Proposed Plan
National Institute of Standards and Technology
National Building and Fire Safety Investigation of the World Trade Center Disaster

Goals:

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

Objectives:

The primary objectives of the NIST-led technical investigation of the WTC disaster are to:

1. Determine why and how the World Trade Center Buildings collapsed after the initial impact of the aircraft;
2. Determine why the injuries and fatalities were so low or high depending on location, including all technical aspects of fire protection, response, evacuation, and occupant behavior and emergency response;
3. Determine the procedures and practices that were used in the design, construction, operation, and maintenance of the World Trade Center Buildings; and
4. Identify, as specifically as possible, building and fire codes, standards, and practices that warrant revision and are still in use.

Guiding Principles:

- Aggressive, comprehensive, thorough, independent, and objective technical investigation that is fully informed of the concerns and issues of all interested parties and within the limits of available resources.
- Open and inclusive process in planning and conducting the investigation, and in publishing and disseminating findings and recommendations.
- Focus on fact-finding and analysis of the facts, validating/verifying existing knowledge, and creating new technical and/or scientific knowledge for the purpose of improving practice, standards, and codes and to reduce future risks.
- Non-technical issues are outside scope of investigation: No findings of fault or negligence of any individual or organization.

Source of Information for Plan Development:

Formulation of the NIST investigation plan will draw on many sources of information and embrace information from outside NIST. These include external experts and groups (industry, academia, and government), FEMA/ASCE Building Performance Assessment Team (BPAT) study (FEMA Report 403, May 2002), NIST experts in building and fire safety, and the public-at-large. NIST will hold a public meeting in New York City on June 24, 2002 to gather comments and suggestions on the scope of the NIST investigation detailed in this plan. Written public comments also will be accepted (e-mail: wtc@nist.gov, fax: 301-975-6122), preferably before June 30, 2002. The refined plan will be made available for public comment before it is adopted as final.

Program Context for the Investigation:

The ***NIST response plan*** consists of three key program elements – including an investigation – to be conducted in parallel (see attached graphic #1). These are:

- First, a 24-month ***building and fire safety investigation*** into the factors contributing to the probable cause of collapse of the Twin Towers (WTC 1 and 2) and WTC 7. The goal of this program element is to investigate the building construction, the materials used, and the technical conditions that contributed to the outcome of these disasters following the initial impact of the aircraft. What is learned in examining WTC 1, 2 and 7 is expected to benefit buildings of all designs.

- Second, a multi-year ***research and development (R&D) program*** to provide the technical basis for improved building and fire codes, standards, and practices. This program element addresses work in critical areas such as structural fire safety, prevention of progressive collapse, and equipment standards for first responders. It includes BPAT recommendations for WTC 3, 4, 5, and 6, Bankers Trust, and peripheral buildings as well as recommendations for future studies to address specific issues of broader scope not covered by the BPAT. Outputs and recommendations will be introduced into the voluntary consensus process that is used to develop building and fire codes and standards in the U.S.

- Third, an industry-led ***dissemination and technical assistance program (DTAP)*** that will provide practical guidance and tools to better prepare facility owners, contractors, designers, and emergency personnel to respond to future disasters. The DTAP will also be an important complement to the R&D effort in gaining acceptance of proposed changes to practice, standards, and codes. In addition, it will address BPAT recommendations for training and education of stakeholders.

The NIST response plan complements, is responsive to – and goes beyond – the BPAT efforts. The plan addresses all major recommendations contained in the BPAT report (see attached graphic #2). NIST has also identified other critical issues that need study, especially in areas that impact life safety and engineering practice.

Scope and Rationale for Investigation:
NIST agrees with the BPAT recommendations that additional studies of the Twin Towers and WTC 7 should be conducted. The NIST investigation – one component of the proposed NIST response plan – will focus on these buildings. The results of such an investigation could lead to major changes in both U.S. building and fire codes and in engineering practice, despite the unique design features or circumstances under which the buildings collapsed. The lessons to be derived from such an investigation will be applicable to a broad range of buildings types, not just the specific buildings that are studied. The following examples are illustrative:

The Twin Towers and WTC 7 are the only known cases of total structural collapse where fires played a significant role. These disasters provide a unique source of information to understand the complexities associated with the dynamics of building fires and the collapse vulnerability of buildings to fires. The investigation expects to analyze that information to validate generally applicable methodologies for use in fire safety design and retrofit of structures, and to evaluate the performance of fireproofing materials and connections used in steel structures.

In addition, these building disasters provide a unique source of information to investigate:
- The safety and performance of open-web steel trussed joists under fires. This type of trussed joist is used in commercial and institutional buildings nationwide.

- New mechanisms – not considered previously – that could initiate progressive collapse in buildings as a result of fires and impact loads, and the critical role of pivotal components such as transfer girders and floor diaphragms.
- The mechanical and metallurgical behavior of many different grades of structural steel under fire using steel recovered from the WTC site that is being stored at NIST.

There are equally important lessons for life safety – which were outside the scope of the BPAT study.

- Firefighting technologies and practices for tall buildings, including occupant behavior, evacuation, emergency response, and the performance of active fire protection systems such as sprinklers, manual suppression, fire alarms, and smoke management systems.
- The control of fire spread in buildings with potentially large open floor plans, and the effectiveness of compartmentation as a means to isolate fires in such buildings.

There are also important lessons for engineering practice that were not the focus of the BPAT study.

- The performance of the design, construction, and approval processes used to assure safety whenever an innovative structural system is used or there is a need for variances from building and fire codes – and whether such practices are adequate to detect and remedy inherent vulnerabilities.
- The provision of adequate structural reserve capacity to accommodate abnormal loads such as blast, impact, and accidental fires – especially those that can be anticipated prior to construction – balanced properly against the need to achieve design efficiency.

The NIST investigation will strive to study the disaster holistically, paying particular attention to the interplay between the building, the occupants, and the emergency responders. The review, analysis, modeling, and re-creation testing work will be based upon a solid foundation of technical evidence provided by building documents, video and photographic records, oral history data, emergency response records, and recovered structural steel.

Technical Approach:
The technical approach of the NIST investigation will include the following phases over an estimated 24 month period:

- **Identification of Technical Issues and Major Hypotheses Requiring Investigation:** opportunity for public input (e.g., open meeting; website; Federal Register notice) in developing investigation plan; expert panels to solicit input (experts in structural and fire protection engineering; experts in construction, maintenance, operation and emergency response procedures of tall buildings); findings and recommendations of FEMA-funded BPAT study and technical issues identified by other experts; analysis of inputs to establish priorities for investigation; review by Federal Advisory Committee.

- **Data Collection**: inputs from building owners and operators, local authorities, consultants, and contractors; data and information collected by the FEMA/ASCE BPAT study; building and fire protection design calculations, records, plans, and specifications; construction, maintenance, operation records, building renovations and upgrades; video and photographic data; field data; interviews and other oral and written accounts from building occupants, families of victims, emergency responders, building operators, and other witnesses; emergency response records including audio communications; and other records.

- **Analysis and Comparison of Building and Fire Codes and Practices:** analysis and comparisons of codes and standards then and now, and specifications used for WTC buildings; review and analysis of practices used for design, construction, operation, maintenance, repair, renovations, and upgrades.

- **Collection and Analysis of Forensic Evidence:** structural steel, material specimens and other forensic evidence to the extent they have been collected or are otherwise available; metallurgical and mechanical analysis of steel to evaluate quality and estimate maximum temperatures; analysis of fire and elevator control panels.

- **Modeling, Simulation, and Scenario Analysis:** aircraft impact on structures and estimated damage to interior and core structure and residual structural capacities; role of jet fuel and building contents in resulting fire; fire dynamics and smoke movement; thermal effect on structures and the effectiveness of fireproofing; effect of fire on structural response and vulnerability and the role of connections, flooring system, and core and exterior columns; occupant behavior and response including influence of communications and barriers to egress; evacuation issues including egress, control/fire panels, emergency response, and communications; fire protection system design and vulnerability; hypotheses for structural collapse including evaluation of system vulnerability to progressive collapse; probable collapse mechanisms and associated uncertainties.

- **Testing to Re-Create Scenarios and Failure Mechanisms:** small and some real-scale re-creation tests to provide additional data and verify simulation predictions, especially for the effects of fires (e.g., use and adequacy of standard fire ratings, behavior of connections and assemblies).

- **Technical Findings and Recommendations:** preparation of interim and final reports; peer review by established NIST Editorial Review Board; augmented NIST review to include senior management and legal; review by Federal Advisory Committee; public comment period; finalize and disseminate via published reports, web, and media.

- **Dissemination and Deployment of Findings:** develop and disseminate proposed changes to codes and standards based on findings; participate with industry and emergency response community in their adoption and acceptance into codes and standards.

Currently, the NIST investigation plan includes eight projects that would provide the focus for the technical work. These are: (1) analysis of building and fire codes and practices; (2) baseline structural performance and aircraft impact damage prediction; (3) forensic analysis of structural steel; (4) investigation of active fire protection systems; (5) prediction of the thermal and tenability environment; (6) structural fire response and collapse; (7) occupant behavior, egress, and emergency communications; and (8) fire service technologies and guidelines. These projects are interdependent, and when considered together will meet the NIST investigation objectives (see attached graphic #3). The graphic shows how each project contributes to the investigation objectives – some projects contribute to more than one objective. A detailed description of each of these eight projects is in Attachment 1.

Technical Expertise:
The NIST investigation will use world-class technical expertise from both within and outside NIST. External experts will be drawn from academia, practice, and government and used on an as needed basis in various phases of the investigation. Several of these experts may well have contributed to the BPAT study.

Federal Advisory Committee:
NIST will charter a Federal Advisory Committee to help guide all aspects of the NIST investigation. The Committee will provide advice on scope, approach, work plan, and schedule; review and provide advice on results, findings, and recommendations; and review and provide advice on interim and final technical reports. Committee meetings will be announced in the Federal Register. Members of the Panel will be recognized for distinguished professional service, possess broad technical expertise and experience, and have a reputation for independence, objectivity, and impartiality. Members shall reflect the wide diversity of technical disciplines and competencies involved in the WTC investigation, including structural engineering, fire protection engineering, metallurgy, firefighting, human behavior, and property insurance. Members of this committee will be selected to avoid conflicts of interest – they shall not: be current or former NIST employees, be the recipient of an active NIST grant or contract, represent or be affiliated with parties affected directly by the investigation, participate in the conduct of the investigation, or participate in litigation on matters directly and specifically within the scope of the NIST investigation. The Advisory Committee will provide independent review of the NIST investigation ensuring that it is conducted objectively, thoroughly, and with the highest integrity.

NIST Secretariat:
The Director of NIST has established a secretariat to coordinate NIST-level activities in support of the investigation and to maintain ongoing liaison with the Executive Branch, the Congress, the public, and the media. NIST recognizes that there will be significant public and media interest in the investigation. NIST has assigned a spokesperson to provide press announcements and coordinate media briefings during the course of the investigation. NIST will also provide information via reports and briefings to the Executive Branch and the Congress at their request. The secretariat includes representatives of the Building and Fire Research Laboratory, Congressional and Legislative Affairs, Budget, Public and Business Affairs, NIST Counsel, Program Office, Acquisition and Logistics, Occupational Health and Safety, and the Management and Organization Division.

Liaison with the Professional Community, the Public, and Local Authorities:
NIST will maintain ongoing liaison with the professional community, the public, and local authorities over the course of the investigation through briefings, presentations, and opportunity for comment on key investigation reports. NIST will assign a special liaison to interact with the families of building occupants and first responders. NIST recognizes the vital role that those individuals and groups have to play in providing input on the NIST investigation. NIST also believes that it is appropriate and important to keep these families and organizations informed about the progress of the investigation.

Impact and Outcomes:
The NIST investigation will be valuable in establishing the probable technical causes of the disaster after aircraft impact, replacing speculative observations with objective and fact-based findings, deriving the lessons learned from the disaster, and identifying needed improvements to building and fire standards, codes, and practices and to the safety of tall buildings nationwide. Implementation of the results of the NIST investigation – in conjunction with those of the R&D and Dissemination and Technical Assistance elements of the NIST response plan – will help restore public confidence by making tall buildings safer nationwide, enhance the effectiveness and safety of fire and emergency responders, and better protect building occupants and property in the future.

The results of the NIST investigation will also support and guide future work to develop and disseminate guidance and tools, assess and reduce vulnerabilities, and produce the technical basis for cost-effective changes in national practices and standards. A private sector coalition – representing the key industry, standards, codes, and professional organizations – has worked with NIST to establish the response plan (see page 2) to meet these longer-term needs. The goal of the longer-term program is to produce cost-effective retrofit and design measures and operational guidance for building owners and emergency responders.

National Building and Fire Safety Investigation of the World Trade Center Disaster		
Technical Area	**Project #**	**Outputs**
Identification of Technical Issues and Major Hypotheses	**Planning Phase**	• Public Meeting to gather comments on scope of NIST investigation plan. • Report(s) on NIST Investigation Plan Approach and Process. • Major Hypotheses and Technical Issues for Investigation
Analysis of Building and Fire Codes and Practices	**1**	• Report(s) on Analysis of Building and Fire Codes and Practices to determine the procedures and practices that were used in the design, construction, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of the World Trade Center Buildings 1, 2, and 7, and to provide input to other investigation projects.
Baseline Structural Performance and Aircraft Impact Damage Prediction	**2**	• Report(s) on Baseline Structural Performance and Aircraft Damage Prediction to evaluate the role of structural system design and the abnormal loads from aircraft impact on the collapse of the WTC towers.
Forensic Analysis of Structural Steel	**3**	• Report(s) on Forensic Analysis of Structural Steel to determine properties and quality of the metal, weldments, and connections, and to provide data for other investigation projects.
Investigation of Active Fire-Protection Systems	**4**	• Report(s) on Investigation of Active Fire-Protection Systems to document and evaluate their performance on September 11, 2001 and to assess their role in fire spread, emergency response, and the fate of occupants and responders.
Prediction of Thermal Environment	**5**	• Report(s) on Prediction of Thermal and Tenability Environment for use in evaluating the behavior and fate of occupants and responders and the structural performance of the buildings.
Structural Fire Response and Collapse	**6**	• Report(s) on Structural Fire Response and Collapse to identify most probable structural collapse mechanisms for World Trade Center Buildings 1, 2, and 7.
Occupant Behavior, Egress, and Emergency Communications	**7**	• Report(s) on Occupant Behavior, Egress, and Emergency Communications to determine the behavior and fate of occupants and responders – both those who survived and those did not – and to determine the performance of the evacuation system on September 11, 2001.
Fire Service Technologies and Guidelines	**8**	• Report(s) on Fire Service Technologies and Guidelines to determine the fire service procedures and practices for World Trade Center Buildings 1, 2, and 7, and the fate of emergency response personnel.
Technical Findings and Recommendations	**Reporting Phase**	• Interim and Final Reports on the Technical Findings and Recommendations of the Investigation, including probable technical causes of the disaster.
Dissemination and Deployment of Findings	**Via R&D and DTAP**	• Dissemination and Deployment of Findings via proposed standards and codes changes and participation with industry in their adoption and acceptance into codes and standards.

Attachment 1
Description of Investigation Projects

Project #1: Analysis of Building and Fire Codes and Practices

Purpose: To obtain, review, and analyze applicable building code provisions and project documents and to determine the procedures and practices that were used in the design, construction, and maintenance of the structural, passive fire protection, and emergency access and evacuation systems of World Trade Center Buildings 1, 2, and 7, and to provide input to other investigation projects.

Technical Approach: This project focuses on gathering information that governed the design, construction, and maintenance of the WTC buildings as related to structural and fire safety performance. The major sources of information will be historical records that have been maintained by various entities involved in the design, construction, and maintenance of the structural system, the passive fire protection systems, and the elevator system. Oral history will be obtained from knowledgeable individuals to augment the information in historical records. In addition, building code provisions that governed the project will be compared with code provisions of other major cities that governed tall buildings at the time of design and construction of the WTC buildings. A summary will be prepared of those aspects of the structural, passive fire protection, and elevator systems that may have bearing on the structural performance, occupant evacuation, and loss of lives on September 11, 2001. This project is divided into eight tasks as follows:

Task 1—Review design calculations and project documents. Available documents related to the original design will be reviewed to establish the design loads and methods used to proportion structural components. Special effort will be devoted to documenting the approval process for those aspects of the structural system used in the WTC towers that were not covered by the provisions of the governing code and to document abnormal loads anticipated at the time of the original design of the WTC towers. Available project and as-built drawings (structural, mechanical, architectural) will be obtained for use by other investigation projects.

Task 2—Review building construction. Available construction documentation (such as construction logs, change orders, test and inspection reports) will be reviewed. Significant events encountered during construction (and over the life of the buildings) that may have impacted the performance of the structural, passive fire protection, and elevator systems will be identified and documented. The architectural configuration will be established for the affected stories of WTC 1 and 2 and WTC 7 on September 11 before the attacks.

Task 3—Review passive fire protection features. Those codes and standards that applied to the passive fire protection features of the WTC buildings will be reviewed. This includes documentation of the passive structural fire protection system used in the buildings such as fireproofing, compartmentation, fire stops, and enclosures around egress paths. The structural integrity and fire safety performance of the enclosure shaft for the elevators and stairs will be studied. The maintenance records of the passive fire protection systems will be reviewed. Relevant modifications made to the passive fire protection systems during the service life of the buildings and after the 1993 bombing will be documented.

Task 4—Review emergency access and evacuation systems. Review the design, operation, maintenance, and inspection of the emergency access and evacuation systems in the WTC towers and the condition of these systems at the time of collapse of the buildings. Collect the

relevant literature and review existing U.S. and international standards and identify design characteristics and maintenance practices applied to such systems in WTC 1 and 2 that affected their performance on September 11, 2001. Standards and practices for firefighter lifts and FDNY policies will be reviewed to evaluate the potential effectiveness of such technology in improving firefighter effectiveness and reducing firefighter losses.

Task 5—Code comparisons. The New York City, the New York State, and national model codes that were in effect when the buildings were designed will be documented. Specific provisions in those codes will be compared with design requirements for the WTC 1, 2 and 7 buildings. Focus will be on the structural loading criteria and provisions for structural fire protection – including emergency access and evacuation. Code provisions will be compared for high-rise construction in other large cities with those that governed the design of the WTC towers. Current model code provisions will also be compared with those then in effect that governed the design and construction of the WTC buildings.

Task 6—Review maintenance records. A review will be conducted of maintenance and renovation that may have affected the structural system and the passive fire protection system. The objective is to develop the most accurate representation of the structural systems, including the condition of the structural fire protection, as they existed in the portions of the buildings affected by aircraft impacts on September 11, 2001.

Task 7—Document structural modifications following the 1993 bombing. The structural modifications that were made after the 1993 bombing will be reviewed to determine whether they may have affected the structural system of the WTC buildings.

Task 8—Report preparation. The results of this project will be synthesized into a chapter to describe the design, construction, and maintenance of and modifications to the WTC buildings. The structural configuration, passive fire protection systems, and emergency access and evacuation system at the time of the attack will be described. In addition, the internal condition of the architectural and mechanical systems will be documented with input from other investigation projects. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion[1]:

1. Interim report that documents the design basis for the WTC buildings and describes the process by which the innovative structural system was approved and the abnormal loads from aircraft impact anticipated in the original design of the WTC towers (6 months).

2. Interim report that summarizes pertinent construction data for the WTC buildings (9 months).

3. Interim report that documents code provisions related to high-rise construction and structural fire safety (9 months).

4. Interim report that documents maintenance and modifications that may have affected the structural and passive fire protection systems within the affected regions of the buildings. This includes modifications resulting from the 1993 bombing (10 months).

[1] Estimated time-to-completion is from start of investigation.

5. Interim report on regulations and practices related to the passive fire protection features systems in the buildings (9 months).

6. Interim report on the design, operation, maintenance, and performance of emergency access and evacuation systems in the WTC towers (6 months).

7. Draft chapter for final report that describes the design, construction, and maintenance of and modifications to the structural, passive fire protection, and emergency access and evacuation system, and that documents the probable conditions of the buildings at the time of the attacks on September 11, 2001 (16 months).

Project #2: Baseline Structural Performance and Aircraft Impact Damage Prediction

Purpose: To evaluate the role of the structural system design and the abnormal loads from aircraft impact on the collapse of the WTC towers by: (1) developing reference structural, mechanical, and architectural (SMA) models of the WTC towers, (2) establishing baseline performance of each of the towers under design loading conditions (especially gravity and wind), (3) estimating probable damage to the SMA systems of the towers due to aircraft impact, (4) comparing differences between anticipated and actual abnormal loads posed by aircraft impact, and (5) estimating the structural reserve capacities of the towers to accommodate abnormal loads under service conditions and after aircraft impact.

Technical Approach: This project focuses on establishing the baseline performance of the WTC towers, evaluating the effect of the aircraft impact on their response, and estimating the probable damage to the structural, mechanical, and architectural (SMA) systems. In addition, a comparison will be conducted between the response and damage to the towers due to the actual impact of the Boeing 767 aircraft and the abnormal load condition of a Boeing 707 aircraft impact anticipated at the time of the original design. This project will also evaluate the reserve capacities of the towers immediately after impact. Since the structural design of the towers included many innovations such as the use of perimeter tube system, prefabricated exterior column elements, wind tunnel testing, and damping devices in the floor system, this project will establish the baseline performance of the structural system under design gravity and wind loads. This project is divided into six tasks as follows:

Task 1—Develop SMA models of the two towers. The structural plans for the two towers will be studied to select appropriate structural modeling strategies for the different response analysis objectives. The models will need to recognize the special features of the structural system such as the floor diaphragms consisting of open-web steel trussed joists and composite slab, the exterior prefabricated column elements, and the variety of connection details used in the towers. The models will have levels of complexity ranging from frame elements representing the entire structural system to detailed finite element meshes of shell elements of the structures in the vicinity of the level of impact. These models – after third-party review – will be used for various phases of the investigation dealing with the structural performance of the towers. To simplify modeling efforts, a database for the two towers that includes geometries, dimensions, and material properties of the various structural members will be developed. CAD models will be developed to represent both mechanical and architectural systems. Mechanical models will include HVAC, elevators, and water supply systems while architectural models will include interior layouts, stairways, fire suppression systems, etc.

Task 2—Analyze the structural models of the towers under design loading conditions to establish the baseline performance, including estimation of structural reserve capacities and the diaphragm action provided by the floor system.

Task 3—Simulate the aircraft crash into the towers to estimate the extent of damage to SMA systems. The analysis of the aircraft crash will be performed at various levels of complexity ranging from energy and momentum conservation calculations to state-of-the-art, three-dimensional, and large-deflection finite element analyses of both the aircraft and the towers. The simulations will account for the speed, direction, and mass and stiffness distribution of the aircraft. This task will use WTC tower steel properties, including high strain rate properties, obtained from the project on Forensic Analysis of Structural Steel. The primary purpose of this task is to provide estimates of the probable damage to structural systems – including floors and

exterior tube and interior core columns, and the load redistribution provided by the outrigger truss system – rather than the damage done to the aircraft. Therefore, the level of complexity of the aircraft model will be selected to achieve this analysis objective. Multiple simulations of the impact accounting for the various sources of uncertainty will be used to provide bounds for the extent of damage to mechanical and architectural systems. Structural models of the damaged towers will be developed for use in subsequent analyses.

Task 4—Analyze the towers under anticipated abnormal loads due to the impact of a Boeing 707, flying at the speed assumed when the towers were designed, to estimate the extent of damage and the reserve capacity after impact. The results of this analysis will be compared with information that may be available on the damage estimated in the original design of the towers. A comparison between the results of tasks 3 and 4 will be conducted to compare the differences in the response and damage between the anticipated and actual abnormal loads posed by aircraft impact.

Task 5—Determine the response of the towers immediately after the impact. The focus of this task is to quantify the structural reserve capacity (or margin of safety against collapse) under existing service loads following the loss of exterior and core columns and floors due to the aircraft impact. This task will help to determine how the towers responded and the mechanism by which they remained standing immediately after the aircraft crashes and prior to collapse, and specifically to evaluate how close they were to collapse immediately after the crashes.

Task 6—Report preparation. The results of this project will be synthesized into a chapter to describe the baseline structural performance of the towers under design conditions, estimates of damage to the SMA systems due to aircraft impact, and the reserve capacity of the structural components under design and abnormal loads and subsequent to damage by aircraft impact. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. First-order estimate of the damage to the towers. Models for Boeing 767 and 707 aircraft obtained (4 months).

2. Reference structural, architectural, and mechanical models of the towers. Third-party review of SMA models (6 months).

3. Interim report on estimation of the local and global response of the towers to aircraft impact including damage to structural, architectural, and mechanical systems (12 months).

4. Reference structural models of the damaged towers (13 months).

5. Interim report on baseline performance of the two towers under gravity and wind loads (14 months).

6. Response analysis of the WTC towers to actual and anticipated abnormal loads from aircraft impact (15 months).
7. Interim report on estimation of the structural reserve capacity of the towers under design and abnormal loads as well as immediately after aircraft impact (17 months).

8. Draft chapter for final report that describes the baseline structural performance of the towers under design conditions, and estimates damage to the SMA systems due to aircraft impact and the reserve capacity of the components of the tower structures damaged by aircraft impact (18 months).

Project #3: Forensic Analysis of Structural Steel

Purpose: To analyze structural steel available from WTC Buildings 1, 2, and 7 to determine properties and quality of the metal, weldments, and connections, and provide data for other investigation projects.

Technical Approach: This project is divided into six tasks as follows:

Task 1—The physical evidence (structural steel components and connections) and other data, such as specifications for the steel, which are available, will be collected and cataloged. This information will identify the location of steel pieces within the buildings and determine what steel and properties were specified.

Task 2—Failure mechanisms and damage will be documented based on visual observations of recovered steel, especially focused on available columns, connectors, and floor trusses. The cause of extreme erosion seen on some parts of the steel columns will be studied.

Task 3—The metallurgical and mechanical properties of the steel, weldments, and connections, including temperature dependence of properties, will be determined. The grades of steel in the exterior columns will be identified, as well as those in core columns (if available), welds, spandrels, trusses, truss seats, and fasteners. The identification will include composition, microstructure, mechanical, and impact properties. This project will provide steel property data, including models of elevated temperature behavior for relevant steels, to estimate damage to the towers from aircraft impact, evaluate structural fire response, and study the initiation and propagation of structural collapse.

Task 4—Steel properties will be correlated with the material properties specified for construction of the buildings. An assessment of the quality of the steel compared with that specified for the construction will be made.

Task 5—The steel will be analyzed metallographically to estimate maximum temperatures reached. It is recognized that high temperature exposure before the collapse may be difficult to distinguish from exposure during post-collapse fires.

Task 6—Report preparation. The results of this phase of the investigation will be synthesized into a chapter to describe the results of the forensic analysis of the structural steel available from the WTC towers. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Catalog of available structural steel and relevant specifications (4 months).

2. Documentation of failure mechanisms and damage from visual observations (4 months).

3. Interim reports on the metallurgical and mechanical properties of the steel and connections, including temperature dependence of properties.
   a. Identification of steel in the exterior columns, core columns (if available), welds, spandrels, trusses, truss seats, and fasteners based on composition, microstructure,

room temperature tensile properties, and impact properties (partial results in 4 months, complete in 12 months).

b. *Data to support airplane impact modeling studies* – high strain rate mechanical properties and impact properties of columns, spandrels, bolts, and welds on columns (partial in 4 months, complete in 14 months).
c. *Data to support models of steel frame performance in fire* – creep and high temperature tensile properties of columns, bolts on columns, trusses, truss seats, and bolts or welds associated with truss seats (partial results in 4 months, complete in 12 months).
d. *Data to support models of steel during collapse* – high strain rate room temperature tensile properties of truss seats and associated bolts and welds (partial results in 5 months, complete in 16 months).
e. Models of elevated temperature deformation as a function of load, temperature and time history for relevant steels (some steels in 6 months, complete in 16 months).

4. Estimation of maximum temperatures reached by collected structural steel (complete in 12 months).

5. Database of microstructural changes with temperature in the various classes of steels for future use by building fire community (16 months).

6. Comparison of steel properties to applicable material specifications (12 months).

7. Draft of chapter for final report that describes the results of the forensic analysis of the structural steel available from the WTC towers (18 months).

Project #4: Investigation of Active Fire Protection Systems

Purpose: To document and evaluate the performance of the installed active fire protection systems in the World Trade Center Buildings 1, 2, and 7 on September 11, 2001 and assess their role in fire spread, emergency response, and the fate of occupants and responders.

Technical Approach: This project is divided into six tasks as follows:

Task 1—Information available from the Port Authority and its contractors and consultants will be used to document previous fire events in WTC Buildings 1, 2, and 7.

Task 2—The active fire protection systems – including the installed sprinkler, manual suppression, fire alarm, and smoke management systems in WTC 1, 2, and 7 – will be documented.

Task 3—The design of the active fire protection systems will be analyzed relative to applicable building codes and standards at the time of installation. The maintenance, modifications, and inspection records for these systems will be reviewed. Modifications made after the 1993 bombing incident will be documented. The design requirements, including capacity and redundancies, will be compared with those in other major cities.

Task 4—A comprehensive set of questions will be developed to collect information from building operators, first responders, building occupants, and families of victims on the operation of and damage to the fire safety systems on September 11, 2001. These questions will be included in the information gathering that will be coordinated with other investigation projects, in particular the efforts related to fire service technologies and guidelines, building and fire codes, and occupant behavior and egress.

Task 5—The information collected in tasks 1-4 will be reviewed and analyzed by a panel of fire protection engineers with expertise in the operation and capabilities of active fire protection systems to establish the facts regarding the performance of these systems in WTC 1, 2, and 7 on September 11, 2001. NIST will interpret and analyze these facts and document its findings. This analysis will review the role and effectiveness of active fire protection systems in large compartment fires.

Task 6—Report preparation. The results of this project will be synthesized into a chapter to describe the installed active fire protection systems in WTC 1, 2, and 7, and the performance of these systems on September 11, 2001. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Collection of information on previous fires in WTC Buildings 1, 2, and 7 (3 months).

2. Comprehensive set of questions developed to collect information on operation of and damage to fire safety systems on September 11, 2001 (3 months).

3. Interim report on design, installation, and maintenance of and modifications to active fire protection systems present in WTC 1, 2, and 7, and compare with applicable codes in New York City and other major cities (5 months).

4. Interim information on instructions and information provided by the fire alarm system to the building occupants and fire service and the operation of the smoke management systems (6 months).

5. Synthesis of collected information that will be used to establish the facts and analyze the performance of the active fire protection systems (12 months).

6. Draft of chapter for final report that describes the installed active fire protection systems in WTC 1, 2, and 7, and evaluates the performance of these systems on September 11, 2001 (18 months).

Project #5: Prediction of Thermal and Tenability Environment

Purpose: Reconstruct, with assessed confidence/uncertainty limits, the time-evolving temperature, thermal radiation, and smoke fields in World Trade Center Buildings 1, 2, and 7 for use in evaluating the behavior and fate of occupants and responders and the structural performance of the buildings.

Technical Approach: This project is divided into seven tasks as follows:

Task 1—Guidance on the initial conditions for modeling the fires, the rates of fire spread, the floors on which the structural collapses appear to have begun, etc., will be developed through the acquisition of available and relevant photographic and video images of damage to the three buildings, review of accounts from occupants and responders, and the cataloging and analysis of such images and accounts.

Task 2—The types of combustibles and estimates of the mass loading will be characterized by gathering data on the internal construction materials, furnishings and contents. The types of combustibles and estimates of mass loading will be compared with data from prior surveys of similar occupancies. Other fuel sources in WTC 7 will be identified and documented. The extent of the dispersed aviation fuel in WTC 1 and 2 will be estimated based on input from the Baseline Structural Performance and Aircraft Impact Damage Prediction project.

Task 3—Existing data on the fire performance of floor, wall, and ceiling systems will be compiled, complemented by additional measurements as needed, to determine air access for the combustion, to identify fire paths for intercompartment fire spread, and to identify those paths that were capable of contributing to the collapse of the buildings.

Task 4—The thermal properties of the structural insulation systems and the effects of vibration, impact, and shock on their thermal performance will be determined to estimate the thermal environment on the outside of the protected structural members. Also included will be indication of whether chemical interaction between the insulation materials and the steel at elevated temperatures could contribute to degradation of structural performance in the time available.

Task 5—The capabilities of NIST's Fire Dynamics Simulator (FDS) will be extended, using knowledge gained from the previous tasks, to reconstruct the temperature, thermal radiation, and smoke fields within the three buildings as a function of time and location. Reduced-scale experiments will be used to guide and evaluate the accuracy of key FDS sub-models.

Task 6—FDS will be used to simulate fully involved fires in the three buildings, with and without the initial damage from the aircraft or incident debris, for evaluating the extent to which that damage affected the thermal environment experienced by the structure. Parameters in the re-creation of the fires will enable estimation of the roles of jet fuel and building contents, ventilation system, compartment damage, pressurized core, and fire protection system on growth and spread of fire. Uncertainty and confidence intervals will be estimated for the accuracy of the reconstructions. The effectiveness of compartmentation in controlling fire spread in these buildings on September 11, 2001 will be analyzed.

Task 7— Report preparation. The results of this project will be synthesized into a chapter to describe the time-evolving temperature, radiation, and smoke fields in WTC 1, 2, and 7 and the effectiveness of compartmentation in controlling fire spread in these buildings on September 11,

2001. All experiments, model assumptions and operations, and reconstructions will be documented. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. First analysis of photographic and video images of damage to WTC buildings 1, 2, and 7 (3 months).

2. Compilation of data on construction materials and systems, furnishings and contents, and other fuel loads (4 months).

3. Evaluation of the thermal performance of structural insulation system(s) (8 months).

4. Completion of experiments to guide FDS sub-model development (10 months).

5. First prediction of the fire dynamics in one of the WTC towers (12 months).

6. Evaluation of pathways for fire ventilation and for compartment-to-compartment fire growth in the three buildings (14 months).

7. Completion of reduced-scale demonstration experiments (15 months).

8. Final predictions, with uncertainties, of the time-varying temperature, thermal radiation and smoke fields in WTC 1, 2, and 7 (16 months).

9. Draft chapter for final report that describes the time-evolving temperature, radiation, and smoke fields in WTC 1, 2, and 7 and the effectiveness of compartmentation in controlling fire spread in these buildings on September 11, 2001 (18 months).

Project #6: Structural Fire Response and Collapse

Purpose: To determine the response of structural components and systems to the fire environment in the World Trade Center Buildings 1, 2, and 7, and to identify probable structural collapse mechanisms.

Technical Approach: This project is divided into seven tasks as follows:

Task 1—Evaluate the response of floor and column systems under fire conditions. The following sub-tasks will be performed:

a. Develop structural model of floor truss and slab system including supports (i.e., connections to columns). Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
b. Develop structural model of both interior (core) and exterior column system for the floors of interest. Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Obtain thermal and mechanical properties of steel truss and connections as well as steel columns sections at elevated temperatures.
e. Obtain thermal insulation properties of spray-on fire proofing.
f. Estimate, using transient thermal analysis, the time-temperature relationship for the floor truss and column systems. Consider both unprotected and protected steel.
g. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the floor truss system, including support reactions (connection forces), and the column system.

Task 2—Evaluate the response of the WTC towers without and with aircraft impact damage under fire conditions. The following sub-tasks will be performed:

a. Develop structural model of floors of interest (location and number of floors to be determined) to evaluate the response of the WTC towers without aircraft impact. Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
b. Develop structural model (including aircraft damage) of floors of interest (impact floors and floors above that are involved in fire). Obtain information from project on Baseline Structural Performance and Aircraft Impact Damage Prediction.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Estimate, using transient thermal analysis, the time-temperature relationship for the structural components. Consider both unprotected and protected steel.
e. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the floors of interest.
f. Identify components critical to collapse initiation.

Task 3—Conduct tests of structural components and systems under fire conditions. In the course of the investigation, it may be necessary to re-create the predicted thermal environment and structural response of components such as floor truss seat connections, floor truss assemblies, and exterior prefabricated column-spandrel elements. Such tests would be used to validate analytical models and to provide response data that are otherwise unavailable.

Task 4—Evaluate failure hypotheses for the WTC towers. The following sub-tasks will be performed:

a. Identify candidate hypotheses for initiation and propagation of collapse.
b. Evaluate hypotheses for collapse initiation and propagation, including the role played by floor diaphragms and connections.
c. Estimate uncertainty and confidence intervals for probable collapse initiation and propagation mechanisms.
d. Identify most probable collapse mechanism(s).

Task 5—Report on the performance of open-web steel trussed joists in fire. The past performance of open-web steel joist systems in fire will be investigated. This study will include fire incident reports, insurance investigation reports, etc. Test reports (ASTM E119 or others) of steel joist systems in fire will be obtained and evaluated. Data obtained both domestically and, where possible, internationally will be included in the investigation. The results of this review will be compared with the floor truss system used in the WTC towers.

Task 6—Predict the response of WTC Building 7 under fire conditions. The following sub-tasks will be performed:

a. Develop model of structural system.
b. Obtain fuel loads for various tenants and internal building operating systems (e.g., power generation) from project on Prediction of Thermal and Tenability Environment.
c. Obtain thermal environment predictions. Consider both standard fires (e.g., ASTM E-119 and ASTM E-1529) and real fires based on fire dynamics simulations.
d. Obtain properties of steel at elevated temperatures from project on Forensic Analysis of Structural Steel.
e. Estimate, using transient thermal analysis, the time-temperature relationship for the structural system.
f. Evaluate, using thermal-mechanical analysis, the time-dependent structural response of the structural system including transfer girder system.
g. Identify most probable collapse mechanism.

Task 7— Report preparation. The results of this project will be synthesized into a chapter to describe the response of structural components and systems to the fire environment in the World Trade Center Buildings 1, 2, and 7, and to identify probable structural collapse mechanisms. The performance of open-web steel trussed joist systems in fire will be documented. In addition, the role of pivotal components such as floor diaphragms, connections, and transfer girders in collapse initiation will be documented. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Evaluation of the response of floor system under fire conditions (9 months).

2. Evaluation of the response of column system under fire conditions (12 months).

3. Evaluation of the response of the WTC towers with no aircraft impact under fire conditions (16 months).

4. Evaluation of the response of the WTC towers with aircraft impact under fire conditions (17 months).

5. Report on the performance of open-web steel trussed joist systems in fire (6 months).

6. Completion of design, construction, and testing of critical components (16 months).

7. Evaluation of the response of WTC Building 7 under fire conditions (17 months).

8. Draft chapter for final report that describes the response of structural components and systems to the fire environment in the WTC 1, 2, and 7, and the probable structural collapse mechanisms. The performance of open-web steel trussed joist systems in fire and the role of pivotal components such as floor diaphragms, connections, and transfer girders in collapse initiation will be documented (18 months).

Project #7: Occupant Behavior, Egress, and Emergency Communications

Purpose: To determine the behavior and fate of occupants and responders – both those who survived and those who did not – by collecting and analyzing information on occupant behavior, human factors, egress, and emergency communications in World Trade Center Buildings 1, 2, and 7, and evaluating the performance of the evacuation system on September 11, 2001.

Technical Approach: This project is divided into six tasks as follows:

Task 1— Baseline information on the evacuation of the WTC buildings on September 11, 2001 will be developed through a comprehensive, systems-oriented, and interdisciplinary data collection effort focused on occupant behavior, human factors, egress, and emergency communications (including instructions given, interpretation of instructions, and response to instructions). This will involve the collection of new data from people affected by the WTC attacks (e.g. building occupants and first responders via direct accounts from survivors and families of victims), especially those who had to evacuate the buildings. Experts in human behavior and statistical sampling will be used to develop a data acquisition strategy that considers various data collection methods such as interviews and surveys. Inputs and suggestions will be obtained from groups with an interest in the content of the data collection effort. Additionally, written accounts, transcripts of (emergency) communications, published accounts, and other sources of egress related information will be obtained, in coordination with other data collection efforts for the investigation.

Task 2—Archival records from prior WTC evacuation incidents (e.g., 1977 blackout, 1980 bomb scare, 1990 power outage, and 1993 bombing) and practice evacuations will be collected. These records will be compared and contrasted with the September 11th incident evacuation. Changes made to the evacuation procedures following the earlier incidents and in recent years will be evaluated in the context of the experience on September 11, 2001.

Task 3—Pre-event data will be recorded for WTC Buildings 1, 2, and 7. This information includes, but is not limited to, physical aspects of building egress components, such as stairs (width, number, location, vertical continuity), evacuation lighting, back-up power, elevators (number, operational before and after impact, role in evacuation), and active fire protection systems (sprinklers, manual suppression, fire alarms, smoke control). Building plans, emergency plans, type and frequency of evacuation drills, occupancy level and distribution on the morning of September 11th, and communications will also constitute pre-event data. This information will provide a baseline for evaluating the performance of the egress system.

Task 4—The information collected in task 1 will be stored in a database. Additionally, information from third-party sources, such as television interviews and newspaper articles, as well as other relevant published material will be analyzed, examined, and assembled in the database.

Task 5—The data will be analyzed to study the movement of people during the evacuations, decision-making and situation awareness, and issues concerning persons with disabilities. A timeline of the evacuation will be developed using the results of these analyses together with other data sources. This timeline will be compared with the timeline of the structural response, the development of the interior conditions (fire and smoke), as well as activation of the active fire protection systems. The characteristics of the WTC evacuation designs and protocols will be evaluated, including the performance of stairs and elevators, emergency communications,

and building tenability. The designs will also be compared with building code requirements and practices for tall buildings in other major cities worldwide. The observed evacuation data will be compared with predictions obtained using alternate egress models to better understand occupant behavior and identify needed improvements to existing egress models. In addition, the evacuation experience on September 11, 2001 will be compared with previous evacuation incidents in these buildings. The results of the analyses will be reviewed in the context of occupant protection practices for tall buildings, including the consideration of full evacuation and phased evacuation strategies.

Task 6— Report preparation. The results of this project will be synthesized into a chapter to describe the occupant behavior, egress, and emergency communications in WTC 1, 2, and 7, and the performance of the evacuation system on September 11, 2001. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Completion of data collection design strategy (4 months).

2. Collection of archival data and pre-event data (4 months).

3. Completion of data collection effort and database development (9 months).

4. Completion of analysis of occupant behavior, egress, and emergency communications as defined in task 5 (17 months).

5. Draft chapter for final report that describes the occupant behavior, egress, and emergency communications in WTC 1, 2, and 7 and the performance of the evacuation system on September 11, 2001 (18 months).

Project #8: Fire Service Technologies and Guidelines

Purpose: To determine fire service procedures and practices for World Trade Center Buildings 1, 2, and 7, and the fate of emergency response personnel by (1) documenting the performance of first responders and their equipment on September 11, 2001, (2) identifying the effects of available alternatives related to emergency first responder technology, training, and operational procedures, and (3) identifying R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events.

Technical Approach: This project is divided into four tasks as follows:

Task 1—Emergency response data will be collected and analyzed to document first responder fatality, command and control procedures and performance, and written records (e.g., dispatch logs, recorded radio communications, run logs from surviving responding units, 911 records, data recorded by Port Authority operations, and any other documents identified as critical to the investigation). This will include operations and function of communications systems, on-site emergency information systems, fire alarm panels, elevator control panels, standpipes, fire hoses, and other pre-positioned emergency equipment, etc. Oral history data will be collected from surviving first responders, witnesses, and those in control of emergency operations, in coordination with other data collection efforts for the investigation. A panel of emergency responder experts will be convened to review the data and conduct a fact-based analysis of the emergency response on September 11, 2001.

Task 2—NIST will interpret the factual analysis to determine the effect on responder successes of factors such as:

- pre-planning, training, and standard operating procedures at the time of the incident;
- the influence that building design (e.g., height, stairways, elevators, smoke control systems), the impact of systems failures (e.g., water supply, sprinklers, standpipes), and command and control procedures had on life saving operations and safety of rescue personnel;
- barriers to efficient performance in and surrounding buildings and strategies employed to overcome barriers;
- how operational procedures, including command and control, may have been altered to manage the incident;
- the effectiveness of fire and emergency response protocols for tall buildings;
- the ability to fight large fires on the upper floors of tall buildings;
- the impact that the 1993 bombing of the WTC had on codes and standards that affected first responders in tall buildings (what recommendations were made and what changes were made in training, tactics, and operational procedures); and
- the resources available for initial situation assessment and incident management, and practices for predicting the possibility of structural collapse.

Task 3—The emergency response practices used in New York City will be compared with practices used in other major cities to evaluate the effectiveness of the responders on September 11, 2001.

Task 4— Report preparation. The results of this project will be synthesized into a chapter to describe: the performance of first responders and their equipment on September 11, 2001; identify the effects of available alternatives related to emergency first responder technology,

training, and operational procedures; and identify R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events. The project staff will contribute to drafting the final investigation report for review by the Federal Advisory Committee.

Outputs and Preliminary Estimate of Time-to-Completion:

1. Documentation of the activities of emergency responders, including their injuries and fatalities (8 months).

2. Evaluation of the degree of success of responders in preserving life and property and the factors that limited that success (14 months).

3. Identification of the key factors where R&D may improve the capability of responders to protect the public, first responders, and vital physical infrastructure during extreme events (16 months).

4. Draft chapter for final report that describes the performance of first responders and their equipment; identify the effects of available alternatives related to emergency first responder technology, training, and operational procedures; and identify R&D needs in support of their capability to protect the public, first responders, and vital physical infrastructure during extreme events (18 months).