

*December 2002*

## DETECTING TERRORISM:

# Aircraft Crash Impact Analyses Demonstrate Nuclear Power Plant's Structural Strength

### **Purpose of the Study**

The Sept. 11, 2001, terrorist attacks on the United States have drawn public attention to the potential for a crash of a large modern aircraft into structures that are part of our nation's critical infrastructure, including power plants.

Aircraft impact issues were addressed in the licensing process for all 103 U.S. nuclear power reactors; however the evaluations were based on the premise that such a crash would be accidental. On this basis, the potential for aircraft impact is small, and has been evaluated using probabilistic assessment methods. The results of these evaluations indicate that for all but a few nuclear power plant sites—those located near major airports—the probability of a crash is low and a resulting requirement for aircraft impact evaluation was not included in the licensing by the U.S. Nuclear Regulatory Commission.

Nonetheless, the nuclear power industry is confident that nuclear plant structures that house reactor fuel can withstand aircraft impacts, even though they were not specifically designed for such impacts. This confidence is predicated on the fact that nuclear plant structures have thick concrete walls with heavy reinforcing steel and are designed to withstand large earthquakes, extreme overpressures and hurricane force winds. The purpose of this study is to validate that confidence.

### **Results of the Analyses**

Detailed results of the independent analyses will not be released to the public because of security considerations. However, the following are the general findings of the analyses:

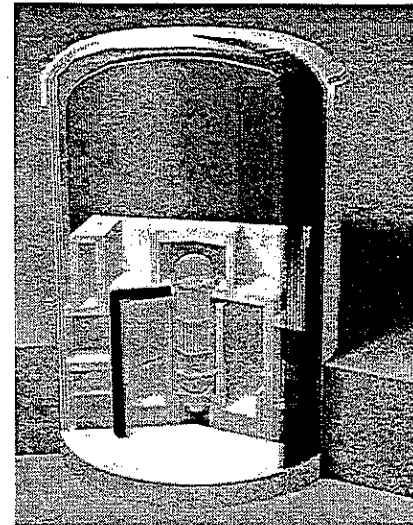
#### **Containment Buildings**

Computer analyses of models representative of all U.S. nuclear power plant containment types have been completed.

The wing span of the Boeing 767-400 (170 feet)—the aircraft used in the analyses—is slightly longer than the diameter of a typical containment building (140 feet). The aircraft engines are physically separated by approximately 50 feet. This makes it impossible for both an engine and the fuselage to strike the centerline of the containment building. As a result, two analyses were performed. One analysis evaluated the “local” impact of an engine on the structure. The second

analysis evaluated the “global” impact from the entire mass of the aircraft on the structure. In both cases, the analysis conservatively assumed that the engine and the fuselage strike perpendicular to the centerline of the structure. This results in the maximum force upon impact to the structure for each case.

The analyses indicated that no parts of the engine, the fuselage or the wings—nor the jet fuel—entered the containment buildings. The robust containment structure was not breached, although there was some crushing and spalling (chipping of material at the impact point) of the concrete.



**Boiling Water Reactor  
Containment Structure**

### **Used Fuel Storage Pools**

The wing span of the Boeing 767-400 (170 feet) is substantially greater than the longest dimension of a typical used fuel pool wall (60 feet). The aircraft engines are physically separated by approximately 50 feet. This makes it impossible for both an engine and the fuselage to strike the mid-point of the pools. As a result, two analyses were performed for both a pressurized water reactor pool and a boiling water reactor pool. One analysis evaluated the “local” impact of an engine on the mid-point of the pool wall. The second analysis evaluated the “global” impact of the fuselage and the portion of the wings that could realistically hit the mid-point of the representative fuel pool wall. In both cases, the analysis conservatively assumed that the engine and the fuselage strike perpendicular to the mid-point of the pool wall. This results in the maximum impact force being applied directly to the structure for each case. The wall’s mid-point would deflect (bend inward) more from this force than for an impact closer to the end of the wall.

The stainless steel pool liner ensures that, although the evaluations of the representative used fuel pools determined that there was localized crushing and cracking of the concrete wall, there was no loss of pool cooling water. Because the used fuel pools were not breached, the used fuel is protected and there would be no release of radionuclides to the environment.

### **Used Fuel “Dry” Storage Facilities**

Due to the extremely small relative size of a dry fuel storage container compared to the Boeing 767-400, it is not possible for the entire mass of the aircraft to strike the container. Therefore, the analysis evaluated the worst case of a direct impact of an engine on the dry storage containers.

For the vertical concrete-encased steel containers, two impact points were evaluated. One evaluated a mid-plane impact to create maximum deflection.



**Used Nuclear Fuel Storage Containers**

The other evaluated a strike near the top of the structure to create a maximum “tip-over” force on the structure. Based on results from the vertical steel, concrete encased container, the all-steel vertical container was only impacted at mid-plane. For the horizontal container, the evaluated impact point is the center of the concrete loading door.

For the concrete encased canisters, the steel canister containing the used fuel assemblies was not breached although there was crushing and cracking of the concrete enclosure at the area of impact. For the vertical steel container, the container was dented, but not breached. Because the dry storage structures were not breached, there would be no release of radionuclides to the environment.

### **Used Fuel Transportation Containers**

Due to the extremely small relative size of a fuel transport container compared to the Boeing 767-400, it is impossible for the entire mass of the aircraft to strike the container. Therefore, the analysis evaluated the worst case of a direct impact of an engine on the representative fuel transport cask.

The analyses show the container body withstands the impact from the direct engine strike without breaching. The forces on the container are comparable to the forces used in tests containers must undergo before designs are approved by the NRC. Additionally, the container remains attached to the rail car and the rail car does not tip over. Because the fuel transport container is not breached, there would be no release of radionuclides to the environment.



**Container for Transporting Used Nuclear Fuel**

### **Analysts and Expert Peer Reviewer Qualifications**

The Nuclear Energy Institute requested that EPRI perform this study for the nuclear industry. EPRI is a non-profit energy research consortium that provides science and technology-based solutions to global energy customers. The analysts were carefully selected by EPRI for their demonstrated capabilities in the dynamic analysis of heavily reinforced concrete structures, experience in impact analysis related to commercial and military applications, and experience in commercial nuclear power plant design. The analysts are employed by ABS Consulting and ANATECH Corporation. They include Dr. Joe Rashid, Dr. Randy James, Greg Hardy, Dr. Jorma Arros and Kelly Merz. The work was guided by Dr. Bob Kassawara, a licensed civil engineer who is a recognized expert in the area of dynamic response of nuclear power plant structures.

The results of the analysis were in-line peer reviewed by Drs. Bob Nickell and Bob Kennedy. Dr. Nickell is a world recognized expert in the dynamic analysis of structures and used fuel containers. Dr. Kennedy is a world renowned structural analyst.

Additional detail on the qualification of the analysts is contained in an appendix to this report.

## **General Approach**

The impact of the selected commercial aircraft on containment buildings, used fuel pools, dry fuel storage facilities and used fuel transportation containers was analyzed using sophisticated computer models. The analysis codes employed are widely recognized as "state of the art" codes and have been benchmarked against empirical test data derived from the impact of various objects on concrete structures.

Because the design of U.S. nuclear plant structures varies, representative structures were analyzed that are typical of the structures that exist across the industry. The design parameters utilized in selecting the representative structures were biased to be conservative. For example, in analyzing the capacity of containment structures to withstand an aircraft impact, design parameters included rebar quantity, concrete thickness, concrete strength, steel containment liner existence and strength, and the height-to-width ratio of the containment building. The representative structures were selected on the basis of their conservative values for these parameters, i.e. below median values for the spectrum of plant designs. In this way, there is assurance that the structures analyzed represent actual plant structures.

The aircraft impact analysis of the representative nuclear plant structures incorporates best estimate calculation methods in order to provide results that are as realistic as possible.

## **Selection of Aircraft Analyzed**

The reference aircraft chosen for this analysis is the Boeing 767-400. The maximum takeoff weight for this aircraft is 450,000 pounds, which includes 23,980 gallons of fuel. It has a wing span of 170 feet, an overall length of 201 feet, a fuselage diameter of 16.5 feet, and two engines weighing 9,500 pounds each.

This aircraft was selected for the following reasons:

- The weight of the Boeing 767-400 envelopes 88 percent of all commercial flights in the United States employing Boeing aircraft.
- It is the most widely used "wide body" aircraft in the U.S. commercial fleet.
- The weight of the engines on the Boeing 767-400 envelopes almost 90 percent of commercial aircraft engines, including wide body jets such as the Boeing 747,

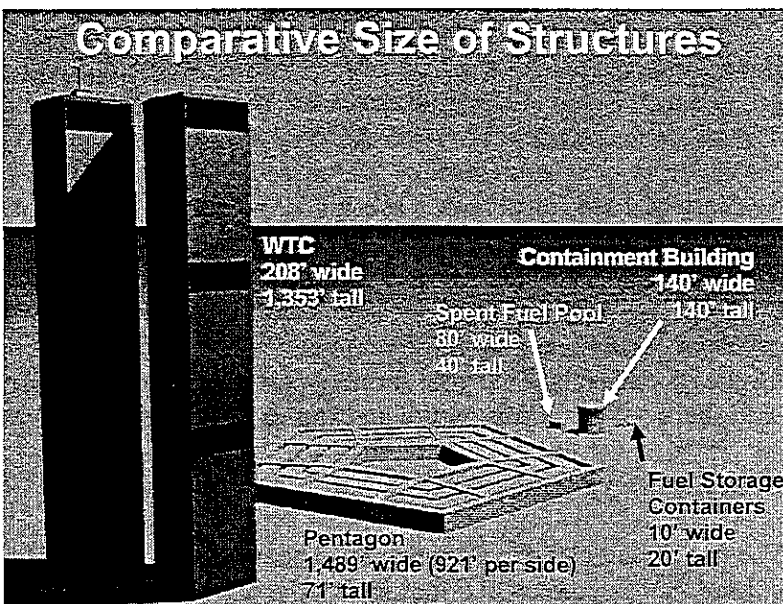
Boeing 757, DC-10, MD-11, A-330, and the L-1011.

- The weight of the Boeing 767-400 is at the 85<sup>th</sup> percentile of Boeing commercial aircraft.
- Boeing aircraft account for almost two-thirds of the commercial aircraft registered in the United States.

The assumed speed of the aircraft is 350 miles per hour, which is approximately the speed at which a jetliner struck the Pentagon on Sept. 11, 2001, based on reported flight recorder data and analysis of security camera video that captured the impact. In addition, this speed is reasonable for this evaluation where it is assumed the pilot can maintain flight maneuverability and impact structures at the precise analyzed locations. Although there is sufficient available engine thrust on the 767-400 to increase the speed at the altitudes of the analyzed structures, precision flying close to the ground at speeds greater than 350 miles per hour is extremely difficult, according to experienced pilots. A less-experienced pilot would have great difficulty controlling the aircraft. Thus, the probability of the aircraft striking a specific point on a structure—particularly one of the small size of a nuclear plant—is significantly less as speed increases.

### Typical Characteristics of Analyzed Structures

The structures that are the subject of this report are considerably smaller than the World Trade Center and Pentagon buildings that were attacked by terrorists on Sept. 11, 2001. Moreover, it is unlikely that a terrorist pilot could strike nuclear plant structures at the conservative impact points assumed in the analyses. The figure below provides a perspective of the size of nuclear power plant structures relative to the World Trade Center and Pentagon.



### Containment Structures

Pressurized water reactor (PWR) containments typically consist of heavily steel-reinforced concrete cylinders ranging in thickness from 3.5 feet to 4.5 feet, capped by a hemispherical dome of steel-reinforced concrete. The cylinder is typically 140 feet high, with a 140-foot diameter.

Reinforcement bars that form a cage within the concrete are typically Grade 60 #18 steel bars on 12-inch to 15-inch centers. A #18 rebar is two and one-quarter inches in diameter – about the size of a man's forearm. The wing span of the 767-400 (170 feet) is greater than the diameter of the typical PWR containment, making it impossible to impact the entire aircraft mass on the containment structure even with a perpendicular strike on the building centerline. Pressurized water reactors constitute about two-thirds of the 103 reactors operating in the United States.

Boiling water reactor (BWR) containments typically consist of a steel containment vessel surrounded by a reinforced concrete shield that typically has a thickness of four feet or greater and is housed within the reactor building. The primary containment of a BWR is typically one-third the diameter of a PWR containment. The location and dimensions of the primary containment inside the reactor building make it an extremely difficult structure to hit with an aircraft.

### **Used Fuel Storage Pools**

Used fuel pools that store fuel assemblies after they are removed from the reactor core are typically rectangular structures (40 feet by 60 feet) with a depth of at least 40 feet. The wall thicknesses are typically 4.5 feet to 6.5 feet of steel-reinforced concrete. The reinforcing bars typically are 1.25 inches in diameter. The interior of the concrete pool is covered with a stainless steel liner plate. Fuel assemblies are covered by a minimum of 25 feet of water within the pool.

Used fuel pools at PWRs are commonly located within an auxiliary building near the containment. Many of the PWR pools are located in the interior of the building, making it impossible for an aircraft to strike the pool at full force and thus providing considerable protection from an aircraft strike. For those PWR pools that are part of the exterior wall of an auxiliary building, most have a substantial portion of the pool below ground level, similarly providing considerable protection from an aircraft strike.

BWR fuel pools typically are located at an elevated position in the reactor building, outside of primary containment. For these reasons, a representative PWR spent fuel pool located at ground level with one wall of the pool forming part of an exterior wall and a representative elevated used fuel pool that forms part of an exterior wall for a BWR, were analyzed.

### **Used Fuel Dry Storage Facilities**

The dry fuel storage facilities that have been built at 18 nuclear power plant sites permit storage of used fuel assemblies at a location on the site other than the used fuel pool. Used fuel must be cooled for at least five years in the fuel pool before being placed into dry storage containers. These dry storage systems utilize air and natural convection heat removal to provide cooling for the canister containing the used fuel.

Three types of dry fuel storage facilities were analyzed. The dimensions of all of the dry fuel storage facilities—small, low-profile structures—make them an extremely difficult target to strike.

1. A vertical stainless steel container (typically two inches thick with a four-inch thick cover) surrounded by steel-reinforced concrete (26 inches thick) within a steel shell. The structure is 18 feet tall and weighs 270,000 pounds.
2. A vertical stainless steel container approximately sixteen feet high, eight feet in diameter with a wall thickness of about 15 inches. The container weighs approximately 200,000 pounds to 300,000 pounds when loaded with fuel. The lid bolted to the top of the container, and the bottom which is welded on, are typically 10 inches to 12 inches thick.
3. A cylindrical stainless steel canister approximately 15 feet long, 4 feet in diameter and over one-half inch thick placed in a horizontal reinforced concrete container that weighs approximately 250,000 pounds.

### **Used Fuel Transportation Containers**

Used fuel transportation containers are used to transport used fuel offsite to another nuclear power plant site for storage and, ultimately, to a permanent disposal facility. Used fuel must be cooled for at least eight to 10 years in the fuel pool before being transported. These transportation casks utilize natural convection heat removal to provide cooling for the canister containing the used fuel.

The analyzed transport container weighs 250,000 pounds and is mounted on a skid attached to a flatbed rail car. The rail car and skid weigh an additional 66,000 pounds. The cylindrical container is approximately eight feet in diameter and 17 feet long, making it a difficult target to strike with an aircraft.

### **Conservative Assumptions of the Analyses**

The analyses of representative structures that house nuclear fuel included several conservative features that provide additional assurance that nuclear power plant structures housing nuclear fuel can withstand direct aircraft crashes

### **Containment Buildings**

- For each analyzed structure, the aircraft and engine were assumed to strike perpendicular to the centerline of the structure, thereby subjecting the containment building to the maximum force of the aircraft. Because the containments are curved structures, missing the centerline reduces impact forces.

- The analysis assumed that the maximum takeoff weight of the Boeing 767-400 impacts the structure. In reality, fuel would be consumed during both takeoff and travel to the structure, reducing the overall weight of the aircraft.

#### **Used Fuel Storage Pools**

- Both the engine and the aircraft fuselage were assumed to strike at the mid-point of the pool wall, which is the area where the potential for inventory loss is greater. Impact at other locations would result in reduced consequences.
- Both the engine and the aircraft fuselage were assumed to strike perpendicular to the surface of the wall. Lesser impact angles would impart less force to the wall.
- The exact location of used fuel pools is not visible from a plant's exterior. It would therefore be extremely difficult for an attacker to identify and strike the pool.
- Intervening structures at many nuclear plants significantly inhibit the terrorists' ability to hit the used fuel pools.

#### **Used Fuel Dry Storage Facilities**

- The engine strikes perpendicular to the centerline of the vertically designed structures, thereby subjecting the structure to the maximum force of the engine. Because the dry storage facilities are curved structures, missing the centerline reduces impact forces.
- The engine strikes at mid-height of the vertically designed structures. Given that the fuselage of the Boeing 767-400 is approximately the same height as the dry storage facility, the probability that an engine could strike at the mid-height of the structure is extremely low.
- The engine strikes the exact center of the front concrete door plug of the horizontally designed structures. The center of the door is less than ten feet off the ground and is smaller in diameter than the engine itself, making such an impact point extremely unlikely.

#### **Used Fuel Transportation Containers**

- The engine strikes perpendicular to the centerline of the structure, thereby subjecting the structure to the maximum force of the engine. Because the transportation container is a curved structure, missing the centerline reduces impact forces.
- The engine strikes at mid-plane of the structure. Given the short length of the container relative to the wingspan of the aircraft, striking exactly at mid-plane has a very low probability.



## Conclusion

The study determined that the structures that house reactor fuel are robust and protect the fuel from impacts of large commercial aircraft.

*For more information on nuclear power plant security and other industry issues, contact the Nuclear Energy Institute at 202.739.8044 or [www.nei.org](http://www.nei.org).*

## Appendix

### Analysts and Expert Peer Reviewer Qualifications

#### ABS Consulting

ABS Consulting is one of the leading risk consulting companies offering state-of-the-art engineering services to the highly protected industry sectors (nuclear, energy, chemical, offshore, marine, insurance, and government). ABS specializes in identifying risks and quantifying losses in the event of extreme man-made and natural hazards, including aircraft or missile impact, terrorist attack, toxic material releases, earthquakes, hurricanes, fires, explosions and human error.

ABS Consulting has experts in the fields of structural dynamics, sophisticated finite element analysis, probabilistic risk assessment, dispersion modeling, engineering mechanics, and explosion/blast analysis. ABS personnel participate in many technical standard committees including ANS, ASME, AISC, ASCE, API, and CMA. The three principal participants in this EPRI/NEI aircraft impact study (Greg Hardy, Jorma Arroos and Kelly Merz) have authored over 40 technical papers in the subject areas.

ABS Consulting has 15 U.S. offices and 32 international offices, with over 900 employees.

#### ANATECH

ANATECH is a San Diego based firm of consulting engineers that has gained international recognition for the development and application of advanced engineering analysis methods for complex structural systems. ANATECH has extensive expertise in the use of non-linear analytical methods to establish structural capacities and failure modes for loadings that are beyond the conventional design basis of structures. A cornerstone for this work is the ANATECH concrete and steel material response model, ANACAP, which is widely recognized and extensively validated for advanced modeling of concrete structures. The key personnel at ANATECH involved with the security issues for aircraft crash impact are Y. R. (Joe) Rashid and Randy J. James.