a room cannot be confirmed from the incomplete floor plan layout shown in Figure B-2.

Intense flaming was also taking place on the 96th floor near windows 96-236 and 96-237. Much more of the façade is now visible through the smoke than earlier. In particular, this is an indication that fires on the 92nd floor and 94th floor, which were generating large quantities of smoke at earlier times, have largely died down.

Figure 8-43. Photograph of the east face of WTC 1 recorded at 9:34:20 a.m. Column and floor numbers have been added.

Fire spread on the south face during this period was not extensive. Extremely intense fires were already present on the western sides of the 95th, 96th, and 97th floors at the start of the period. With time these fires slowly died down.

Figure 8–44 provides a view of the south face at 9:19:15 a.m. The general appearance of the fires is little changed from that in Figure 8–27, which was recorded near 9:16:40 a.m. The intense jets of flames coming from windows 96-352, 96-353, and 96-354 on the 96th floor remain a prominent feature. This image provides a particularly good view of the area on the 93rd floor, near column 330, where the steel panel section, which was found near the corner of Cedar and West Streets, is believed to have originated. Extensive damage is evident in the vicinity, but it is not possible to visually confirm that the section is actually missing. There is a long section of what appears to be a pipe hanging below the suspected opening that appears to be attached to a cylindrical object. Recall that a long section of pipe was seen in photographs of the detached panel section lying in the street (see Figure 6-16 and Figure 6-17). The presence of piping near the suspected origin for the panel section provides further support that the panel section actually did come from this spot.

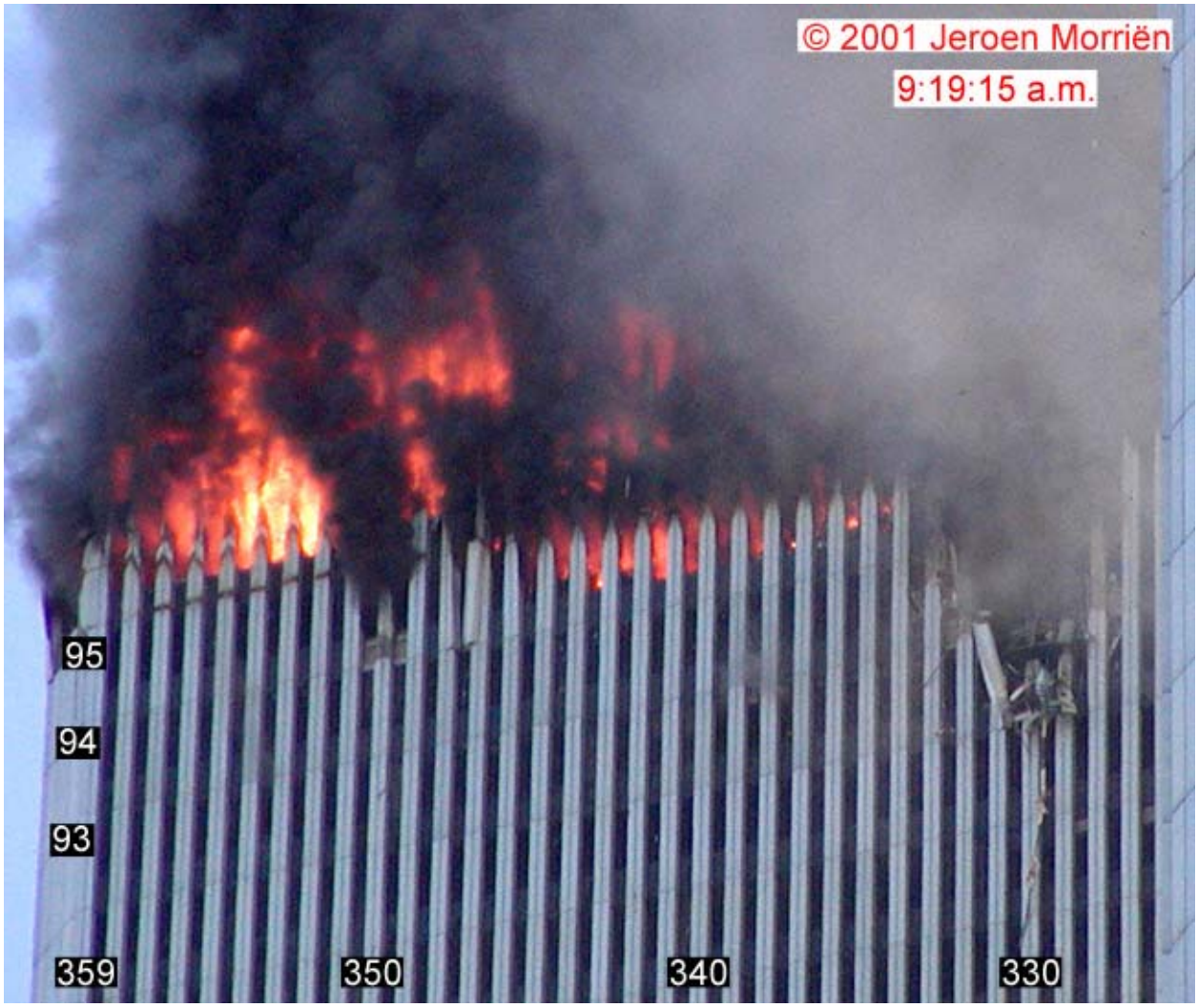

Figure 8-44. This cropped image shows a portion of the south face of WTC 1 at 9:19:15 a.m. The photograph has been enhanced and column and floor numbers have been added. The corner of WTC 2 is visible at the far right side of the image.

A later view of the burning area on the south face is shown in Figure 8–45, which was recorded around 9:25:28 a.m. There are a large number of pages of paper visible in the photograph. A video of the west face showed that these pages had traveled from the west face of the tower, where they had been released from an upper window. The fires present at this time remain quite intense and extensive, but there have been some changes since 9:19:15 a.m. The fires at the western edge of the 96th floor appear to be dying down and have receded back into the windows, while the strong jets of flame evident in Figure 8–44 on this floor are not as distinct. The fires on the 95th floor appear to have grown stronger. There is now flame extension from windows 95-340 to 95-343. The flames near the center of the face indicate that the fires on either the 96th floor or 97th floor, or both, extend continuously from the west edge of the south face to very near the center, i.e., column 330.

Figure 8-45. This cropped photograph shows the south face of WTC 1. It was taken around 9:25:28 a.m. with an assigned time uncertainty of 15 seconds. The original image has been enhanced and rotated. Column and floor number have been added. A number of pages of paper are present in the photograph.

Even though fires have been burning on the south face for well over a half hour, there is no indication in Figure 8–45 that the flames have begun to spread toward the east. With the exception of broken windows on floors well above the fire, the appearance of the east side of the façade has not changed since the aircraft impact.

Figure 8–46 shows a view of the south face taken at 9:33:13 a.m. By this time, the intense fires on the 96th and 97th floors near the western edge of the face have diminished greatly, and flames are no longer prominent in the windows nearest the edge, while flames closer to the center have receded back into the windows. It is now possible to observe individual windows on the 96th, 97th, and 98th floors all the way from the western edge to windows 96-344, 97-344, and 98-344. Note that it appears as if these windows on the 98th floor are missing. It is not possible to conclude this definitely, since it is possible that smoke may have been deposited on the windows, which would make them dark and thus appear to be missing. In either case, there are no obvious flames present in this area of the 98th floor.

In contrast to the 96th and 97th floors, the fire on the 95th floor has grown more intense during the almost 8 min since Figure 8–45 was taken. Flames extend from more windows, and the fire has even spread roughly three windows toward the west. An isolated fire is now visible on this floor at window 95-326. This is an early indication that fire spread toward the east had begun on this floor.

The smoke markings on the column covers in Figure 8–46 have an interesting appearance. On the western edge of the 96th floor, the columns display the distinct carets that are expected when flames have extended through adjacent window. Interestingly, carets are not evident on the columns immediately above on the 97th floor. However, the columns do appear quite dark. It may be that the intense fires on the 96th floors have deposited so much soot on the floor above that the carets are not visible.

A line of deposited soot is visible at the top of columns 95-351 to 95-357 at the western side of the 95th floor. These markings can be seen more clearly in Figure 8–44. No smoke is apparent coming from the windows, and it appears likely that the glass is still in place for these windows. The formation of these marks may be an indication that fire gases and smoke were leaking from the tower at locations where windows still had intact glass. Presumably, the leaks took place through the expansion joints located between column covers on different floors.

During the period from 9:18 a.m. to 9:35 a.m., the fires on the west face were relatively quiet. Very few photographs or videos available in the database for this period provide close shots of this face from the ground. However, two news helicopters were stationed to the west of the site. These helicopters were hovering several miles away over News Jersey, but at times their cameras zoomed in on WTC 1 close enough to provide details of the fires. Due to the large distances and the helicopter heights, these images have the potential to image fires deep within the building.

Figure 8-46. This cropped image shows a portion of the south face of WTC 1 at 9:33:13 a.m. The photograph has been enhanced, and column and floor numbers have been added.

One such image taken from a video recorded at 9:19:45 a.m. is shown in Figure 8–47. The fire distribution is consistent with that observed from the ground at 9:14:46 a.m. in Figure 8–31. A flaming region is prominent at the south edge of the 97th floor over windows 97-401 to 97-405. While these flames appear to fill the windows, they do not seem to extend out of them. Further toward the north on the 97th floor, a number of relatively small fires are visible through the lowest portions of the window openings. Most of these flames are observed between the intensely burning corner and the center of the face. When viewing the video, it appears as if this gentle burning is relatively continuous across this length. The only location on the face where flames are apparent even further to the north is in window 97-455. Keeping in mind that the bases of the windows are raised 15 in. from the floor, it is clear that most of the intense fires that were burning earlier on the west side of the 97th floor have died down to a condition in which widely distributed flames are gently burning near the floor on the remaining fuel. A comparison of Figure 8–47 with Figure 8–30, which was recorded at 9:10:58 a.m., provides a good visual measure of how much the fire intensity on this floor has decreased over this nearly 9 min period.

The only other floor on which flames are apparent in Figure 8–47 is the 96th. A region of fire, which fills the window openings, runs from window 96-404 to perhaps window 96-410. The flames in windows 96-408 and 96-409 extend from these windows. As discussed above, fire was present in the

same general location around 9:11 a.m. (see Figure 8–30). Two regions of small flames around windows 96-412 and 96-414 are visible just to the north of the flaming area. Even though these flames are similar in appearance to the dying flames just above on the 97th floor, there is a major difference. Based on the visual evidence, there has not yet been an intense burning phase in this region of the 96th floor. The absence of smoke marks on the nearby aluminum cladding is consistent with this conclusion.

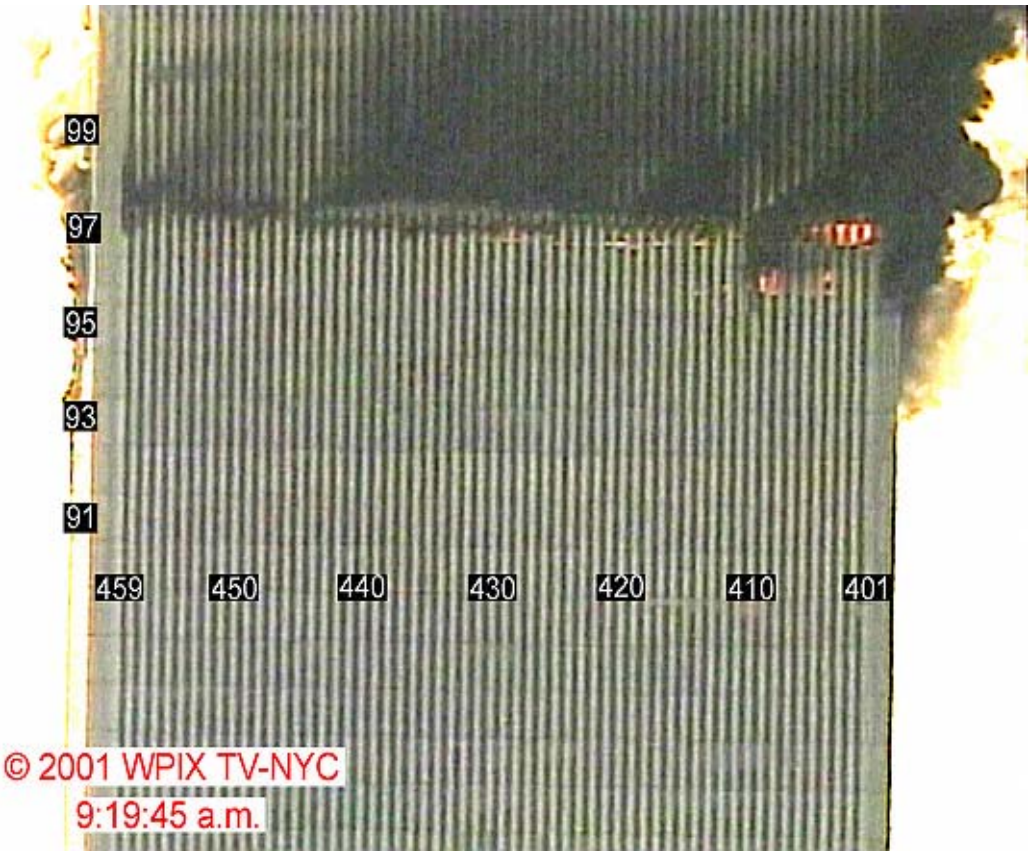

Figure 8-47. This image of the west face of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:19:45 a.m. The image has been enhanced by adjusting the intensity range, and areas to the left and right of the tower are saturated. Column and floor numbers have been added.

It is interesting to compare Figure 8–47 with the view of the south face shown in Figure 8–44. These images were taken approximately 30 s apart. While there are intense flames issuing from numerous windows on the 95th, 96th, and 97th floors on the west side of the south face, from the west flames are only observed near the south corners of the 96th and 97th floors, and they do not appear to be nearly as intense. These observations indicate that either the flames on the south face are isolated near the outer wall or that interior portions of these floors are actually hidden from view by obscuring smoke or walls. There is no indication of fire on the 95th floor from the west. Figure B-4 in Appendix B shows that there were a group of rooms in the southwest corner of this floor with a wall extending to column 95-350. The walls associated with these rooms may still be in place, protecting the west side of the floor from the fire raging on the south face. One piece of visual evidence argues against this conclusion. In Figure 8–44, smoke is observed coming from windows 95-349 and 95-350, and there is evidence of façade damage below both of these windows. This suggests that both windows were removed during the aircraft impact

and subsequent fireball. It is unclear if such damage could have taken place without severely damaging the wall located between these two windows.

Figure 8–48 shows a closer view of the south side of the west face captured from a news helicopter video recording at 9:24:23 a.m. The general appearance is very similar to that of Figure 8–47. The relatively intense fires burning at the south edges of the 96th and 97th floors are still present. A number of small, apparently isolated, fires can be seen on both of these floors. On the 96th floor there are now indications of fires as far north as window 96-417. This is slightly farther than observed at 9:19:45 a.m. and suggests that these low-level fires are slowly moving toward the north along the outer west wall of the 96th floor. The image has sufficient resolution to just identify, albeit with some uncertainty, whether window glass is still in place, or not. It appears that the glass is missing from those windows where the small fires are visible and is intact in windows at the intervening locations.

Figure 8-48. This image of a portion of the west face of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:24:23 a.m. The image has been enhanced by adjusting the intensity range, and the area to the right of the tower is saturated. Column and floor numbers have been added.

Figure 8–49 shows another view of the west face of WTC 1 taken from a video that was recorded from a helicopter at 9:34:48 a.m. The fires on the south ends of the 96th and 97th floors are no longer as prominent as they were earlier. In fact, at this distance and clarity it is difficult to identify fires in these locations. There is evidence of low-intensity fires further to the north on both the 96th and 97th floors. The most visible flames on the 96th floor are in windows 96-224 to 96-226. This area is north of where flames were observed earlier, indicating that the fires are continuing to spread slowly toward the north.

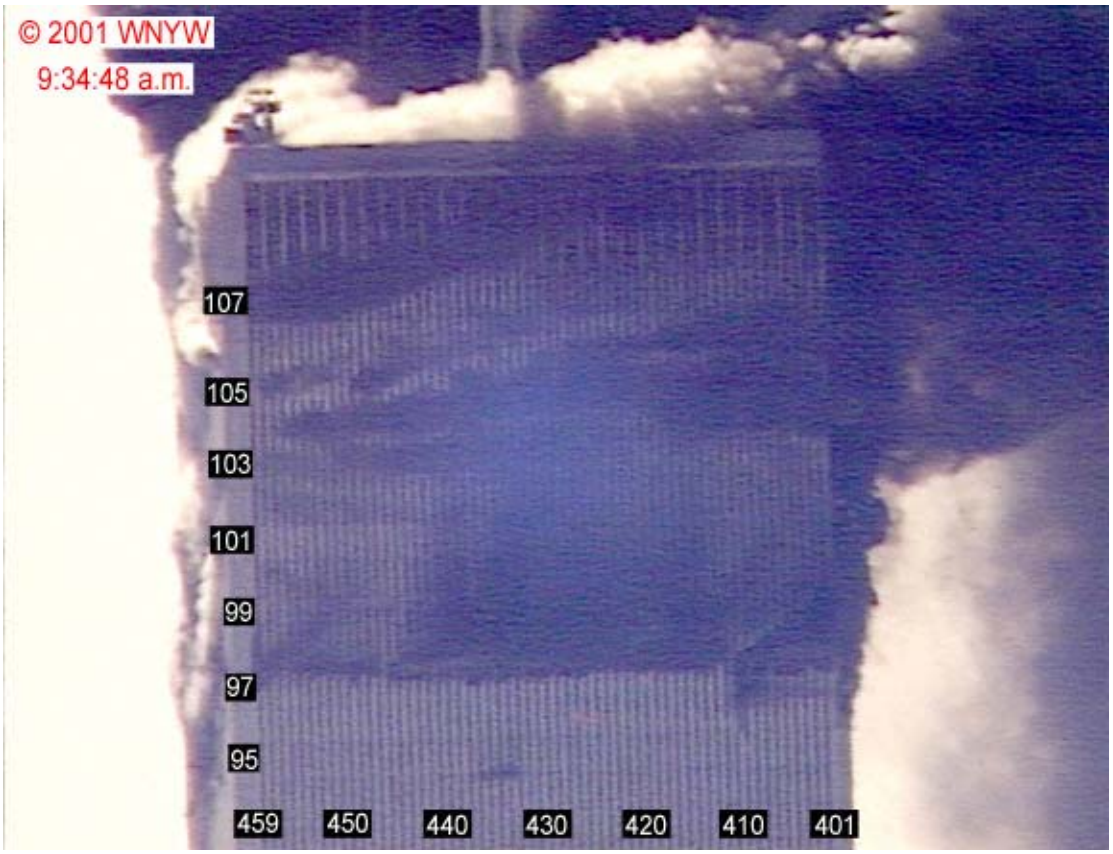

Figure 8-49. This image of the west face of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:34:48 a.m. The image has been enhanced by adjusting the intensity range, and some areas to the left and right of the tower are saturated. Column and floor numbers have been added.

Even at the distance from which Figure 8–49 was taken, a black mark is visible running across the tops of windows 94-433 to 94-436 on the 94th floor. These marks are not evident in Figure 8–47, which was taken at 9:19:45 a.m. This suggests that smoke began to flow from these windows at some point between these two times. A review of video recordings shows that visible smoke was apparent coming from these windows starting around 9:26 a.m. As discussed earlier, windows had been opened in this general area as early as 9:04 a.m. Recall also that several windows are open just to the north on the 95th floor. There is still no indication of smoke coming from these windows.

Even though the fires on this face appear to have nearly died down by the end of the period, there are still large quantities of smoke flowing from windows that have been broken out higher on the tower. In particular, heavy plumes of smoke are coming from the north side of the 107th floor and from the south side of the 104th floor. The plumes from the higher windows seem to be heavier than those coming from the floors where fires had been observed on this face, i.e., the 96th and 97th floors.

Figure 8–50 compares maps for open windows on the four faces of WTC 1 for times near the start and end of the current time period. These maps capture the general trends that emerge from the detailed discussion of fire behavior during the period. In particular, on the north face fires on the 93rd, 94th, 96th, and 97th floors breeched walls and entered northeast corner rooms, and the contents inside began burning. A new region of fire grew along the north face on the 94th floor to the west side of the aircraft impact

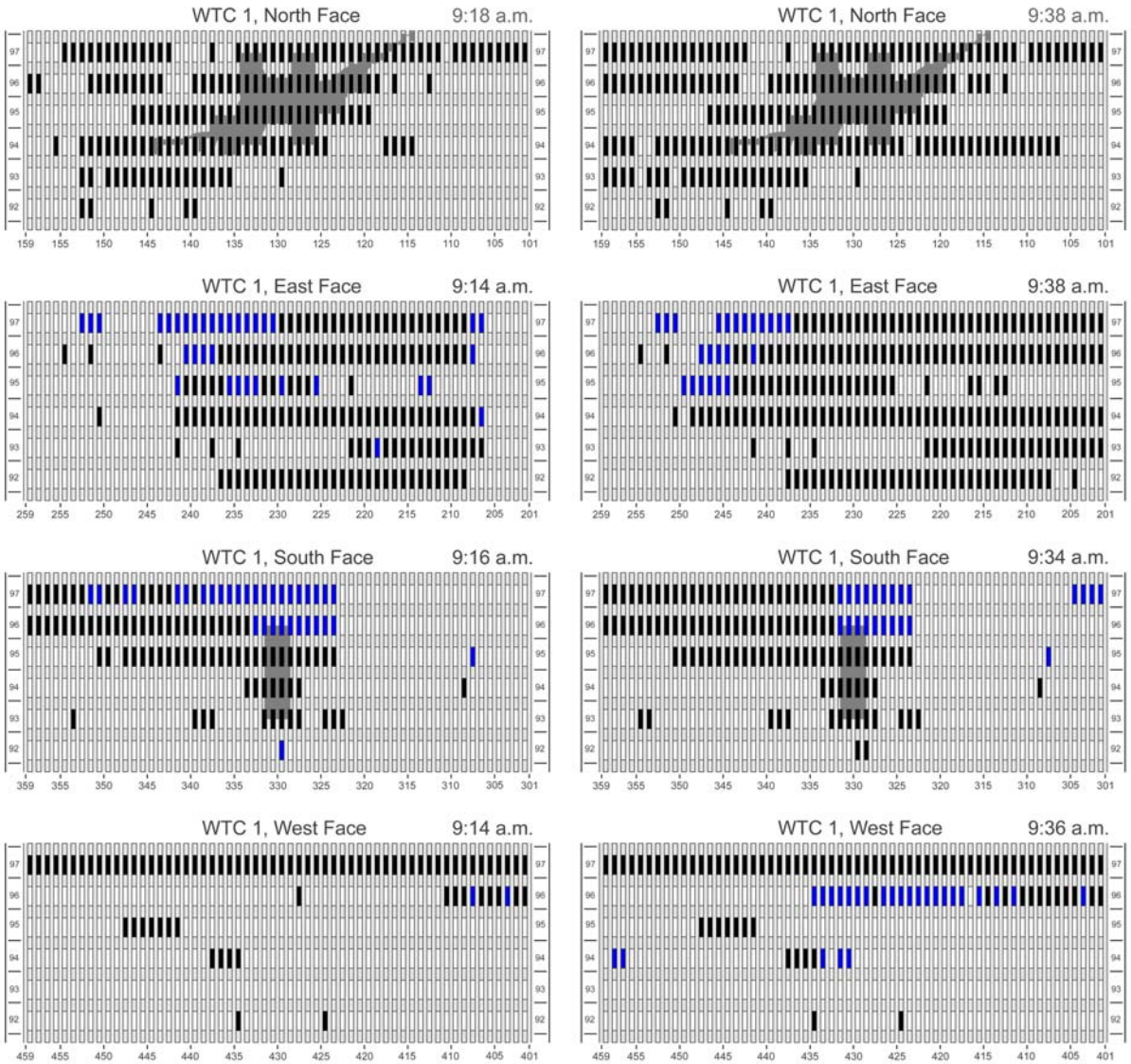

Figure 8-50. Maps for the 92nd through the 97th floors compare missing window glass for the four faces of WTC 1 at two times, around 9:18 a.m. and roughly 17 minutes later. The color coding used for the maps is indicated in Figure 5-1.

cavity. The changes in window conditions on the east face reveal that the fires that entered rooms at the northeast corners of the 93rd, 94th, 96th, and 97th floors also removed windows on the east faces of the rooms. It is also clear that fires that were originally present near the center of the face on the 94th, 95th, 96th, and 97th floors had begun to slowly spread toward the south. On the south face there was very little fire spread during the period. The same is true for the west face, but there are indications that fires on the 96th floor had begun to spread from the southwest corner back toward the north face.

Maps such as Figure 8–50 do not provide an overall view of the fire intensity behavior. A much better indication is obtained by tracking changes in the combined window and fire maps and smoke maps included in Appendices C to F. These show that many areas which began burning at earlier times had burned out or were now only gently burning. It is becoming clear that while the fires show a variety of local behaviors, e.g., intense burning with external flames and smoke or burning with little external flaming and little smoke release, that at most locations the fires are going through a typical life cycle that involves a growth phase, a maximum burning phase, and a dying and extinguishment phase. It is difficult to determine average times and ranges for these phases, but the changes are occurring at time scales on the order of tens of minutes.

The effects of the life cycle of the fires are also apparent in comparisons of the integrated fire maps prepared for the different time periods. Figure 8–51 shows integrated fire maps on the four faces for the current period from 9:18 a.m. to 9:35 a.m. These maps can be compared with the maps for the two earlier periods shown in Figure 8–33 and Figure 8–14. Such a comparison indicates that there are many windows where fire was observed during the earlier periods where it is no longer visible. These include windows near the aircraft impact area on several floors of the north face, windows on multiple floors around the center of the east face, and many windows on the 97th floor on the west face.

On the north and east faces the windows with observed fire appear to surround areas near the centers of the faces where the fires had already died or were dying down. This suggests that fire spread along the north and east peripheries of these floors has occurred primarily by horizontal fire movement in both directions away from regions initially ignited near the centers of the faces. The fire distribution on the south face indicates that fire spread and growth had occurred differently than on the north and east, with large fires growing and spreading nearly simultaneously on multiple floors at the western side of the face. The integrated fire distribution on the west face reflects both the very rapid fire spread that was observed earlier across the 97th floor and the much slower fire spread from west to east that was observed on the 96th floor.

During this period, the areas of most intense burning, as indicated by total identified fire area and fire intensity, visible on the tower periphery were on the east face and the western side of the south face. Even though the fires were spreading toward the south on the east face, flames were still not observed over a large area of the southeast quadrant façade of the tower.

An interesting result of the life cycle of the fires manifests itself on the east face. On this face fires developed on multiple floors shortly after the plane strike. These fires generally grew at locations well away from the north ends of the floors and extended roughly to the center of the face. As already seen, by 9:35 a.m. many of these fires were spreading toward the south, while the fires that had grown earlier had essentially died down. As a result, the spreading fires developed the appearance of rising waves that were moving to the south across the east face.

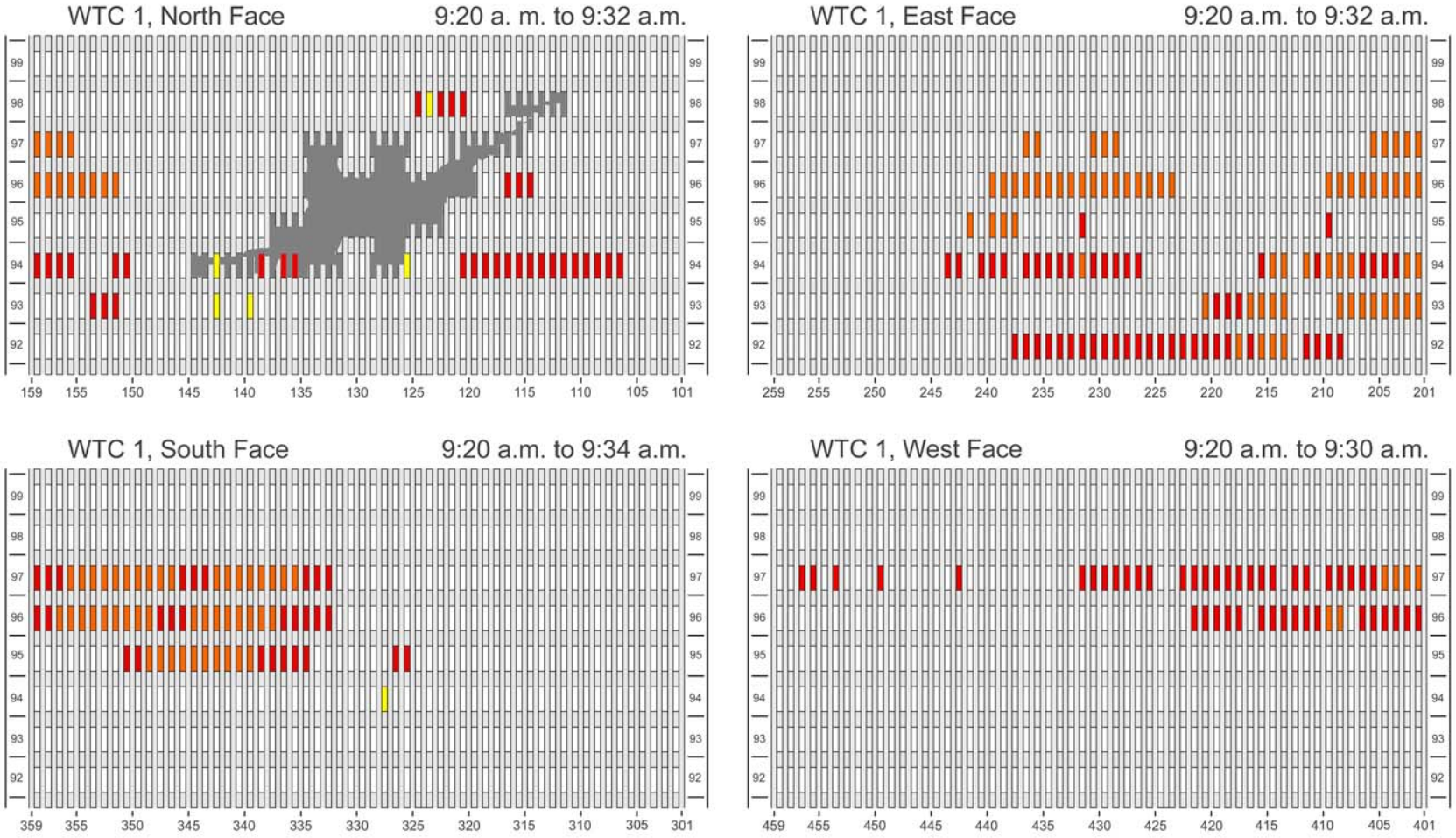

Figure 8-51. Maps of integrated fire observations between 9:19 a.m. and 9:35 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

The table in Appendix M indicates that, during the period from 9:18 a.m. to 9:35 a.m., relatively few people were observed falling from WTC 1. The people fell from all four faces, and, for those cases where origins are available, came from floors well above the floors where fires have been observed. These observations are generally consistent with the conclusion that fire growth during this period was more limited as compared to the two earlier time periods described above, and that at many locations fires, that had grown earlier, were dying down or even burning out.

The table in Appendix L summarizes observations concerning streamers. Most of the streamers recorded during this period were observed early in the period. In cases where origins are identified, the streamers were coming from areas where new fires had appeared, such as in the rooms on the northeast corners of the 96th and 97th floors and from the 94th floor to the west of aircraft impact cavity on the north face. The number of streamer observations during the period was reduced as compared to the earlier periods, most likely because the rate of flame spread had decreased.

8.5 9:35 A.M. TO 9:59 A.M.

This period takes the timeline for WTC 1 fire behavior up to the time that WTC 2 collapsed. This is an appropriate break point, since the collapse of WTC 2 had some immediate effects on WTC 1 (discussed in the following section). The collapse also created conditions that dramatically affected the quantity and quality of the visual imagery of the remaining tower.

A portion of a photograph showing the fire floors on the north face of WTC 1 at 9:37:38 a.m. is reproduced as Figure 8–52. This photograph was taken just under three minutes later than the image shown in Figure 8–38. The fire on the 98th floor has spread over a wider area and has grown in intensity during this time. Fires are observed (not continuously) from window 98-122 to window 98-150. Even though the flames extend over roughly half the length of the floor, and in some locations appear to fill the volume behind the windows, there is very little smoke and flame evident coming from the 98th floor windows. This is likely another case where the fire gases are exhausting elsewhere than through nearby windows.

Only a few small isolated fires are visible elsewhere on the north face. A low-level fire is still burning on the 94th floor to the west of the aircraft impact cavity. This is the remnant of the fire that first appeared in this area around 9:18 a.m. No fire spread past the wall located at column 94-106 is evident despite the fact that fire was present at window 94-106 by 9:21 a.m. There are also two relatively small fires visible on the 93rd floor.

At 9:40:48 a.m. a small fire suddenly appeared on the 92nd floor in window 92-155. Thirty-five seconds later this flame seemed to disappear. At 9:41:25 a.m. another small flame grew in window 92-157. Light smoke started coming from window 92-158 at 9:41:38 a.m., and two seconds later flames rapidly grew in windows 92-155 to 92-157. Figure 8–53 is a photograph of the east side of the north face that was taken at 9:42:27 a.m., which is less than a minute after the rapid fire growth took place on the 92nd floor. Flames are visible in the four open windows 92-155 to 92-158. The floor plan layout included in Figure B-1 shows that these four windows were inside a room at the northeast corner of the tower. The western wall for this room was located at column 92-155. The figure is clear enough to observe that the glass in the two adjoining windows, 92-153 and 92-154, was intact, and there is no evidence for fire at these windows. The floor plan layout shows that both of these windows were located in a small room just

to the west of the corner room. The next two windows to the west are missing, having been broken during the aircraft impact and fireball. These two windows were in another separate small room. The visual evidence indicates that fire has not yet reached this room. Most of the remaining windows in view on this floor have glass in place.

Figure 8-52. This enhanced and cropped photograph shows the north face of WTC 1 at 9:37:58 a.m. Column and floor numbers have been added.

On the 93rd floor there are two isolated regions of flame visible. One of these is at window 93-139 and the second is at windows 93-151 and 93-152. Many of the windows on this floor are open. The only fire evident on the 94th floor is a small spot fire in the cavity created by the aircraft. The fire on the northeast corner, which developed rapidly around 9:25 a.m. (see Figure 8–36) and filled windows 94-155 to 94-158 with flames, has already died down to a level where it not visible from this vantage point. The image provides sufficient detail to determine that the glass for windows 94-153 and 94-155 is still in place. This is an example where the apparent flame movement does not align with the wall placement indicated by the floor plan layout. The layout in Figure B-3 indicates that the wall for the room in this corner terminated at column 94-154. It is surprising that window 94-154 is not broken. No flames are visible on the 95th to 97th floors.

Figure 8–53 provides a clear view of the fires on the 98th floor, which extend from beyond the center of the floor on the west side to at least window 98-154 on the east. Even though the flames appear to be continuous, close inspection shows that in many windows there is simply an orange glow, suggesting that the fires are burning away from the windows at interior locations. The number of windows where flames are directly visible is limited. The only areas where flames appear to fill the windows are near the center of the face and around window 98-153.

Figure 8-53. This sharp photograph shows the eastern portion of the north face of WTC 1 at 9:42:27 a.m. The original version has been cropped and enhanced. Column and floor numbers have been added.

The fires on the north side of the 98th floor do not appear to be as intense as those observed at many other locations on the tower faces. Even so, they were large enough to break out the glass in multiple windows. Windows that were closed prior to the fire are now open. A review of the streamer observations summarized in Appendix L shows that numerous streamers were observed on the north face coming from the 98th floor during the early part of this time period when the fires were growing. Their source locations were spread out across the floor. This provides additional evidence that the streamers formed in regions where fires were breaking window glass.

At 9:39:51 a.m., light smoke started coming from window 94-101 on the 94th floor. This is the first visual evidence on the north face that fire had moved into the northwest-corner room with a wall at column 94-106 (see Figure B-3). It had been over twenty minutes since fire was first observed on the west side of the aircraft impact cavity and rapidly spread as far as window 94-106, before stopping. Since the initial evidence for fire inside this room appeared on the north face, it is likely that the fire passed through the wall that ended at column 94-106. At 9:40:47 a.m. the flow of smoke from window 94-101 abruptly became much heavier. A video taken at 9:40:55 a.m. showed small fires burning at the head casings of windows 94-101 and 94-102. The summary of streamer observations in Appendix L includes streamers falling from window 94-102 at 9:42:26 a.m. and window 94-101 at 9:43:51 a.m. A small flame became visible in window 94-105 at 9:40:59 a.m., and there was a burst of flame from windows 94-104 and 94-105 at 9:41:53 a.m.

Figure 8–54 includes a photograph of this area taken at 9:53:05 a.m. Windows 94-101 to 94-105 are clearly open. The fires in the corner room have already died down to the point where they are no longer visible from this vantage point. All of the windows on the 94th floor within the view of the image are missing. At the same time, windows on the 92nd, 93rd and 95th floors and windows 98-101 to 98-108 on the 98th floor still have glass panes in place.

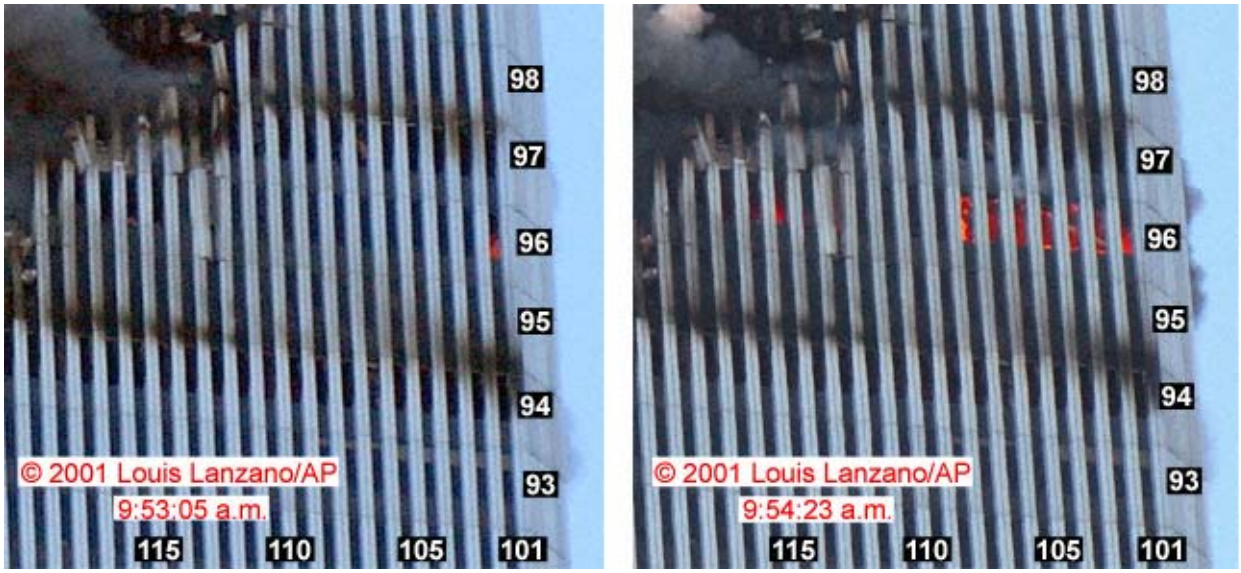

Figure 8-54. Two photographs of the west side of the north face of WTC1 taken at 9:53:05 a.m. and 9:54:23 a.m. are compared. The original photographs were cropped and enhanced. Column and floor numbers have been added.

In the photograph taken at 9:53:05 a.m., a small fire can be seen at the western edge of the 96th floor in window 96-101, while the glass for windows 96-102 to 96-110 is still in place. Videos show that there was a flash of light at window 96-101 at 9:53:00 a.m., which was likely associated with this window opening. At 9:53:20 a.m. the fire in window 96-101 grew visibly larger. During the following 13 s, fire appeared, moving from west to east over windows 96-102 to 96-107. This fire is evident in the second photograph included in Figure 8–54, which was taken at 9:54:23 a.m. The adjacent window, 96-108, was still in place at this time. According to the floor plan layout shown in Figure B-5, one of the walls for the room at this corner was located at column 96-108.

Even though the glass panes for windows 96-108 to 96-111 are still in place, a fire is visible growing rapidly further to the west in windows 96-112 to 96-115. The fire seen in window 96-113 is one of the few examples where flames are observed through a closed window. As discussed below, a significant fire was observed on the west face near the northwest corner prior to the rapid fire growth in the northwest corner room. This suggests that the fire broke into this corner room through the south wall located at column 96-456 (see Figure B-5). Note that there were two adjacent rooms attached to the south side of this wall. Fire movement from the south is also the likely source for the fire seen in windows 96-112 to 96-115.

A photograph of the north face of WTC 1 taken at 9:57:59 a.m., i.e., one minute prior to the collapse of WTC 2, is shown in Figure 8–55. Several changes have taken place since the photographs in Figure 8–53 and Figure 8–54 were taken. The fires on the 98th floor have died down considerably, with fire primarily evident on the east side of the north face. The fires on the 92nd and 96th floors have also spread a little further. On the 96th floor, windows 96-108 to 96-111 are now open, and flames are visible in these windows. On the 92nd floor, the panes for windows 92-153 and 92-154 are missing, and flames are visible through these windows, as well as windows 92-151 and 92-152. Recall that walls for rooms in this area were located at columns 92-152 and 92-155 (see Figure B-1). This photograph has sufficient resolution to identify details inside the windows. It appears as if both of these walls are still present.

Videos show that the fire spread on the 92nd and 96th floors occurred at roughly the same time. On the 92nd floor, a low-level fire appeared in windows 92-152 to 92-154 at 9:54:33 a.m. This was followed by a sudden burst of flames from the area at 9:55:05 a.m. On the 96th floor, fire appeared suddenly in window 96-107 at 9:53:58 a.m. At the same time the smoke flow from window 96-101 decreased greatly. A couple of seconds later the fire was visible in window 96-108, and within 17 s flames could be seen through the four windows that previously had been closed.

At 9:58:25 a.m. a bright flame appeared on the 92nd floor in window 92-149. Videos show the fire falling and lodging at the bottom of the window. This may have been burning polyurethane falling from the top of the window that would normally have formed a streamer. Distant videos show that a continuous band of flames was present from the east edge of the 92nd floor to this window. Window 92-149 is just to the east of the west wall for the third room running along the outer wall from the east edge (see Figure B-1). The fire seemed to be systematically working its way through these rooms from east to west.

A number of close-up photographs and videos that provide views of the east face are available during the current time period. Figure 8–56 shows a series of three photographs that were taken around 9:37 a.m. They show the lower floors where fires have been burning. Note that the fires that are present on the 96th and 97th floors are not visible. In the right-most photograph fire is visible near the northeast corner of the

Figure 8-55. This image shows the north face of WTC 1 at 9:57:59 a.m. The original has been rotated, cropped, and enhanced. Column and floor numbers have been added.

Figure 8-56. This series of three photographs shows various locations along the east face of WTC 1 around 9:37 a.m. Column and floor numbers have been added.

92nd floor in windows 92-201 to 92-207. Flames first appeared in this area around 9:33 a.m., and at 9:34:20 a.m. flames were coming from these windows. These flames had already begun to die down two and a half minutes later. The smoke markings on the adjacent column covers are interesting. They are a combination of carets and horizontal bands. There is also a smoke band above these windows. These markings suggest that while flames did extend from the windows, they were not intense enough or sustained for a long enough time to create well-defined carets. Well-defined carets are present just above on the 94th floor, as well as on numerous column covers on the 96th floor.

The same photograph provides an indication of the degree to which the flames that were present earlier on the 94th and 96th floors have died down. Only a couple of isolated fires are observed on the 94th floor, and no flames are obvious in windows 96-201 to 96-220.

In the center photograph of Figure 8–56, the fires that were present earlier on the 93rd, 94th, and 95th floors near the center of the east face have also died down and are no longer evident. There is still considerable evidence of interior fires on the 92nd floor, but the flames still do not seem to have progressed beyond window 92-237. As discussed earlier, flames were observed at window 92-237 at 9:21:01 a.m. The fires on the 92nd floor have caused some interesting effects on the surrounding façade. The variations in the types of smoke marks on the column covers adjacent to the windows have already been mentioned. Inspection shows that in the area immediately above windows 92-223 to 92-228, the aluminum spandrel covers have partially disappeared. The shapes of the missing areas indicate that they mostly likely melted due to heating from the hot fire gases flowing from below. In fact, spots of what appear to be solidified drops of aluminum can be seen on windows below this floor. Based on the melting temperature of aluminum, the fire gases leaving these windows must have been well in excess of 600 ºC. Even though these gases were quite hot, they have not broken out the glass in the windows immediately above on the 93rd floor, which are heavily coated with soot, but remain in place.

The left-most photograph in Figure 8–56 shows the southern part of the east face. A jet of fire is coming from the 94th floor at window 94-246, and flames are visible in nearby windows. The carets on many nearby column covers indicate that flames have extended from many of these windows. The heavy smoke coming from window 94-149 indicates the fire on this floor has moved slightly toward the west since 9:34:20 a.m. (see Figure 8–43).

Figure 8–57 is a frame from a video of the east face taken at 9:38:44 a.m., which shows all of the floors with fires. This photograph was taken more directly from the east than Figure 8–56 and, therefore, provides a better indication of fire locations. Starting at the lower part of the figure, the fire on the

92nd floor is visible over a length from near window 92-223 to window 92-238. Despite the extent of the flames, visible smoke is only coming from near window 92-237. On the 93rd floor, flames are evident at the northeast corner and also in a region running from approximately window 93-213 to window 93-221. Flames are coming from the several windows on the 94th floor, centered near window 94-248, and flames extend over at least seven windows. A short flaming region is present on the 95th floor, centered near window 95-239.

Figure 8-57. This image of the east face of WTC 1 was captured from a video recorded at 9:38:44 a.m. It has been enhanced by adjusting the intensity levels. Column and floor numbers have been added.

There is an intense flaming region on the 96th floor, with flames extending a large distance from windows 96-237 and 96-238. Videos of this face around this time show that this intense flaming lasted several minutes. The intense region of burning has only moved a few windows to the south since 9:25:27 a.m. (see Figure 8–42). In contrast, very little flame is visible on the 97th floor, directly above, even though fires have burned to roughly the same location as on the 96th floor. Videos recorded at around the same time also indicate there was very little fire on this floor.

On the 98th floor, there is a localized jet of flame coming from window 98-215. A review of photographs and videos recorded around this time reveals that this flame was not apparent in close-up shots taken around 9:37 a.m. and that it is seen for the first time in more distant videos around 9:37:57 a.m. Recall that by this time a wide-spread fire had been observed on the north face of this floor for around 10 minutes. Unlike the fire that has just appeared on the east face, the flames did not extend from the north face and appeared to be of relatively low intensity. It is interesting that the first appearance of

flames on the east face was at a window well away from the north face. It is not possible to conclude whether the fire has moved from the north side of the building or has grown as a separate isolated fire.

A close-up photograph of the east face, taken just over eight minutes later (at 9:46:47 a.m.) than Figure 8–57, is shown in Figure 8–58. There have been several major changes in the fire distribution on the face during this time. The most dramatic change is on the 98th floor. Fire is now visible from window 98-208 to window 98-217. There is extensive external flaming from a large number of these open windows. The windows to the north of column 98-208 appear to have intact glass. The floor plan layout shown in Figure B-7 indicates that a wall for a room in the northeast corner terminated at this column.

On the 92nd floor, the fire, which had paused at window 92-237 for nearly 20 min, now has flames coming from window 92-248. At 9:39:28 a.m. there was a burst of flame from window 92-239. A photograph taken at 9:38:28 a.m. did not show any indication of fire having moved from its original location. In a photograph taken at 9:42:27 a.m., fire was present in window 92-240, but the windows further to the south still had intact glass. In a more distant photograph taken at 9:44:24 a.m., smoke appeared to be coming from a few more windows towards the south. Videos of the area show flames suddenly burst from window 92-248 at 9:45:06 a.m. Windows to the west of 92-248 were still intact in Figure 8–58 at 9:46:47 a.m.

In Figure 8–58, only small isolated fires are visible on the 93rd floor. On the 94th floor, the fire has continued its slow progress toward the south end of the face. Flames are now visible coming from window 94-250. This window had been open since the aircraft struck just over an hour earlier. Flames are visible in about ten windows to the north of this location. On the 95th floor, a smaller area of flame is present in roughly the same windows as on the 94th floor.

A large fire continues to rage on the 96th floor. Flames are apparent from around window 96-231 to at least window 96-247, with long flames extending from windows 96-244 and 96-246. At 9:38:44 a.m. much of this area was hidden by smoke, and no flames were apparent to the west of window 96-240. At this earlier time, the major area of flame extension was from around window 96-237. It is clear that the area of intense burning on this floor has moved south about eight windows during the intervening period. Unlike at the earlier time, a region of fire is now evident on the 97th floor in windows 97-231 to 97-237.

In areas of the face below and to the north of the current active fire areas there is little visual evidence of smoke or flames in the open windows. This indicates that fires observed earlier at these locations have either gone out or are now burning at very low levels. Figure 8–58 provides a good view of the various markings on the face described earlier, including the smoke marks on the column covers and partially melted spandrel covers.

Figure 8–59 includes a photograph of the east face that was taken roughly eight and one half minutes (at 9:55:08 a.m.) after that shown in Figure 8–59. The fire burning on the 98th floor has continued to spread. It now extends from window 98-225 on the south to window 98-201 on the north. There is flame extension from windows 98-208 to 98-223. The fire has clearly moved into the room on the northeast corner, but the fire inside the room is burning at a lower intensity than the main fire region to the south.

Figure 8-58. This image shows the east face of WTC 1 at 9:46:47 a.m. The original image has been cropped, rotated, and enhanced. Column and floor numbers have been added.

Figure 8-59. This photograph shows the east face of WTC 1 at 9:55:08 a.m. The original has been rotated, cropped, and enhanced. Column and floor number have been added.

The fire on the 92nd floor has not moved further south than window 92-248 during the interval, but it has grown larger in the immediate area. The windows from window 92-240 to window 92-248 appear to be filled with flames, and there is some flame extension in the area. The fire on the 94th floor also seems to have remained in place, but it has decreased in intensity. The appearance of the fire on the 95th floor is little changed from the earlier photograph.

The changes in the appearance of the fire burning on the 96th floor are somewhat surprising. At 9:46:47 a.m. flames were evident all the way to window 96-249, with flame extension from window 96-248. At 9:55:08 a.m. the major flame region has apparently moved back to the north and is centered near window 96-235. Flames extend out of windows 96-234 and 96-235. The floor plan layout in Figure B-5 indicates that the space in this general area was open with no walls that could provide an explanation for this behavior. On the 97th floor there is a long flame coming from near window 97-237. This is roughly the same location where less vigorous flames were observed earlier.

A video recorded during the period indicates that numerous flame flare-ups repeatedly formed and then disappeared on the 96th and 97th floors. As suggested by the discussion in the preceding paragraph, the flares tend to change position along the 96th floor, moving between the two locations seen in Figure 8–58 and Figure 8–59. On the 97th floor the flares seemed to be localized at one location.

The most noteworthy change in the east face fire behavior between 9:55:08 a.m. and the time when WTC 2 collapsed at 9:58:59 a.m. was the growth of intense fire in the area of the room in the northeast corner of the 98th floor. At the end of the period the fires on this floor filled the openings from window 98-201 to at least window 98-223. There was a strong flame jet at window 98-223, with a narrow four-window wide length to the east where the flames were far less intense. Flame jets were observed on other floors as well.

The imagery of the south face during this period is much less extensive than was available for the north and east faces. During this period, the fire distribution and intensities changed greatly. It has not been possible to detail these changes with the same degree of detail available for the north and east faces. However, the major changes have been captured.

Figure 8–60 shows a partial view of the south face of WTC 1 taken from a video recorded at 9:39:35 a.m. WTC 1 is behind WTC 2, which appears to the right in the image. The first column that is visible on WTC 1 is column 343. The top of the 95th and higher floors are visible. Flames are visible on the 95th, 96th, and 97th floors, but the fire intensity appears to have decreased from that observed in Figure 8–46, which was taken at 9:33:13 a.m. Note that it is possible to see parts of the 98th floor through the smoke, and no flames are apparent.

Figure 8-60. This image of the south face of WTC 1 was captured from a video recorded at 9:39:35 a.m. It has been enhanced by adjusting the intensity levels. WTC 1 is on the left behind WTC 2. Another building appears in the foreground. Column and floor numbers have been added.

During this time period, a news helicopter recorded video of the towers from the south. Occasionally, the video operator would zoom in on the towers sufficiently that flames could be observed and their floor location determined. Insufficient detail was resolved to allow the identification of individual windows. During one of these close-up periods, an intense jet of flame erupted on the 98th floor from near window 98-347 at 9:40:36 a.m. This is the earliest indication of fire on the 98th floor for the south face. The video also shows that the fire grew rapidly after it first appeared. Within 90 s it had spread to near the center of the face.

The photograph in Figure 8–61 was taken shortly after the initial rapid fire growth on the south face took place on the 98th floor. The exact time of the photograph is unknown. The assigned time of 9:41:30 a.m. has an uncertainty of just over one minute. The fire on the 98th floor has already covered a number of windows, and flames are extended from many of these. Significant fires are also evident on the 95th, 96th, and 97th floors. The intensities of these fires have continued to decrease relative to earlier times. Burning is also present on the 94th floor near the center of the face, where the panel section is believed to have been displaced during the aircraft impact. Flames were not evident at this location in Figure 8–46, which was taken at 9:33:13 a.m.

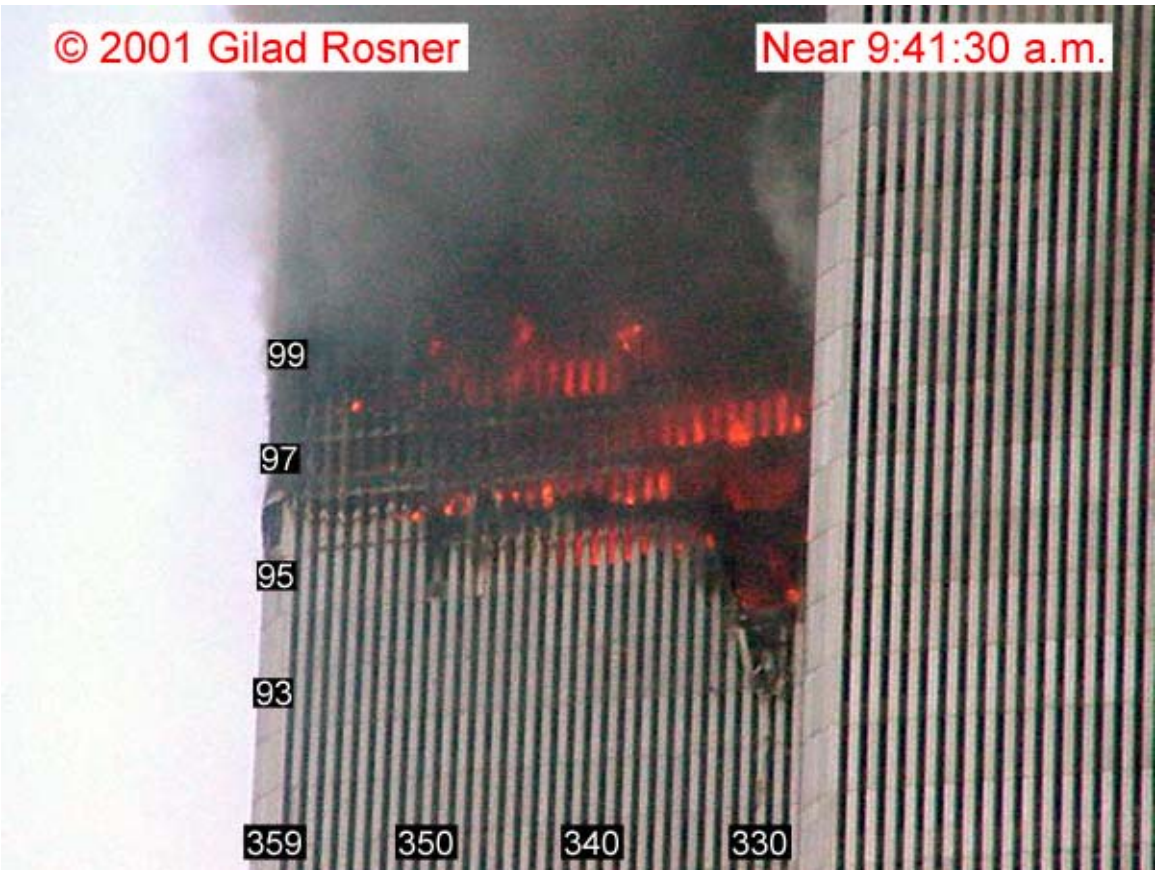

Figure 8-61. This untimed photograph shows the south face of WTC 1. It is estimated that it was taken between 9:40:40 a.m. and 9:42 a.m. Column and floor numbers have been added.

Another photograph (not shown) taken around this same time (estimated to be 9:42:25 a.m.) shows a fire distribution on the west side of the south face similar to that seen in Figure 8–61. However, unlike Figure 8–61, this image also shows the east side of the face. Small flames are visible on the 94th floor in windows 94-328 and 94-327 to the immediate east of the area where the panel section is believed to have been dislodged. Flames are also visible higher up on the 95th floor (windows 95-328 to 95-324) and the 97th floor (windows 97-330 to 97-325). Further to the east a small spot fire is visible inside window 94-308 on the 94th floor and light smoke is coming from the window. This window remains the only open window on this section of the façade, and it has been open since the aircraft impact. This small fire is the first indication that fire has spread into locations near the southeast corner of the tower on any floor.

Figure 8–62 shows a partial view of the south face recorded at 9:43:13 a.m. The intensity of the fire on the 98th floor has increased markedly from that seen in Figure 8–61. Fire is now evident from at least window 98-335 to window 98-356. Well over ten of the windows on this floor have large extended flames. Forty seconds later the fire on the 98th floor had grown still more intense as shown in the somewhat closer view of the area reproduced in Figure 8–63. Flames are evident as far west as window 98-357. It is clear from this photograph that, while the intensities of the fires on the 95th, 96th, and 97th floors have decreased from earlier times, vigorous burning is still taking place on each of these floors. A small fire is burning on the 94th floor in window 94-332.

Figure 8-62. This cropped photograph of the south face of WTC 1 was recorded at 9:43:13 a.m. The image has been rotated and enhanced. WTC 2 appears at the right. Column and floor numbers have been added.

Comparison of Figure 8–60 to Figure 8–62 verifies the observation from the video that an intense fire appeared on the south face of the 98th floor shortly after 9:40 a.m. and very rapidly covered most of the western half of the face.

Figure 8–64 shows a long-distance view of the south face taken at 9:52:27 a.m., or roughly eight and a half minutes after Figure 8–63. Compared to the earlier time, fire intensities on floors 95 to 98 have decreased markedly. The fire on the 98th floor is still burning vigorously, but does not seem to have moved significantly following its very rapid spread around 9:41 a.m. The fires on the 96th and 97th floors are much less intense than observed earlier, being evident at only limited locations on the west side of the face, with very little flame extension. While the intensity of the fire on the 95th floor has decreased, there are still relatively intense flames near the center of the face. Flames are evident just to the east of the area where the panel section is missing, i.e. near windows 95-327 and 95-328.

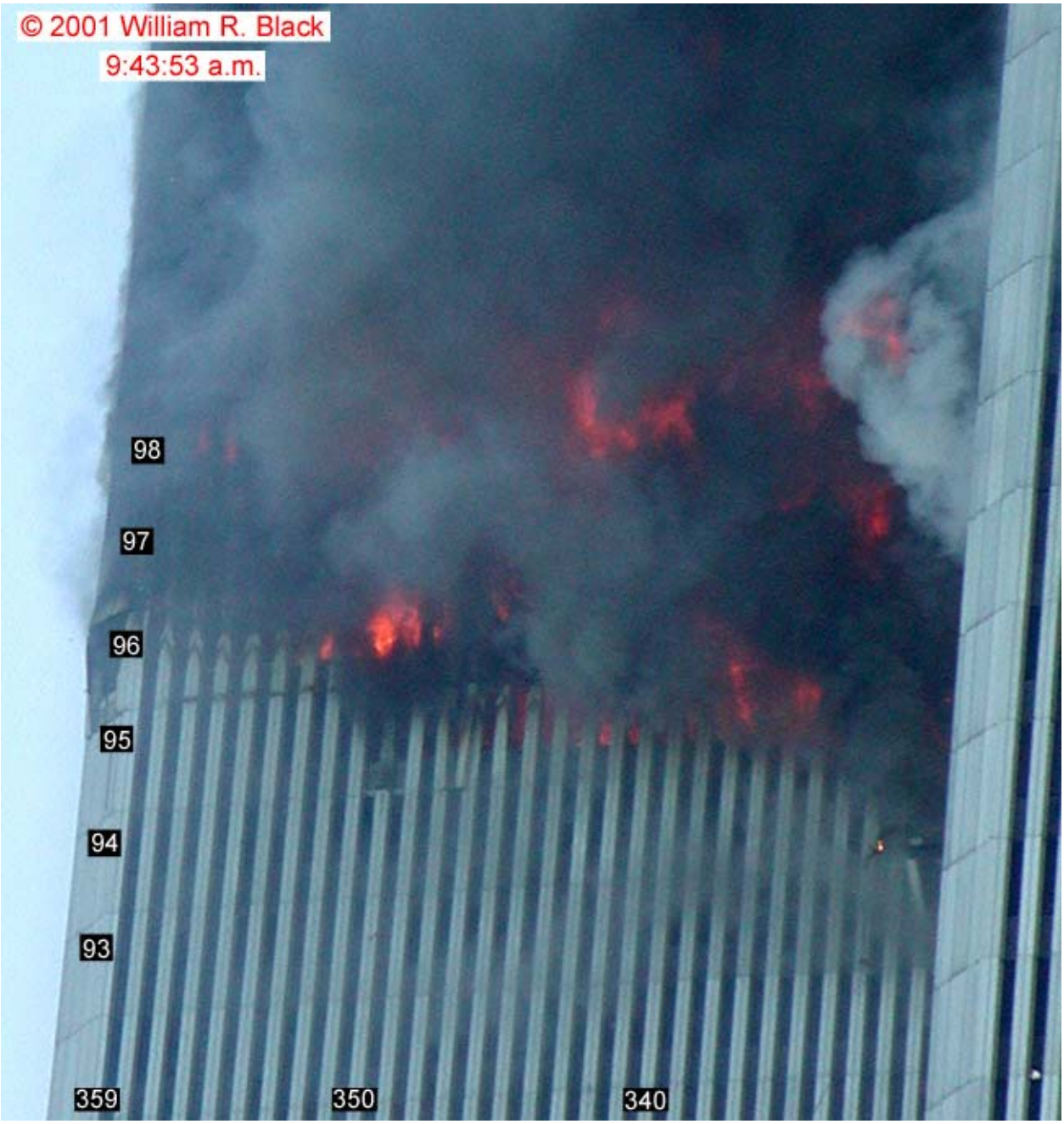

Figure 8-63. This cropped photograph of the south face of WTC 1 was recorded at 9:43:53 a.m. The image has been rotated and enhanced. WTC 2 appears at the right. Column and floor numbers have been added.

Even though it has been over an hour since the aircraft struck WTC 1, the majority of flames observed on the south face are still present to the left, i.e., west, of column 330. However, unlike earlier times, there are indications that fires have begun to burn in the southeast quadrant of the tower. There appears to be a small fire visible near window 94-315 in Figure 8–64. In another photograph, taken at roughly the same time, flames with a similar intensity are visible at window 94-314. Figure 8–65 provides a view of the south face at 9:53:47 a.m. taken from the southwest. While flames are not apparent in this area of the 94th floor from this angle, smoke is visible coming from at least two locations on the 94th floor to the

east of the center. Window glass appears to be missing in other nearby windows. Taken together, these observations suggest that a relatively low intensity fire is present at this time on the 94th floor on the east side of the south face.

Figure 8-64. This cropped photograph shows the south face of WTC 1 at 9:52:27 a.m. The intensity levels have been adjusted and column and floor numbers have been added. For reference purposes, the missing aluminum panel on the southwest corner of the towers is on the 96th floor, and the heaviest fire is on the 98th floor.

In Figure 8–65 there are indications of smoke coming from windows on the 93rd floor just to the right of the area where the panel section is believed to be missing. Higher floors on the east side are partially obscured by smoke, but there are no indications of intense fires or heavy smoke on this side for levels above the 94th floor. This figure provides a good qualitative indication of the relative intensity of the recently developed fire on the 98th floor as compared to the fires that had been burning longer on the 95th to 97th floors.

As seen by comparing Figure 8–65 and Figure 8–66, which was taken at 9:55:56 a.m., the intensity of the fire on the west side of the 98th floor decreased rapidly over the next two minutes. Even though bright fires are still evident, the flames have receded back into the building at most windows. In Figure 8–66, it

is clear that intense flames are present over several floors in the area at the center of the face where the panel section is likely missing.

Figure 8-65. A photograph shot from the southwest shows the west and south faces of WTC 1 at 9:53:47 a.m. The original image has been cropped and enhanced. Column numbers for the west face and floor numbers have been added.

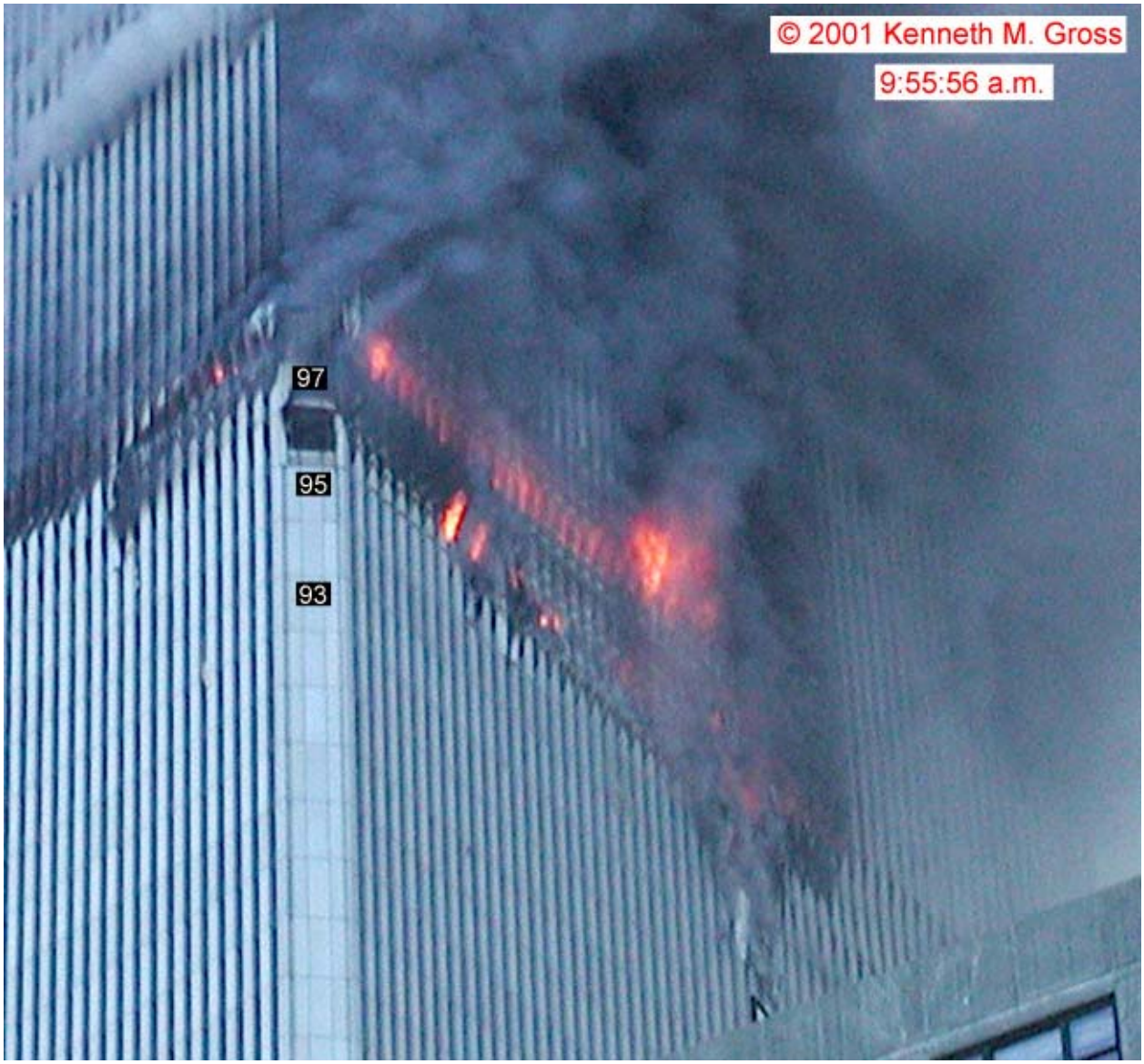

Figure 8-66. A photograph shot from the southwest shows the west and south faces of WTC 1 at 9:55:56 a.m. The original image has been cropped and enhanced. Floor numbers have been added.

An image of WTC 1, taken roughly a minute prior to the collapse of WTC 2, is shown in Figure 8–67. This photograph was shot from a helicopter looking down on the southwest corner of the tower. The fire on the 98th floor of the south face continues to burn intensely at this time, with limited flame extension from windows. Fires present on the 95th to 97th floors have continued to decrease in size, with one exception. On the 96th floor long flames extend from the area near the center of the south face where the panel section is believed to be missing. From this angle there is no indication of flames on the eastern side of the face.

Figure 8-67. This cropped photograph showing the southwest corner of WTC 1 was shot from a helicopter around 9:58:11 a.m. The time has an uncertainty of 30 s. The original image has been cropped and enhanced.

Long-distance videos of the south face shot from a news helicopter show the same behaviors for the fires as discussed above. At the time WTC 2 fell, the dominant feature on the south face of WTC 1 was the bright orange band of fire on the 98th floor, extending from the west edge to near the center of the face. Much less intense areas of fire could also be seen on the 95th, 96th, and 97th floors. On the 95th floor, a short length of flame was evident just to the west of column 95-330. On the 96th floor, the flame region appeared to extend from just above the area of the missing panel section over several windows toward the east. This observation suggests that fires on this floor were beginning to move along the exterior walls into the southeast quadrant of the tower. A small length of flame could also occasionally be seen in roughly the same location on the 97th floor. From this distance no flames were visible over the remainder of the face toward the east.

The relative amounts of fire visible on the various floors for the west face of WTC 1 during this period were much less than observed on the other faces. Nonetheless, as will be shown, there were indications of considerable fire movement during this time. In Figure 8–49, which was taken from a helicopter at 9:34:48 a.m., only low-level flames were apparent, primarily on the 96th floor. Figure 8–68 shows a similar image taken at 9:41:03 a.m. The areas where fires are observed have increased dramatically.

Fires are now visible near the center of the 94th floor just to the right of the black mark at the top of the columns covers, which starts at column 94-433, and very close to the north edge of the face. Flames are

also present on the 96th floor near the center of the face. This fire has apparently continued its movement to the north, since at 9:34:48 a.m. its northern edge appeared to be near window 96-426, and it can now be seen at least as far as window 96-433. While the flames are not completely visible in the frozen frame shown in Figure 8–68, by reviewing the video it is apparent that this low-intensity fire covers at least thirteen windows.

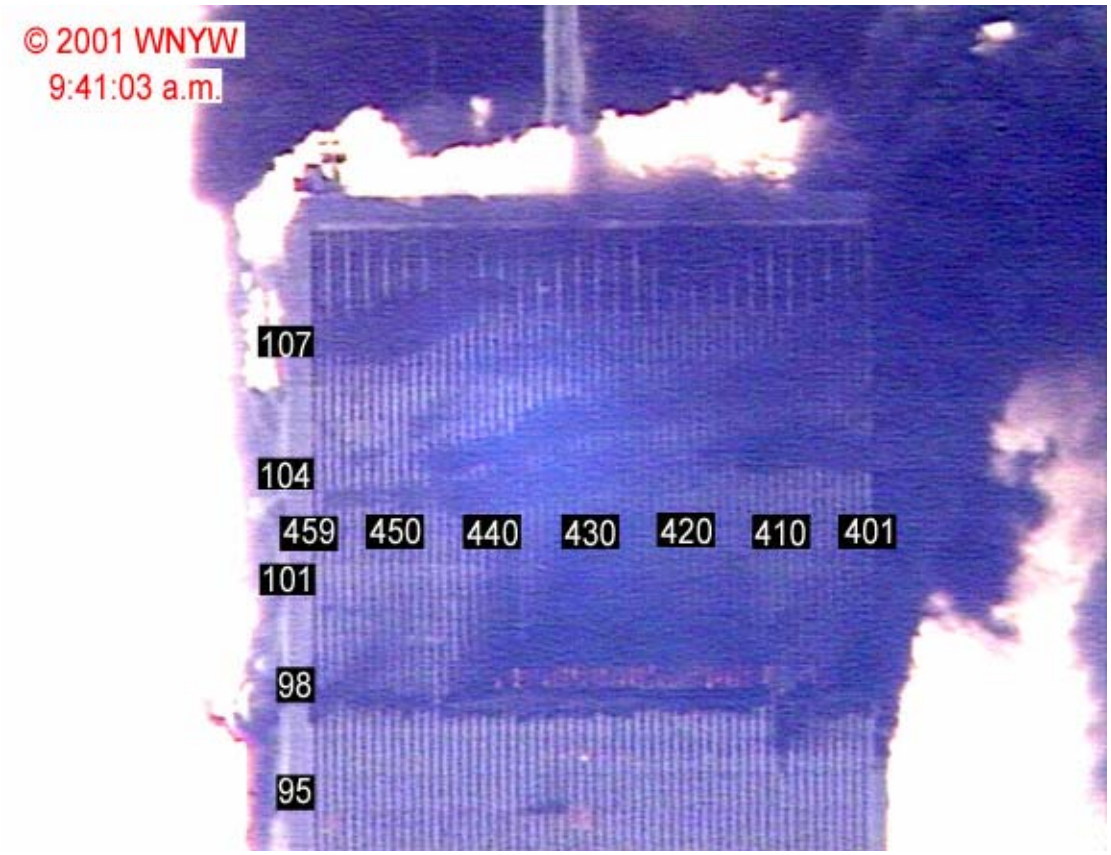

Figure 8-68. This image of the west face of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:41:03 a.m. The image has been enhanced by adjusting the intensity range, and areas to the left and right of the tower are saturated. Column and floor numbers have been added.

The most dramatic change in the fire distribution is on the 98th floor. At the earlier time there was no indication of fire on the west side of this floor, while in Figure 8–68 flames can be seen over a length running from the south edge of the face to at least window 98-440. From the available imagery, it has proven difficult to determine precisely when this fire appeared, but a review of helicopter video suggests it occurred between 9:38:10 a.m. and 9:39:05 a.m. Given the low intensity of the fire, such apparent rapid fire spread is difficult to understand.

The development of the fire visible in Figure 8–68 on the 94th floor near window 94-430 was sudden. A video shot from a helicopter shows that it appeared at 9:39:08 a.m. The observations of falling people summarized in Appendix M also suggest that fire reached the area shortly after 9:35 a.m. At 9:38:37 a.m. a person was observed falling from this floor near the center of the face. During the next 97 s, at least six more people fell from the same vicinity. Appendix M lists the windows from which some of these people fell. The windows were either 94-435 or 94-437. There was an additional person who came from this

floor who is not included in Appendix M, since this person was not observed falling. Imagery shows that an eighth person began to climb down the outside of the building from window 94-433 around 9:38 a.m. Just prior to 9:58 a.m., this person was still climbing down the tower face near the 84th floor.

The floor plan layout for the 94th floor in Figure B-3 shows that there were a series of rooms located along the west face. It indicates that window 94-433 was in a room with walls located at columns 94-430 and 94-434, and windows 94-434 to 94-437 were in a second room with walls at columns 94-434 and 94-438. Recall that the glass in windows 94-434 to 94-437 was broken out shortly after 9:00 a.m. and that light smoke was later observed coming from these windows. This smoke flow explains the black band across the tops of the covers for columns 94-433 to 94-437, evident in Figure 8–68.

Given the facts that a large amount of aviation fuel was released on the 94th floor during the aircraft impact and the visual evidence indicates that some fraction of it immediately ignited, it is surprising that the fires required nearly an hour to reach and engulf these rooms at the center of the west face. Up to this time conditions in the area were habitable. This observation provides additional evidence that room walls on the aircraft impact floors were intact and acting as effective fire breaks.

The other area of fire visible on the 94th floor at the north edge of the west face in Figure 8–68 also appeared abruptly. The video, shot from a helicopter, shows that fire first became visible in window 94-457 at 9:39:54 a.m. This window was located in the northwest corner room, with walls terminating at columns 94-106 and 94-454 (see Figure B-3). Recall that the first visual evidence for fire in this room from the north was at 9:39:51 a.m. The evidence suggests that windows opened on the north and west sides of the room nearly simultaneously, indicating that flashover occurred in the room at this time.

The amount of close-up visual material of the west face is relatively limited, but a close-up video was shot around 9:40 a.m. from just across West Street that provides details concerning the fires and conditions of windows. Figure 8–69 shows a frame captured from this video that was recorded at 9:40:06 a.m. At this time every window visible (windows numbered 420 to 432) on the 96th, 97th, and 98th floors is open, while the glass appears to be intact on the 95th floor and floors above the 98th.

On the 98th floor, a red glow is present in all of the windows, indicating that a fire is burning away from, but near the windows. This is consistent with the appearance of the fires on this floor in Figure 8–68, which was recorded a short time after Figure 8–69. Flames are visible at the tops of several of the windows, particularly windows 98-427, 98-429, and 98-430. It is clear that the flames are positioned just inside of the open windows near the tops of the window frames. The burning material appears to be located on the tops of plates that are hanging down from above. Several of these plates are also visible in windows on the 96th and 98th floors in windows where flames at the tops of windows are not present. It is likely that the plates are actually hanging aluminum head casings (see the discussion in Section 4.2.2) that have dropped down from above the windows as the result of heating. These observations provide additional visual evidence that the burning areas that were frequently observed at the tops of open windows were due to burning polyurethane that was exposed when the aluminum head casings located just inside the tops of the windows at the ceiling dropped down.

There is no indication of active fire on the 97th floor in the video frame. However, the presence of carets at the tops of the aluminum column covers attests to the intensity of the fires that burned on this floor earlier. On some of the columns, portions of the aluminum column covers near the tops of windows appear to have melted.

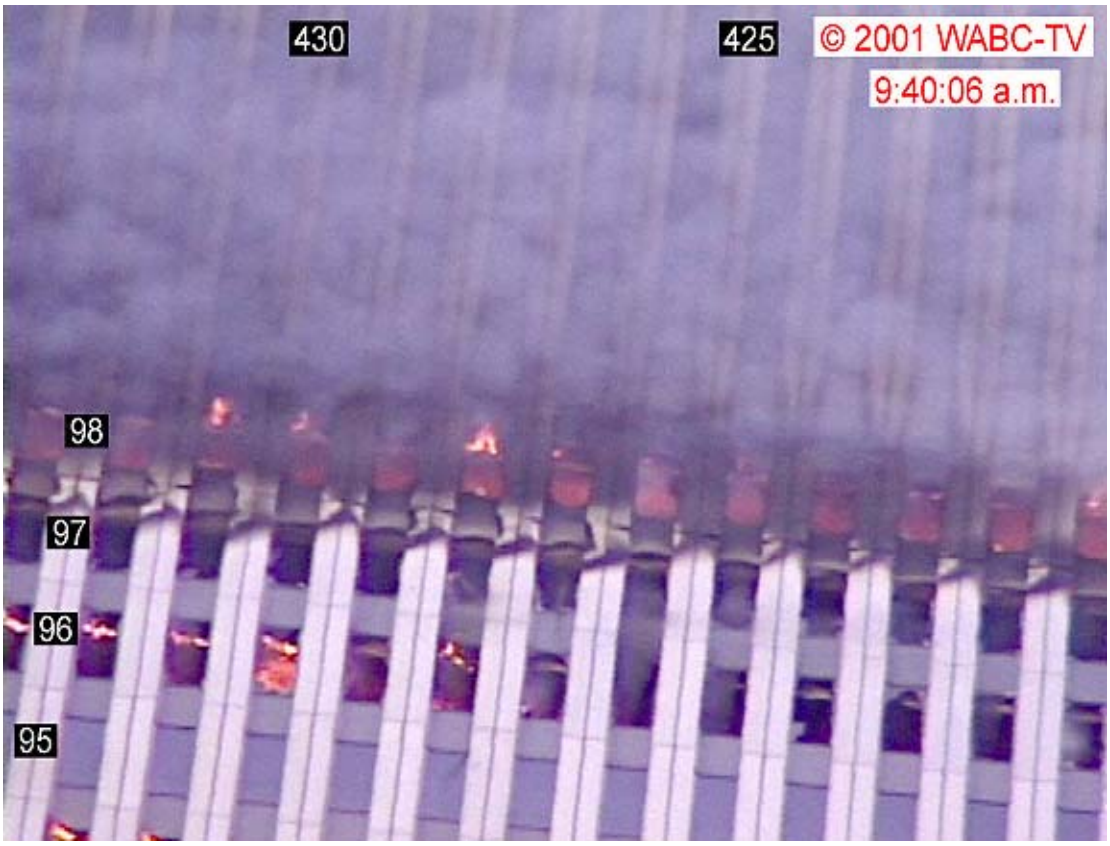

Figure 8-69. This close up view of the west face of WTC 1 was captured from a video recorded at 9:40:06 a.m. It has been enhanced by adjusting the intensity levels. Column and floors numbers have been added.

Even though fires are clearly present on the 96th floor in the vicinity of the windows at 9:40:06 a.m., they appear to be burning with low intensity. This is consistent with videos shot from helicopters that showed that the fires on this floor were visible intermittently and were located close to the floor. With the exception of the fires at the tops of the windows, flames fill only one opening, window 96-429, and there are no indications of flames coming from the windows. There is very little smoke flowing from this floor, and there are no smoke marks at the tops of the column covers.

In the lower left-hand corner of Figure 8–69, flames can just be seen at the tops of windows 94-430 and 94-431 on the 94th floor. These flames appear to be due to burning thermal insulation, similar to the fires visible on the 96th and 98th floors.

Shortly after the video frame in Figure 8–69 was recorded, the camera zoomed out and revealed a larger area of the west face. Figure 8–70 shows a captured frame from this video recorded at 9:40:14 a.m. The image provides sufficient detail to determine whether windows are open or closed. On the 94th floor the only windows in the image that are open are windows 94-430, 94-431, and 94-433 through 94-437. Fires burning at the tops of windows 94-430 and 94-431 can be seen, along with an orange flame in window 94-434. This image was recorded during the period that people were observed falling and climbing down from windows 94-433 to 94-437. The presence of flames in the immediate vicinity suggests that the people had no other means of escape from the spreading fire.

Windows 95-441 to 95-447 are open on the 95th floor. As discussed earlier, with the exception of 95-442, these windows have been open since around 9:00 a.m. The columns next to these windows are unmarked, which means that there has been little or no smoke flow from these windows up to this time.

With one exception, window 96-416, all of the windows on the 96th floor as far north as window 96-434 are open. Light flames are visible at the tops of several of the windows, and flames are present in window 96-429. Despite the fact that these windows have apparently been opened by nearby fires on this floor, there is very little or no smoke coming from any of the windows, and, with the exception of column covers near the south end of the floor, the covers are unmarked.

There are no flames evident in the open windows across the entire extent of the 97th floor visible in Figure 8–70. The carets and smoke marks on the column covers near the tops of the windows on this floor contrast sharply with the appearance of the column covers at the top of the 96th floor.

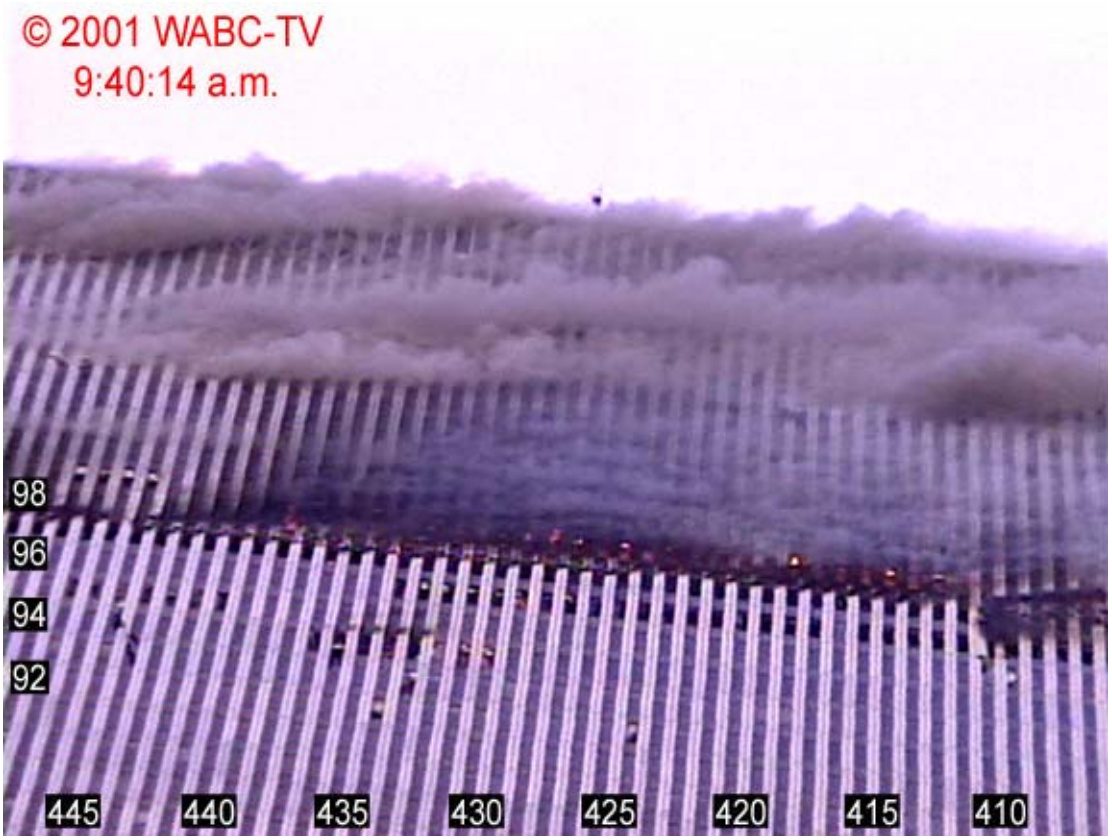

Figure 8-70. This view of the west face of WTC 1 was captured from a video recorded at 9:40:14 a.m. It has been enhanced by adjusting the intensity levels, and some locations above the building are saturated. Column and floors numbers have been added.

The expanded view of Figure 8–70 shows that fire is visible on the 98th floor from roughly window 98-411 to window 98-439. Further to the north, the window glass appears to be intact. Bright fires are present at the tops of several of the open windows. Larger flames are also present in windows 98-428 and 98-439. Even so, compared to the intense burning observed on the other faces of the tower, these fires appear to be burning relatively gently at this time.

The smoke flows coming from some of the open windows above the 98th floor are quite heavy. At other open windows relatively little smoke is present. The four open windows on the 99th floor, windows 99-445 to 99-448, are an example of the latter behavior.

Another view of the west face taken from a video recorded from a news helicopter at 9:47:46 a.m. is shown in Figure 8–71. Since 9:41:03 a.m. (compare with Figure 8–68), the fires on the 94th floor have continued to spread; now appearing at several different locations ranging from the north edge of the face to window 94-425. By comparing the fire locations with the floor plan layout shown in Figure B-3, it is discovered that fires have entered seven of the eight rooms located along the west face, running from the north edge to as far south as column 94-425 The one exception is the room with walls at columns 94-438 and 94-442. Even though the fire area is extensive, the flames are not very vigorous. There is no apparent external flaming, and no smoke is visible coming from the windows.

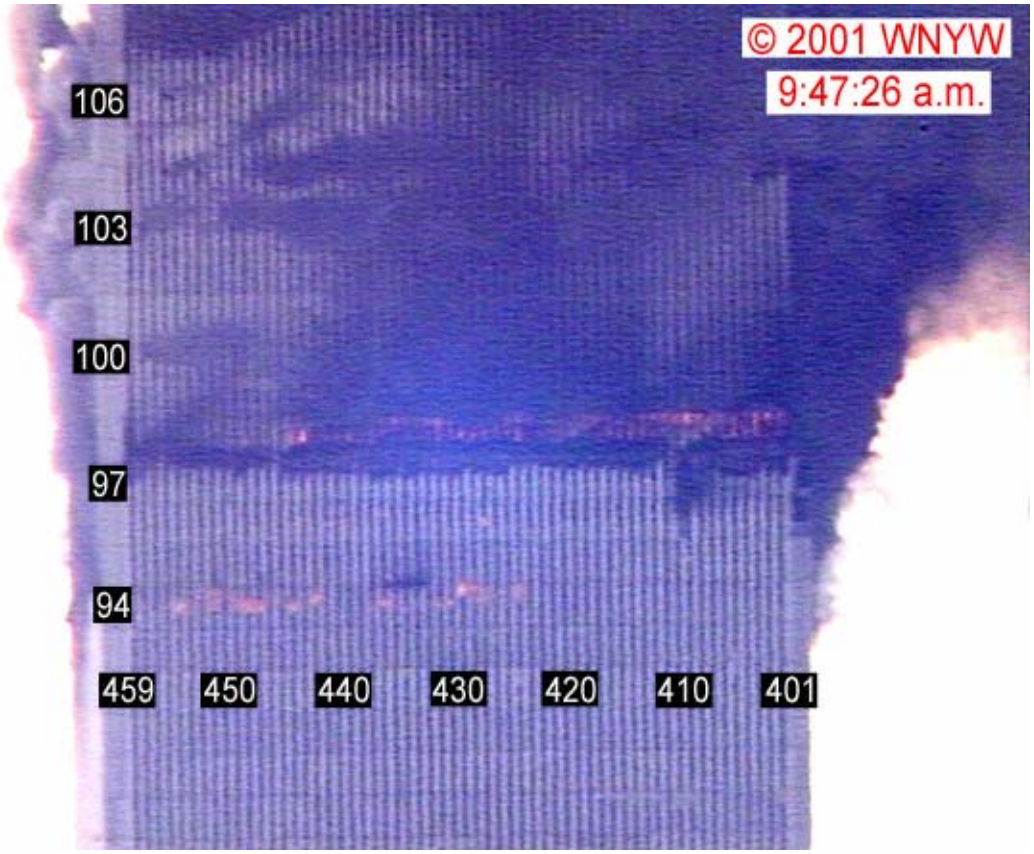

Figure 8-71. This image of the west face of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:47:26 a.m. The image has been enhanced by adjusting the intensity range, and areas to the left and right of the tower are saturated. Column and floor numbers have been added.

Small fires are still evident on the 96th floor. In the video the flames appear intermittently over a range of windows that reaches as far north as window 96-441. As at the earlier time, there is no smoke or flame coming from the windows.

The fire on the 98th floor has continued to spread north. It now extends from the south edge continuously to at least window 98-444. From this distance, the fire still appears to be located away from the west wall. There is little indication of fire or smoke coming from the windows on this floor.

A much closer view of the north side of the west face recorded at roughly the same time as Figure 8–71 is shown in Figure 8–72. Even though this image is assigned a time of 9:47:34 a.m., there is an associated uncertainty of 30 s. The closer image provides confirmation of many of the conclusions drawn from Figure 8–71. On the 94th floor fire is visible at many of the windows, and a number are open from window 94-424 to window 94-459. The glass panes between windows 94-438 and 94-442 are indeed in place, with no indication of fire in the room located between these columns (see Figure B-3). The five windows along the west face in the northeast corner room are open. The adjacent room to the south has walls at columns 94-450 and 94-454 (Figure B-3). The fire is apparently just growing in this room since flames are visible, but three of the four windows are in place. Flames are visible, and most of the windows are missing for the next two rooms to the south. Window 94-424 is open, but the panes are still in place in nearby windows. This indicates that the observed fire has moved one room further south since 9:41:03 a.m.

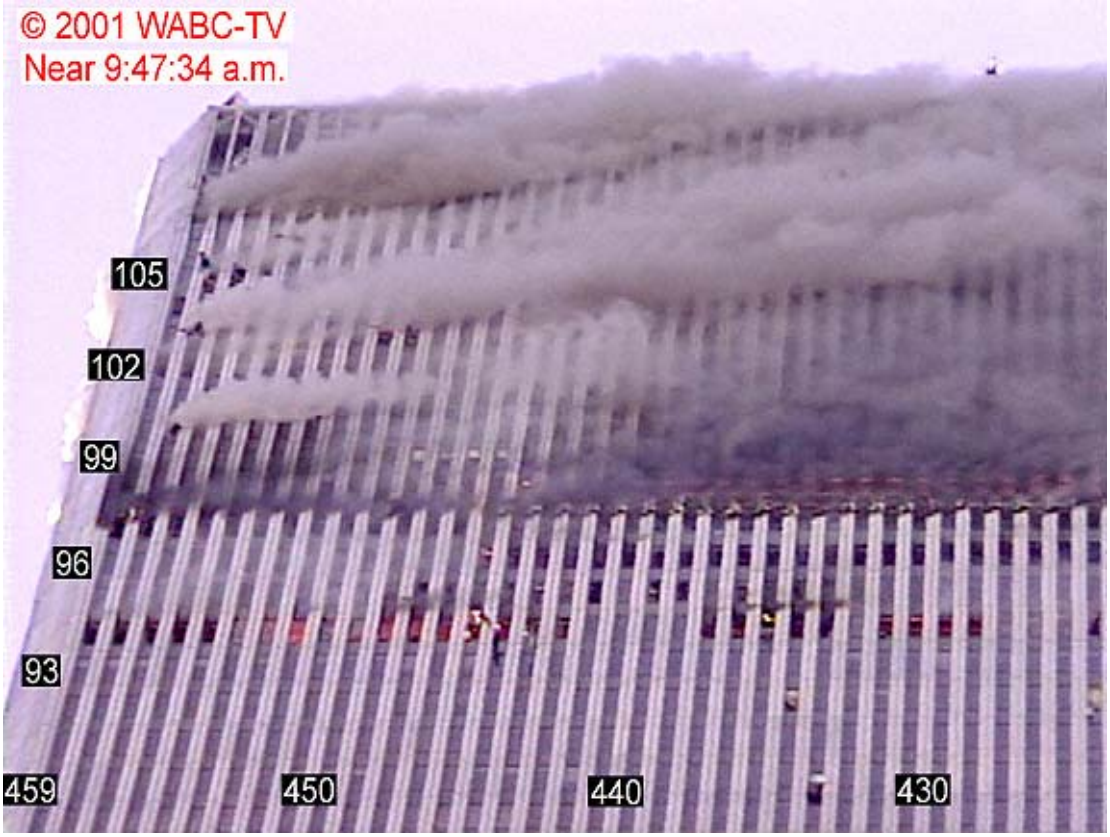

Figure 8-72. This view of the west face of WTC 1 was captured from a video recorded at 9:47:34 a.m. There is a 30 s uncertainty in the assigned time. The image has been enhanced by adjusting the intensity levels, and some locations above the building are saturated. Column and floors numbers have been added.

On the 95th floor, two additional windows (95-438 and 95-439) have opened since 9:40:14 a.m. Since there is still no indication of fire in this area, it is possible that people have broken out the glass. Very

little fire is visible on the 96th floor, but there is an area of flame at the top of window 96-447. Windows to the north of this location are still in place. The northern advance of the fire on the 98th floor has reached roughly the same location. Fire is visible at the top of window 98-444, and window 98-445 appears to be open. A deep red glow on this floor from the windows that are open indicates that burning areas continue to be located well away from the windows.

Another frame taken from a video shot from a helicopter at 9:51:58 a.m. is shown in Figure 8–73. Fire development on the west face has continued. The largest differences as compared to Figure 8–71, which was recorded at 9:47:26 a.m., are the appearance of fire at multiple windows on the 96th floor near the north edge of the west face and the spread of the fire toward the south on the 94th floor. It has not been possible to determine exactly when the fire at the north edge of the 96th floor appeared, but it was between 9:50:09 a.m. and 9:51:19 a.m. The flames are visible in windows 96-453 to 96-455. The floor plan layout in Figure B-5 indicates that these windows were inside a room with internal walls at columns 96-452 and 96-456. Fire is not yet visible from windows in the room on the northeast corner with walls at columns 96-456 and 96-108. On the 94th floor flames are now visible in windows 94-423 and 94-424. This indicates that a fire was growing within the room with walls located at columns 94-421 and 94-425. (see Figure B-3) The appearance of the fire on the 98th floor did not change dramatically over the four and a half minute period between the images.

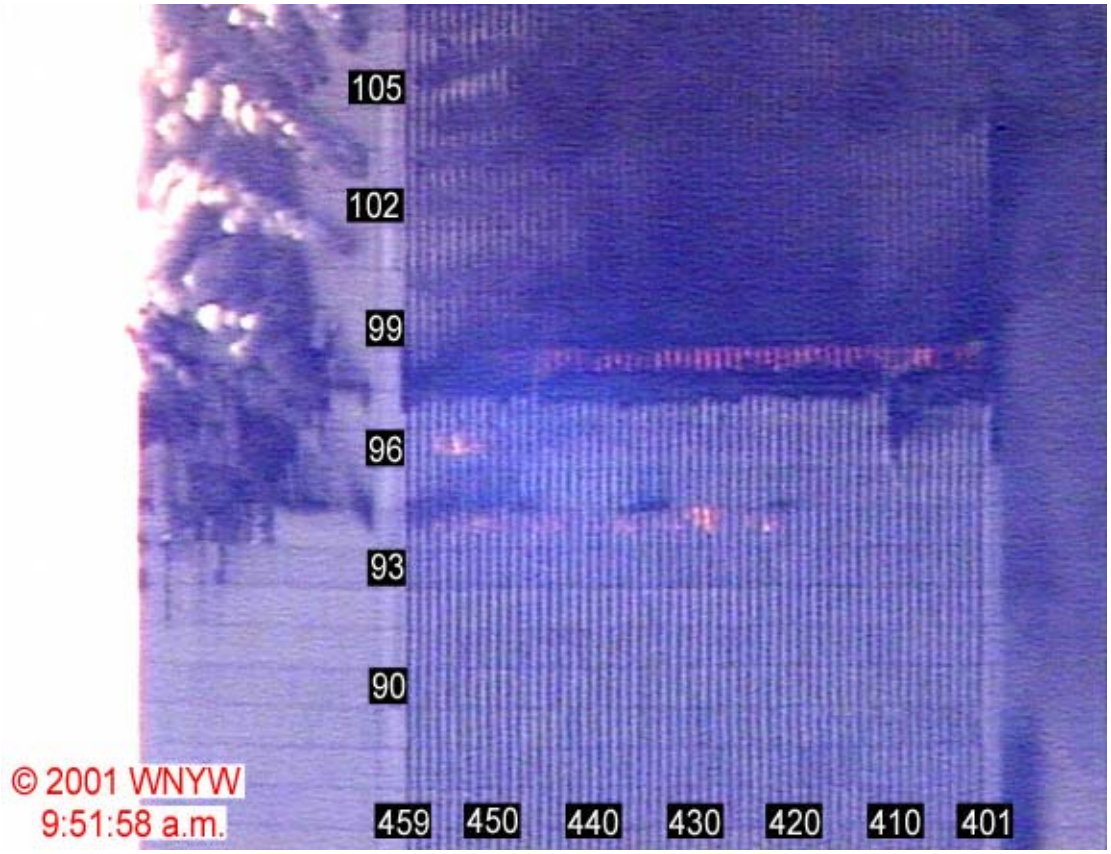

Figure 8-73. This image of the north and west faces of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:51:58 a.m. The image has been enhanced by adjusting the intensity range, and areas to the left of the tower are saturated. Column and floor numbers have been added.

Video footage shows that a dark stream of smoke suddenly appeared near the north edge of the 96th floor at 9:53:08 a.m. Recall that window 96-101 on the north face had opened just 8 s earlier. These observations suggest that the release of smoke was associated with the nearly simultaneous opening of north and west windows in the northwest corner room on this floor. The fact that flames were first visible in the room immediately to the west indicates that the fire most likely moved into the corner room by passing through the wall at column 96-456. In Figure 8–65, which was taken at 9:53:47 a.m., flames are visible at the tops of windows 96-455, 96-456, and 96-457 and lower down in windows 96-452, 96-453, and 96-454. A small fire is evident at window 96-429; otherwise, there is very little evidence of the fires that have spread across the entire west face of this floor after starting at the south edge and moving north.

Fires are visible on the west face of the 94th floor in Figure 8–65. The smoke marks at the tops of the covers for columns 94-121 and 94-122 are distinct, indicating that the fire has opened windows in the room with walls at columns 94-421 and 94-425 (see Figure B-3). The dark red glow of the fire on the 98th floor that extends north from the south edge of the west face is also visible in Figure 8–65. This particular photograph provides a graphic illustration of the differences in burning behavior observed on the west and south faces for fires on this floor. Compare the intense flames extending from multiple windows of the 98th floor on the south face with the red glow present on the west face.

The appearance of the west face at 9:56:10 a.m. is shown in Figure 8–74. The fire distribution has not changed dramatically since 9:51:58 a.m. The amount of smoke coming from the fire floors remains small, and much of the face is visible. For the purposes of later discussion note that while significant smoke is coming from open windows on the south side of the 104th floor, it does not appear to be heavier than from other open windows near the top of the tower. There are no visible indications of a fire on this floor.

The photograph shot from a helicopter shown in Figure 8–67 was taken less than a minute before the collapse of WTC 2. The appearance of the west face of WTC 1 at this oblique angle is consistent with the fire distributions described above.

Observed window conditions for the four tower faces at the beginning and end of the period are compared in Figure 8–75. The windows that opened during the period, which generally implies the presence of an active fire, are consistent with the fire-spread observations discussed above. On the north face, windows opened along a long length of the 98th floor and near the eastern edge of the 92nd floor. The growth of the large fire on the east side of the 98th floor is reflected in the large increase in open windows at the later time. On the other floors the fires on the east face appear to be moving relatively deliberately toward the south, but note the large increase in the number of open windows on the 92nd floor. Windows also opened on the east side of the 92nd floor near the north edge. The maps for the south face are consistent with observations that major fire growth during the period was on the 95th and 98th floors. There was evidence of a small fire on the east side of the south face on the 94th floor, but in general, the fires on the south face still have not moved in this direction much beyond the center of the face. Note that most of the windows on the eastern side of the face at the later time are marked as not visible. This is because the imagery available does not allow the conditions of these windows to be assessed. The imagery does indicate that there was no significant smoke or fire coming from windows on the fire floors above the 94th floor. By far, the largest changes in window condition during the period were on the west face. Large numbers of windows have been opened on the 94th, 96th, and 98th floors. These changes are even more remarkable when the nature of the fires, which generally appeared to be gently burning, is recalled.

Figure 8-74. This image of the north and west faces of WTC 1 is a frame captured from a video recorded by a news helicopter at 9:56:10 a.m. The image has been enhanced by adjusting the intensity range. WTC 2 appears in the background to the right. Column and floor numbers have been added to WTC 1.

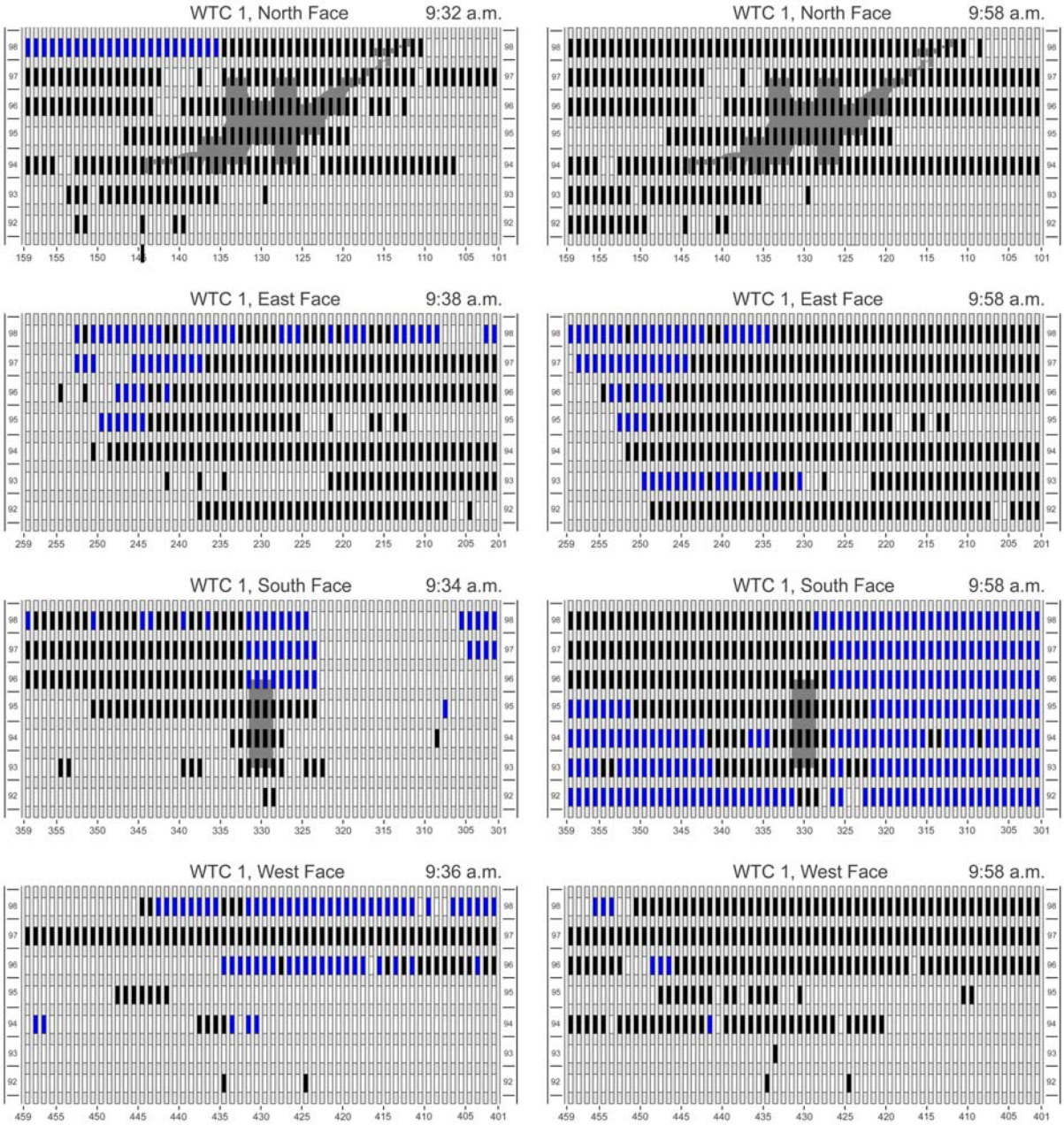

Figure 8-75. Maps for the 92nd through the 98th floors compare missing window glass for the four faces of WTC 1 at two times, around 9:35 a.m. and at 9:58 a.m. The color coding used for the maps is indicated in Figure 5-1.

Maps of integrated fire behavior for the four tower faces for the period from 9:35 a.m. to 9:59 a.m. are shown in Figure 8–76. These maps can be compared with the corresponding versions in Figure 8–51 for 9:19 a.m. to 9:35 a.m. This comparison highlights the growth of fires on the north face across much of the 98th floor, on the 96th floor to the west of aircraft impact cavity, and on the 92nd floor near the east edge of the face. Other areas of fire that were identified during the earlier time period were no longer visible during the current period.

On the east face, major fire growth and spread took place on the 92nd (on south side) and 98th (on north side) floors. On the 94th through 97th floors the large fires that were present earlier near the centers and on the north sides of the face have died down and at most locations are no longer visible. The remaining fires on these floors were on the south side of the face and were spreading slowly toward the south.

On the south face, the fire that appeared near the center of the western half near the end of the previous period continued to spread in both directions and filled in the length of windows between the western edge and center of the face. Extensive fires were still present on the western sides of the 95th through 97th floors, but these fires decreased in both extent and intensity during the period. Relatively small flames were observed briefly in three windows on the east side of the 94th floor.

The changes in the west face integrated fire distributions between the two periods mirror the large changes observed in the window maps. Areas of fire appeared along extensive lengths of the 94th and 98th floors during the period. At the same time, fires on the 96th floor completed their slow migration from the south edge of the 96th floor to the north edge. Fires that were visible on the 97th floor during the earlier periods had died down by the start of the current period.

The most distinctive change in the window condition and integrated fire maps between 9:35 a.m. and 9:59 a.m. was the wide-spread appearance of fire on the 98th floor. By roughly twenty minutes after a growing fire first became evident on the north side of the 98th floor, fire was visible on this floor in two long bands. One of these bands started near the center of the south face, ran to the southwest corner and extended north on the west face to at least window 98-444. The second band began near window 98-119 on the north face and ran around the northeast corner to the vicinity of window 98-223 on the east face. The observed fire behavior of these rapidly developing fires varied from face to face. On the east and south faces very intense flames were observed extending large distances from open windows, while on the west and north sides, the fires appeared much less intense and to be burning at interior locations removed from the outer walls. These observations are reflected in the integrated fire distribution maps shown in Figure 8–76.

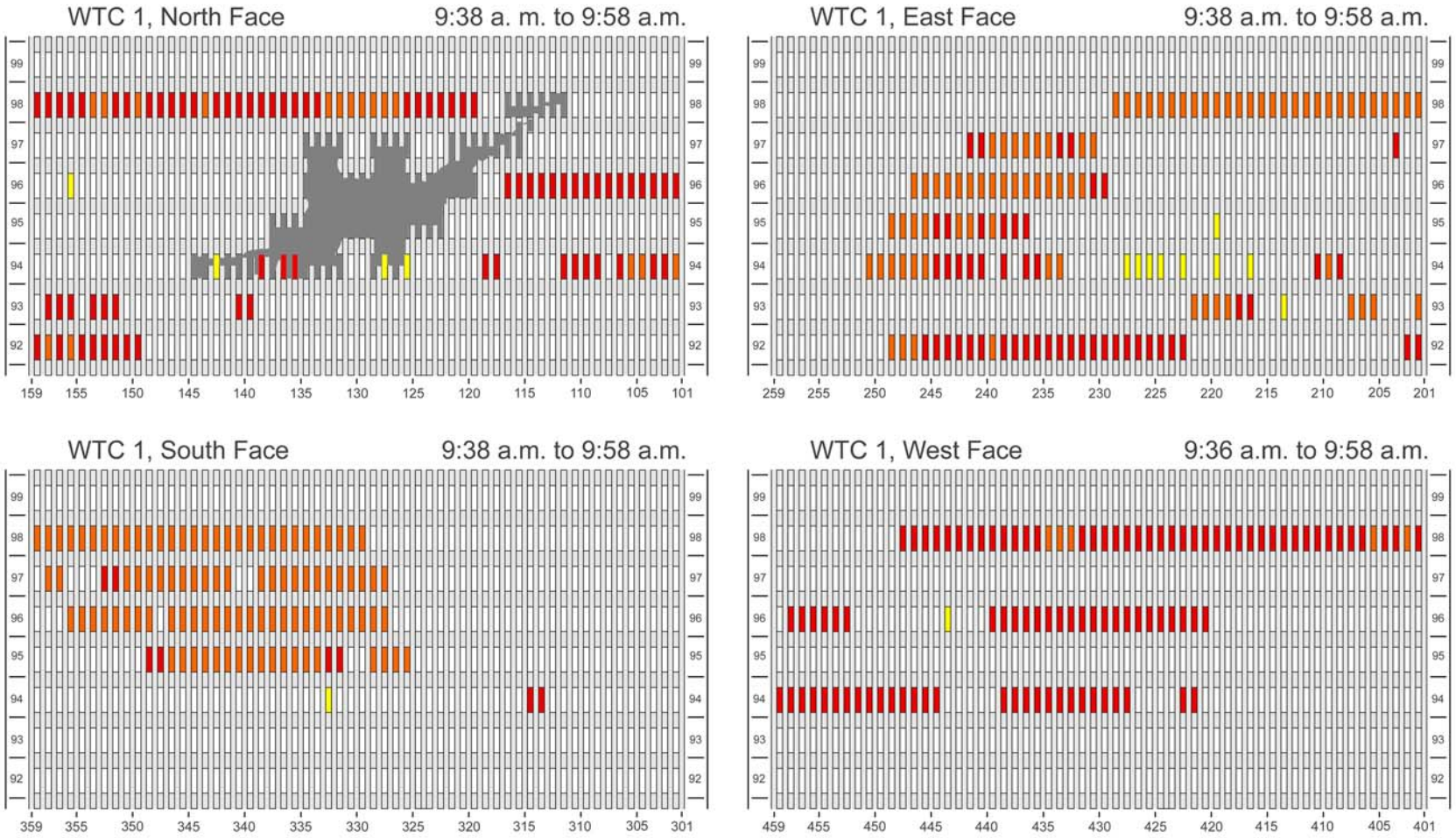

Figure 8-76. Maps of integrated fire observations between 9:36 a.m. and 9:59 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

The large number of people who fell from the west side of the 94th floor around 9:39 a.m. was discussed above. The table in Appendix M indicates that additional people were observed falling on the north, east, and west sides of the tower during the period. Many of these people were identified as falling from floors above those where active fires had been observed. It is likely that most, if not all, of these additional people came from windows above the fire floors. There does not appear to be a distinct pattern in the location or timing of these additional observations.

The observations summarized in Appendix L show that a large number of streamers were created during the period. The vast majority were observed on the north face. Many of these were detected falling from windows on the 98th floor, where significant fire spread was taking place. Others came from the 94th floor from areas where fire spread was also observed. Given the extensive fire growth over several floors on the west face and on the 92nd and 98th floors on the east face, it is likely that large numbers of streamers were created on both of these faces as well. It has proven more difficult to detect these streamers because there are fewer close-ups of these faces, and the lighting made it more difficult to see them as compared to those on the north face. It should also be mentioned that it has not been possible to time exactly a considerable number of videos and photographs in the database which show views of the south and west faces of WTC 1. Many of these images were shot during the current time period and do show streamers falling from these two faces.

After WTC 2 fell at 9:58:59 a.m., the number of detailed views of WTC 1 decreased markedly. As a result, the time line and façade maps become less certain. Therefore, this is an appropriate point to quantitatively compare the changes in window condition that took place between the time of the aircraft impact on WTC 1 and the collapse of WTC 2. Façade maps for these two times are compared for the four faces of WTC 1 in Figure 8–77. Only a quick glance is necessary to recognize how extensive the fire spread and growth has been on the 92nd through 98th floors.

The maps also provide some insights into several general fire behaviors. Perhaps the most significant is the absence of significant window breakage on the east side of the south face and the adjoining area on the east face. This indicates that on most of these floors the fires have not yet migrated to the outer walls in these locations. Similarly, the fires that grew fairly early on the eastern sides of the 92nd and 93rd floors have not yet spread to the western faces of these floors. On the 94th floor the fires that were originally ignited on the east face have burned across the north face and the northern portion of the west face, but there is still an apparently unburned area near the southwest corner. Even though there have been significant fires on the eastern and southern sides of the 95th floor, significant lengths of window glass remain in place on the northern and western sides of this floor.

The spread sheets containing information about window conditions following the aircraft impact and just prior to the WTC 2 collapse have been analyzed in the same manner used to generate the summaries included in Table 8–1. The results are included in Table 8–2 for the 92nd through the 98th floors. Keeping in mind the uncertainty introduced by windows that are not visible and the possibility that a limited number of windows may have been opened by people, the change in the number of open windows provides a rough estimate of the fire spread over the period. The results for individual floors are available for comparison in Table 8–2. In general, the changes in open windows on individual faces and floors are consistent with the general fire spread behaviors already described. The overall changes in open windows provide an indication of the total fire spread during the period. These numbers are obtained by summing the number of open windows on all of the floors and faces for the two times. The results are summarized in Table 8–3.

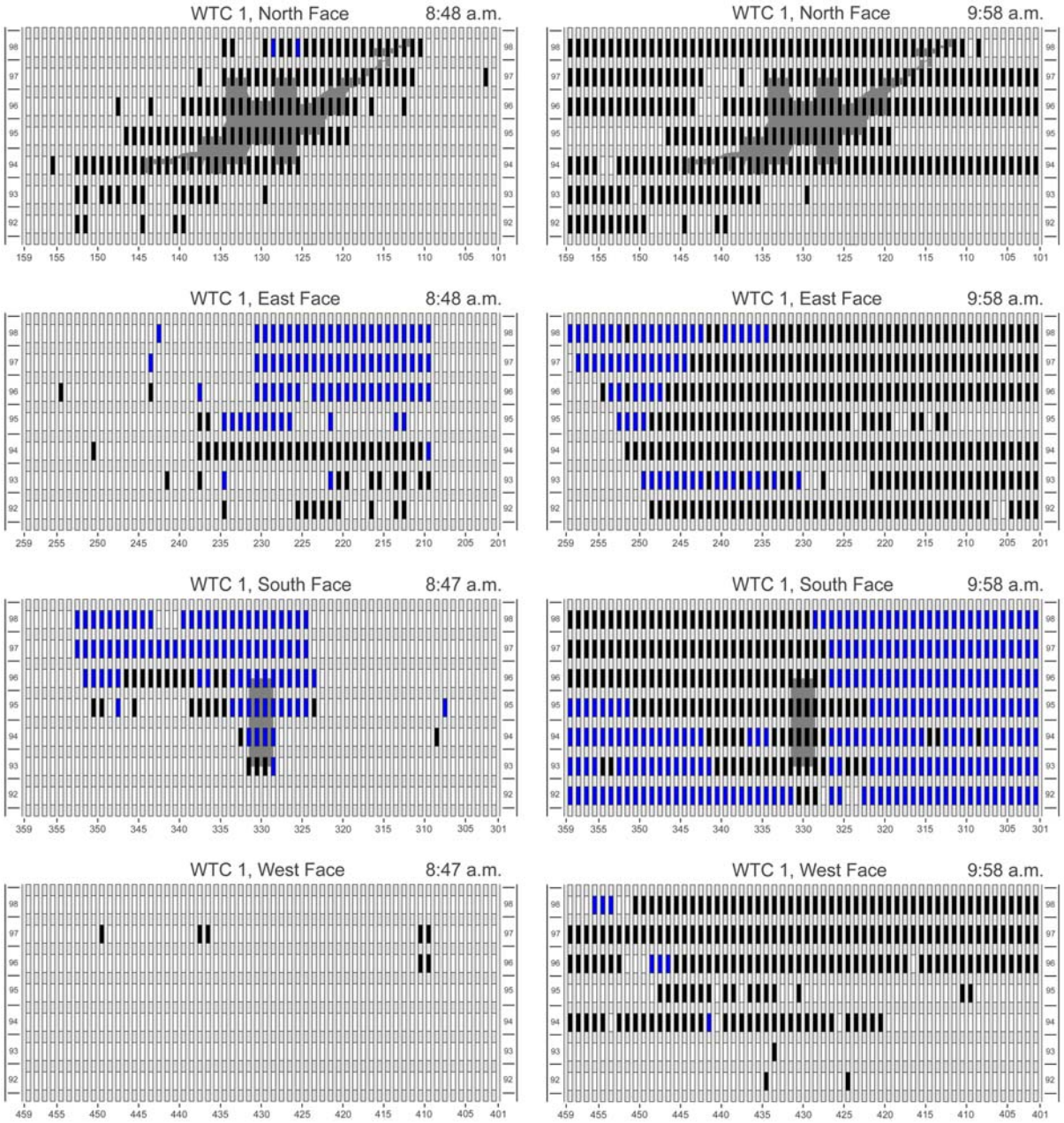

Figure 8-77. Maps for the 92nd through the 98th floors compare missing window glass for the four faces of WTC 1 at two times, immediately following the aircraft impact on WTC 1 at 8:46:30 a.m. and just prior to the collapse of WTC 2 at 9:58:59 a.m. The color coding used for the maps is indicated in Figure 5-1.

Table 8-2. Comparison of Window Conditions on the Four Faces of WTC 1 Near the Times of Aircraft Impact on WTC 1 and Collapse of WTC 2.

	Around 8:47 a.m.				**Around 9:58 a.m.**		
	Open Window	**Glass in Place**	**"Can't See"**		**Open Window**	**Glass in Place**	**"Can't See"**
Floor	North Face 8:47 a.m.				North Face 9:58 a.m.		
98	19	36	3		50	8	0
97	25	32	1		52	6	0
96	22	34	2		55	3	0
95	28	30	0		28	30	0
94	29	29	0		56	2	0
93	14	44	0		24	34	0
92	5	53	0		13	45	0
Floor	East Face 8:48 a.m.				East Face 9:58 a.m.		
98	0	35	23		36	0	22
97	0	35	23		43	1	14
96	2	34	22		48	4	6
95	2	44	12		33	21	4
94	29	28	1		51	7	0
93	10	46	2		27	16	15
92	10	48	0		46	12	0
Floor	South Face 8:48 a.m.				South Face 9:58 a.m.		
98	0	32	26		30	0	28
97	0	29	29		32	0	26
96	11	29	18		32	0	26
95	9	37	12		29	0	29
94	2	52	4		15	0	43
93	3	54	1		19	0	39
92	0	58	0		3	3	52
Floor	West Face 8:47 a.m.				West Face 9:58 a.m.		
98	0	58	0		50	5	3
97	5	53	0		58	0	0
96	2	56	0		51	4	3
95	0	58	0		16	42	0
94	0	58	0		35	22	1
93	0	58	0		1	57	0
92	0	58	0		2	56	0

Table 8-3. Summary of Open Windows Observed on Faces (92nd to 98th Floors) of WTC 1 at 8:48 a.m. and 9:58 a.m.

Face	Number of Open Windows 8:48 a.m.	Number of Open Windows 9:58 a.m.
North	142	278
East	53	284
South	25	160
West	7	213
Total	227	935

The changes in the number of open windows on the individual faces of WTC 1 are consistent with the observed fire behaviors. The largest increases were on the east and west faces. The façade maps in Figure 8–77 show how extensive the fire spread was on these faces during the period under consideration. There was also considerable fire spread observed on the north face, but the percentage increase in the number of open windows is smaller due to the large number of windows that were opened when the aircraft struck. The smallest increase in total open windows was for the south face. This reflects the fact that the fires did not migrate substantially into areas on the eastern side of this face during the 1 hr and 13 min period.

The total number of windows opened by the fire is remarkable. The number increased by more than a factor of four as compared to the number of windows that were broken open immediately following the aircraft impact and subsequent fireballs. This represents an increased total open area of just over 8,200 ft^2. This large area of open windows substantially increased the amount of outside air available for the fires. This suggests that there was a very strong interaction between the breaking open of the windows and the observed fire spread and growth behavior.

8.6 RESPONSE OF WTC 1 TO THE COLLAPSE OF WTC 2

At 9:58:59 a.m. WTC 2 began to collapse, and roughly ten seconds later debris reached the ground. Very shortly after the collapse began, fire and smoke were pushed out of the south face of WTC 1. Figure 8–78 contains two frames taken from a video showing the south faces of the towers. The first frame was recorded just as WTC 2 began to collapse, and the second was shot seven seconds later. In both frames the fire burning on the 98th floor of WTC 1 is very distinct. At the earlier time there does not appear to be external flames, but in the second frame long flames extend from near the center of the face. Review of the video indicates that these flames were pushed out of WTC 1 starting four seconds after collapse initiation. Closer inspection shows that an area of flame is visible on the western side of the 96th floor at the later time that was not evident seven seconds earlier. It is significant that flames do not appear elsewhere on the face at the later time, perhaps indicating that large flames are only present near the periphery of the face at these locations.

Figure 8-78. Two frames taken from a video shot from a news helicopter show the south face of WTC 1 just as WTC 2 starts to collapse at 9:58:59 a.m. and 7 seconds later. WTC 1 and WTC 2 are to the left and right, respectively. Images have been enhanced by adjusting the intensity levels.

Figure 8-79. This cropped photograph was shot from the southwest and shows WTC 1 and the collapsing WTC 2 at 9:59:04 a.m. The image was enhanced by adjusting the intensity levels, and some bright areas are saturated.

Figure 8–79 includes a photograph that was shot at 9:59:04 a.m. and shows the flames coming out of the 98th floor windows while WTC 2 collapses nearby. Flames have also been pushed out of open windows on the 96th floor near the western edge of the south face. Fires are also visible on the west face of WTC 1 on the 94th, 96th, and 98th floors, but flames are not visible outside of the windows. In the photo it appears as if debris from WTC 2 is either striking WTC 1 or just passing by on the east side.

Videos show that on the north face of WTC 1 no flames were pushed out of the windows as WTC 2 was falling, but that fires on the 92nd, 94th, and 96th floors brightened noticeably. On the east face, flames

near the south edge on both the 92nd and 96th floors flared out at roughly the same time the changes were observed on the north and south faces. Fires on the north side of the east face at the 98th floor were already extended from the windows and did not appear to change.

It appears that a positive pressure pulse generated by the collapse of WTC 2 pushed gases through open windows in WTC 1. Recall that a similar response was observed when the aircraft struck WTC 2 (see Section 8.2). The pressure pulse seems to have been widespread, but flames were pushed out of the tower at a limited number of points. This suggests that at 9:59 a.m. the areas of intense burning in WTC 1 were limited to a few locations. This is in general agreement with the visual observations. Shortly after the collapse of WTC 2, the flow of smoke from the north face of WTC 1 stopped momentarily. The period of decreased smoke flow lasted for approximately 40 s.

Videos shot from the east show that debris from WTC 2 did indeed pass in an arc across the east face of WTC 1. The damage created by this debris to the façade of WTC 1 can be seen in Figure 8–80 near the bottom of the photograph. This damage was only visible for a short period before dust rose upward from below and hid the area. The highest marks on the building are just below the mechanical equipment room on the 75th and 76th floors. The damage appears relatively superficial, and it is considered unlikely that it affected the subsequent fire behavior. Videos and eyewitness accounts indicate that large amounts of dust and some debris entered the lower floors of WTC 1 during the collapse of WTC 2. It is not known if damage at these lower locations could influence the fires near the top of the tower, but it seems unlikely.

8.7 9:59 A.M. TO 10:18 A.M.

The collapse of WTC 2 resulted in changes in the quantity and quality of visual material showing the faces of WTC 1. People near the site were forced to flee or seek shelter. Many photographers and videographers located further away changed their focus to the large dust clouds that covered much of lower Manhattan. The dust reached levels near the top of WTC 1 and obscured the faces. This was particularly true on the east and south sides. As a result, the visual information following the collapse of WTC 2 is considerably less detailed than prior to this time. This is unfortunate because significant changes in fire behavior and distribution took place prior to the collapse of WTC 1 at 10:28:22 a.m.

The most complete information during the current period is available for the north face of WTC 1. A view of this face at 10:05:27 a.m. is shown in Figure 8–81, which is a frame captured from a video. Remarkably little fire is visible in the image. Small flames are present near windows 92-146, 96-106, and 98-152. More extensive fires were evident at each of these locations at 9:57:59 a.m. (see Figure 8–55). Apparently, these fires had died down in the intervening seven and a half minutes.

The photograph shown in Figure 8–82 was shot from a helicopter looking down on the north face of WTC 1 at 10:09:32 a.m. Considerably more flame is visible than could be seen in Figure 8–81. The difference is due to the angles from which the images were taken. The video frame shown in Figure 8–81 was taken from the ground a few blocks away from the WTC site, while the photograph in Figure 8–82 was shot from a much greater distance looking down into the windows. In effect, the latter photograph is looking much deeper into the building. On the 92nd floor a length of flames is evident extending from the eastern edge of the tower to window 92-146. At 9:57:59 a.m. flames were only visible as far as window 92-149. Windows further to the west were still intact. The fire has moved into the room that has walls terminating at columns 92-146 and 92-149 (see Figure B-1).

Figure 8-80. This cropped photograph shows the east face of WTC 1 at 9:59:16 a.m., i.e., 17 s after WTC 2 began to collapse.

Figure 8-81. This view of the north face of WTC 1 was captured from a video recorded at 10:05:22 a.m. The image has been enhanced by adjusting the intensity levels. Column and floor numbers have been added.

A single isolated flame is also evident at window 92-136, which indicates that the fire has apparently bypassed the next room to the west and entered the room with walls at columns 92-132 and 92-138. It has not been possible to determine exactly when this fire appeared, since it was not visible in videos shot from the ground around 10:08 a.m., but was easily seen just after 10:10 a.m.

Low intensity fires are also visible in Figure 8–82 on the west sides of the 94th and 96th floors and over much of the eastern half of the 98th floor. These are locations where much larger fires were present at earlier times, and these fires are likely the remnants. They were not visible from the ground around this time because they were low intensity and were burning near the floors, where they were hidden from view.

In Figure 8–82 there is no evidence of fire on the north face near the west edge of the 98th floor. At 10:10:15 a.m. a burst of heavy smoke was released from window 98-105, and less than two seconds later smoke came from window 98-102. A series of photographs taken around this time indicates that fire appeared in window 98-102 between 10:10:19 a.m. and 10:10:20 a.m. A photograph recorded at 10:10:55 a.m. showed flames were present in windows 98-101 to 98-108 and that flames were coming from windows on the adjacent west face.

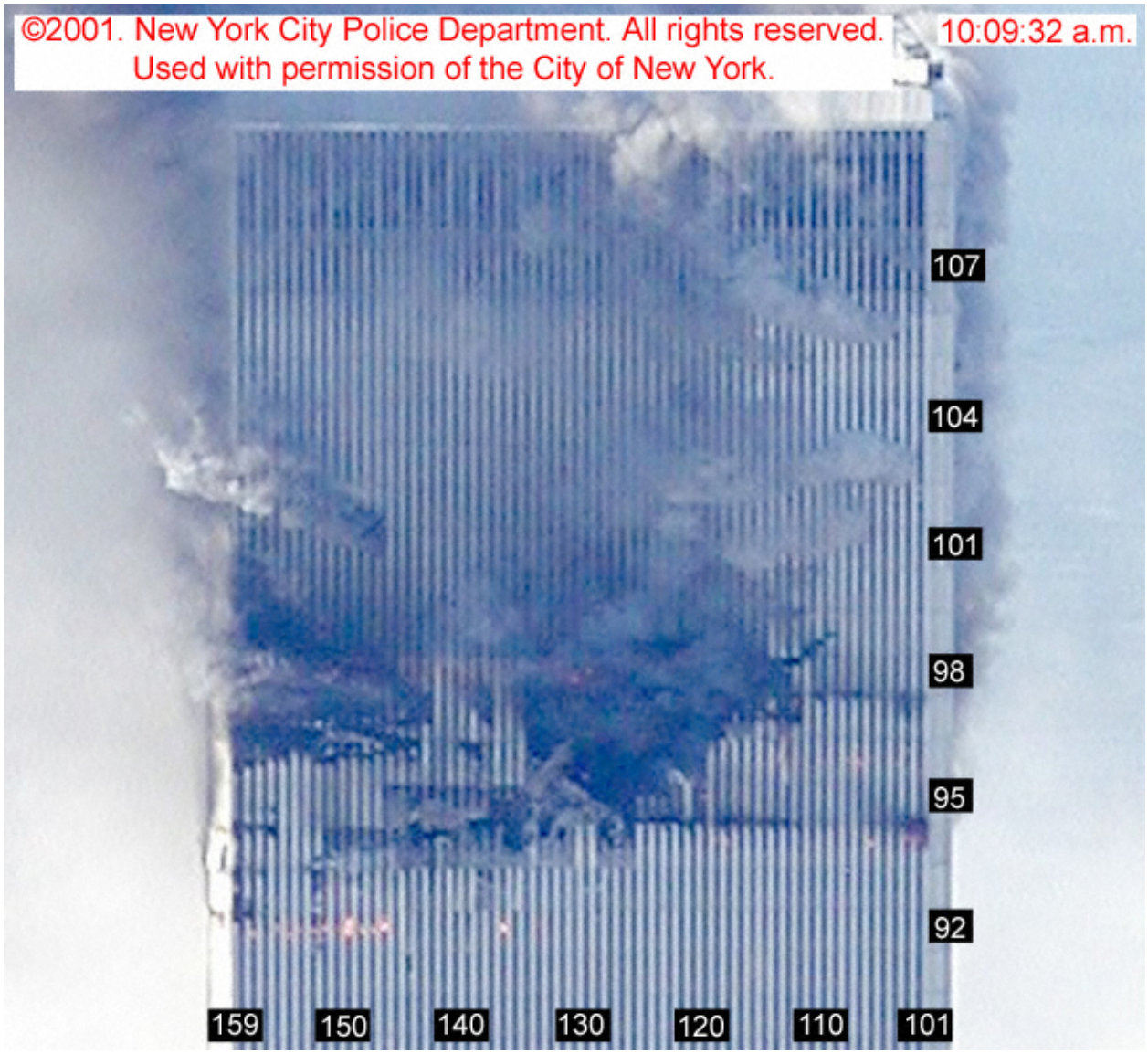

Figure 8-82. This cropped photograph was shot from a helicopter looking down on the north face of WTC 1 at 10:09:32 a.m. The intensity levels have been adjusted and column and floor numbers have been added.

Figure 8–83 shows the north face at 10:11:41 a.m. The fire at the western edge of the 98th floor is visible in windows 98-101 to 98-110. On the 92nd floor there are bright flames present in windows 92-131 and 92-132. These two windows are on the west side of the room on this floor that has walls ending at columns 92-132 and 92-138 (see Figure B-1). The windows to the west of this point appear to still have glass in place. There appear to be some small fires on the east side of the 92nd floor, but flames are not observed elsewhere from this vantage point.

Figure 8-83. This photograph shows the north face of WTC 1 at 10:11:41 a.m. The original image has been cropped, rotated, and adjusted for intensity levels. Column and floor numbers have been added

A view of WTC 1 shot from the northwest at 10:15:10 a.m. is shown in Figure 8–84. The fire on the 92nd floor has grown and moved toward the west. Flames are now visible as far west as window 92-121. As seen in Figure B-1, there was a large open area on the 92nd floor that ran between walls that terminated at columns 92-105 and 92-132. A fire is now burning on the east side of this open area, having apparently appeared in the room around 10:11:14 a.m. (see Figure 8–83). At the time the photograph in Figure 8–84 was taken, the glass for windows to the west of column 92-121 still appeared to be in place. It is interesting that even though a fire was growing in the area, there was no smoke coming from the open windows. This must be another case where the smoke was venting elsewhere.

Compared to the north face, it proved much more difficult to characterize the fire behavior on the east face of WTC 1 during this period. Two videos shot from the northeast at fairly long distances (it is not possible to distinguish individual windows) provided the best indications for the fire behavior during this time. One of these videos demonstrates one of the reasons for this difficulty. After the initial dust cloud created by the nearby collapse of WTC 2 cleared, it was still possible to see the upper parts of the east face of WTC 1. However, at 10:00:19 a.m. a dust cloud rose from below and totally obscured the floors where fires were present.

Just prior to the arrival of the dust from below, intense fires were visible on the east face. Flames were coming from windows on the 94th, 96th, 97th, and 98th floors. The flames appeared to be more intense than they were just prior to the collapse. It is not possible to determine exactly from which windows the flames were coming, but the fires had the same general distribution as seen at 9:55:08 a.m. (see Figure 8–59). The flames on the 98th floor were isolated on the north side of the face, while the fires on the other three floors were approaching the south face. The flames observed on the 94th and 97th floors

were in roughly the same locations as earlier, but the fire on the 96th floor appeared to have spread further to the south, with extended flames coming from perhaps as far south as window 96-250.

Figure 8-84. This photograph of WTC 1 shows the north and west faces of WTC 1 at 10:15:10 a.m. The image has been cropped and rotated, and the intensity levels have been adjusted. Column and floor numbers have been added.

The dust obscuring the top of the east face did not begin to clear until around 10:06:25 a.m. At this time it was possible to see the glow of fires on the face through the dust that still remained. In general, the north side of the east face was more visible than the south side. The only fire visible at this time was the band of flames on the 98th floor. This fire seemed to be located at roughly the same windows as in Figure 8–59, which was taken at 9:55:08 a.m. The flames did not appear to be extended from the windows to the degree they were at the earlier time, but external flames were discernable at the windows near the southern end of the fire area. According to the floor plan layouts in Figure B-7, there were no internal walls present near the center of the east-side periphery of the 98th floor. It is unclear why the fire did not appear to spread further south during this period.

During the following three minutes, the fire conditions visible in the videos of the east face did not change appreciably. The face was still partially shrouded in smoke and dust. The apparently stationary fire along the northern length of the 98th floor was the only fire bright enough to identify on the face. Around 10:09:30 a.m. external flames became visible on the western side of the 97th floor. It is difficult to estimate the exact window location, but it appeared to be further west than where extended flames were observed on this floor prior to the collapse of WTC 2, i.e., perhaps near window 97-245 as compared to window 97-237 at the earlier time. Shortly afterward, around 10:09:55 a.m., flames were observable on the 96th floor at a location close to the south end of the face, perhaps several windows from the edge. Based on the floor diagram in Figure B-5, it is likely that these flames were coming from inside the room that had walls ending at columns 96-252 and 96-256.

Figure 8–85 shows a photograph of the north and east face of WTC 1 that was taken at 10:09:30 a.m. It demonstrates the degree to which the east face was hidden by smoke and dust. The fire on the 98th floor of the east face is partially visible. While intense, the flames that are visible do not appear to be coming out of the windows.

In a somewhat closer video of the east face shot near 10:11:25 a.m., the flames on the 96th, 97th, and 98th floors were visible at roughly the same locations observed two minutes earlier. The flames on the 96th and 97th floors were extended from the windows. It appeared in this video that flames were coming from windows at the southern edge of the face on the 96th floor. This would indicate that fire had entered the room on the southeast corner of the 96th floor that had internal walls ending at columns 96-256 and 96-308 (see Figure B-5).

At 10:15:39 a.m. intense flames were observed briefly over a substantial length of the 97th floor in one of the long-distance videos. The southern-most extent of the flames was closer to the south edge (roughly estimated to be near window 97-246) than observed earlier.

Figure 8–86 shows a partial view of the east face from a photograph taken at 10:17:33 a.m. The most prominent feature is the fire on the 98th floor. At 9:55:08 a.m. (see Figure 8–59) this fire had extended as far south as window 98-224, and there were many windows with extended flames. In Figure 8–86 flames are coming from window 98-229. During the just over 23 minutes in between the photographs, the fire had moved five windows to the south. The fire on the north side of the face has begun to die down. The longest external flames are now located near window 98-225.

Flames are also visible on the 96th and 97th floor extending south from near windows 96-240 and 97-240 to the last windows (96-245 and 97-245) that can be seen in the image. Closer inspection of Figure 8–86 shows what appears to be a small fire on the 101st floor near window 101-224. There is some ambiguity

because of the flames coming from below, but the fire visible higher up seems to be well isolated. This observation suggests that fire has spread upward on the east face by jumping over a couple of floors.

Figure 8-85. This photograph shows the east and north faces of WTC 1 at 10:09:30 a.m. The intensity levels have been adjusted.

The quality of the imagery available for the south face of WTC 1 following the collapse of WTC 2 was similar to that for the east face. As a result, it became difficult to provide the detailed information concerning fires on this face that was possible before 9:59 a.m.

A video shot from a news helicopter provided distant views of the south face of WTC 1 following the collapse of WTC 2. The jet of flame observed coming from the 98th floor during the collapse of WTC 2 has already been described. At 10:00:53 a.m. the top of the south face was still visible, and the video zoomed in sufficiently to identify floors with intense fires. In addition to the line of fire present on the western side of the 98th floor, there was an intense fire burning on the 97th floor near the center of the face. Just after this time, dust rose from below and totally obscured the floors with fire.

Around 10:06:20 a.m. the dust began to clear sufficiently that flames could be seen on part of the south face. The flame distribution appeared similar to that immediately following the collapse of WTC 2, with a line of fire visible on the western half of the 98th floor and flames near the center of the face on the 97th floor. For the next several minutes the face was most often obscured by the dust. At 10:10:34 a.m.

the dust cleared sufficiently to detect the presence of a fire on the east side of the south face. There appeared to be a fire burning on the 96th floor that extended from near the eastern edge to at least half way to the center of the face. A fire was also visible on the 97th floor. These flames were more difficult to identify. This fire seemed to be concentrated more toward the center of the face.

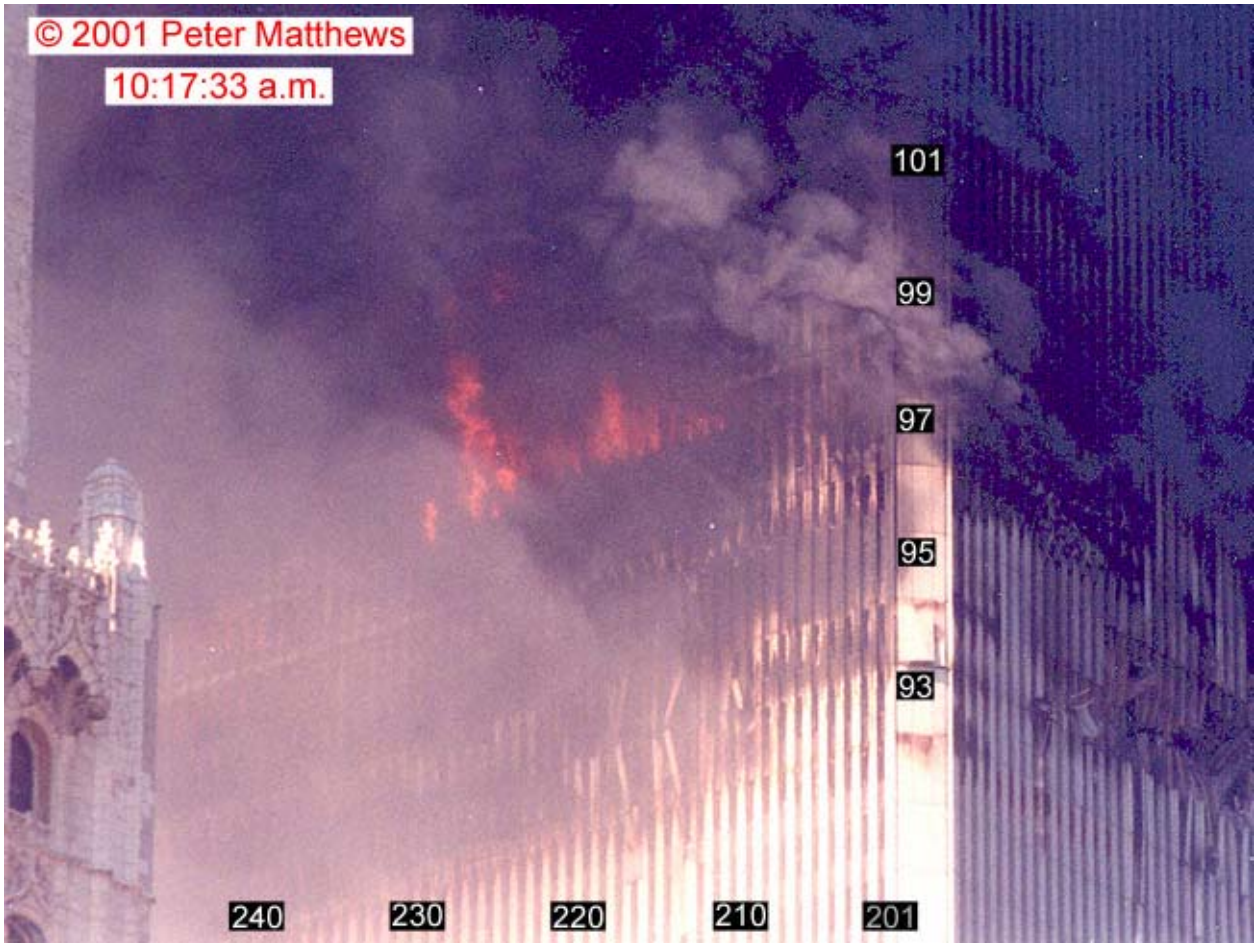

Figure 8-86. This photograph shows the north and east faces of WTC 1 at 10:17:33 a.m. The original has been cropped and enhanced by adjusting the intensities. Column and floor numbers have been added.

Figure 8–87 shows one of the clearer views of the south face captured from the news helicopter video. It was shot at 10:12:53 a.m. With one major exception, fires are distributed much as described above. The bright flames on the east sides of the 96th and 97th floors and the west side of the 98th floor are easily seen. In addition, an intense jet of flame is apparent on the west side of the face. This external flame, which is over a story tall, appears to be coming from the 99th floor. This is an indication that the fires had now progressed upward to this floor. Near the center of the face, there is a smoke plume coming from one of the lower floors. It is difficult to be sure, but this smoke appears to be coming from the 92nd floor. If correct, this suggests that a fire was burning on the south side of the 92nd floor.

A short video shot from a point on the ground to the south of the WTC complex provided a view of the fires on the south face. The exact time when the video was recorded was not determined, but was estimated to have been around 10:17:45 a.m. by comparing the observed fire distribution with that seen in

the video shot from a news helicopter. There is a relatively large uncertainty associated with this assignment since many of the views from the helicopter video around this time were taken from such a distance that the fires were not visible. A frame captured from this video is shown in Figure 8–88. It provides additional support for many of the observations based on Figure 8–87.

Figure 8-87. This view of the south face of WTC 1 was captured from a video recorded by a news helicopter at 10:12:53 a.m. The image has been enhanced by adjusting the intensity levels.

The line of fire on the 98th floor is still quite distinct. There is an intense external flame on the eastern side of this fire located at a point to the east of the center of the face. This fire appears to be moving toward the east. Two tongues of flame are evident coming from the floor above, i.e., the 99th floor, near the center of the western half of the south face. The video shows that the entire region between the two tongues of external flames is involved. The fire on the 97th floor on the eastern side of the face is just barely visible. Flames are not visible on the 96th floor. The smoke plume coming from windows lower down near the center of the face is also visible. Even though individual floors are not resolved in this image, the location of the smoke relative to other details indicates that it is indeed coming from the 92nd floor.

While limited, the visual information available indicates that fire had spread into areas on the east side of the south face of WTC 1 during this time period. A major fire has also grown on the 99th floor on the western side of the face.

Approval needed for image.

Figure 8-88. This image shows the south face of WTC 1. It was captured from a video shot from the ground and has been enhanced by adjusting the intensity levels. The estimated time of 10:17:45 a.m. is based on a comparison of the fire distribution with a video recorded from a news helicopter and could be off by as much as a few minutes.

One of the more interesting fire spread behaviors associated with WTC 1 was observed on the west face shortly after the collapse of WTC 2. A video shot from a news helicopter shows that a short burst of flame occurred from a 104th floor window on the south side of the west face at 10:01:15 a.m. A large fire then grew rapidly in this area. By 10:01:33 a.m. the fire had grown large enough to be visible in a very long distance view of the west face shot from a second news helicopter. It is difficult to provide an explanation for the appearance of flames at a location that is three floors higher than any other floor where fire has been observed up to this time and five floors higher than a floor with a major fire.

Figure 8–89 shows an image of the west face shot from a news helicopter at 10:01:30 a.m. The flames on the 104th floor are coming from several windows centered near window 104-411. Heavy black smoke is venting from multiple windows over a much larger area. It is informative to compare the appearance of the smoke in Figure 8–89 with that in Figure 8–74, which shows the west face at 9:56:10 a.m. The smoke has clearly become much heavier and darker.

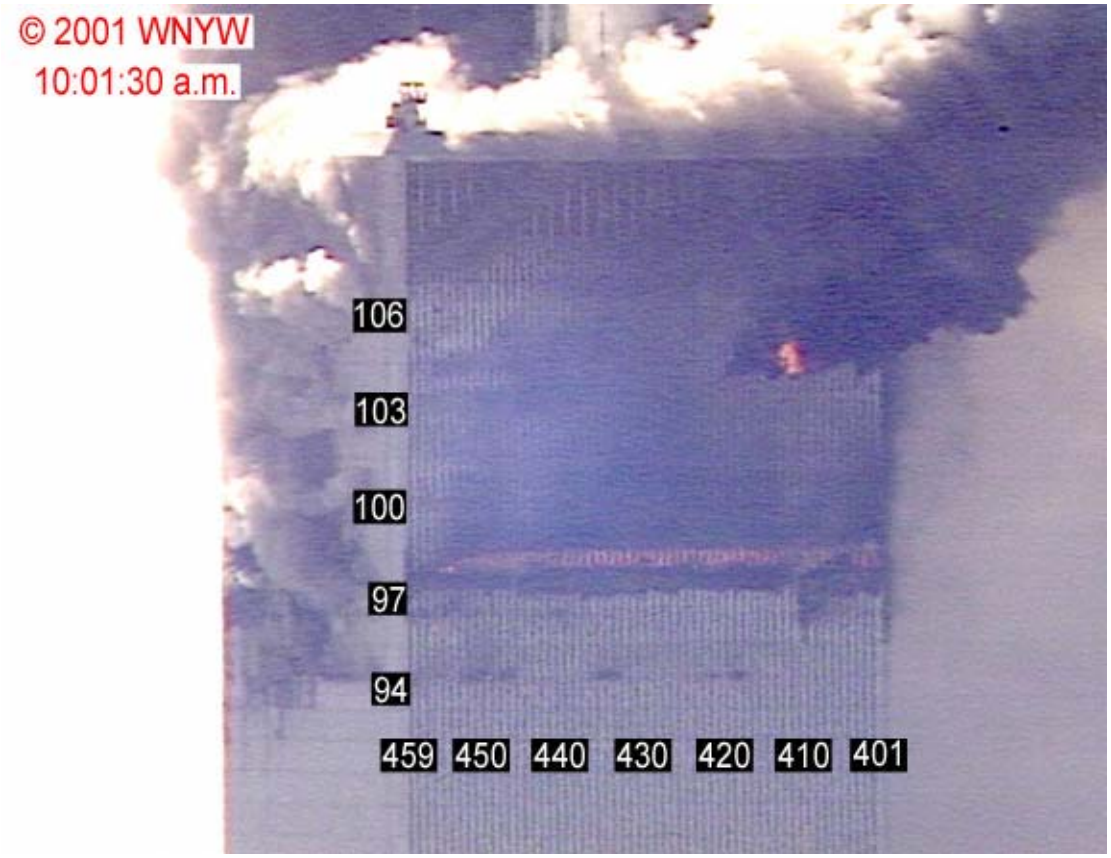

Figure 8-89. This image of the north and west faces of WTC 1 is a frame captured from a video recorded by a news helicopter at 10:01:30 a.m. The image has been enhanced by adjusting the intensity range, and some areas are saturated. Column and floor numbers have been added.

The deep orange glow along the 98th floor in Figure 8–89 indicates that the interior fire on this floor is continuing to burn along much of the length of the west face. The fire on this floor has moved north since around 9:58 a.m. Flames can now be seen as far as window 98-455. The floor plan layout shown in Figure B-7 indicates that there were two rooms along the west face in the northwest corner of the 98th floor. Fire has entered the southernmost of these rooms, which had interior walls at columns 98-452 and 98-456. There is as yet no visual evidence for fire on the west side of the corner room with walls at columns 98-456 and 98-108.

Flames are still visible inside the room located on the northwest corner of the 96th floor. Isolated areas of flame are also visible on the 94th floor. Smoke is evident as far south as window 94-417 on this floor. At 9:56:10 a.m. smoke on the column covers was only visible as far south as column 94-421. In the intervening period the fire on this floor has continued to spread to the south, having entered the room with walls located at columns 94-417 and 94-421 (see Figure B-3).

The fire on the 104th floor continued to grow and spread during the next few minutes. At 10:03:15 a.m. it covered a length from window 104-405 to window 104-412, with intense flames extending from these windows. At the same time the fire on the 94th floor in the room with walls at columns 94-417 and

94-405 continued to move south, with flames visible in windows 94-413 to 94-920. Meanwhile, the appearance of the fire on the 98th floor changed little.

Another view of the west face taken from a video shot from one of the news helicopters at 10:07:06 a.m. is shown in Figure 8–90. The fire on the 104th floor is still raging, with flames coming from windows 104-404 to 104-414. On the 98th floor the deep orange glow from the internal fire is still present along nearly the entire length. A small flame extends from window 98-455, but the fire does not yet appear to have moved into the room on the northwest corner. On the 94th floor the most intense fire is observed in windows 94-412 to 94-414. Smoke is also evident coming from window 94-408. This smoke had appeared abruptly six seconds earlier.

Figure 8-90. This image of the north and west faces of WTC 1 is a frame captured from a video recorded by a news helicopter at 10:07:06 a.m. The image has been enhanced by adjusting the intensity range, and some areas are saturated. Column and floor numbers have been added.

In Figure 8–90 there is no visual indication of fire on the west side of the 95th floor. However, the summary of observations of falling people in Appendix M provides evidence that fires were moving into the area. At 10:06:11 a.m. a person fell from the west side of the 95th floor. During the next minute and forty-five seconds 12 more people fell from the same floor. For some of these people, the windows that they fell from have been identified. They ranged from window 95-424 to window 95-428. These windows were closed at 9:40:14 a.m. as seen in Figure 8–70.

A video recorded at 10:06:56 a.m. with similar detail as Figure 8–90 had a very similar appearance, i.e., there was no indication of a fire on the 95th floor. At this point the video zoomed out, and it was no longer possible to see details of the floors. By the time the video zoomed back in on the building at 10:08:11 a.m. interior flames were visible inside numerous windows on the 95th floor.

Figure 8–91 shows a photograph of the west face recorded shortly afterward at 10:09:27 a.m. Flames are visible on the 95th floor in windows 95-430 to 95-447. A video of the west face indicates that fire was present as far south as window 95-425 by 10:10:10 a.m. The images indicate that an extensive fire that had not been visible three minutes earlier appeared over a large length of the west side of the 95th floor.

The sudden appearance of such an extensive fire has two possible explanations. The first is that the fire grew rapidly in place from smaller fires that were initially hidden from the outside. Such rapid fire

Figure 8-91. This photograph, showing the west face of WTC 1 and an oblique view of the south face, was recorded at 10:09:27 a.m. The image has been cropped and enhanced by adjusting intensity levels. Column and floor numbers have been added.

growth has been observed when nearby windows are broken or interior walls are breeched. The other explanation is that a fire burning over a broad section of the floor spread from interior regions of the tower toward the west wall. A review of the floor plan layout for this floor shown in Figure B-4 indicates that there were no separated rooms with interior walls along the west face of the floor, except at the corners. These fires were growing in a large open space. The absence of walls and the fact that the area was tenable immediately prior to the fire becoming visible support a conclusion that the fire spread to the west face from interior locations on this floor. Recall that fires had previously been visible on this floor on both the east and south faces (see the earlier discussion).

At some point between 10:07:12 a.m. and 10:07:55 a.m., smoke began coming from the west windows in the room at the northwest corner of the 98th floor. In Figure 8–91 a flame is evident in window 98-458 at 10:09:27 a.m. This flame was not evident in a lower resolution video of the area taken at the same time, but flames did become visible in windows 98-456 to 98-458 starting around 10:10 a.m., with some flame extension from windows apparent. Recall that heavy smoke and flames appeared from the north windows inside this room starting at 10:10:15 a.m. The opening of so many windows in such a short period indicates that flashover took place in this room around this time. The flames coming from the west windows are visible in Figure 8–83, taken at 10:11:41 a.m.

The orange glow seen in Figure 8–91 over much of the 98th floor indicates that the interior fire present on this floor continued to burn at this time. By entering the room on the northeast corner around 10:10 a.m., this fire had completed its spread across the entire west side of the floor. Recall that the fire had entered the adjacent room with walls at columns 98-252 and 98-256 (see Figure B-7) around 10:00 a.m.

Small areas of isolated flames can be seen in several windows on the 94th floor in Figure 8–91. There appears to be a somewhat larger fire present at window 94-408 and windows immediately to the north. The smoke stream that appeared at 10:07:00 a.m. from window 94-408 is still apparent. Windows to the south appear to be intact. The fact that the fire did not appear to move south in the nearly 150 s period between these images is somewhat surprising because the floor plan layout (see Figure B-3) indicates that the fire was burning in a room with walls at columns 94-405 and 94-417. The fire might have been expected to spread to the southern wall of this room. Videos shot from the west indicate that the stream of smoke coming from window 94-408 was present until the end of the current period at 10:18 a.m.

Videos showed an interesting fire behavior on the 94th floor at 10:10:14 a.m. Bright flames lasting less than 4 s suddenly appeared coming from the lower regions of windows 94-447 and 94-448. These two windows were located in a room with walls extending to columns 94-446 and 94-450 (see Figure B-3). The table of streamer observations included in Appendix L indicates that streamers were observed falling from both of these windows around 10:13:35 a.m. These observations suggest that these windows were intact until just after 10:10 a.m. and that a significant fire was not present inside this room until this time.

Figure 8–91 provides a good view of the fire on the 104th floor of the west face. Flames continue to come from the open windows, and fire is evident from window 104-403 to window 104-416.

Figure 8–92 shows an image of the west face of WTC 1 recorded at the end of the current time period at 10:18:01 a.m. With a few exceptions, the appearance is similar to that seen around 10:10 a.m. The fire on the 95th floor has spread in both directions across the face. Low intensity flames can be seen in windows over a length from window 95-413 to window 95-455. Even though the fire extends over a long length of the face, there is very little smoke, and there are no flames coming from the windows on this

floor. The absence of significant smoke marks on the columns near the tops of the windows is consistent with these observations. Based on the floor plan layout shown in Figure B-4, the fire on this floor has penetrated the room with walls at columns 95-452 and 95-456, but there is no indication that it is yet inside the room on the northwest corner with walls at columns 95-456 and 95-108.

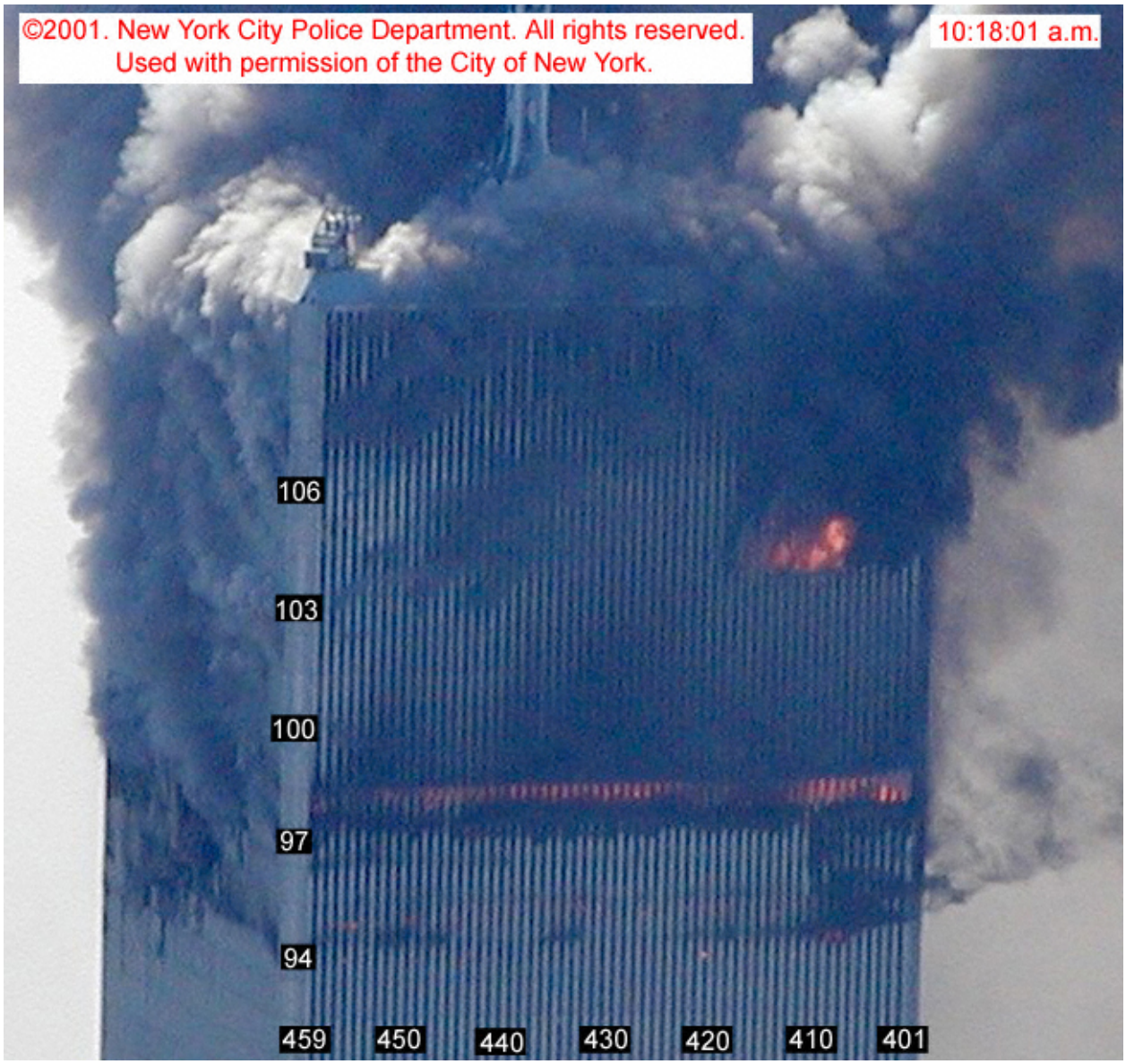

Figure 8-92. This cropped photograph of the west face of WTC 1 and an oblique view of the north face was shot at 10:18:01. The image was enhanced by adjusting the intensity levels, and column and floor numbers have been added.

Relatively small fires are observed at several locations on the 94th floor. Heavy smoke continues to come from window 94-108. In fact, heavy smoke and fire are apparent at windows 94-108 and 94-109. The fire on the 98th floor can still be seen across most of the west face, and it is still primarily an interior fire. Heavy smoke and flames continue to come from the fire on the 104th floor. The location of the fire appears to be the same as earlier.

Unlike the earlier time periods discussed above, maps of window condition will not be compared for different times. This is due to the poorer quality of the imagery available after the collapse of WTC 2, particularly on the east and south faces.

Integrated fire maps for the four faces of WTC 1 based on the data sheets prepared for times between 10:00 a.m. and 10:18 a.m. are shown in Figure 8–93. It should be remembered that observations during this period were hampered by partial obscuration of the east and south faces and the quality of the available imagery. As a result, only relatively large fires will be characterized on these faces, and there is likely some uncertainty in the window assignments for fire location. Figure 8–93 can be compared with Figure 8–76 which shows a similar plot for the period between 9:36 a.m. and 9:59 a.m.

On the north face of WTC 1, the principal areas of fire spread between 9:59:59 a.m. and 10:18 a.m. were on the 92nd floor, with fires moving from east to west across the face, and on the western side of the 98th floor with fires moving onto the face from the west. Flames continued to die down in areas on other floors where intense fires had been present earlier.

As mentioned, it was much more difficult to characterize the fire behavior on the east face during the period due to dust obscuration and the limited availability of visual material. In general, observations were consistent with earlier conclusions. The fire on the north side of the 98th floor was present throughout the period, burning more intensely at the beginning and spreading slowly toward the south. Fires on the 96th and 97th floors were observed to have moved further south on the face as well. It appeared that the fire on the 96th floor reached the south edge of the face by the end of the period. No information could be identified for fires on the 92nd through 95th floor. An interesting observation was the appearance of a fire on the 101st floor (not shown in Figure 8–93) during the period, suggesting that the fire jumped upward a couple of floors.

Substantial fire spread and growth was observed on the south face during this period. The new areas where substantial fires were observed were on the east side of the face on the 96th and 97th floors and on the west side of the 99th floor, where a fire spread over a large fraction of this side of the floor. The spread of the fires onto the east side of the face are significant because, with the exception of relatively small fires observed in this area on the 94th floor prior to the collapse of WTC 2, this side of the face was not subjected to fire for well over an hour following the aircraft impact. There was also evidence of the growth of a fire near the center of the 92nd floor.

The most prominent feature of the fire growth on the west face was the appearance (not included in Figure 8–93) of an intense fire with extended flames on the 104th floor shortly after the collapse of WTC 2. This fire continued to burn intensely during the entire period. The fire on the 98th floor continued moving toward the north, reaching the north face during the period. A relatively low-intensity fire appeared on the 95th floor and subsequently covered a large fraction of the floor across the face. The fire burning on the 94th floor continued to spread toward the south early in the period, but then seemed to halt near window 94-108 for several minutes.

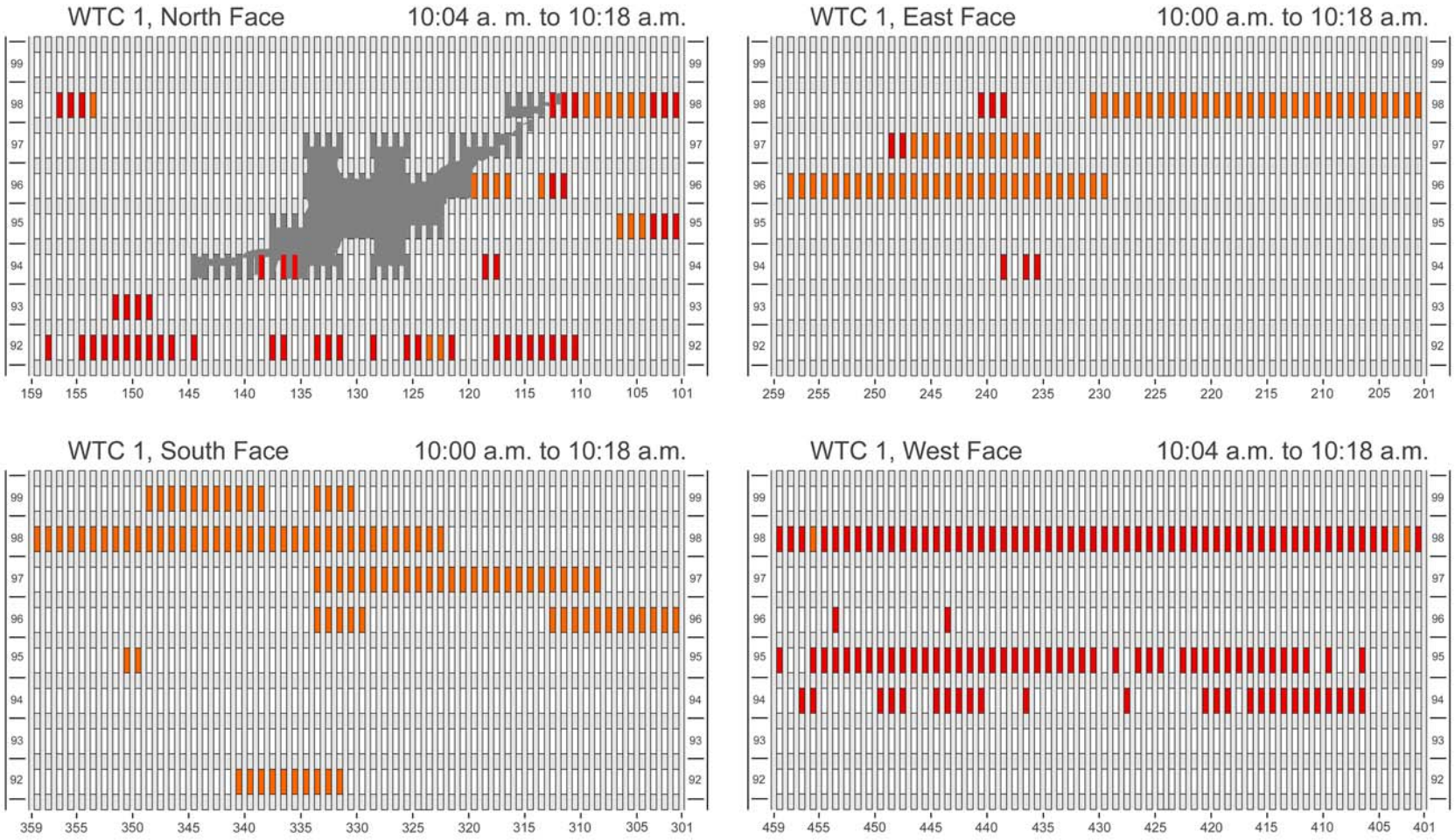

Figure 8-93. Maps of integrated fire observations between 10:00 a.m. and 10:18 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

The large number of people observed falling from the 95th floor around 10:07 a.m. has already been discussed. The table in Appendix M reveals that other people were observed falling from locations well above the fire floors on the north and west faces during the period. Most of these were seen near the end of the period.

The number of streamers observed between 9:58 a.m. and 10:18 a.m. was very limited as shown by the table in Appendix L. This is likely a consequence of the poorer quality of the visual material as well as the fact that much of the observed fire spread was on the east and south sides, which were obscured by dust.

8.8 10:18 A.M. TO COLLAPSE OF WTC 1

Figure 8–94 provides a view of the north face of WTC 1 at 10:18:45 a.m. Comparison with Figure 8–84 shows that, during the just over three and a half minutes between the images, the fire on the 92nd floor continued to move toward the west. In the later image fire is visible as far west as window 92-110. At the earlier time windows to the west of window 92-120 appeared to be intact, with fire present in window 92-121. Despite the presence of flames over a significant length of the floor, the fires appear to be burning at low levels at separated locations. There is essentially no smoke coming from the open windows on the north side of the floor. This indicates that the smoke is likely venting elsewhere.

In Figure 8–84 there was no indication of fire in the room located on the northwest corner of the 95th floor, where a fire is evident in windows 95-101 to 95-104 in Figure 8–94. Videos show that there was a puff of smoke from this area at 10:18:16 a.m. As another video zoomed in, fire was visible in window 95-102 at 10:18:20 a.m. At 10:18:28 a.m. fire suddenly appeared simultaneously at the tops and bottoms of windows 95-101 and 95-103 and shortly thereafter at the bottom of window 95-104. These windows are in the corner room with walls that extended to columns 95-108 and 95-456 (see Figure B-4). Recall that there was no evidence for fire in this room on the west face at 10:18:01 a.m. The visual evidence suggests that a fire grew in this room very shortly after this time.

Fire is present on the 98th floor to the right of the aircraft impact area. This fire has decreased in intensity since 10:15:10 a.m.

At 10:18:48 a.m. an event took place within the tower that created a pressure pulse of sufficient magnitude to force smoke out of numerous windows on the north face, as well as from the other faces. The most obvious effect of this pressure pulse was the release of a dense line of smoke along a length of the 92nd floor on the north face, extending from roughly window 94-110 to window 94-139. This smoke release was evident in numerous videos, including a number shot at great distances. Figure 8–95 compares two frames taken from a video showing the north face just prior to the smoke release and the appearance just over 4 s later. Even though the video was shot from a distance, the line of smoke that has appeared from the 92nd floor is readily apparent. It is significant that until this time very little smoke had been observed coming from the open windows on this floor, even though fires had been burning on the floor for some time.

Closer inspection of this video, as well as others, shows many additional effects of the pressure pulse at other locations on the tower. Smoke and/or dust were pushed out of windows on the east side of the north face at the 94th floor. This material is responsible for the light-colored “smoke” seen near the eastern edge of the building immediately above the darker smoke released from the 92nd floor in Figure 8–95.

Figure 8-94. This image of the north face of WTC 1 was captured from a video shot at 10:18:45 a.m. It has been enhanced by adjusting the intensity range. Some portions of the image to the left of the tower are saturated. Column and floor numbers have been added.

On the western side of the north face there is a region of increased smoke flow higher up in the vicinity of the 95th to 98th floors. While it is difficult to see in the frame recorded at 10:18:51 a.m., it is clear in the video that a large flame was pushed out of windows on the 95th floor by the pressure pulse. Comparison of the two frames shows that smoke is present on the west face in this same area at the later time, which was not apparent earlier.

Figure 8–96 shows a closer view of the north face recorded at 10:18:59 a.m. This image is taken from the same video as Figure 8–94, which was recorded 14 s earlier. The effects of the changes in the smoke and fire described above are easily seen. The black line at the tops of the column covers on the 92nd floor created by the smoke release is visible. The fire on the western edge of the 95th floor has grown dramatically, and flames now extend from windows 95-105 and 95-106. Heavy smoke is now coming from windows on the 95th floor as well as windows at the western edge of the face on the 96th and 97th floors. Smoke is also now flowing from window 102-101 on the 102nd floor.

Figure 8-95. Two images of the north face of WTC 1 captured from a video are shown. The times are 10:18:47 a.m. and 10:18:51 a.m.

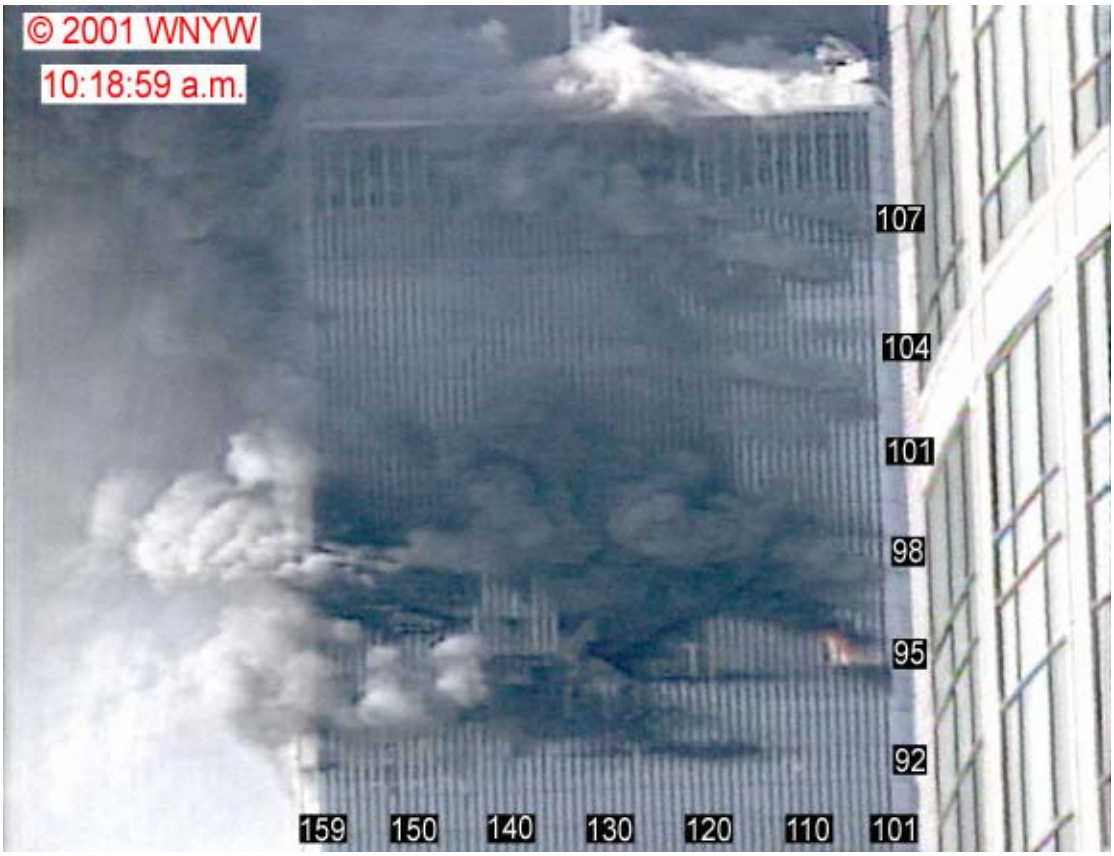

Figure 8-96. This image of the north face of WTC 1 was captured from a video shot at 10:18:59 a.m. It has been enhanced by adjusting the intensity range. Column and floor numbers have been added.

A video shot from the west shows that heavy smoke was pushed out of windows on the 95th and 98th floors on the north side of the west face at the same time the changes were observed on the north face. This video also shows what appears to be a jet of smoke being ejected from a lower floor on the south face of the tower. A view of this jet is highlighted in Figure 8–97, which shows a frame taken from the video 5 s after the start of the pressure pulse, i.e., at 10:18:53 a.m. The smoke coming from the 92nd floor on the north face is also highlighted. The video also shows a large amount of debris falling along the north and south faces of the tower around the time of the pressure pulse.

The available imagery from the south and east around this time provides insufficient detail to detect the effects of the pressure pulse on these faces.

The fact that smoke and fire were pushed out of the tower from numerous windows over multiple floors confirms that a significant pressure pulse was generated inside the building. Similar behaviors were observed when the second plane impacted WTC 2 and when WTC 2 collapsed. While it seems likely that the pressure pulse was generated by some sort of collapse within the tower, e.g., a portion of the core settling or a partial floor collapse, it has not been possible to determine the nature of the event or even its general location based on the visual record.

Figure 8-97. This image showing the west face and an oblique view of the north face was captured from a video shot from a news helicopter at 10:18:53 a.m. The highlighted areas with adjusted intensities indicate smoke and/or dust plumes that were pushed from the north and south faces by a pressure pulse that passed through the tower at 10:18:48 a.m.

Figure 8–98 shows an image of the north face cropped from a photograph that was taken a minute later than Figure 8–96. Light smoke continues to come from the 92nd floor, where low level fires are apparent in windows 92-112 to 92-132. The fire that grew rapidly on the 95th floor immediately following the pressure pulse is still burning intensely, with flames coming from windows 95-106 and 95-107. A review of the floor plan layout for this floor in Figure B-4 shows that this fire is burning within a corner room with walls located at columns 95-456 and 95-108. Apparently, at this time the wall at column 95-108 has halted the spread of the fire toward the east. There does appear to be a fire even further to the east on this floor near window 95-115. A low level fire continues to burn on the 96th floor, with flames visible from windows 96-113 to 96-118. Heavy smoke is still flowing from windows on the 96th and 97th floors.

With the exception of the fires that grew on the 96th and 97th floors shortly after the aircraft impact, it has generally been observed that very little smoke and/or extended flames flowed from open windows on the north face where fires were visible. This has been interpreted to indicate that the smoke from these fires was venting elsewhere within the tower. The fact that smoke and fire continued to vent from the north face following the pressure pulse may be an indication that the internal ventilation pathways were changed as the result of the event responsible for the pressure pulse.

Figure 8-98. This cropped photograph shows the north face of WTC 1 at 10:19:59 a.m. The image has been enhanced by adjusting the intensity range. Column and floor numbers have been added.

A view of the north face at 10:23:30 a.m. is shown in Figure 8–99. The fire on west side of the 92nd floor has grown dramatically since the photograph in Figure 8–98 was taken, three and a half minutes earlier. Heavy flames fill the openings from window 92-108 to window 92-114, and a nearly continuous region of flame is apparent from window 92-108 to window 92-132. The floor plan layout for the 92nd floor in Figure B-1 shows that a large open area extended along the north face between walls located at columns 92-132 and 92-105. Figure 8–99 indicates that nearly this entire area was involved in fire at this time. A small fire is evident in window 92-104, while windows 92-101 to 92-103 and window 92-105 appear to be closed. This indicates that a fire has moved into the northwest corner room with walls located at columns 92-105 and 92-455. Interestingly, in an almost identical photograph recorded five seconds earlier, the fire in window 92-104 was not visible, and all of the glass for windows in the corner room appeared to be intact. This suggests that the fire in the northwest corner room of this floor had just become large enough to break windows at this time. This close-up photograph also reveals that small spot fires continued to burn on this floor at the eastern side, where larger fires had been present earlier.

Videos reveal that the heavy fire near window 92-110 began to grow rapidly around 10:21:30 a.m. Smoke was observed coming from windows in the area somewhat earlier. In the videos the small fire present in window 92-104 is barely visible around 10:23:30 a.m. At 10:24:04 a.m. a bright flame suddenly appeared in window 92-103, and smoke was released from this window. A stream of smoke appeared from window 92-101 at 10:24:07 a.m., and an intense puff of smoke came from the same window at 10:24:21 a.m. Rapid fire growth occurred at this point, with flames clearly visible in windows 92-101 to 92-103. Apparently, flashover occurred in the northwest corner room around this time.

Figure 8-99. This cropped photograph shows the north face of WTC 1 at 10:23:30 a.m. The image has been rotated and enhanced by adjusting the intensity range. Column and floor numbers have been added.

By 10:23:30 a.m. the fire in the northwest corner room of the 95th floor had begun to die down, and the flames that were outside of windows at the time of Figure 8–98 had receded back into the building. The carets created by these external flames on the aluminum covers for columns 95-105 to 95-108 are very distinct in Figure 8–99. Dull orange flames can be seen through windows 95-108 and 95-109, indicating that a fire was present on the other side of the wall located at column 95-108 (see Figure B-4). It is not clear whether the glass in these windows has broken or not. A small spot fire is also visible in window 95-115. The dying fire on the western side of the 96th floor is not visible in Figure 8–99, but small flames can be seen higher up on the 98th floor.

Over the next several minutes, the fire on the western half of the north side of the 92nd floor continued to grow more intense, while the other fires on the north side of the floor continued to decay. Figure 8–100 shows a photograph of a portion of the north face of WTC 1 taken at 10:28:06 a.m. This is roughly 16 s before the tower began to collapse. The large fire burning on the 92nd floor at this time is evident. Flames can also be seen on the north edge of the west face, indicating that the fire has turned the northwest corner and begun moving south on the west face.

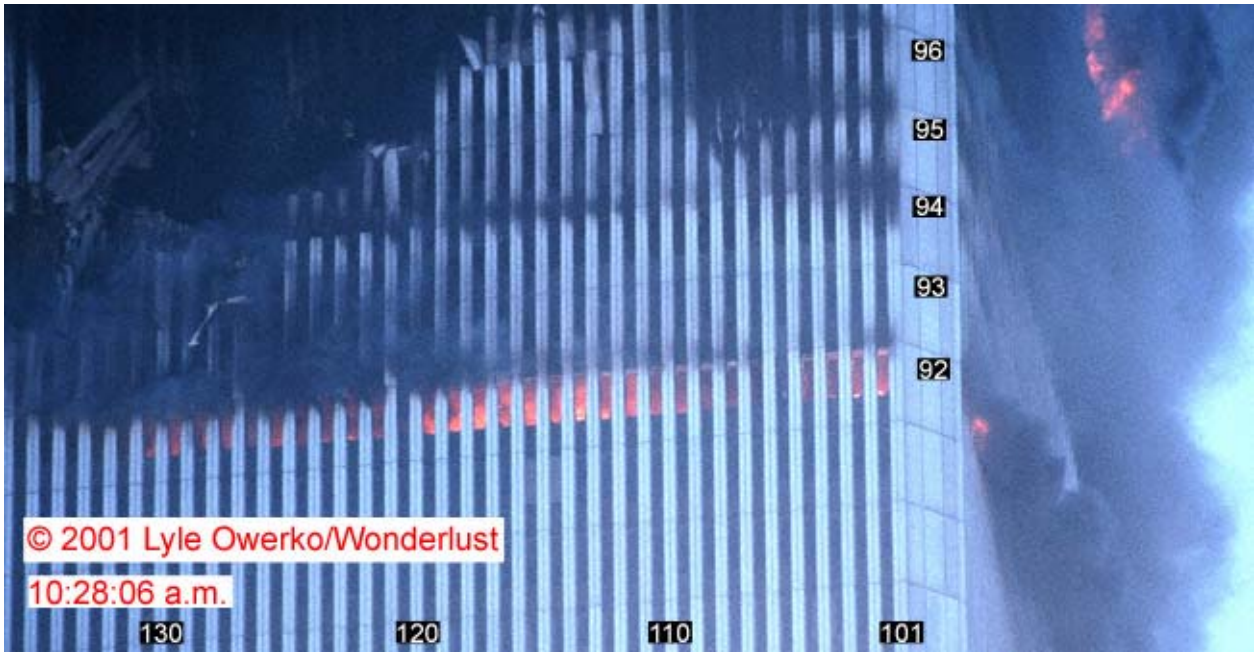

Figure 8-100. This cropped photograph shows a portion of the north face and an oblique view of the west face for WTC 1 at 10:28:06 a.m. The intensity levels of the image have been adjusted, and column and floor number have been added.

This photograph has sufficient resolution and contrast to allow a determination of whether windows are open or intact. It appears as if three windows on the 92nd floor, windows 92-105, 92-106, and 92-120, still have glass in place. The other windows visible on this floor are open.

The photograph in Figure 8–100 was shot from a ground location relatively close to and slightly west of the tower. For this reason it may not provide as complete a view of interior fires as some of the other images shown earlier. Nonetheless, it is clear that the fires that were easily identified minutes earlier on the 95th, 96th, and 97th floors are not visible and must be burning at relatively low levels. The fact that the fire on the 92nd floor is so prominent supports this conclusion.

Windows on the west side of the north face on the 91st and 93rd floors were still closed just prior to the collapse of the tower. This indicates that fire had not moved into the northwest corner of the tower on the 93rd floor by this time. Fire had been present on the other floors between the 92nd and 98th floors as indicated by open windows and earlier observations. It is evident in Figure 8–100 that windows on the 95th floor from window 95-108 to window 95-113 still have glass in place, even though the pane in window 95-108 appears to be broken. This indicates that the fire observed through these windows in Figure 8–99 did not become intense enough to break the windows.

The photograph shown in Figure 8–101 was shot 1.4 s after WTC 1 began to collapse. The lines of dust visible coming from the 98th floor on the north and west faces of the tower may be an indication that the collapse began near this floor. As the building collapsed it acted as a piston, forcing air downward onto other floors. The resulting pressure increase forced gas flows out of open windows on lower floors. As a result of this process, fire and smoke were pushed out of the building.

Approval needed for image.

Figure 8-101. This cropped photograph shows the north face of WTC 1 at 10:28:23 a.m. The image has been enhanced by adjusting the intensity levels. Column and floor numbers have been added.

In the photograph a large area of fire is being pushed from windows on the 92nd floor on the west side of the north face and the north side of the west face. This is the region where an intense fire had grown during the previous ten minutes or so. Fire is evident coming from windows across the large room on this floor with walls at columns 92-105 and 92-132 (see Figure B-1), as well as from the room in the

northwest corner with internal walls at columns 92-455 and 92-105. The large volume of fire being pushed out of the windows provides an indication of how widespread the flames were in this area of the tower. Smaller flames are also visible coming from windows 92-146 to 92-152 on the eastern side of the face. This indicates that fires had continued to burn in two of the small rooms located along the north face (see Figure B-1).

Flames were also pushed out of windows located in the northwest corner room on the 95th floor with walls at columns 95-108 and 95-456 (see Figure B-4). This is an area that had been burning earlier, but had appeared to have died down just prior to the initiation of the collapse. It is clear from this photograph that a significant fire was still burning in the immediate vicinity. The absence of visible fire being expelled elsewhere on the north face provides additional evidence that intense fires observed at other locations on the north face at earlier times had either died down or gone out.

Figure 8–102 shows a view of the east face of WTC 1 recorded at 10:18:15 a.m. The face is still partially obscured by dust rising from below. The fire distribution is similar to that derived from the partial view of the east face shown in Figure 8–86 at 10:17:33 a.m. The largest fire is on the 98th floor and extends from roughly window 98-210 to window 98-228. There still appears to be some flame extension from open windows, but the large flames evident in Figure 8–86 are not present. Flames fill several adjacent windows on the 97th floor centered near window 97-244. Flames are also present on the 96th floor, but do not appear as intense as those seen on the 97th floor. There is definitely a fire burning higher up on the 101st floor near window 101-225. Recall that this fire was also visible in Figure 8–86, but that its presence could not be confirmed due to the intense fire burning lower down on the 98th floor.

In a video shot from a long distance around 10:19 a.m., intense flames could be seen occasionally coming from the southern edge of the east face on the 96th floor and more towards the center on the 98th floor. Around 10:19:43 a.m. this video zoomed in somewhat closer, though still at a relatively long distance, and a fire distribution very similar to that in Figure 8–102 could be discerned. With one exception to be described below, after this time the available videos showing the east face were shot from extremely long distances. In these videos only intense fires with long flames extending from windows were visible.

The long-distance videos indicate that around 10:20:30 a.m. a large extended flame appeared near the center of the east face. This flame was most likely on the 98th floor near the southern end of the fire that had been burning on the northern half of this floor since well before 10:00 a.m. (see Figure 8–59 and Figure 8–102). Several videos show that around 10:21:15 a.m. there was an intense burst of flame from the tower at a location roughly halfway between the center of the east face and the south end. This new region of intense fire rapidly expanded in both directions, and within 30 s a line of fire was visible that covered roughly one fifth of the width of the east face.

This area of flame on the southern side of the east face is visible in Figure 8–99, which was taken at 10:23:30 a.m. The fire is burning intensely with extended flames. Figure 8–103 shows a lower-resolution photograph taken at 10:23:41 a.m. that provides a slightly less oblique view of the east face in which it is easier to identify the flame location. The area where flames are visible coming from open windows has been highlighted. Flames can be seen on the 98th floor at two apparently separated locations. One of these is near the center of the face, and the second is well to the south. Even though the flames appear to be separated, videos and Figure 8–99 show that the flaming region was continuous over

this length. A small area of fire is also visible on a lower floor. This fire is most likely on the 97th floor near the location where fire was present (near window 97-145) in Figure 8–102 at 10:18:15 a.m.

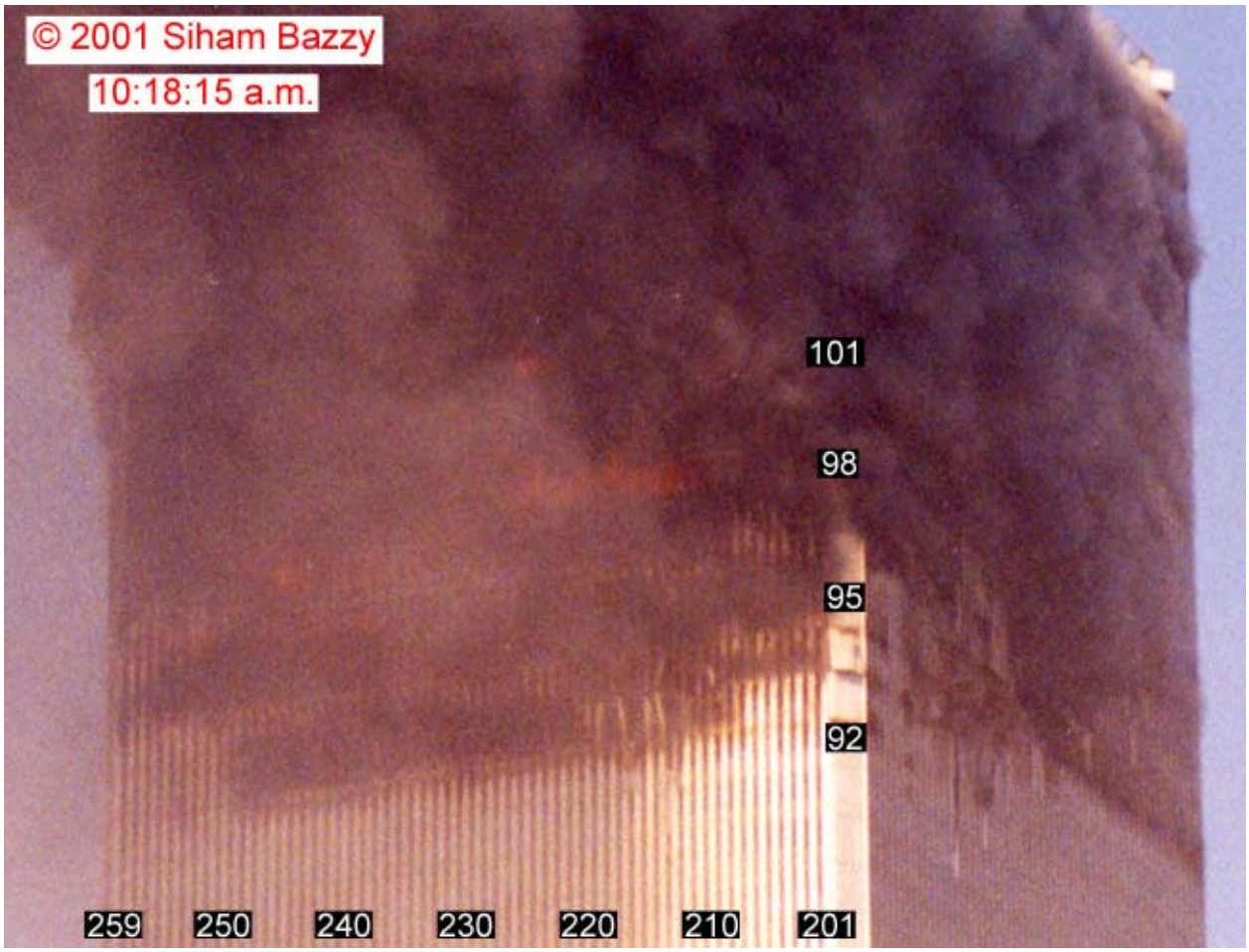

Figure 8-102. This cropped photograph showing the east and north faces of WTC 1 was shot at 10:18:15 a.m. It has been enhanced by adjusting the intensity levels. Column and floor numbers have been added.

An image of the east face shown in Figure 8–104 taken from a video recorded at 10:24:05 a.m. provides another view of the fire burning on the south side of the 98th floor. Since this image was recorded from further east than Figure 8–103, it is easier to identify the location of the burning area. It does extend from near the center of the face toward the south. An area of fire on the 97th floor is visible immediately below. At 10:18:15 a.m. a similar area of fire was visible near window 97-245 (see Figure 8–102). This location is consistent with the apparent position of the fire in Figure 8–104. This suggests the intense fire present on the 98th floor roughly covers windows 98-230 to 98-245.

The long-distance videos show that the line of fire visible on the 98th floor remained the dominant feature on the east face until WTC 1 collapsed at 10:28:22 a.m. While the distance of the video makes it difficult to draw definitive conclusions, the following trends were identified. After the apparent rapid spread of the fire between 10:21 a.m. and 10:22 a.m., the fire continued to spread toward the south at a much reduced rate. It was well short of the south face when WTC 1 collapsed. After burning very intensely for

several minutes, the fire had begun to diminish and was not as easily identified during the last two minutes prior to the collapse.

Figure 8-103. This cropped photograph shows the north face and an oblique view of the east face of WTC 1 at 10:23:41 a.m. The intensity levels in an area of the east face have been adjusted to highlight an area of extended flame.

Roughly three seconds prior to the initiation of collapse at 10:28:22 a.m., the line of fire began to brighten noticeably, and intensely burning flames were coming from the 98th floor as the collapse began. As observed on the north face, flames were expelled from the east face by the pressure increase generated by the collapse. Figure 8–105 shows a frame taken from one of the long-range videos roughly two seconds after the collapse of WTC 1 began. The fire expelled from the 98th floor on the southern side of the east face is very bright. There was no apparent expulsion of fire from lower floors on this face. This supports the conclusion that the fire on the 98th floor was the largest fire present on this face at the time of collapse. In this same video a flame appeared much higher up on the south side of the east face roughly

one and a half seconds after Figure 8–105 was recorded. It has not been possible to identify the origin of this expelled flame, but it does suggest that a fire was burning on a higher floor on this side of the tower.

Figure 8-104. This frame was taken from a video recorded at 10:24:05 a.m. It was shot from the northeast and shows the north and east faces of WTC 1. The image has been enhanced by adjusting the intensity levels.

Views of the south face of WTC 1 are limited during the current time period. Fortunately, several photographs taken from a helicopter flying relatively close to the tower provide a good indication of conditions on this face roughly halfway through the period.

As already noted, a long-distance video shot from a news helicopter located to the south around 10:17:45 a.m. showed a fire distribution similar to that seen in Figure 8–88. Review of the same video shows that the fire on the 98th floor moved to the east sometime between 10:18:40 a.m. and 10:19:25 a.m. The intensity of the flames burning in the new area was greater than that observed prior to the fire movement.

Fires burning on the east side of the south face on the 97th floor and along a length running from just to the east of the center of the face to the western side of the 99th floor were also visible. The fire on the 97th floor seemed to be centered near the middle of the eastern half of the floor and covered roughly one quarter of the width of the tower. This is in the same area of the floor where fire can be seen in Figure 8–88. The flames appeared to be most intense at the right side of the visible fire length. The fire on the 99th floor extended to the west more that three quarters of the way across the tower. These flames were more intermittent and less intense than those observed on the 97th and 98th floors.

The video shows that the same general fire pattern was present over the next couple of minutes. It is possible that the fires on the 97th and 98th floors moved slightly to the east. The fire on the 98th floor had flames out of the windows over a wide width. On the 97th floor the fire was generally less intense, but large flames would occasionally appear, especially on the eastern side of the burning length. The fire burning on the 99th floor became less prominent as time passed.

Figure 8-105. This frame taken from a video recorded at 10:28:24 a.m. shows WTC 1 from the northeast.

Figure 8–106 shows WTC 1 shot from the southwest at 10:22:44 a.m. The photographer was in a helicopter looking down on the tower. Individual floors are identifiable. Floor numbers can be assigned by noting that the floor with the missing aluminum panel on the southwest corner is the 96th floor. Fires are visible on both the south and west faces. Focusing on the south face, the most prominent feature is a flame jet emanating from an open window on the 98th floor on the east side. Flames are also coming out of nearby windows on this floor. Regions of fire are also visible on the 99th floor at locations starting on the west side of the face and reaching a position just to the east of the center of the face. From this angle, there are no flames evident on the 97th floor. Otherwise, the flame distribution is consistent with that described above.

As the helicopter flew toward the south, the photographer continued to take pictures. Figure 8–107 shows a photograph taken 15 s later at 10:22:59 a.m. Since the helicopter was further south, this image has a more direct view of the south face than in Figure 8–106, and the view of the west face is from a more oblique angle. The fire distributions on both faces look quite different in the two photographs. This

demonstrates the strong effects that the angle from which an image was taken could have on fire observations.

Figure 8-106. This cropped photograph showing the south and west faces of WTC 1 was shot from a helicopter at 10:22:44 a.m. It has been enhanced by adjusting the intensity levels.

In Figure 8–108 the image shown in Figure 8–107 has been blown up further to provide an enhanced view of the south face fires. Column and floor numbers have been included. The floor numbers have been placed on both edges of the tower so that the inclined floors can be more easily identified.

An important observation is readily apparent in Figure 8–108. Many of the columns on the south face in the vicinity of the 95th floor to 98th floors were bowed inward at this time. The easiest way to identify this bowing is to start lower down on the building and use your eyes to follow a particular column

upward. The bowing appears as a curvature in the column. The bowing is most apparent on the eastern side of the face. It may be present on the western side as well, but it is more difficult to identify because of angular effects along with the blackening of the column covers on the western side of the face. Recall that this blackening occurred as a result of the heavy smoke released on this side of the face by earlier fires on the 95th and 96th floors. The degree of column bowing is analyzed in the Investigation report dealing with the structural steel (NIST NCSTAR 1-3C) and compared with building response calculations in NIST NCSTAR 1-6.

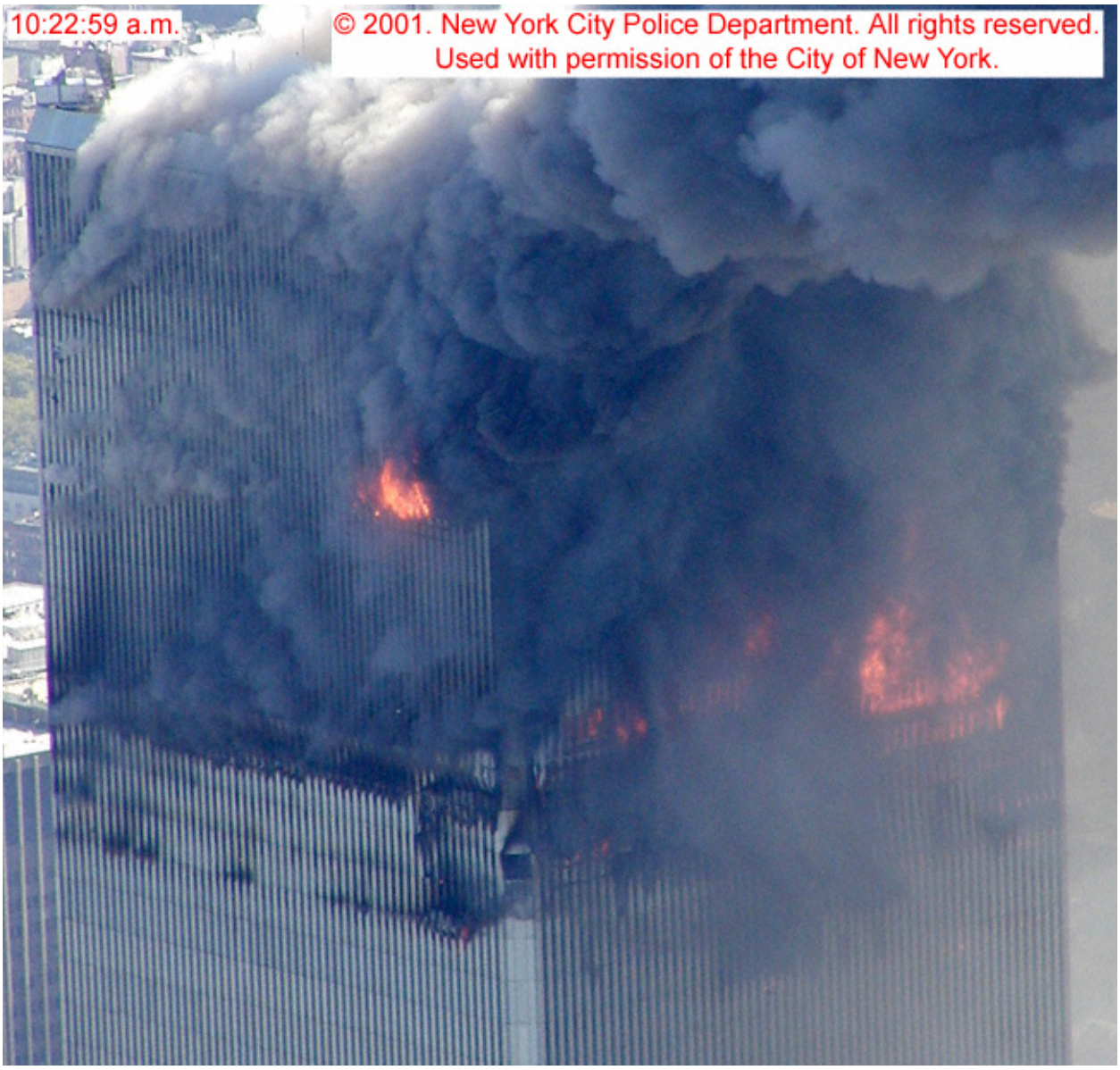

Figure 8-107. This cropped photograph showing the south and west faces of WTC 1 was shot from a helicopter at 10:22:59 a.m. It has been enhanced by adjusting the intensity levels.

Figure 8–108 shows that there were extensive fires on the south face of WTC 1 at 10:23 a.m. There is visual evidence for the presence of active fires on the 92nd floor upward through at least the 101st floor.

Consistent with conclusions based on long-range images, the most intense fire is on the east side of the 98th floor. Flames that appear to be at least two stories in height are coming from windows 98-308 to 98-322. There are also large fires visible on the east side of the 97th floor and the west side of the 99th floor. On both floors the flames cover roughly half the width of the tower. In this photograph the flames on these floors do not appear to extend from the open windows. In reviewing the videos, it is clear that flames on both floors occasionally formed large external flares around this time. In fact, such a flare is visible coming from near window 97-308 in another photograph (not shown) taken from the helicopter at 10:22:50 a.m.

Figure 8-108. This photograph showing the south face of WTC 1 is a blowup of a portion of Figure 8–107. It was shot from a helicopter at 10:22:59 a.m. It has been enhanced by adjusting the intensity levels, and column and floor numbers have been added.

It is interesting that the fires on the 97th and 98th floors do not appear to have spread to the east end of the face. The last window with fire on the 97th floor appears to be window 97-308. A check of the floor plan layout in Figure B-6 shows that there was a room in the southeast corner of this floor with walls at columns 97-256 and 97-308. Recall that the fire spreading south on the east face of this floor did not

appear to have reached the south edge at this time. These observations suggest that the walls of this room were acting as a fire barrier. A similar room was present and acting as a fire barrier on the 98th floor (see Figure B-7).

There is an area of fire on the 100th floor. Flames can be seen extending from windows 100-334 and 100-335, and flames are present near window 100-338. There also appear to be flames coming from a higher floor (101st floor?) on the east side of the face, but this is somewhat ambiguous due to the large flames coming upward from the 98th floor.

Glowing areas from internal fires near the eastern edge of the south face are visible on the 94th, 95th, and 96th floors. Recall that the presence of relatively small fires had been observed in this area of the 94th floor prior to the collapse of WTC 2. The fires on the 96th floor had been more intense earlier, as they were observed in long-range shots of the south face (e.g., see Figure 8–87).

Small flames are also visible on the 96th floor near the western edge of the building. This area began burning around 9:00 a.m. On the 97th floor just above, which began burning somewhat later, no flames are evident. The fact that the fires at the southwest corner of the 96th floor continued burning for an unusually long period may be an indication that there was a pile of debris in this location. This would be consistent with the removal of the cover aluminum panel from the southwest corner of the 96th floor during the aircraft impact and subsequent fireball.

Even though flames are visible on the 94th floor on both the eastern edge of the south face and near the southern edge of the west face, it appears as if much of the 94th floor along the south side of the building has not yet burned. This would suggest that the fire burning on the eastern side of the face reached this location by progressing down the east side of the floor. Recall that the fire on the east face had spread in this direction and had been observed near the south face.

Smoke appears to be coming from the 93rd floor from roughly window 93-318 to window 93-324. These windows were closed earlier. Even though flames are not visible at this location, this suggests that there may be a fire burning nearby. Smoke is also coming from multiple windows on the 92nd floor, and small spot fires are evident in several windows, including 92-312, 92-314, 92-333, and 92-334. This suggests that fires that were initially ignited on the east side of the tower shortly after the aircraft impact on the 92nd floor have also worked their way to the south face.

At some point between 10:24:20 a.m. and 10:24:55 a.m., heavy smoke began to pour from one or more south face windows on the 94th floor near the west edge. A burst of external flame occurred in the area at 10:25:10 a.m. In Figure 8–108 heavy flames and smoke can be seen coming from window 94-405 on the west face at 10:22:59 a.m. This window was located in a southwest corner room with walls at columns 94-405 and 94-353 (see Figure B-3). These observations indicate that the fire moving south along the west wall of the 94th floor entered this room and created flashover conditions around 10:23 a.m.

In the next few minutes following the time when Figure 8–108 was taken, the long-distance helicopter video showed that the line of fire on the south face of the 98th floor continued to burn vigorously. The fire on the 99th floor appeared to move toward the east and also began to burn very intensely. It eventually reached a location more than halfway between the center of the face and the east edge. Occasionally, the fire on the 97th floor could also be seen.

Figure 8–109 shows a long-distance photograph of WTC 1 that was shot at 10:28:08 a.m., i.e., 14 s prior to collapse. Even at this distance the intense fires burning on the east side of the south face on the 98th and 99th floors are readily apparent.

Figure 8-109. This cropped photograph taken from the south southwest shows WTC 1 at 10:28:08 a.m.

At 10:28:22 a.m. WTC 1 began to collapse. Unfortunately, the long-distance helicopter video is not particularly clear at this time. Even so, it is possible to see a large amount of flame being pushed from the tower on the south face by the pressure increase due to the collapse. The expelled fire appears to come from three separate locations on the south face. The first is from the vicinity of the intense fire burning on the east sides of the 98th and 99th floors. The second is from the fire burning on the western edge of the 94th floor. The location of the third area was more difficult to identify. It appears to come from the center of the eastern half of the face from near the 94th floor. It created a huge flame that at first was driven downward. So much fuel and heat were pushed out of the tower that a fireball formed and began to rise. The fireball burned out nearly 4 s after the collapse began.

Figure 8–110 is a frame taken from the video just after initiation of the collapse. Two areas have been highlighted that show the areas of fire pushed out of windows on the east sides of the 98th and 99th floors and the west side of the 94th floor. The third area of fire coming from lower down on the east side of the face is barely visible. A second frame from the video sequence is shown in Figure 8–111. It was taken 2.3 s after the frame in Figure 8–110. The highlighted area includes a rising fireball that was formed by the fire pushed out of the tower from lower down on the east side of the south face.

During the period immediately following 10:18 a.m., the west face of WTC 1 was also filmed from a news helicopter. No close views of the face were taken, but at certain times the camera zoomed in sufficiently to allow fire and smoke to be observed. A large amount of smoke was pushed from multiple windows near the north edge of the 95th floor when the pressure pulse described earlier occurred at 10:18:48 a.m. A fire that was already visible in window 95-454 grew larger shortly afterward and filled windows 95-454 and 95-455. The floor plan layout shown in Figure B-3 indicates that this fire was burning inside a room with walls located at columns 95-452 and 95-456. Even though smoke was coming from windows 95-456 to 95-458, fire was not visible at the distance of the video. This remained true until at least 10:20:55 a.m.

As discussed earlier and can be seen in Figure 8–90, Figure 8–91, and Figure 8–92, the fire moving south on the west side of the 94th floor had reached window 94-407 by 10:07 a.m. and apparently remained at this location until at least 10:18 a.m. At some point between 10:19:15 a.m. and 10:20:45 a.m., this fire moved south two windows, and flames were visible in windows 94-405 and 94-406. Recall that there was an interior wall located at column 94-405 (see Figure B-3), and it is somewhat surprising that the fire had not appeared in these windows earlier.

In the helicopter video shot from the west the orange glow from the fire burning on the 98th floor was barely visible. The intense fire that had grown on the 104th floor continued to burn vigorously.

A close-up photograph of the west face taken at 10:22:40 a.m. from a helicopter looking down on the tower is shown in Figure 8–112. Fires are visible on the 94th, 95th, and 98th floors. In general, the fire distributions are consistent with the discussion immediately above.

On the 94th floor fires can be seen at many locations between windows 94-405 and 94-448. Most of the fires are burning at isolated locations near the floor. The only window where flames are protruding out is 94-405. The presence of carets on nearby column covers is consistent with the intense fire seen earlier at windows 94-407 and 94-408. The smoke marks at the tops of the column covers indicate that at many locations only light smoke or no smoke had passed through the open windows. This agrees with earlier observations that the fires burning on the west side of the 94th floor were relatively gentle at most locations. In Figure 8–112 windows 94-438 to 94-441 appear to be open, and flames are visible in windows 94-438 to 94-440. These windows were clearly intact at 9:47:34 a.m. in Figure 8–72. The floor plan layout in Figure B-3 indicates that these four windows were located in a room with walls at columns 94-438 and 94-441. Fire had clearly spread into this room since 9:48 a.m. Many other windows on this floor that had intact glass at the earlier time are also open in Figure 8–112.

Figure 8-110. This image showing the south face of WTC 1 was taken from a video shot from a news helicopter at 10:28:23 a.m. The intensity levels of the image have been adjusted. Two areas showing flames that were pushed out of the tower as it started to collapse are highlighted.

Figure 8-111. This image showing the south face of WTC 1 was taken from a video shot from a news helicopter at 10:28:25 a.m. The intensity levels of the image have been adjusted. An area showing a fireball generated by fire pushed from the tower by the collapse is highlighted.

Figure 8-112. This cropped photograph was shot from a helicopter at 10:22:40 a.m. and shows the west face of WTC 1 from above. The image has been enhanced by adjusting the intensity levels, and column and floor numbers have been added.

Fires are visible on the 95th floor over most of the length of the west face. At most locations the fires look similar to those on the 94th floor, appearing to burn with low intensities near the floor. Exceptions are the most intense flames located in the room having walls at columns 95-452 and 95-456 (see Figure B-4) and the fire in windows 95-408 to 95-411. The fire on the north side has already been described, while the fire on the south side is located next to a room with walls at columns 95-404 and 95-408. Over most of this floor there are no smoke marks on the column covers despite the wide spread fires. This observation most likely means that the smoke from fires on this side of the 95th floor vented within the building elsewhere.

From the angle from which Figure 8–112 was taken the internal fires on the 98th floor are only visible near the center of the floor and at a few locations on either end. This fire has clearly died down considerably since Figure 8–92 was taken at 10:18:01 a.m. Carets are visible at the tops of the column covers near the two ends, but very little marking is evident elsewhere. This suggests that the only places flames came out of windows were from fires burning inside the corner rooms (see Figure B-7). Consistent with earlier observations, the absence of column cover marks elsewhere indicates that neither fire nor smoke flowed from most 98th floor windows on the west face where fire was present.

There is no indication of fire on the 96th or 97th floors on the west face. Both of these floors were on fire much earlier and have apparently completely burned out. It is worthwhile to point out once again the difference in column cover markings between the two floors. Heavy smoke and fire came from most of the windows on the 97th floor, as revealed by the numerous carets on the covers. On the other hand, the 96th floor seemed to burn much more like the fires seen on the 94th and 95th floors, i.e., gently with little smoke and fire coming from windows.

There are no indications of fire or open windows on the west side of the 92nd floor or 93rd floor. Apparently fires burning elsewhere on these floors had not yet reached this face.

An image of the fires on the 104th floor at 10:22:40 a.m. is shown in Figure 8–113. It was cropped from the same photograph as Figure 8–112. It shows that after first appearing twenty minutes earlier, this fire continued to burn very intensely with long flames extending out of the windows. Visible flames and column cover smoke marks indicate this fire has burned from window 104-403 to window 104-418. Despite the intensity of the fire, it has not spread significantly since its initial growth period, as indicated by comparison with earlier photographs.

Close-up imagery of the west face over the next several minutes was very limited. Figure 8–114 shows an image of the face recorded at 10:26:54 a.m. that provides sufficient resolution to resolve windows and floors. Fires are visible at several locations on the face. Some changes have taken place since Figure 8–112 was taken at 10:22:40 a.m. Fire has appeared in the two adjacent rooms nearest the northwest corner of the 92nd floor (see Figure B-1), which have walls at columns 92-452 and 92-455 and share an east wall that terminates at column 92-105. Flames are now present in windows 92-454 to 92-458. Videos shot from the northwest and southwest show that heavy smoke first appeared in this area at 10:25:21 a.m. As already discussed, a similar stream of smoke came from window 92-101 on the north face at 10:24:26 a.m. These observations indicate that flashover occurred in these rooms around this time.

Figure 8-113. This cropped photograph shows a view of the west face of WTC 1 shot looking down from a helicopter at 10:22:40 a.m. The image has been enhanced by adjusting the intensity levels, and column and floor numbers have been added.

Flames are also visible in Figure 8–114 on the 94th floor in windows 94-101 to 94-104 that were not visible in Figure 8–112. This is consistent with the conclusion (discussed above) that flashover occurred in the southwest corner room of this floor (see Figure B-3) around 10:23 a.m. Flames also extend a significant distance from open windows in this room on the south face.

In the earlier photograph (Figure 8–112) a bright flame was evident at window 95-408 on the 95th floor, but windows further to the south appeared to be closed. In Figure 8–114 bright fires can be seen in windows 95-404 and 95-405. This indicates that fire had entered the room along the west face having walls at columns 95-404 and 95-408 (see Figure B-4). Based on this photograph, the windows in the corner room with walls at columns 95-350 and 95-404 may still be closed.

The interior fire near the center of the 98th floor is still visible in Figure 8–114. Flames are also visible in the windows located in the room on the 95th floor that had walls at columns 95-452 and 95-456, but the flames appear to have died down somewhat since 10:22:40 a.m. The flames seen at other locations on the

94th and 95th floors in the earlier photograph are not apparent at the later time. This is not surprising since this photograph was shot from the ground, albeit at a large distance, and fires burning near the floors should not be visible.

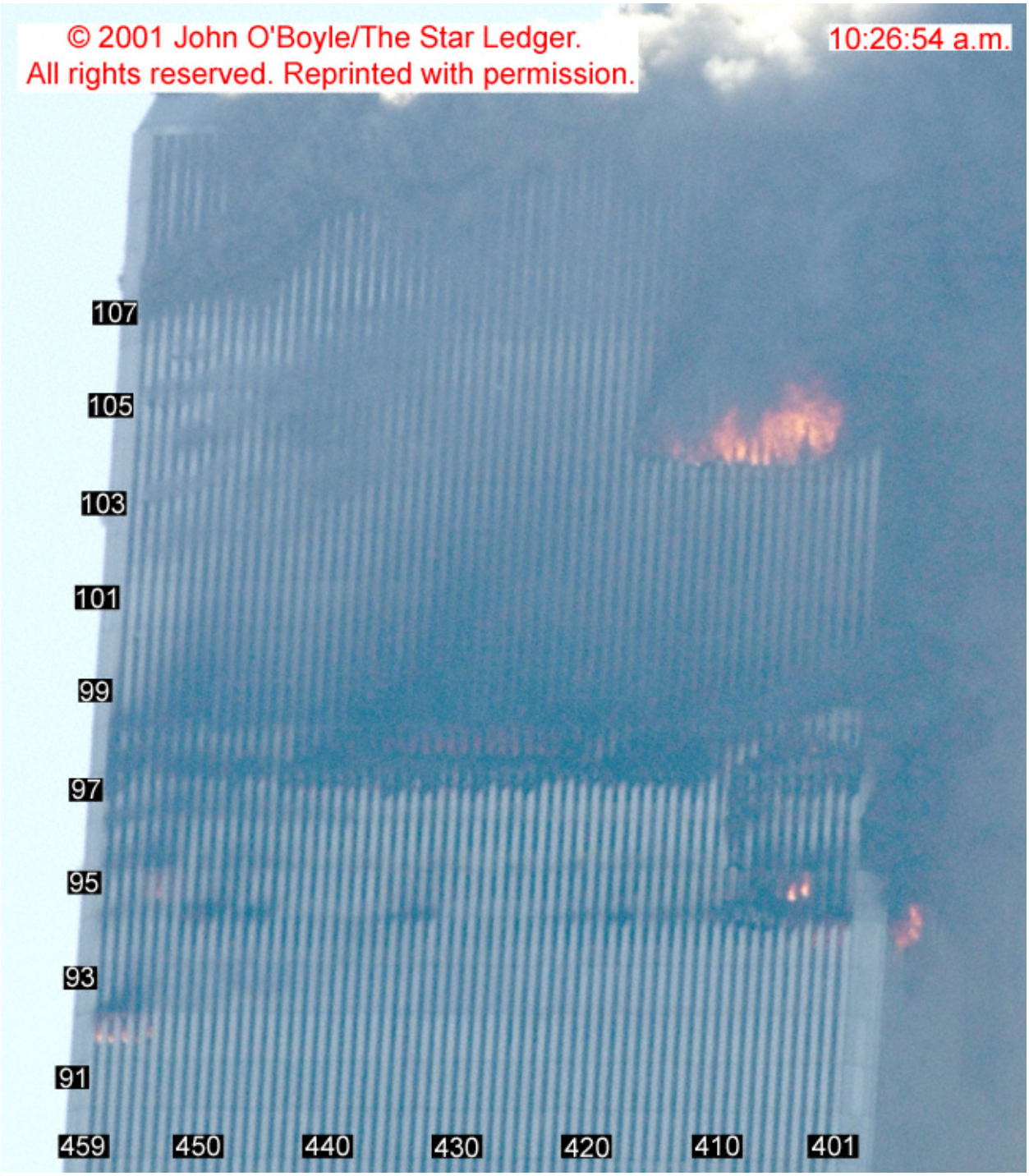

Figure 8-114. This cropped photograph showing the west face of WTC 1 was taken at 10:26:54 a.m. The image has been enhanced by adjusting the intensity levels, and column and floor numbers have been added.

Multiple videos show that an intense jet of smoke and flame exited near a 92nd-floor window, 92-155, at 10:27:40 a.m. The reason for this release of flame is difficult to understand since fire had been observed in the room where this window was located much earlier.

A video shot from the northwest shows that smoke was forced out of west face windows on the north edge of the face and two locations closer to the center of the face, locations where smoke had not be observed previously, approximately two seconds before the collapse of WTC 1 began. At the same time smoke and fire began to flow from the 94th floor at the south edge. Recall that a noticeable brightening of the fire burning on the 98th floor on the east face was also observed just seconds prior to the collapse. These observations indicate that a pressure pulse passed through the tower seconds before the actual collapse was identified visually.

As the tower collapsed, the resulting pressure increase pushed intense flames out of windows at the northern edge of the 92nd floor, at the northern edge of the 95th floor, at the southern edge of the 94th floor, and from the intensely burning region on the 104th floor. Some of these flames are visible in Figure 8–101. These locations are consistent with the most recent observations of active fires on the west face.

The results of integrating the fire data sheets for the period between 10:18 a.m. and 10:28 a.m. are shown in Figure 8–115. The same cautions apply as for the analogous data shown in Figure 8–93. In particular, data for the east and south faces should be considered approximate due to the quality of imagery for these faces during the period.

Comparison of Figure 8–93 and Figure 8–115 shows that during the final time period prior to the collapse of WTC 1, intense fires grew in or spread to several locations, including the western half of the north side of the 92nd floor, the southern half of the east side of the 98th floor, and the eastern halves of the south sides of the 98th and 99th floors.

In addition to the large fire that developed on the north side of the 92nd floor, localized fires were visible on the 95th, 96th, and 98th floors. The fire on the 95th floor grew noticeably larger following a pressure pulse that pushed smoke and fire from multiple open windows at 10:18:48 a.m. Areas of flame were pushed out of windows on the 92nd and 95th floors when the tower collapsed.

On the east face a very intense flame developed on the south side of the 98th floor during the final ten minutes of the event. The external flames generated by this fire were some of the largest observed coming from WTC 1. It is likely that fires continued to burn on other floors on this side of the tower, but the imagery was not sufficient to create a complete record of these fires. There is evidence that a fire developed on this side of the 101st floor (not shown in figure).

During the final ten minutes before collapse very large fires were burning on multiple floors on the eastern side of the south face. This was the area that had been relatively isolated from fire during the first hour of the event. The fires on the 98th and 99th floors were particularly intense. The fire on the 99th floor appeared to have migrated from the west side of the face. The source of the 98th floor fire is more problematic since intense fires were observed earlier on this floor on the west side of the south face and at roughly the same time on the nearby east face. Whatever the source, the presence of extended regions of external flames on both the east and south faces shows that the fires in the southeast quadrant of the 98th floor were particularly intense during the period immediately prior to collapse.

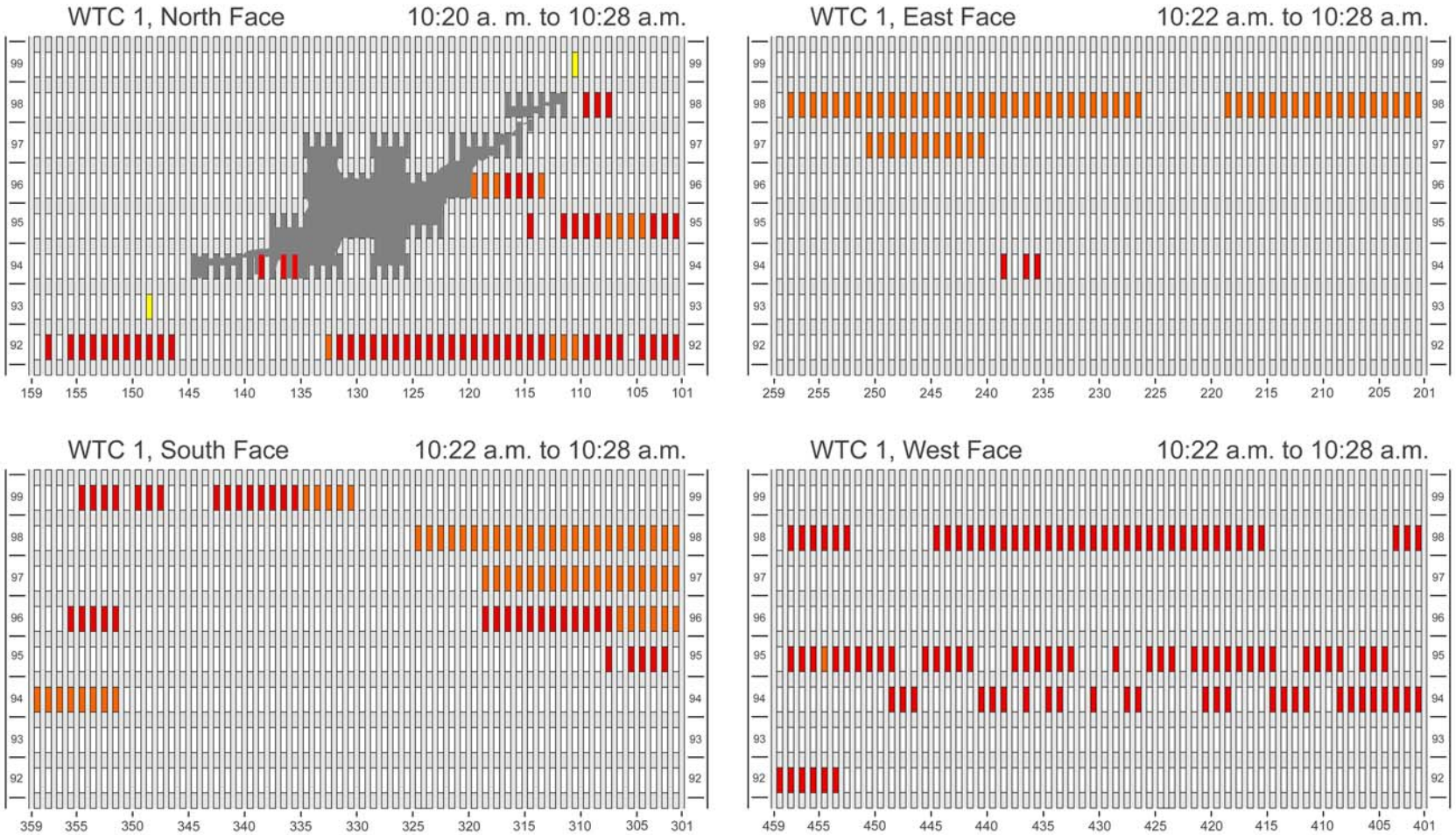

Figure 8-115. Maps of integrated fire observations between 10:20 a.m. and 10:28 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

With the exceptions of the 92nd floor, where a large fire burning on the north face worked its way around the northwest corner, and the 94th floor, where the fire spreading from the north passed around the southwest corner; only limited fire spread took place on the west face during the period. In general, fires that were burning on the 94th, 95th, and 98th floors earlier, while still widespread, became less intense and were less visible than earlier. A large fire on the west face that grew on the 104th floor shortly after the collapse of WTC 2 (not shown in Figure 8–115) continued to burn intensely throughout the period. Most of the 92nd floor, the exception being at the northern edge, and the 93rd floor appeared to be fire free on the west side when the tower collapsed.

Two pressure pulses that were large enough to force smoke and fire from open windows on multiple faces and floors were observed during the period. The first occurred at 10:18:48 a.m. and the second just seconds prior to the collapse of the tower at 10:28:22 a.m. The sources for these pressure pulses are unknown, but it seems likely that they resulted from significant structural changes within the tower.

During the final period of the fires in WTC 1, no streamers were observed falling from the tower (see the table in Appendix L). This is most likely due to the quality of the imagery available, which was mostly long distance for the east and south faces where the most intense fires were located, rather than to a cessation of streamer formation.

The summary in Appendix M indicates that people were observed falling from the upper floors of the north and west faces during the final minutes before the tower collapsed. Even though most were seen falling on the north face, it is possible that additional people fell on the other faces and were not identified due to the quality of the imagery. The fact that people continued to fall from upper floors suggests that conditions on these floors were continuing to deteriorate.

8.9 SUMMARY AND ADDITIONAL DISCUSSION OF OBSERVATIONS FOR WTC 1

The initial externally observed damage pattern on WTC 1 caused by the impact of American Airlines Flight 11 and the subsequent fireballs was asymmetric. The aircraft impact caused major damage to the north face and nearby floor areas, including the removal of two full panel sections and the severing of additional columns, localized floor collapse, and pulverization of the concrete, in addition to a large amount of uncharacterized internal damage. On the east face numerous windows were broken open on the 94th and lower floors toward the center of the face. Significant damage was present on several floors of the south face over an area extending from near the center of the face to the western edge. The most severe damage appeared to be on the 96th floor. The west face had relatively minor initial damage. Fireballs were observed emanating from the aircraft impact cavity on the north face and from the east and south sides of the tower. Pieces of at least one landing gear passed all the way through the tower and were observed at the corners of Cedar and West Streets and Rector and West Streets. A panel section with an aircraft tire embedded in one of its windows was pushed out of the center of the south face and fell to the corner of Cedar and West Streets.

In less than a minute following the burnout of the fireballs created by the release of the aviation fuel, the fires visible at openings made in the tower died down considerably. This has been tentatively attributed to the depletion of available air within the tower. After a few minutes, growing fires were observed at or near locations on the periphery of the tower where the fireballs had vented, including the west side of the

aircraft impact cavity on the 97th floor, close to the center of the east face on the 94th floor, and on the western side of the 96th floor on the south face. These fires almost certainly grew from small fires ignited by the burning aviation fuel and utilized air from the nearby openings. The general locations of these initial fires were consistent with the expected dispersal patterns for the aviation fuel based on the locations where the two wing fuel tanks impacted the tower.

The subsequent fire growth and spread in the towers is discussed below. In Figure 8–116 to Figure 8–119, maps for integrated fire intensities for the six time periods have been grouped together for each face and plotted in sequence. These time sequences provide a convenient visual overview of the fire growth and spread in WTC 1. It may prove helpful for understanding the fire behavior to refer to them while reading the following summary.

More than 5 min after the aircraft impact, growing fires suddenly appeared on the 97th floor at multiple façade locations that seemed to be initially undamaged (i.e., the window glass was intact) following the aircraft impact and fireballs. On the north face, an area to the east of the aircraft impact cavity, on the side opposite where the starboard fuel tank is suspected to have released aviation fuel, began to burn intensely. Shortly afterward, a fire appeared on the 97th floor on the west face and spread very rapidly to cover more than a third of the length of the face. This fire was intense, with flames extending from multiple windows. A second occurrence of rapid fire spread a few minutes later carried the fire even further to the south. Within ten minutes of the aircraft impact, a fire, which may have been present earlier but hidden by smoke coming from lower floors; was identified on the 97th floor on the east face near windows 97-208 to 97-210. This fire quickly spread to cover at least 18 windows.

The development of multiple fires and their rapid growth and spread over much of the 97th floor is not a typical behavior for building fires. While not conclusively demonstrated, a plausible explanation for the rapid growth is that this fire spread was accelerated by the presence of aviation fuel. Such a fire spread mechanism would require that the fuel was widely distributed over the 97th floor along the east, north, and west faces during the aircraft impact and that a significant fraction of the fuel did not burn inside and/or was not expelled from the floor by the resulting fireballs. There is some evidence to support the conclusion that a major fraction of the aviation fuel dispersed on the 97th floor did not initially ignite. No significant visible damage was observed on the east, south, or west faces of this floor immediately after the aircraft impact, suggesting that overpressures sufficient to break window glass or remove portions of the curtain wall were not generated on this floor. The conclusion is weakened somewhat because portions of the floor were hidden by heavy smoke for a time.

During this early phase, a fire also rapidly grew on the 96th floor on the north face to the east of the aircraft impact cavity. It is likely that this fire was also accelerated by aviation fuel dispersed into the area during the aircraft impact. Unlike for the 97th floor, fire growth and spread on the west side of the 96th floor was not apparent during this early period. A possible explanation for this observation is that most of the fuel that was released into this area from the aircraft's starboard fuel tank was either burned inside immediately or pushed out of the area by the overpressure generated by burning on this floor, subsequently forming the fireball observed on the south face and resulting in the damage observed on this floor. As a result, only limited amounts of liquid fuel likely remained to accelerate fire spread.

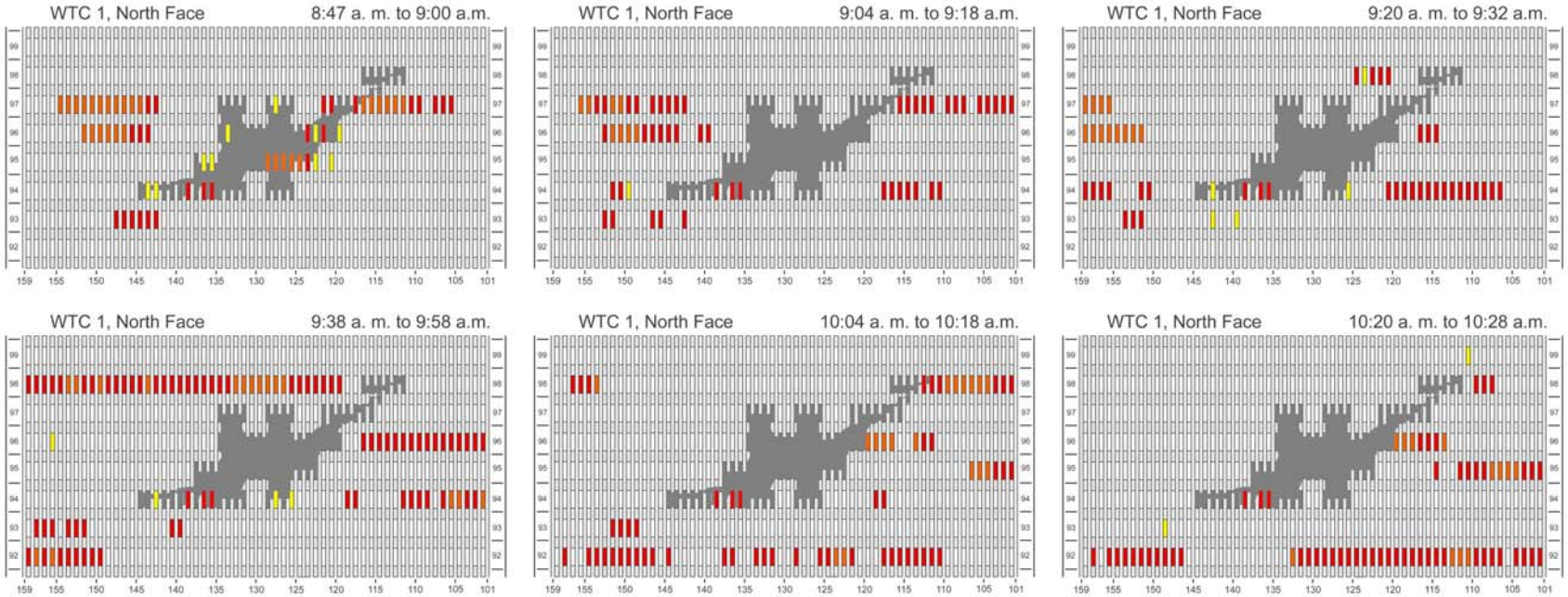

Figure 8-116. Maps of integrated fire intensity data for the north face of WTC 1 are plotted in sequence for the six time periods. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

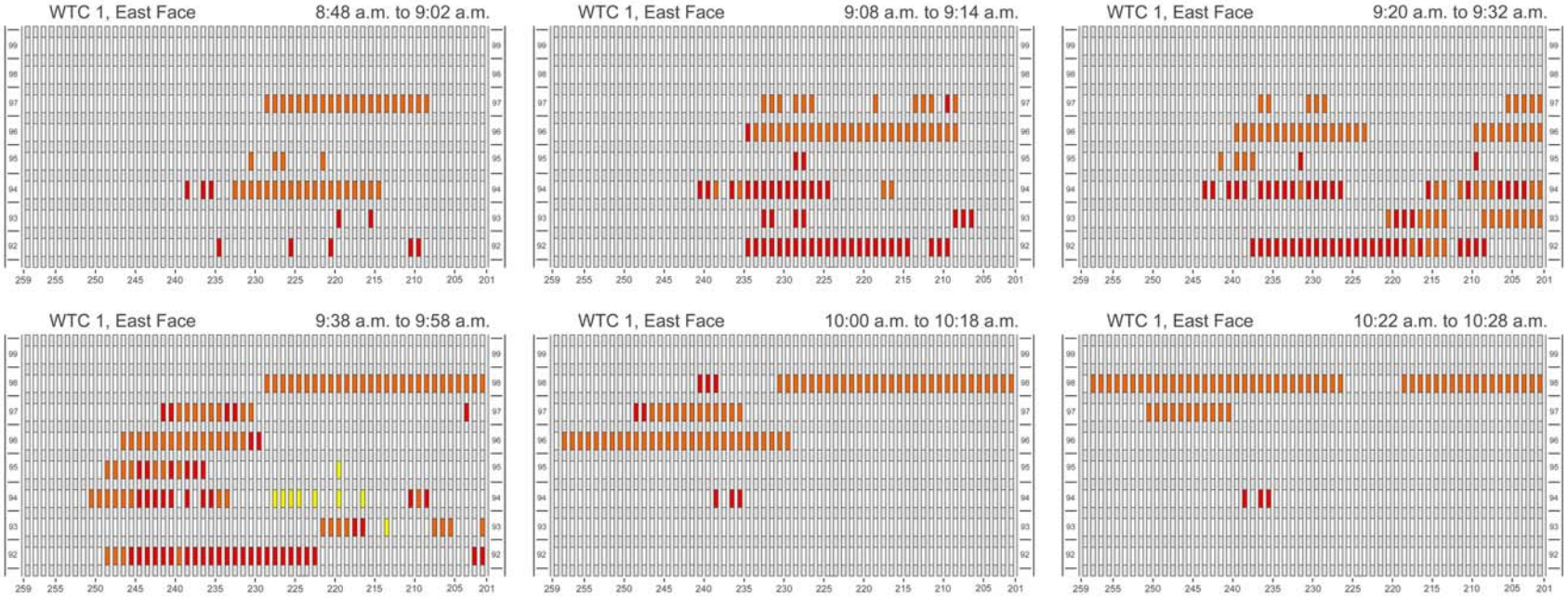

Figure 8-117. Maps of integrated fire intensity data for the east face of WTC 1 are plotted in sequence for the six time periods. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

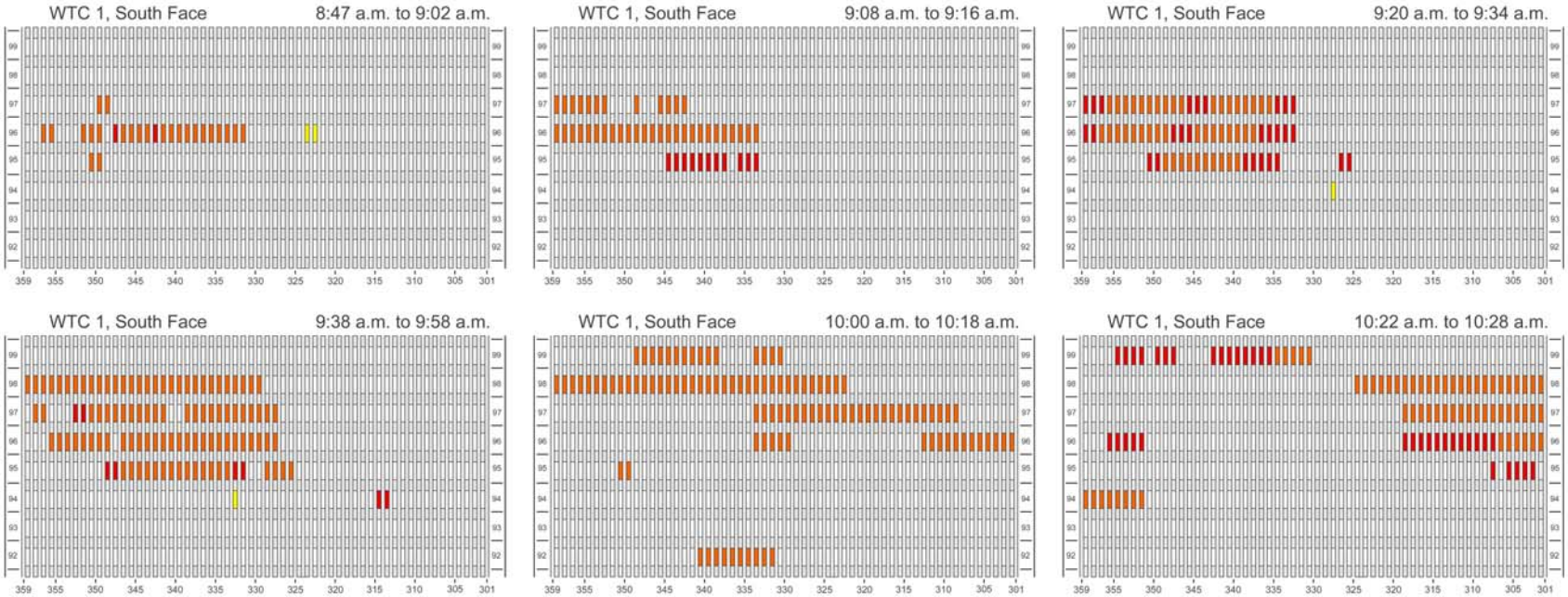

Figure 8-118. Maps of integrated fire intensity data for the south face of WTC 1 are plotted in sequence for the six time periods. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

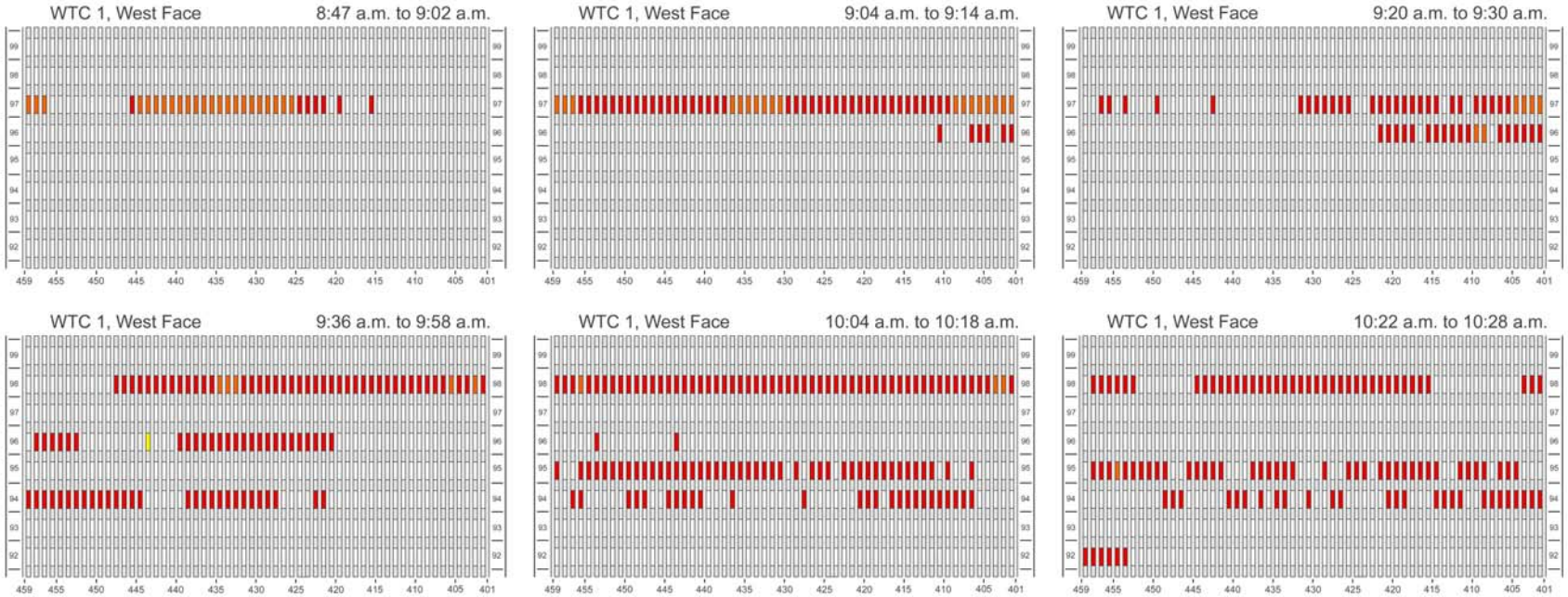

Figure 8-119. Maps of integrated fire intensity data for the west face of WTC 1 are plotted in sequence for the six time periods. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

Very shortly after the aircraft struck WTC 1 people on floors above the impact floors began to break open windows, and smoke was observed flowing from many of the open windows. These observations indicate that smoke quickly filled the top volume of the tower, presumably flowing upward through damaged elevator and ventilation shafts. The resulting deterioration in conditions is likely the reason that people were observed falling from these upper floors.

During the period between the times when WTC 1 was struck by American Airline Flight 11 and WTC 2 was struck by United Airlines Flight 175, the fires initially ignited by fireballs on the 97th floor to the west of the aircraft impact cavity on the north face, toward the center of east face on the 94th floor, and on the western half of the south side of the 96th floor grew larger and began to spread into apparently unburned areas. There was also evidence, based on increases in amounts of smoke coming from the area and human behavior, that fires had begun to grow on the east side of the 92nd and 93rd floors. These fires were attributed to aviation fuel spilling down onto these floors from the 94th floor.

Visual evidence suggests that walls for rooms at various locations, particularly corner rooms, were effectively slowing fire spread.

When WTC 2 was struck by the second aircraft, it generated a pressure pulse that was transmitted to WTC 1 and pushed smoke and fire out of the tower from numerous open windows located on multiple floors. The resulting fireball also generated pressure variations that were strong enough to modify the gas flows throughout the upper portion of WTC 1.

After the aircraft struck WTC 2, the fires on the north face entered a quiet phase during which additional fire spread was minimal and fires that had grown earlier began to die down. This lull lasted until around 9:18 a.m. During the same period, fires at some locations on the east face decayed, while fires at other points grew and spread. Large fires that had developed earlier on the 94th and 97th floors near the center of the face started to die down, with flames spreading across the face in both directions away from the initially ignited areas. Extensive fires grew on the east sides of the 92nd and 96th floors, covering much of the northern halves of these floors, with the exception of locations near the northeast corners.

Fire growth and spread on the south face was extensive. The fire on the 96th floor spread to cover much of the western half of the floor and continued to burn intensely. New fires appeared on the western sides of the south face on the 95th and 97th floors and began to spread. Despite the intense fires burning on the western side of the face, there was, as yet, no indication of fire growth on the eastern side of the south face.

By 9:18 a.m. fire had spread across the entire length of the western side of the 97th floor. Initially, flames and heavy smoke had come from many of these windows during the period of rapid fire spread, but both decreased abruptly as the fire spread to the south edge of the face. In contrast to the extensive fires on the 97th floor, the only visible fire area at this time on the west side of the 96th floor was near the south edge of the face. This area was adjacent to an intense fire that had been burning on the south face for many minutes. The strong contrast between the fire behaviors on the west side of the 96th and 97th floors provides further evidence that there were large differences in the role of aviation fuel on fire development on these two floors. No fire was visible on other floors of this face at this time.

During the 17 min period after 9:18 a.m., a considerable amount of fire spread was observed on the north face of WTC 1. Fires first appeared in the northeast corner rooms on the 96th and 97th floors, after

penetrating walls that had slowed the fire spread. Before 9:35 a.m. the corner rooms on the 93rd and 94th floors were also engulfed by flames. Fire growth and spread also occurred on the 94th floor on the west side of the aircraft impact cavity starting around 9:18 a.m. By 9:35 a.m. most of the windows, with the exception of those in a room on the northwest corner, on the 94th floor on either side of the aircraft impact cavity had been opened by these fires. Around 9:28 a.m. a small fire appeared near the center of the north face on the 98th floor. Within a few minutes, this fire spread and grew to cover a substantial length of the face.

Unlike the fires that developed on the north face shortly after the aircraft impact, the fires that grew and spread during the 9:18 a.m. to 9:35 a.m. period generally did not generate external flames or release heavy smoke through the windows. The exceptions were fires burning inside the rooms on the northeast corner rooms.

The fires burning in the northeast corner rooms on the 93rd, 94th, 96th, and 97th floors also opened the windows on the east sides of these rooms. At the beginning of the period, large fires were burning near the centers of the 92nd and 96th floors on the east side of the tower. Similar fires that had started earlier on the 94th and 97th floors were beginning to die down. By the end of the period, most of the fires near the center of the face were decreasing in intensity. On the 94th, 96th, and 97th floors the fires had begun spreading relatively slowly toward the south edge of the face. The life cycle of these fires—initial growth, intense burning, and decay phase—caused the fires moving toward the south to develop a wave-like appearance. Unlike the fires on the north face, fires burning on the east face often extended out of the windows and created heavy smoke flows.

Intense fires generating external flames and copious quantities of smoke burned over the western halves of the 96th and 97th floors on the south face between 9:18 a.m. and 9:35 a.m. During the period, the burning on both floors appeared to pass through a maximum intensity, and the fires were beginning to subside by 9:35 a.m. A fire of similar intensity had grown to cover over 40 % of the length of the 95th floor, extending as far west as window 95-350. A small fire was also visible on the 95th floor just to the east of the center of the face. This was an early indication of fire spread from the center of the south face towards the east.

Fires were visible on the west face on the 96th and 97th floors. Large fires were present at the southern edge of the face on both floors. Elsewhere on the 97th floor, the intense fires that had earlier covered the entire face continued to die down, and only low intensity flames were visible. Flames with similar intensities were visible burning on the 96th floor, but, unlike on the 97th floor, this fire was spreading slowly to the north. By 9:35 a.m., the flames had reached a location near the center of the face. The difference in burning behaviors between the intense fire that had earlier spread rapidly south on the 97th floor and the relatively low intensity fire that was spreading north on the 96th floor is notable.

The most significant fire growth during the period from 9:35 a.m. until the start of the collapse of WTC 2 at 9:58:59 a.m. took place on the 98th floor. Flames were first observed on this floor on the north face starting around 9:30 a.m. By 9:35 a.m., these flames had spread to cover many windows. Shortly afterward, fires appeared on the 98th floor on the east, south, and west faces. By 9:59 a.m., flames were burning on the 98th floor in two long bands, with one band starting near the center of the south face and extending around the southwest corner and along the west face to at least window 98-444 and the second beginning near window 98-119 on the north face and running around the northeast corner to the vicinity of window 98-223 on the east face.

The reasons for such unusually rapid fire spread are not known. It has been argued that similarly rapid fire spread observed on the 92nd, 96th and 97th floors shortly following the aircraft impact was accelerated by the presence of aviation fuel. This explanation seems less likely for the 98th floor because the analysis in Section 6.5 suggests that little fuel should have been released onto this floor and because the observed flame and smoke behaviors are not consistent with the involvement of large amounts of liquid fuel. Other possible explanations include the earlier ignition of multiple small fires on the 98th floor, which grew and coalesced into the observed fires or the presence of a large fire burning in the core on the 98th floor that simultaneously spread outward toward the perimeter faces, becoming apparent when it reached the faces and began to open windows.

The fires on the 98th floor reinforced the trend in which fires burning on the north and west faces of WTC 1 appeared to burn with lower intensity, e.g., without generating external flames or large quantities of smoke, while fires on the east and south faces often appeared to be much more intense. Figure 8–65 shows a particularly striking example of this behavior.

The fire that had been burning on the 92nd floor near the center of the east face since around 9:00 a.m. began to spread after 9:30 a.m.. On the north edge, it moved around the northeast corner of the tower and began moving systematically west across a series of rooms on the north face, while on the south side it moved much closer to the southeast corner. Fire spread in both directions involved the fire passing through walls that had earlier inhibited its progress. Other fires on the east face on the 94th, 95th, 96th, and 97th floors continued relatively slow movement toward the south.

While an intense fire developed on the west side of the south face on the 98th floor, similar fires that had grown earlier on the same side of the 95th, 96th, and 97th floors continued to die down. There were early indications of fire spread onto the eastern half of the face on the 94th and 95th floors. Even so, very little burning had taken place on this side of the face during the one hour and 13 min since the aircraft impact.

There was a great deal of fire spread observed on the west face, but relatively less fire growth. The fire that had been slowly working its way north on the 96th floor reached the northwest corner of the tower and penetrated the rooms located there. With the exception of fires burning within rooms, very little flame or smoke was observed coming from windows that were opened as the fire moved by. Fires also spread into several rooms located on the west side of the 94th floor, at one point apparently forcing a large number of people who sought refuge in the area to jump from the tower. These fires seemed to be spreading from the fire that developed earlier on the north face on the west side of the aircraft impact cavity, but there were indications that the fire skipped over certain rooms as they moved south.

The collapse of WTC 2, starting at 9:58:59 a.m., generated a pressure pulse within WTC 1 that forced smoke and fire from windows on all four sides of the tower. This was especially apparent for the intense fire burning on the western half of the 98th floor on the south face. Following the collapse, there was a short period of time when smoke flow from WTC 1 was greatly reduced.

Fire growth and spread continued in WTC 1 during the 19 min following the collapse of WTC 2. On the north face, most of the fire spread was observed on the 92nd floor. The fire that had earlier spread into rooms along the north face from the east face worked its way across the floor from east to west. By the end of the period, the fire had entered a large open area on the west side of the face. Similarly, a fire spreading north on the west face on the 98th floor entered a room on the northeast corner and appeared on

the north face. The fires on other parts of the north face that had been heavily involved earlier were either burning at low intensities or had died out.

The fires on the east face were difficult to observe during the period due to smoke and dust obscuration and limited imagery. The principal area of burning was on the 98th floor over the northern half of the face. Fires known to be present on the 94th, 96th, and 97th floors were observed less often. These fires continued to spread slowly to the south, with the fire on the 96th appearing to reach the south edge by the end of the period. The fires that were present on the 92nd and 95th floors at earlier times could not be seen. A small area of fire was observed on the 101st floor near the center of the face.

On the south face, the fire burning on the west side of the 98th floor continued to burn vigorously. During the period, it spread toward the east, passing the center of the face. A new area of fire appeared above the 98th floor fire at the west side of the face on the 99th floor. Fires were also observed on the east side of the face on the 96th and 97th floors. The fire on the 96th floor was near the east edge, suggesting it had spread from the fire that had moved down the east face on this floor. The fire on the 97th floor was more toward the center, suggesting spread to the east by the fire that had been burning on the west side of the south face of this floor for a long period of time. Following a long period during which the southeast quadrant of the tower had appeared to be isolated from the fires burning elsewhere in the tower, substantial fires had now appeared on multiple floors.

There was extensive fire spread apparent on the west face during the 19 min period. The most widespread growth took place on the 95th floor. Early in the period there was no indication of fire on the west side of this floor. Starting just after 10:06 a.m., thirteen people were observed falling from near the center of the floor in a short period of time. Shortly afterwards flames became visible through windows in the same area. These flames appeared to spread rapidly in both directions and by 10:18 a.m. were visible over most of the west face of the floor. Even though much of the west side of the 95th floor was burning, the flames did not appear to be intense. There was very little smoke coming from open windows on the floor, and multiple fires appeared to be burning on isolated fuel sources located near the floor. These fires had similar appearances to those observed earlier on the 94th and 96th floors.

On the 94th floor, the fire that had been spreading deliberately to the south reached window 94-108 and paused for several minutes. Unlike what was observed for most of the windows on the west face of this floor, heavy smoke and flames were visible coming from windows 94-108 and 94-109. There was little indication of flames on the 96th and 97th floors. Earlier fires on these floors had decreased in intensity or burned out.

The extensive fire on the 98th floor continued to burn with a dull orange glow, suggesting a fire located within the interior of this floor. Fire spread continued to the north, with the fire entering the northwest corner room on this floor around 10:10 a.m. and, in the process, completing its spread across the entire face.

Very shortly after the collapse of WTC 1, a fire appeared on the south side of the west face on the 104th floor. This fire grew rapidly, and flames were observed coming from a length of adjacent windows that was more than 15 windows wide. This fire continued burning intensely until the tower collapsed at 10:28:22 a.m.

At 10:18:48 a.m., a pressure pulse pushed large amounts of smoke and fire out of open windows on multiple floors and faces of WTC 1. The most dramatic effect of this pressure pulse was on the 92nd floor, where a long line of smoke appeared from open windows on the north face. Up until this time, there had been very little smoke coming through the open windows from the widespread fires burning on this floor. During the final ten minutes prior to the collapse of WTC, a large fire grew on the 92nd floor in the large open area on the west side of the north face. A large burst of fire was pushed from the area when WTC 1 collapsed.

The pressure pulse at 10:18:48 a.m. also seemed to cause a fire burning in a room in the northwest corner of the 95th floor to suddenly intensify and to extend flames from north face windows. Flames were also pushed out of this area when the tower collapsed. Fires present elsewhere on the north face, such as on the west side of the 98th floor, were dying down.

Imagery of the east face during the final ten minutes before WTC 1 collapsed was inadequate for detailed window-by-window assessment. However, it was sufficient to reveal that starting around 10:21:15 a.m. an intense fire with long flames extended from windows appeared on the south side of the east face at the 98th floor and rapidly spread to cover a length of roughly one fifth of the tower width. This intense fire was the dominant feature on the east face until the collapse. Even though it is likely that fires were burning on several floors at this time, the only other floor where fire was observed was the 97th floor. This fire seemed to be spreading slowly to the south, in much the same way as observed earlier.

When the tower collapsed, flames were pushed from the burning area on the south side of the 98th floor on the east face. This indicates that this remained an area of intense burning at 10:28:22 a.m. It also appeared that flames were pushed from a higher floor on this face, but the exact location could not be identified.

The rapid fire spread and growth seen on the south face following the collapse of WTC 2 continued during the final 10 min before the tower collapsed. Intense fires were burning on the east sides of the face on the 97th and 98th floors, while a large fire that was initially burning on the west side of the face on the 99th floor spread to the east. A fire that had earlier spread along the west face from the north on the 94th floor reached and ignited a room in the southwest corner. There were indications of fires burning above the 99th floor.

The extent of the fires burning on the south face was revealed when the tower collapsed and pushed large flames from three separate locations on the face. The first expelled flame came from the east side of the face where the 98th and 99th floors were heavily involved in fire. The second was from the western edge of the 94th floor where fire had spread into the northwest corner, and the third came from somewhere lower on the east side of the face. The exact location of the fire responsible for the third expelled flame is unknown, but the involved area must have been large because sufficient burning gases and unburned fuel were pushed from the building to generate a short-lived fireball.

Limited fire spread continued on the west face during the 10 min prior to collapse. On the 94th floor, the fire that had been spreading south entered the room located on the southwest corner, while a similar fire spreading south on the 95th floor entered a room immediately adjacent to the southwest corner room. A fire that had been spreading across the north face on the 92nd floor turned the northwest corner and began to spread down the west face.

The extensive internal fires observed along the west side of the 98th floor, which first appeared around 9:40 a.m., were dying down, but were still visible near the center of the 98th floor. Meanwhile, widespread fires on the west side of the 94th and 95th floors continued burning at relatively low intensities. No flames were seen on the west face for the 96th and 97th floors. As observed earlier, very little smoke or external flames were generated by the fires burning on the 94th, 95th, or 98th floors.

It is clear from the previous discussion that extensive fire spread took place in WTC 1 during the 1 hr 41 min 52 s period between the impact of American Airlines Flight 11 and the collapse of the tower. As already noted, there is more uncertainty in maps for window breakage after 9:59 a.m. than prior to this time due to the quality of the imagery. Nevertheless, it is instructive to compare the window façade maps at the time of collapse with those immediately following the aircraft impact in order to additionally characterize the amount of fire spread and changes in ventilation that occurred in WTC 1. Figure 8–120 shows this comparison for the four faces of WTC 1 for the 92nd through 99th floors, where the majority of fire spread took place. It should be kept in mind that isolated fires were observed on other floors, including the intense fire on the 104th floor on the west face and the somewhat smaller fires on the east face on the 101st floor and the 100th and 101st floors on the south face. These fires are included in the summary maps in Appendices C to F.

The maps immediately reveal the large amount of fire spread that took place in this tower. With a few exceptions, fires spread completely over the 94th to 98th floors. The majority of the aviation fuel is believed to the have been released on the 94th to 97th floors. Even so, intense fires grew at several locations on the 98th floor after roughly 45 min and spread over most of the floor by the time tower the collapsed. Upward fire spread to the 99th floor also took place, but large areas of the floor were still unburned when the collapse started. Fires on the 92nd and 93rd floors, which were originally ignited locally on the east side of the tower shortly after the aircraft impact, also spread over large areas, but had not yet completely ignited the west side of these floors when the collapse took place. It should be kept in mind that, while not shown, a large fire also developed on the south side of the west face of the 104th floor, and smaller fires were observed on the 100th and 101st floors.

The information shown visually in Figure 8–120 is summarized numerically in Table 8–4 and Table 8–5. These two tables are similar to Table 8–2 and Table 8–3, which were generated using data from shortly after the aircraft impacted WTC 1 and just prior to the collapse of WTC 2. The results indicate that the total number of open windows on these floors increased by roughly 377 windows between 9:59 a.m. and 10:28 a.m. The increase in the number of open windows between the time from shortly after the aircraft struck WTC 1 and the collapse of the tower was approximately 1,076 windows, or a factor of just over 4.5. This corresponds to an increase in the open area on the façade available to provide air to the fires on these floors of around 12,470 ft^2.

The results in the fire data sheets have been utilized to generate integrated fire data for the entire period between the aircraft impact and the collapse of WTC 1. The results are shown graphically in Figure 8–121 for the four faces of the tower. These maps demonstrate the extensive area of WTC 1 that was subjected to fire. Comparison with Figure 6-19, which shows the fire distribution on the four faces shortly after the aircraft impact, provides a graphic illustration of the amount of fire spread and growth that occurred. The relative numbers of windows in Figure 8–121 where external flames (orange) were observed compared to the total number of windows with observed fire reflects the differences between fire behaviors on the west and north faces as compared to the east and south faces, where external flaming was much more likely.

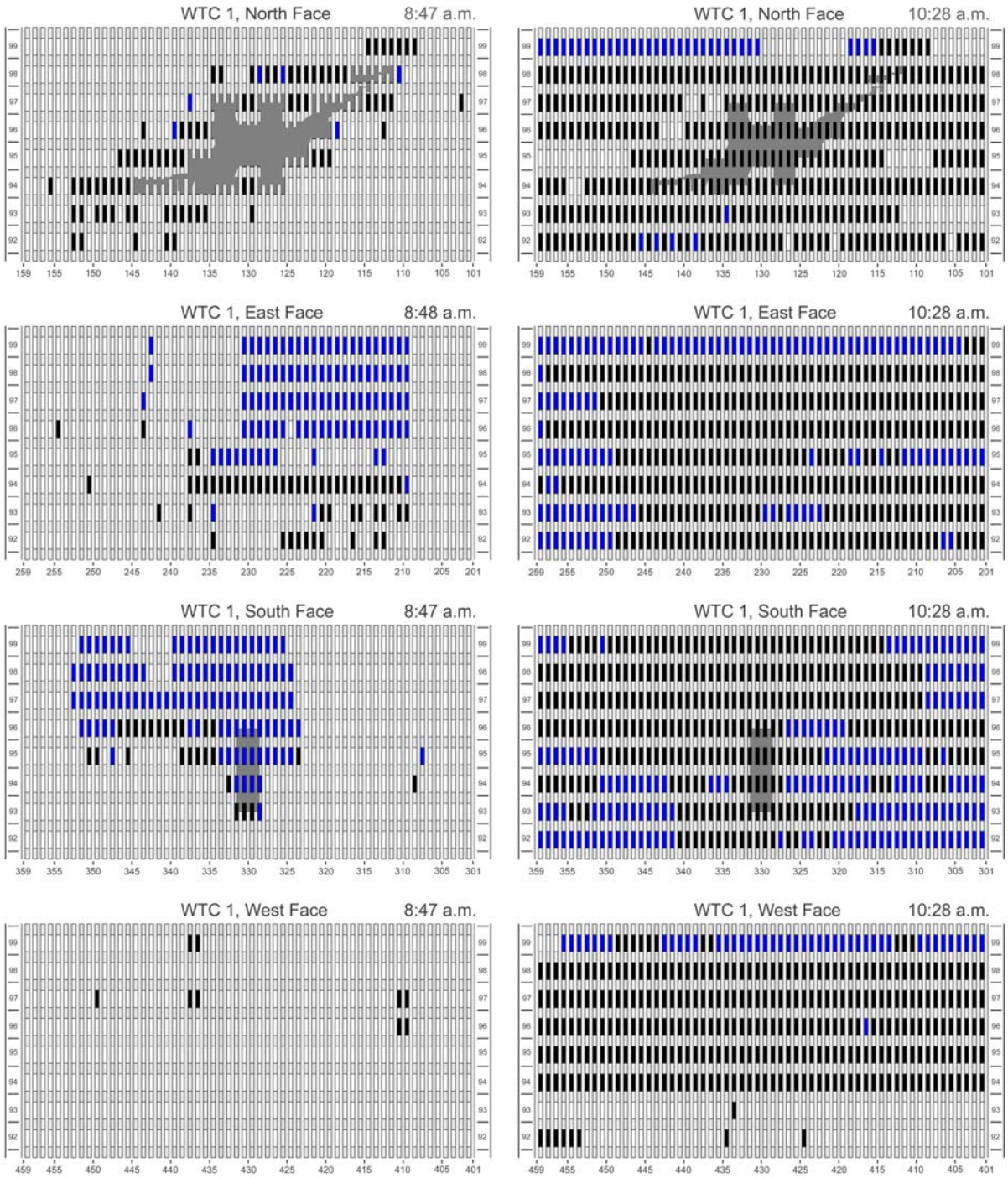

Figure 8-120. Maps for the 92nd through the 99th floors compare missing windows for the four faces of WTC 1 at two times, immediately following the aircraft impact at 8:46:30 a.m. and just prior to the collapse of WTC 1 at 10:28:22 a.m.

Table 8-4. Comparison of Window Conditions on the Four Faces of WTC 1 Near the Times of Aircraft Impact on WTC 1 and Collapse of WTC 1

	Around 8:47 a.m.				**Around 10:28 a.m.**		
	Open Window	**Glass in Place**	**"Can't See"**		**Open Window**	**Glass in Place**	**"Can't See"**
Floor	North Face 8:47 a.m.				North Face 10:28 a.m.		
99	7	51	0		7	18	33
98	19	36	3		58	0	0
97	25	32	1		54	4	0
96	22	34	2		55	3	0
95	28	30	0		40	18	0
94	29	29	0		56	2	0
93	14	44	0		46	11	1
92	5	53	0		51	3	4
Floor	East Face 8:48 a.m.				East Face 10:28 a.m.		
99	0	35	23		4		54
98	0	35	23		57	0	1
97	0	35	23		50	0	8
96	2	34	22		57	0	1
95	2	44	12		33	0	25
94	29	28	1		56	0	2
93	10	46	2		38	0	20
92	10	48	0		46	0	12
Floor	South Face 8:48 a.m.				South Face 10:28 a.m.		
99	0	36	22		40	0	18
98	0	32	26		50	0	8
97	0	29	29		50	0	8
96	11	29	18		50	0	8
95	9	37	12		36	0	22
94	2	52	4		26	0	32
93	3	54	1		26	0	32
92	0	58	0		17	3	41
Floor	West Face 8:47 a.m.				West Face 10:28 a.m.		
99	2	56	0		11	3	44
98	0	58	0		58	0	0
97	5	53	0		58	0	0
96	2	56	0		57	0	1
95	0	58	0		58	0	0
94	0	58	0		58	0	0
93	0	58	0		1	57	0
92	0	58	0		8	50	0

Table 8-5. Summary of Open Windows Observed on Faces (92nd to 99th Floors) of WTC 1 at 8:48 a.m. and 10:28 a.m.

Face	Number of Open Windows 8:48 a.m.	Number of Open Windows 10:28 a.m.
North	149	367
East	53	341
South	25	295
West	9	309
Total	236	1312

One of the more interesting aspects of the fire behaviors in WTC 1 was the variation in the type of burning observed on the different faces of the tower. Fires at most locations on the west and north faces of the tower burned without releasing large amounts of smoke or flame from nearby windows. In many cases the fires appeared to be distributed fires that burned at relatively low intensities. As a result, smoke marks at the tops of nearby column covers were either horizontal lines or were not present. Three major exceptions were observed. Heavy smoke and external flaming were observed for the earliest fires that developed on these faces. These included fires that grew very early on the 96th and 97th floors on the north face to the east of the aircraft impact cavity and the fire that developed and spread very rapidly along the 97th floor on the west face. The second exception was fires that developed within rooms along these faces. It was often observed that such fires would release smoke and external flames and mark nearby column covers with carets. The final exception was the fire that developed on the west face of the 104th floor following the collapse of WTC 2. This fire burned very intensely, while generating heavy smoke and external flames.

In contrast to the behavior on the west and north faces, fires burning on the east and south faces often generated heavy amounts of smoke and external flaming at nearby windows. It was common to observe many adjacent open windows with long extended flames. The tops of nearby column covers were often marked with carets. Examples of such fires were observed on the 94th, 96th, 97th, and 98th floors on the east face and on the 95th, 96th, 97th, 98th, and 99th floors on the south face. Exceptions to the general behavior included fires that developed on the 92nd floor on the east face and fires burning on the east side of the south face on the 92nd and 94th floors.

Various explanations for the different fire behaviors were considered. The most plausible is based on the effects of the prevailing wind. On September 11, 2001 the wind was striking WTC 1 from the northwest and then flowing down the north and west faces. This wind created positive pressures at the windows on these faces that tended to resist gas flows out of the tower. On the east and south faces the effect of the wind was the opposite, creating low pressure areas at the windows that tended to pull gases out of the building. The net effect of these pressure forces would be a tendency for gases to flow internally on a floor, if a pathway was available, from the west and north faces to the east and south faces. Such internal flows provide a possible explanation for the observed fire behaviors.

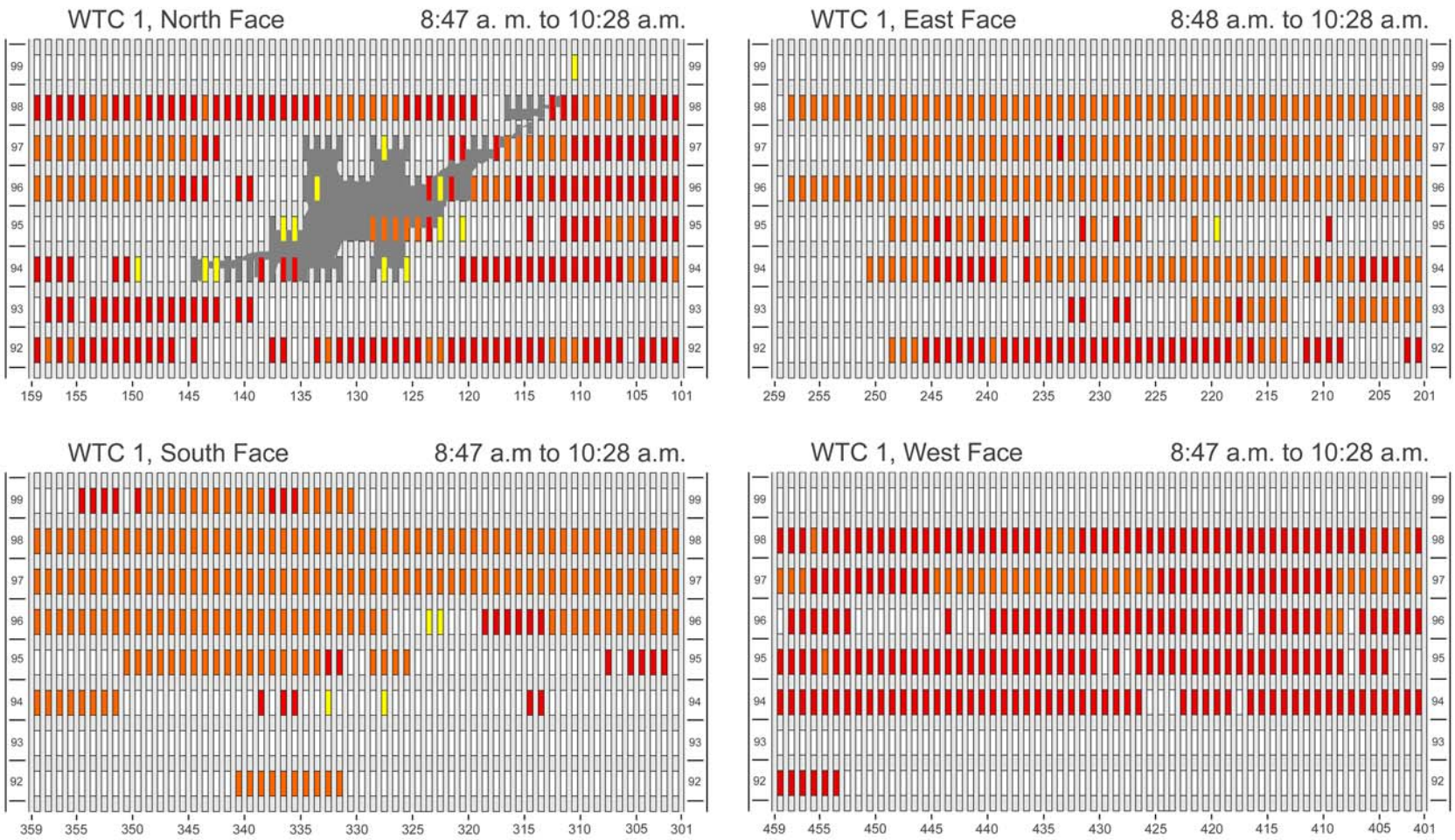

Figure 8-121. Maps of integrated fire observations between 8:47 a.m. and 10:28 a.m. are shown for the four faces of WTC 1. Colors represent the highest intensity fire observed in a window using the color scale defined in Figure 5-1.

The exceptions noted above for the north and east faces actually provide support for this explanation. When the early fires developed on the north and west faces, most windows on the 96th and 97th floors still had glass in place on the east and south faces. As a result, internal pathways connecting the openings on the high pressure and low pressure faces did not exist. Recall that the fire burning on the 97th floor of the west face abruptly stopped releasing smoke and flames from windows on the face at 9:06:27 a.m. when it approached the south edge of the floor. Just prior to this time there was a bright flash of fire from window 97-408 on this floor. It is likely that this was the time when windows on the 97th floor opened up on the south face, providing the required internal flow pathway.

A similar argument explains the fire behavior on the 104th floor. In this case, the fire developed only on the west face, windows on other faces were closed, and internal flows to the east or south faces were not possible.

Since walls associated with rooms were often able to act as effective firebreaks, it might be expected that they would also be able to limit internal flows from open windows on the north and west faces to other open windows at the east and south faces on the same floor. As a result, the effects of positive pressure at windows within the room would be mitigated, and underventilated fires within the room would be expected to generate the external flaming that was sometimes observed.

8.10 REFERENCES

McGrattan, K. B., Ed. 2004. *Fire Dynamics Simulator* (*Version 4*) *Technical Reference Guide*. NIST Special Publication 1018. National Institute of Standards and Technology, Gaithersburg, MD, August.