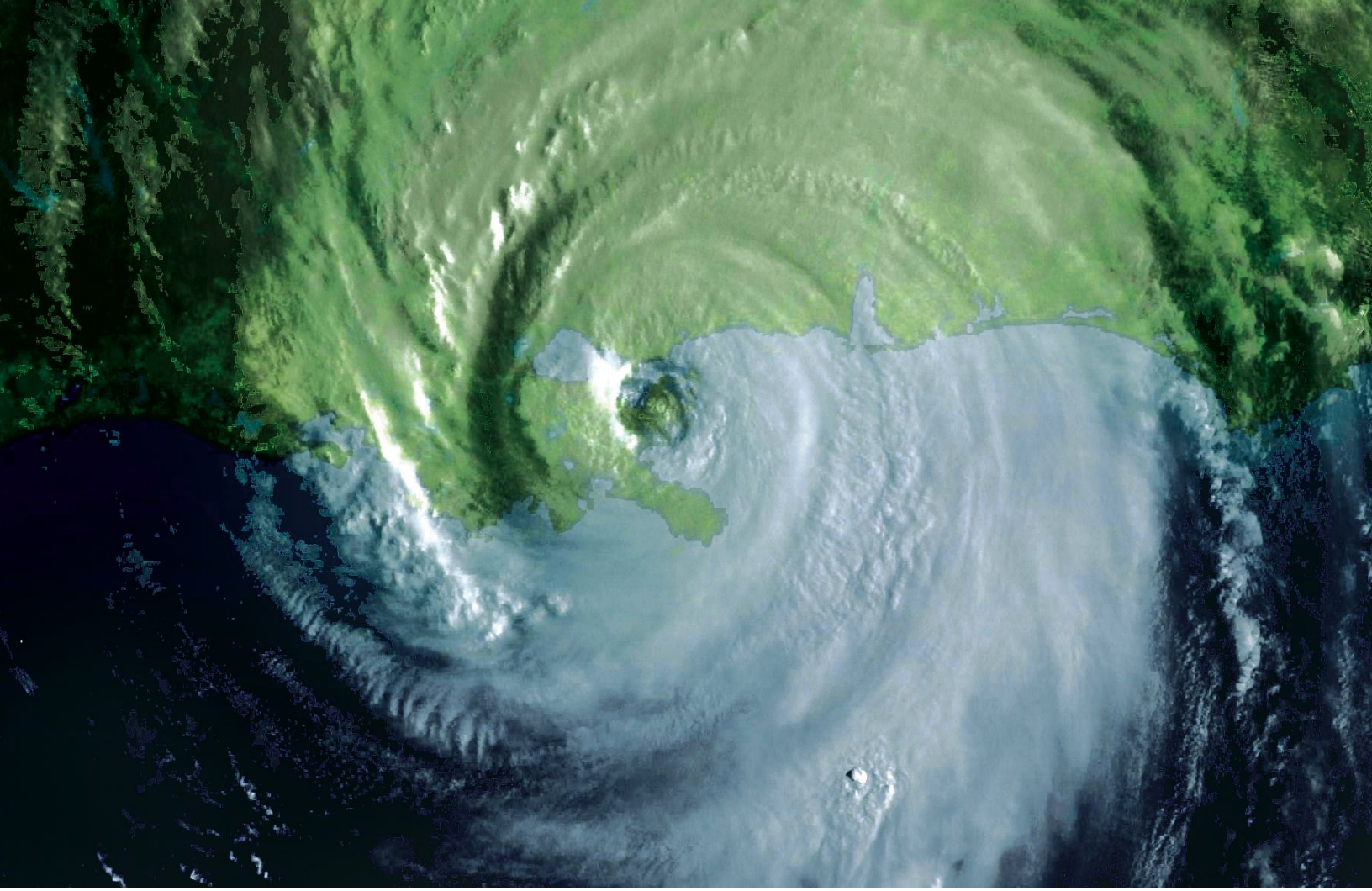

Hurricane Katrina in the Gulf Coast

Mitigation Assessment Team Report

Building Performance Observations, Recommendations, and Technical Guidance

FEMA 549 / July 2006

FEMA

MITIGATION ASSESSMENT TEAM REPORT

HURRICANE *Katrina* IN THE GULF COAST

In response to Hurricane Katrina, the Federal Emergency Management Agency (FEMA) deployed a Mitigation Assessment Team (MAT) to evaluate and assess damage from the hurricane and provide observations, conclusions, and recommendations on the performance of buildings and other structures impacted by wind and flood forces. The MAT included FEMA Headquarters and Regional Office engineers, representatives from other Federal agencies and academia, and experts from the design and construction industry. The conclusions and recommendations of this Report are intended to provide decision-makers with information and technical guidance that can be used to reduce future hurricane damage.

About the Cover

The cover photograph is a National Oceanic Atmospheric Administration (NOAA) image courtesy of the National Environmental Satellite, Data, and Information Service (NESDIS). The NOAA Geostationary Operational Environmental Satellite (GOES)-12 satellite recorded this regional imagery of Hurricane Katrina on August 29, 2005, at 1:15 p.m. Eastern Daylight Time. This image shows a closeup of Hurricane Katrina's center of rotation.

(IMAGE COURTESY OF NOAA/NESDIS VISUALIZATION LABORATORY)

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Dedication

FEMA and the Hurricane Katrina Mitigation Assessment Team are honored to dedicate this report to the memory of Robert T. Pendley, who passed away on June 9, 2006, after a long illness.

Bob dedicated his 30-year career to FEMA mapping and mitigation programs. He began his career as a geographer preparing flood maps, but quickly began to use his talents as a technical writer for FEMA program correspondence, reports, and major publications. At Greenhorne & O'Mara, Bob assisted FEMA in writing proposed and final rule changes and had played a significant role in numerous program and technical documents, including The National Mitigation Strategy, Post-Event Building Performance/Mitigation Assessment Team reports for every major hurricane over the past 13 years, as well as the Oklahoma City bombing and the World Trade Center disaster, the *Coastal Construction Manual*, the *Homeowner's Guide to Retrofitting*, FEMA *Technical Bulletins* series, and the *Home Builder's Guide to Coastal Construction*.

Bob possessed a unique talent of understanding program regulations and requirements, and technical and engineering issues, and combined that knowledge with the ability to write documents that could be read and understood by a wide audience. He also possessed the artistic talent to create technical details and graphics to clearly depict technical and program issues.

Those who knew and worked with Bob know what a special person he was. He touched us all and his work has truly made a difference in our lives and our Nation's ability to understand our vulnerability to hazards and mitigate the potential loss of life and property.

Executive Summary

The North Atlantic hurricane season for 2005 began early and was an unusually active season, breaking the previous recorded hurricane season records for the number of named storms, hurricanes, Category 5 hurricanes, major hurricanes making U.S. landfall, early-season storms, and the strongest hurricane in the Atlantic Basin (see Table 1). On average, about six North Atlantic hurricanes occur every year; by the end of 2005, there had been 15. The annual hurricane season, which generally lasts from June 1 through November 30, was longer than average for the 2005 hurricane season with Tropical Storm Zeta (the 27th named storm) persisting until January 2006.

Table 1. 2005 Hurricane Season Records

Statistic	2005 Total	Previous Record/Year	
Number of named storms	27	21	1933
Number of hurricanes	15	12	1969
Number of Category 5 hurricanes	4	2	1960 and 1961
Major hurricanes making U.S. landfall	4	3	2004
Number of tropical storms before August 1	7	5	1997
Strongest hurricane in the Atlantic Basin	882 mb (Wilma)	888 mb (Gilbert)	1988

mb = millibars
SOURCE: NOAA, NCDC

Hurricane Katrina was one of the strongest storms to impact the coast of the United States during the past 100 years. On August 25, 2005, the storm made its first landfall on the southeast coast of Florida as a Category 1 hurricane. It then crossed south Florida and moved into the Gulf of Mexico, where it gained strength to a Category 5 hurricane, although it weakened before making its second landfall. According to the National Climatic Data Center (NCDC), Hurricane Katrina made its second landfall on August 29, 2005 as a strong Category 3 storm in southeast Louisiana near Buras, with 1-minute sustained winds estimated at 127 miles per hour (mph) or approximately 150 mph 3-second gust, and a minimum central pressure of 920 millibars (mb), the third lowest pressure on record for a U.S. landfalling hurricane. After coming ashore in Louisiana, Katrina continued to move northeastward across Breton Sound, to make a third landfall near Pearlington, Mississippi, as a Category 3 storm with sustained wind speeds estimated at approximately 120 mph or approximately 145 mph 3-second gust.

The hurricane pushed record storm surge onshore in its northeastern quadrant, which caused widespread devastation in southeast Louisiana and along the coasts of Alabama and Mississippi. The storm surge caused failures of the levee system that protects New Orleans from Lake Pontchartrain, and subsequently an estimated 80 percent of the city was flooded. Katrina was the most destructive and expensive natural disaster in the history of the United States, with estimated total economic losses in excess of $125 billion and insured losses of $35 billion, topping the losses of $26.5 billion from Hurricane Andrew in 1992.

One of the key factors of this storm was its strength 24 hours before landfall when it was a large Category 5 hurricane with a minimum central pressure of 902 mb. Although the storm began weakening, with wind speeds significantly decreasing just before making landfall in Louisiana and Mississippi as a Category 3, the storm surge maintained a level more closely associated with a Category 5 hurricane. The surge generated by the storm could not dissipate as rapidly as the wind speeds decreased. Other factors that contributed to high surge elevations were the shallow depth of the offshore shelf and the shape of the shoreline.

In most areas impacted by Katrina, the estimated wind speeds were less than current American Society of Civil Engineers (ASCE) 7-05 design wind speed (the wind standard used by the latest edition of the International Building Code [IBC]). However, along a small portion of the Mississippi coastline, the estimated wind speeds did equal current design wind speeds.

Mitigation Assessment Team (MAT)

In response to a request for technical support from the Federal Emergency Management Agency (FEMA) Joint Field Offices in Montgomery, Alabama; Baton Rouge, Louisiana; and Jackson, Mississippi, FEMA's Mitigation Division deployed a Mitigation Assessment Team (MAT) to Alabama, Louisiana, and Mississippi to evaluate both building performance during Hurricane Katrina and the adequacy of current building codes, other construction requirements, and building practices and materials.

Flood elevations in Hurricane Katrina far exceeded the current design flood elevations along a significant portion of the Gulf Coast of Mississippi and caused levee failures in Louisiana. The high surge was a near design event along some areas of Dauphin Island, Alabama, with surge elevations exceeding those of Hurricane Frederic in 1979 and Hurricane Ivan in 2004. This provided a good opportunity to assess the adequacy of National Flood Insurance Program (NFIP) floodplain management requirements as well as current construction practices in resisting storm surge damage.

Hurricane Katrina was at a design level wind event in small portion of the coast of Mississippi, but overall it was below a design wind event. However, the storm did provide an opportunity to examine building elements that failed and to determine how buildings built to new building codes performed in those areas that did experience near-design wind conditions. The team was also able to collect information about building damage that helps correlate wind speeds to building performance.

The MAT was deployed on September 26 and conducted ground and aerial observations from Dauphin Island, Alabama, along the Mississippi Gulf Coast, through the City of New Orleans to Venice and Grand Isle, Louisiana. The MAT included FEMA Headquarters and Regional Office engineers, representatives from other Federal agencies and academia, and experts from the design and construction industry.

Damage Assessment Observations

Regulatory Standards and Building Codes

All of the communities along the Mississippi Gulf Coast visited by the MAT participate in the NFIP and have adopted floodplain management regulations that meet or exceed minimum NFIP requirements. Prior to Hurricane Katrina, Alabama, Louisiana, and Mississippi did not have statewide building codes for non-state-owned buildings. Many of the communities

in areas that were heavily impacted by Hurricane Katrina had either not adopted up-to-date model building codes that incorporate flood and wind protection or had no building codes at all. A few communities in Louisiana and Mississippi had adopted the IBC where references to floodplain management issues are included in the code. Many communities in these areas had adopted only a floodplain management ordinance and had not adopted a model building code at the time Katrina came ashore. Dauphin Island, Alabama, recently adopted an amendment for deeper pile embedment, and Louisiana and Mississippi have taken steps toward adopting up-to-date building codes.

One of the goals of the MAT was to investigate building failures from flooding inside and outside the Special Flood Hazard Areas (SFHAs) that are shown on the effective Flood Insurance Rate Maps (FIRMs) for the communities. Most of the communities visited by the MAT only enforced minimum flood-resistant design and construction standards, and had not adopted more stringent requirements. One exception is Pascagoula, Mississippi, in Jackson County, which had adopted higher standards that contributed to reduced damage. However, it should be noted that the surge elevations in Pascagoula were lower than those areas farther to the west, which were closer to the storm's landfall.

Flood Damage

Given that Katrina flood levels were well above the design level, the flood damage was severe. High storm surge and waves from the storm caused severe damage to buildings along the coasts of Alabama, Louisiana, and Mississippi. Damage in coastal areas resulted from velocity flooding, wave effects, and waterborne debris impacts, and, in Alabama, severe erosion and scour. Further inland, flood damage was associated more with rising water and inundation. The MAT observed that flood elevations in many areas exceeded the 100-year Base Flood Elevations (BFEs) shown on the current FIRMs by as much as 15 feet. Typically, surge elevations exceeded 23 feet North American Vertical Datum of 1988 (NAVD 88) along the Mississippi coast from Waveland east to Long Beach. The highest recorded surge and wave height elevation was 34.9 feet (NAVD 88).

The failure of levees and floodwalls that protect the City of New Orleans resulted in catastrophic flooding in the Greater New Orleans area, with floodwaters in many areas up to 8 feet above the lowest floor of the building. The BFEs for the levee-protected area are determined based on the certification that the levee will provide protection from the base flood event. Many buildings constructed with the first floor elevation above the BFE were severely damaged or destroyed when the floodwaters rose well above the first floor. The duration of the floodwaters in New Orleans contributed to further damages, with some areas remaining under water for several weeks. This long-duration flooding saturated some types of building materials beyond the point where they could be salvaged and contaminated the materials with chemical and biological substances in the floodwaters. The rampant growth of mold in flood-saturated buildings was another effect of the long-duration flooding.

Recognizing the potential impact of increased flood elevations on long-term recovery efforts and risk reduction, FEMA issued interim Katrina Flood Recovery Maps showing Advisory Base Flood

Elevations (ABFEs) to provide guidance during the rebuilding process. The ABFEs are based on an analysis of historical flood levels throughout the region, including those observed during Katrina.

Destruction or severe flood damage to one- and two-family buildings occurred throughout the study area, especially where the waves exceeded the floor elevation, leaving nothing more than parts of foundations. Damage of this nature was observed to virtually every foundation type. Wind damage could have occurred to the buildings prior to the onset of the most severe flood conditions, but the MAT could not make such a determination; if wind damage had occurred, the evidence was largely removed when the waves and flooding struck the elevated buildings. In areas not subject to severe wave action, flood levels above the floor sometimes floated buildings off their foundations, where connections between the foundations and the buildings were inadequate.

Most one- and two-family buildings built using V Zone construction methods were built with masonry pier foundations. Many of these piers failed in one of four modes due to lateral wave forces, including:

- rotation of the shallow pier footings due to inadequate embedment
- separation of the shallow footing (or slab) at the pier connection due to inadequate reinforcement
- fracture at a mid-height point on the pier due to inadequate reinforcement or poor quality control in the masonry/concrete work
- separation at the top of the pier where the floor system was connected to the pier.

Many of these failures occurred in conjunction with flood levels above the elevated floor, but the same types of failures have been observed after less severe coastal storms.

Severe flood damage also occurred to many one- and two-family buildings elevated on pile foundations, where the flood level exceeded the tops of the piles and connections between the piles and the buildings failed. However, although some piles were cracked or broken, as a type, piles substantially outperformed masonry pier foundations.

Structural damage to multi-family dwellings varied with the severity of waves, flood levels, and construction type. Reinforced concrete and steel-framed structures were generally not significantly damaged unless they were exposed to wave action above the floor level, in which case damages were usually limited to walls and contents (with the structural frame remaining intact). Overall, damages varied from moderate to severe in such cases. On the other hand, wood-framed and masonry buildings tended to suffer more damage where waves rose above the floor level, and minimal to moderate damage in flood areas without hydrodynamic forces, as long as foundation attachments were sufficient to prevent flotation of the buildings.

Damage to commercial buildings was generally consistent with damages observed to residential buildings, and varied with location and severity of flood forces. Coastal low-rise buildings, including strip malls, individual food service/retail, and larger retail facilities also sustained damage from the storm surge and waves. Several buildings along the shoreline lost load-bearing walls, leaving no evidence of the building other than the floor slab. Larger steel-framed commercial

buildings performed better as the structural frame and roof remained intact, but curtain walls and contents were destroyed. Flood impacts on high-rise buildings were less extreme, with most damage limited to parking deck failures and non-structural damage on lower levels.

The floating casino barges and support barges represent a different class of buildings, and consistently experienced severe damage due to their location and exposure to the most extreme wave and flood forces. These barges either sank, were heavily damaged but remained attached to their moorings, or became floating debris that destroyed or damaged many other buildings on land.

Wind Damage

Although most of Katrina's damage was related to flood, widespread wind damage was observed. It was extreme in some areas, even though Hurricane Katrina did not appear to have been a design wind event in most locations. Most of the wind damage was to building envelopes and rooftop equipment.

Structural damage to buildings from wind was not widespread. Those buildings that experienced substantial structural damage typically were older and built before wind effects were adequately considered in design and construction. Newer homes that were substantially damaged were observed to have construction deficiencies pertaining to connections. Structural damage to commercial buildings depended much more on building design and construction than on building location. Relatively weak commercial buildings were destroyed in areas where wind speeds were relatively low, while stronger buildings experienced little or no structural damage in areas exposed to the highest winds.

Hurricane Katrina caused widespread damage to building envelopes and rooftop equipment. Building envelope damage was observed as far west as the New Orleans area and as far east as Dauphin Island, Alabama (a distance of approximately 140 miles). Building envelope damage was also observed as far inland as Poplarville, Mississippi (approximately 40 miles from the Gulf); however, envelope damage was reported at least as far inland as Hattiesburg, Mississippi (65 miles from the Gulf). Although the building envelope damage pales in comparison to that caused by flooding, the wind-induced envelope damage was significant, especially in light of the fact that Katrina was less than a design level storm for wind.

Critical and Essential Facilities Damage

Throughout the Gulf Coast, the poor performance of critical and essential facilities during and after Katrina was widespread. Most critical and essential facilities did not perform any better than the commercial buildings. Facilities such as hurricane evacuation shelters, police and fire stations, hospitals, and Emergency Operations Centers (EOCs) were severely damaged and many were completely destroyed. Some facilities experienced loss of function when critical support equipment such as vehicles and communications equipment was damaged or destroyed. While most of the damage to critical and essential facilities was caused by storm surge, high winds also damaged many other facilities. The poor building performance placed additional burdens on response and recovery personnel as they endeavored to provide assistance to their communities after the event.

This storm has allowed the MAT to build on the body of knowledge recently collected about the performance of critical and essential facilities during the last 2 years of hurricane events. The performance of the building envelopes, particularly for wind, has been generally poor and has allowed wind and wind-driven water to enter buildings, thereby disrupting services and, in many cases, rendering the building useless during and immediately after the storm, and for an extended period after the storm.

Recommendations

The recommendations in this report are based solely on the observations and conclusions of the MAT. They are intended to assist the States of Alabama, Louisiana, and Mississippi in the reconstruction process and to help reduce damage and impact from future storms. The recommendations are also expected to help FEMA assess the adequacy of construction standards and floodplain management requirements and determine whether changes in these standards and requirements are necessary. Lastly, they are also intended to:

- Provide the codes and standards groups and the homebuilding and building official communities with an important historical perspective of this event.
- Show how damages could have been reduced by building to higher standards currently in use in the IBC, and published in various standards, manuals, and design and testing guides.

As the people of Alabama, Louisiana, and Mississippi reconstruct their lives and the Gulf Coast rebuilds, there are a number of ways they can minimize the effects of future hurricanes. A few of the main recommendations resulting from the MAT inspections are included here; additional recommendations are included in Chapter 11.

Flood Recommendations

Based on the widespread devastation of buildings resulting primarily from floodwaters and waves that exceeded regulatory lowest floor elevations, it is strongly recommended that buildings be constructed in anticipation of flood levels that exceed the current BFE. A few of the main recommendations include:

- Adoption of modern building codes, such as the IBC, International Residential Code (IRC), or National Fire Protection Association (NFPA) 5000, is recommended. These codes include up-to-date design and construction provisions that are consistent with the NFIP. The 2006 editions of the IBC and NFPA 5000 incorporate flood load (ASCE 7-05) and flood-resistant construction (ASCE 24-05) standards.
- Follow the guidelines in FEMA's Hurricane Katrina Recovery Advisories, *The ABCs of Returning to Flooded Buildings* and *Initial Restoration for Flooded Buildings*, to facilitate restoration of flooded buildings. Appropriate safety precautions should be taken during repair and reconstruction to minimize health risks for biological and chemical contaminants.

- Use *Recommended Residential Construction for the Gulf Coast: Building on Strong and Safe Foundations* (FEMA 550, publication available July 2006).
- Review the storm surge data and conduct a revised tide frequency analysis. Use modern storm surge models to estimate the BFEs throughout the Katrina impact area.
- Consider identifying and mapping Coastal A Zones onto new FIRMs. Utilize ASCE 24-05 for design and construction of buildings located in Coastal A Zones. As an interim step, use the Katrina Flood Recovery Maps to determine the approximate location of the Coastal A Zone hazard. As shown on the Recovery Maps for Mississippi, the Coastal A Zone will be the area between the approximate limit of the 1.5-foot Wave Zone line and the approximate limit of the 3-foot Wave Zone line.
- Consider evaluating and revising flood hazard mapping and levee certification procedures for areas behind levees.
- For rebuilding efforts, use the Katrina Flood Recovery Maps until the new flood maps are released.

Wind Recommendations

The wind impacts from the storm caused widespread damage to building envelopes as a result of inadequate design, outdated codes, building age, lack of maintenance, and/or poor construction/code enforcement. A few of the main recommendations include:

- Adopt the 2006 IBC and IRC, or 2006 NFPA 5000, for all jurisdictions in each state.
- Roof covering systems, soffits, wall coverings, doors, windows, and rooftop equipment need additional attention by designers, architects, and contractors as specified in Chapter 11. Testing improvements are recommended to assess the performance of exterior insulation and finish systems (EIFS), vinyl siding, and soffits.

Critical and Essential Facility Recommendations

A few of the main recommendations related to improving the performance of critical and essential facilities include:

- Locate all new critical and essential facilities that must remain operational during an event above the 500-year flood elevation and on sites that will not be isolated by floodwaters.
- Develop emergency operations plans that allow building occupants and operations of existing facilities located within the SFHA to be relocated to sites outside of SFHAs before the onset of the storm. If personnel are relocated away from the facility, relocate equipment as well.
- Evaluate flood and wind resistance of existing facilities; where inadequacies are found, either retrofit or build a new facility.
- Design to standards that exceed current code, conduct peer reviews when designing new facilities or retrofitting existing facilities, and implement special inspections during construction.

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Appendices