Key findings not previously reported by the WTC investigation team include the following:

- **Leading hypotheses for the collapse of WTC 1 and WTC 2 (the towers) developed.** These hypotheses identify the chronological sequence of major collapse events for each tower and identify specific load redistribution paths and damage scenarios. Previously, a single working hypothesis was defined for both towers without identification of the load redistribution paths and damage scenarios resulting from aircraft impact and the subsequent fires. The two hypotheses are detailed in the attached sheet.

- **Time delay between the collapses of the WTC towers explained.** Although the WTC towers were attacked by virtually identical aircraft, WTC 1 stood for 103 minutes before it collapsed—nearly twice as long as WTC 2, which survived for 56 minutes. The buildings themselves, although not identical, had many similarities. The time delay between the collapses was due primarily to: (1) the asymmetrical structural damage of the aircraft impact to WTC 2 compared to the aircraft damage to WTC 1; (2) the time it took for heat to soften, buckle and shorten core columns that had fireproofing dislodged by debris impact; (3) the structure's ability to redistribute loads as the core columns shortened; (4) the time it took for fires to traverse from their initial location to the face of the towers where perimeter columns were bowing inward (as seen only minutes before the collapse of each tower); and (5) the time it took for heat to soften and buckle those columns.

- **Post-impact capabilities of the WTC towers assessed.** Demand to capacity ratios—the calculations indicating whether or not structures can support the loads put on them—showed that for the floors affected by the aircraft impacts, the majority of the core and perimeter columns in both towers continued to carry their loads after the impact. The loads from damaged or severed columns were carried by nearby undamaged columns. Although the additional loads strained the load-bearing capabilities of the affected columns, the results show that the columns could have carried them. This shows that the towers withstood the initial aircraft impacts and that they would have remained standing indefinitely if not for another significant event such as the subsequent fires. NIST previously reported that the towers had significant reserve capacity after aircraft impact based on analysis of post-impact vibration data obtained from video evidence on WTC 2, the more severely damaged tower.

- **Fire-induced core column shortening detected.** Due to heating from fires following the aircraft impacts and subsequent buckling, there was a shortening of core columns seen in both towers on floors at or near the fire-affected impact sites. Shortening of the core columns caused the floor system to pull the perimeter columns inward—the observed inward bowing that was seen minutes prior to the collapse of each tower. Significant thermal sagging of the floor system exacerbated the inward pull on the perimeter columns in WTC 2. Vertical loads carried by shortened columns were redistributed to perimeter columns, putting additional strain on their load-bearing capabilities.

- **Role of fireproofing determined.** The structural components that became weakened due to the fires and eventually caused the towers to collapse had their fireproofing dislodged by debris from the aircraft impact. The region of dislodged fireproofing was determined from the predicted path of the debris. Had the fireproofing not been dislodged, the temperature rise of the structural components would likely have been insufficient to cause the global collapse of the towers. Fireproofing dislodged by debris left the components more sensitive to heat than any areas where there was missing or thin fireproofing before the aircraft impacts.

- **Majority of steel found stronger than minimum requirements.** Approximately 87

percent of the recovered WTC steel specimens tested exceeded the required minimum yield strengths specified in the building design criteria; some 13 percent did not. However, the safety of the towers was most likely not affected by the small percentage of steel below the minimum. Building designs routinely allow structures to withstand greater loads than are expected by including significant factors of safety. Moreover, the structural loads on Sept. 11, 2001, were well below this design level.

- **Full-building evacuation presented challenges for occupants.** Based on first-person interview data, an assessment of WTC 1 and 2 occupant preparedness concluded that in both towers:
    - Occupants often were unprepared for the physical challenge of full building evacuation;
    - Occupants often were unprepared to encounter transfer hallways during the stairwell descent; and
    - Mobility challenged occupants were not universally identified or prepared for full building evacuation.
- **Movement in WTC 1 stairwells perceived as a problem.** Although a number of persons who evacuated WTC 1 reported that they perceived a problem with counterflow (the movement of firefighters in the opposite direction) on the stairwells, it was determined not to be a significant factor in the total evacuation time of WTC 1 occupants when compared to other factors including delays in evacuation initiation, evacuation interruption and encountering obstacles in the evacuation path (such as smoke, water and debris).
- Based on first-person interviews, NIST estimates the average surviving occupant spent 48 seconds per floor descending the stairwell, which is about half as fast as previously reported for non-emergency evacuations. NIST also estimates that each stairwell door exited about 37 people per minute, which is comparable to the slowest rate previously reported for non-emergency evacuations. In other words, the average surviving occupants moved slower down stairs and through stairwell exits than previously reported for non-emergency evacuations.

  Firefighters and other first responders reported difficulty in climbing the stairs due to crowding by evacuating occupants. Based on first-responder interviews, NIST estimates that they took an average of 1.4 to 2 minutes per floor to climb up to their maximum height (mostly to floors in the 20s and 30s). Therefore, it would have taken more than two hours for a first responder wearing personal protection equipment and carrying gear to reach the 60th floor using the stairwell, while it would have taken about 1-1/2 hours to do so without equipment and gear.

- **Evacuees did not receive coordinated or informative communications.** During interviews, survivors said that they felt emergency communications could have been more helpful during the evacuation of the towers. Specific knowledge about the location of fires and aircraft impact damage was only occasionally communicated to occupants who requested the information. Those communications were apparently uncoordinated.

  Additionally, some contradictory announcements—first to return to offices and then to start an orderly evacuation—were heard by occupants in WTC 2 immediately prior to the aircraft impact on that tower.

- **Mobility impaired occupants faced special evacuation challenges.** About 6 percent of the surviving occupants reported a pre-existing limitation to their mobility. Examples of these limitations include obesity, heart conditions, pregnancy, advanced age and recent

surgery.

Firefighters and police officers found 40 to 60 mobility impaired occupants on the 12th floor of WTC 1 as they attempted to clear each floor on their way out. The impaired individuals had been placed on this floor to await rescue in an attempt to clear the stairway. Emergency responders were assisting approximately 20 of these persons down the staircase just prior to the tower's collapse.

- **First responder command and control was hampered.** While a significant amount of evidence showed that the different first responder agencies were, for the most part, working together, they were hampered by inadequate information, dispatch and unit assignment records. This included:
    - First responders, including key incident commanders, who did not have adequate information (voice, video and data) on conditions in the WTC towers or an overall perspective of what was happening elsewhere at the WTC site.
    - Large numbers of firefighters who were dispatched to the WTC site before adequate command posts and staff could be assembled to manage them.
    - Self-dispatch by first responders and ambulances that further complicated command and control at the site.
    - Self-dispatch by EMS and private/volunteer ambulance units that contributed to clogging of the streets, making it difficult for assigned responders to get through.
    - Overwhelming of the system for maintaining records of unit assignments at each fire command posts because of the large numbers of units and personnel.

In his presentation to the NCST Advisory Committee today, Sunder outlined the approach NIST is taking to formulate its recommendations for improvements based on the lessons learned from the WTC investigation. NIST, he said, is considering the following:

- Findings related to building performance, evacuation and emergency response, and procedures and practices;
- Whether findings relate to the unique circumstances surrounding the terrorist attacks of Sept. 11, 2001, or to normal building and fire safety considerations, including evacuation and emergency response;
- What technical solutions are needed, if any, to address potential risks to buildings, occupants and first responders, considering both identifiable hazards and the consequences of those hazards; and
- Whether the risk is in all buildings or limited to certain building types (e.g., a distinct height and area, or type of structural system), buildings that contain specific design features, iconic/signature buildings, or buildings that house critical functions.

Sunder also stated that, based on the investigation findings, NIST has identified issues related to practices, standards and codes that are the foundation for the WTC team's final recommendations (see Sunder's presentation at http://wtc.nist.gov/media/NCSTACWTCStatusFINAL101904WEB2.pdf for a detailed list of these issues).

The issues being addressed have been grouped as follows:

- Increased structural integrity;
- Enhanced fire protection, including passive and active systems;
- Improved building evacuation, including egress system design, emergency communication to occupants, occupant preparedness and egress technology; and
- Improved emergency response, including access and firefighting, emergency

communications, and command and control.

Additionally, the issues in each group have been more specifically defined by categorizing under the following three levels:

Level 1

- Practices
- Standards, codes and regulations
- Adoption and enforcement
- Research and development/further study
- Education and training

Level 2

- All tall buildings (buildings over 10 stories in height)
- Selected tall buildings (buildings over 10 stories in height that are at risk due to design, location, use, symbolism, contents, etc.)
- Selected other buildings (other buildings that are at risk due to their use, content, historic status, symbolism, location, etc.)

Level 3

- Related to 9/11 outcome
- Unrelated to 9/11 outcome

As a non-regulatory agency of the U.S. Department of Commerce's Technology Administration, NIST develops and promotes measurement, standards and technology to enhance productivity, facilitate trade and improve the quality of life.

FACT SHEET

Leading Hypotheses for the Collapses of the World Trade Center Towers

The National Institute of Standards and Technology (NIST) World Trade Center (WTC) investigation team has formulated the chronological sequence of major events leading to the eventual collapses of the WTC 1 and WTC 2 towers as a result of the terrorist attacks of Sept. 11, 2001. The leading collapse hypothesis for each tower is based on evaluations of the building's innovative structural system; the effects of the aircraft impact and subsequent fire; the post-impact condition of the fireproofing; the quality and properties of the structural steel used in construction; and the relative roles in the collapse scenario played by the perimeter and core columns, and the composite floor system (including connections).

The two collapse hypotheses are consistent with all evidence currently held by NIST, including photographs and videos, eyewitness accounts, and emergency communications records. However, the hypotheses released today still may be revised for the investigation team's final report, scheduled for release as a draft document for public comment in December 2004 or January 2005.

The leading collapse hypothesis for each tower is as follows:

WTC 1

- Aircraft impact damaged the perimeter columns, mainly on the north face, resulting in redistribution of column loads, mostly to the adjacent perimeter columns and to a lesser extent, the core columns.

- After breaching the building's perimeter, the aircraft continued to penetrate into the building, damaging floor framing, core columns and fireproofing. Loads on the damaged columns were redistributed to other intact core and perimeter columns mostly via the floor systems and to a lesser extent, via the hat truss (the steel structure that supported the antenna atop the towers and was connected to the core and perimeter columns).

- The subsequent fires, influenced by the impact-damaged condition of the fireproofing:
    - Softened and buckled the core columns and caused them to shorten, resulting in a downward displacement of the core relative to the perimeter. This led to the floors (1) pulling the perimeter columns inward, and (2) transferring vertical loads to the perimeter columns; and
    - Softened the perimeter columns on the south face and also caused perimeter column loads to increase significantly due to restrained thermal expansion.
- Due to the combined effects of heating on the core and perimeter columns, the south perimeter wall bowed inward and highly stressed sections buckled.

- The section of the building above the impact zone began tilting to the south as the bowed south perimeter columns buckled. The instability rapidly progressed horizontally across the entire south face and then across the adjacent east and west faces.

- The change in potential energy due to the downward movement of the building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

WTC 2

- Aircraft impact damaged the perimeter columns, mainly on the south face, resulting in redistribution of column loads, mostly to the adjacent perimeter columns and to a lesser extent, the core columns.

- After breaching the building's perimeter, the aircraft continued to penetrate into the building, damaging floor framing, core columns and fireproofing. Loads on the damaged columns were redistributed to other intact core and perimeter columns mostly via the floor systems and to a lesser extent, via the hat truss.

- The subsequent fires, influenced by the impact-damaged condition of the fireproofing:
    - Caused significant sagging of the floors on the east side that induced the floors to pull the perimeter columns inward on the east face;
    - Softened and buckled the core columns on the east side and caused them to shorten, which transferred significant additional load to the perimeter columns on the east face primarily through the floor system and to a lesser extent, the hat truss; and
    - Softened some of the perimeter columns that were exposed to high temperatures toward the northern half of the east face.

- Due to the additional loads on the perimeter columns on the east face and the inward pulling of those columns, the east perimeter wall bowed inward and highly stressed sections buckled.

- The section of the building above the impact zone began tilting to the east and south as both the east perimeter columns and the impact-damaged south perimeter columns buckled. The instability rapidly progressed horizontally across both faces and across the north face.

- The change in potential energy due to the downward movement of the building mass above the buckled columns exceeded the strain energy that could be absorbed by the structure. Global collapse then ensued.

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