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研究報告

Tornado Damage and Impacts on Nuclear Facilities in the United States

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SUMMARY

This report provides an overview of the tornado impact on the safe operation and shutdown of nuclear power plants in the United States. The motivation for this review stems from the damage and failure of the Fukushima nuclear power plant on March 11, 2011. That disaster warrants comparison of the safety measures in place within the global nuclear power industry.

key words: Tornado Damage, Nuclear Facilities, United States

1. BACKGROUND

Nuclear power generation produces 13.5% of the electricity generated worldwide 2). Approximately 20 % of the electricity produced in the U.S. is provided 99 active nuclear reactors 3). In 2014 they produced 798 TWh of electricity, accounting for 30% of all the nuclear power produced worldwide, and making the United States (US) the largest producer of nuclear energy 3).

Commercial nuclear energy production began in US in 1957 with the commissioning of the first nuclear reactor in Shippingport, PA. After some growth since that time, development of new nuclear power plants has slowed, to the point where few nuclear reactors have been constructed in US over the past thirty years, due to public apprehension regarding safety concerns and the risk of nuclear contamination of regions around the plants. The most newly commissioned nuclear power plant was the Watts Bar Plant in Tennessee in 1996 4). Two new reactors began construction in 2013 at the Virgil C. Summer Nuclear Generating Station in South Carolina and the Vogtle Electric Generating Plant in Georgia.

Heightened skepticism of nuclear power generation from the public followed the high profile accidents at the Three Mile Island Nuclear Plant in U.S. and the meltdown failure and subsequent closure of the Russian Chernobyl Nuclear Plant. Many of the currently active nuclear reactors in US will be decommissioned over the next 20 years, taking as much as one fifth of the United States nuclear power production offline over that period. The World Nuclear Association reports that thirteen nuclear

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reactors have been planned and thirteen more have been proposed. However, just four nuclear reactors will come online by 2020 [3)].

Commercial nuclear reactor designs have come a long way over the past 60 years. Figure 1 shows the nuclear reactor development roadmap. The first generation plants built in the 1950s were prototypical designs and are currently outdated with none in service at present. Generation II nuclear reactors came on-stream in the late 1960s and 1980s, and these plants were designed for commercial operation and therefore were economical and reliable, with an expected 40 year life span. The plants had large cross-sections and required large handling units for the fuel waste.

The third generation nuclear plants, Generation III were upgrades on the Generation II reactors, with more efficient production systems, utilized modular construction, and included more passive safety items. The Generation III plants have a 60-year design life. At this time, only four Generation III plants are operational worldwide, and none are located within the United States.

Recently, there has been a further improvement to nuclear plant design, so-called Generation III+ reactors, which use additional passive safety operations that minimize the need for operator intervention.

The AP1000 nuclear plant is a Generation III+ nuclear plant designed by GE's Westinghouse. It harnesses natural forces such as gravity, convection and condensation to maintain a passive safety system that initiates automatically in event of a problem, naturally cooling the core. The support systems of this new plant are simpler than those of previous-generation pressurized water reactor plants and promises to reduce the potential for human error and thereby the need for human intervention. The plants occupy a small space, provide significant cost savings, and faster construction schedules. Generation III+ plants include less piping and valves and redundant systems that are required to be housed within seismic buildings [5)].

2. INTERNATIONAL NUCLEAR FAILURE INCIDENTS

There are three major nuclear accidents that took place in 32 years that attracted international attention, and raised concern from the public regarding the safety of nuclear facilities. Table 1 shows the summary of the damages due to tornado in the world.

2.1 THREE MILE ISLAND, UNITED STATES

On March 28, 1979 at 4 a.m. one of the two Babcock & Wilcox pressurized water reactors at the Three Mile Island experienced a partial meltdown. The accident began after a human operated valve was left open allowing large amounts of coolant to escape. The automatic emergency cooling system then activated but their feed pumps were closed for maintenance. Plant operators were not able to

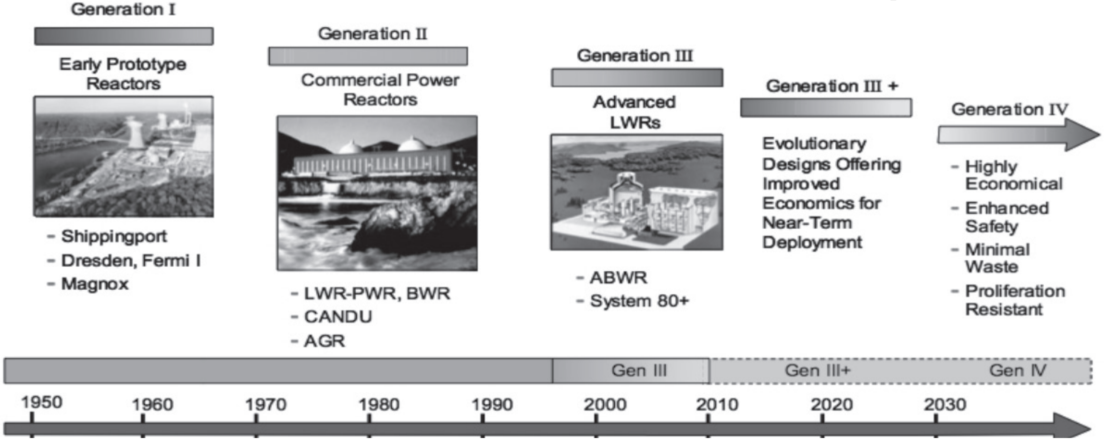

Figure 1 Nuclear reactor development roadmap (Source: A technology roadmap for generation IV Nuclear energy systems by USDOE).

recognize the issues before the reactor coolant was turned into steam that reacted with the now exposed reactor core to produce hydrogen gas that caused a small explosion in the containment structure 6) Radioactive gases and iodine were released into the environment. No fatalities were reported.

2.2 CHERNOBYL, USSR

The Chernobyl nuclear power plant in Ukraine endured a fire and explosion on April 26, 1986 that released large quantities of radioactive particles into the atmosphere. It is known as one of only two nuclear disasters classified as a level 7 event on the International Nuclear Event Scale (the other being the Fukushima Daiichi nuclear disaster in 2011). An unexpected power surge during a systems test of reactor four initiated an emergency shutdown, but a large spike in power output led to a reactor vessel rupture and a series of steam explosions. This allowed air to come into contact with the reactors graphite moderator [4], causing it to ignite. The resulting fire sent a plume of highly radioactive fallout into the atmosphere. The official casualty count was 31.

2.3 FUKUSHIMIA DAIICHI, JAPAN

The incident at the Fukushima Daiichi nuclear power plant in Japan on March 11, 2011 was a series of equipment failures, nuclear meltdowns and releases of radioactive materials. The disaster began during the attempted shut down of the plants reactors right after the magnitude 8.9 earthquake. Backup generators came online to power the reactor's coolant systems, but the tsunami following the earthquake quickly flooded the rooms housing the generators. When the emergency generators failed, power was cut from the pumps circulating coolant. Large amounts of radioactive decay heat then caused the reactors to overheat and turn the coolant into steam.

The ensuing reactions between the steam and exposed zirconium fuel rods produced several hydrogen gas explosions because the reactors could not vent properly 7).

Table 1 International nuclear incidents

Disaster	Reactor Type	Date	Cost of Damage (100 Billion JPY)
Three Mile Island	PWR (Gen II)	28-Mar-79	2.87
Chernobyl	RBMK (Gen II)	26-Apr-86	17.94
Fukushima Daiichi	BWR (Gen II)	11-Mar-11	358.98

3. REACTIONS TO THE FUKUSHIMA PLANT DISASTER

The failure of the Fukushima nuclear power plant following the 2011 earthquake and tsunami in Japan prompted the US Nuclear Regulatory Commission (NRC) to undertake inspections of all the United States nuclear plants, to verify they can withstand the natural disasters and man-made disasters they are at risk of facing. These inspections found that reactors and safety systems in Tornado Alley are designed to withstand wind speeds up to 103 m/s, extreme rotational speeds [1] of 82 m/s, and a pressure drop of 83 hPa, but not all emergency equipment or the buildings that house such equipment, are disaster proof.

Specifically, the NRC found the most vulnerable components are the equipment and vehicles needed to fight fires, and/or to retrieve fuel for emergency diesel generators, and resupply the essential water needed to cool down reactor fuel rods 8). Despite the critical need for these systems during emergencies, the NRC concluded that the plants met the requirements, put in place after the Sept. 11 terrorist attack on the World Trade Center, designed to keep the nuclear fuel cool and the containment structures intact during an emergency.

David Lochbaum, a spokesman for the advocacy group Union of Concerned Scientists, pointed out that the equipment that could be disabled by a tornado ancillary to the nuclear power generation, i.e. they are the "backup of backups, but that this potential [of tornado damage to them] should raise concern nonetheless” 9). The consideration of tornado damage is heightened as populations are living in closer proximity to some plants than they once did. The NRC defines the 16.1 km radius circle around a plant as the Plume Exposure Pathway Emergency Planning Zone 10). In the event of a meltdown or radiation leak the NRC believes this area would be at risk of exposure to, and the inhalation of, airborne radioactive contamination.

The NRC's 2011 inspections found numerous instances where US nuclear plants kept equipment needed to fight fires or to cope with a loss of electrical power in places that were not protected against extreme events 11), but the nuclear plants that have been hit by a tornado have emerged largely unscathed.

4. TORNADO DAMAGE CASE STUDIES

4.1 FERMI NUCLEAR POWER PLANT

In June 2010, an EF 1 tornado impacted the Enrico Fermi Nuclear Power Facility that was built along the shore of Lake Erie in Michigan. Figure 2 shows the Fermi Plant with tornado path. This nuclear plant was a General Electric boiling water reactor constructed in 1972 and it generates with 1100 MW generating capacity. The National Weather Service (NWS) confirmed that a tornado touched down at 2:33 AM on June 6, 2010 at the southwest portion of Detroit Beach, MI, and the tornado tracked 10.5 km in a northeasterly direction. Within six minutes, the tornado reached Estral Beach, MI before moving over Lake Erie. The path width was 460 m with damage consistent with estimated maximum winds up to 49 m/s (EF1) 12). According to U.S. Census data, the 2010 U.S. population within the 16 km plume exposure pathway was 92,377, a 9.5% increase from 2000 13). Stony Point, MI, the closest residential population to the plant has a population of 1,724 and is about 1.87 km away.

The tornado ripped the siding off a building housing emergency equipment and knocked out one of two power sources at the plant. The tornado damaged the plant’s electrical transmission, which forced the plant to be shutdown, leaving 30,000 people without power in the area for about a day. An alert was declared, and the plant was stabilized. No injuries were reported with this tornado.

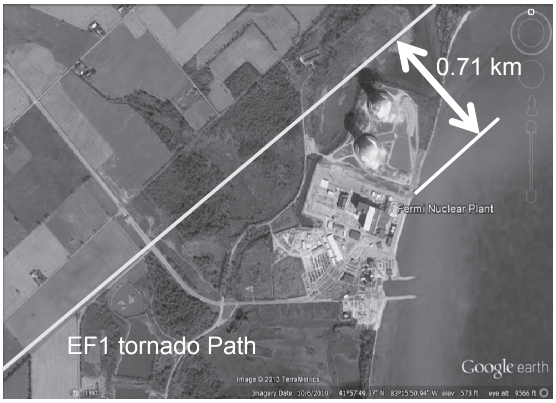

Figure 2 Fermi Plant with tornado path

4.2 BROWNS FERRY NUCLEAR POWER PLANT

Figure 3 shows the Browns Ferry Plant with tornado path. A tornado touched down at 2:05 PM (CST) on April 27, 2011 near Hamilton, Alabama during a significant tornado outbreak in which 358 tornadoes were recorded within a three-day period. High-resolution satellite imagery combined with aerial surveys show a well-defined path of tree and vegetation damage at the start of the storm between 0.8 km and 1.2 km wide indicative of low-end EF-3 wind speeds of around 63 m/s. The tornado crossed the Tennessee River into Limestone County approximately 4.8 km from the Browns Ferry Nuclear Plant. The violent tornado continued its path from the Tennessee River along the Lawrence/Limestone county line northeast through Tanner and into the east Central portion of Limestone County 14).

The Browns Ferry plant has three General Electric boiling water reactors on site. The first, second, and third units began operation in 1973, 1974, and 1976 respectively. Unit one can generate 1,155 MW of electricity while unit 2 and 3 each generate 1,113 MW [15]. According to U.S. census data, the 2010 U.S. population within 16 km of Browns Ferry was 39,930. This is a 12.3% increase from 2000 13).

At 4:01 PM (CST) on April 27, 2011, all three reactors were forced into a hot standby [2] due to a loss of external power caused by the tornado. Diesel backup generators provided power after a brief outage period. An NRC Unusual Event, the lowest level of emergency classification, was declared due to loss of power exceeding 15 minutes. The cooling procedures operated as they were designed with no physical damage or release of radioactive material. Due to widespread transmission grid damage from the storms, Browns Ferry was unable to produce power for the grid and significant blackouts occurred throughout the Southeastern United States. Sirens that alert residents living nearby were also disabled, meaning that police and emergency personnel would have had to use telephones and loudspeakers should an actual nuclear crisis have occurred.

The tornado reached maximum intensity in Limestone County near the community of Tanner. Tanner a town of 2,107 people and about 14 km away from the plant experienced a large amount of EF-4 damage and a narrow corridor of high end EF-4 to near EF-5 damage. Nearly a dozen high-tension power lines were snapped or taken to the ground and concrete power poles were snapped off at the base. Several well-constructed homes with anchor bolting were completely destroyed. Figure 4 and 5 show the destroyed homes near Browns Ferry. One home had the debris lofted over 27 km with large items carried completely away. A large cargo container was picked up and blown approximately 550 m. Several cars were carried airborne for hundreds of yards. In all, hundreds of homes received moderate to major damage along the path with many of these being total losses. 65% of the homes were built between 1960 and 1999. There were 145 injuries and 72 fatalities reported and an estimated 125 billion JPY in property damage. A more detailed report of the structural failures observed in Tuscaloosa can be found at online 16).

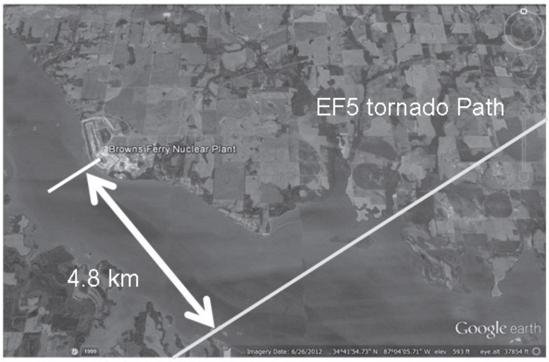

Figure 3 Browns Ferry Plant with tornado path (source: NOAA.gov)

Figure 4 and 5 Destroyed homes near Browns Ferry (Source: The News Courier and Lifesaver Storm Shelters) http://lifesaverstormsheltersofgeorgia.com/tanner-al-tornado-pics-and-article/

4.3 SURRY NUCLEAR POWER PLANT

On April 16, 2011, a tornado touched down at 6:45 PM just south of the Surry Nuclear Power Plant. Figure 6 shows Surry Plant with tornado path. The storm survey determined the damage was consistent with an EF3 tornado with wind speeds of 56 m/s to 74 m/s. The tornado moved across the James River and through the

Kingsmill section of James City County. The tornado then moved northeast across the York River into southern Gloucester County [17].

The Surry nuclear plant has two Westinghouse pressurized water reactors, which began operation in 1972 and 1973 respectively. Each reactor produces 80 MW of power. According to U.S. Census data, the 2010 U.S. population within 16 km of Surry was 127,041. This is a 21.9% increase from 2000 [13]. Williamsburg, VA the closest residential population to the plant has a population of 15,167 and is about 11.6 km away.

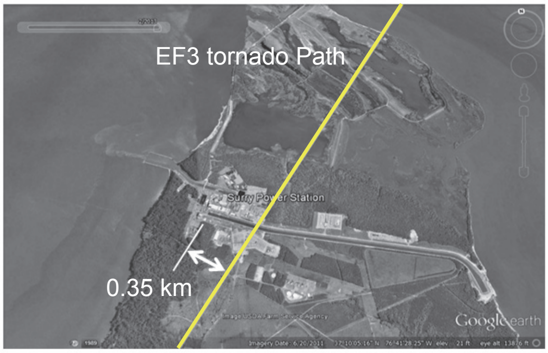

Figure 6 Surry Plant with tornado path (source: NOAA.gov)

Figure 7 Damaged tanker and garage at Surry Power Station (source: NOAA.gov), available at: http://www.erh.noaa.gov/akq/wx_events/severe/apr_16_2011/Surry2.JPG

The tornado badly damaged a fuel tanker on site at the plant that is used to refuel backup generators. Figure 7 shows the damaged tanker and garage at Surry Power Station. The worst damage consistent with an EF3 rating was in Gloucester County 20.6 km away. The tornado had a nearly continuous damage path ranging in width from around 180 m to as much as 800 m wide in Gloucester County. Over 200 homes were damaged and many of them severely damaged. Numerous trees were downed or sheared off. There were 24 injures and 2 fatalities reported.

4.4DAVIS-BESSE NUCLEAR POWER PLANT

The Davis-Besse plant located in Oak Harbor, Ohio on the southwest shore of Lake Erie has a single 879 MW Babcock & Wilcox pressurized water reactor that began construction on Sept 1, 1970 and operating on July 31, 1978. The U.S. Census reports that the 16 km radius surrounding the plant has a population of 18,635 people; which is a 14.1% increase from 2000 [13]. Oak Harbor, Ohio, the closest residential population to the plant is about 11 km away. According to the NRC, Davis-Besse has had two of the top five most dangerous nuclear incidents in the U.S. since it began operation [18].

NWS aerial and ground surveys concluded that an F2 tornado with winds between 51 m/s and 70 m/s touched down in Ottawa County just west of the Davis-Besse power plant on June 24, 1998 between 8:45 and 9:00 PM. The tornado was 91 m in width and traveled in a southeasterly direction for about 5.6 km [19]. Workers at the plant report that they saw the funnel cloud appear next to the cooling tower, but no damage was found. The plant automatically shut down at 8:43 p.m. when the storm damaged the plant's switchyard and cut transmission lines between Davis-Besse and another plant in Pennsylvania. The plant remained shut down for two days. Emergency generators were able to provide power to the plant's safety systems. Significant damage was found in the wake of the tornado. A few barns were completely destroyed and an apartment complex was heavily damaged. The NWS reported that much of the damage they found in the county was attributed to 31 m/s to 36 m/s straight-line winds from the storm system. Ryan Sandler, a NWS meteorologist said, "it is one huge storm, the size of a county." 14 injuries were reported and no fatalities.

4.5 QUAD CITIES NUCLEAR POWER PLANT

The Quad Cities nuclear plant is situated near Cordova, Illinois. Figure 8 shows the Quad Cities Plant with the tornado path. It has two 912 MW General Electric boiling water reactors that came online on December 14, 1972. Approximately 34,350 live within a 16 km radius of the plant. The closest city to the plant is Cordova, IL and it has a population of 672. On March 13, 1990 an EF3 tornado passed about 3.9 km away from the Quad Cities nuclear power plant near Cordova, Illinois. The plant suffered damage to its security fence and the roof blew onto a duct that connects the radioactive waste processing area to a venting stack. No radioactive gas was released. One injury was reported [20].

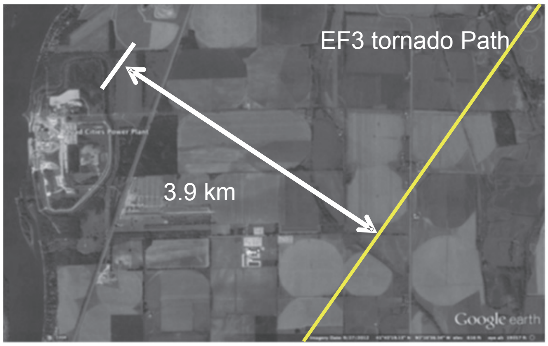

Figure 8 Quad Cities Plant with tornado path (source: Tornado history project 2012)

5. DESIGN SPECIFICATIONS

The General Design Criterion 2 (GDC 2) [21] for protection against natural phenomena for nuclear plants are contained in the NRC's Regulations Title 10 Code of Federal Regulations (10 CFR) Part 50. GDC 2 requires that the design basis for these structures shall reflect:

1. Design loads based upon historical occurrences of natural hazards at the site with an appropriately large safety factor to account for limited data of events.
2. The inclusion of load combinations for normal use and accidental load conditions.
3. The NRC design approach shall ensure that after a design tornado event, that damage will not prevent safety functions from being performed. The safety functions include:
    a. Maintain the integrity of the reactor coolant pressure boundary
    b. The plant maintains the capability to shut down the reactor in a safe shutdown condition (this includes both hot standby and cold shutdown [3] capability)
    c. The plant shall prevent or mitigate the consequences of accidents, which could result in potential offsite exposures

Table 2 Summary of nuclear power plants damages due to tornado in U. S.

Name	Location	Max EF Rating - Year	EF Rating at Plant
Browns Ferry	Decatur, Alabama	EF5 - 1974 EF5 - 2011	N/A EF3
Quad Cities	Cordova, Illinois	EF3 - 1996	N/A
Davis-Besse	Oak Harbor, Ohio	EF2 - 1998	N/A
Enrico Fermi	Monroe County, Michigan	EF1 - 2010	EF1
Surry	Surry County, Virginia	EF1 - 2011	EF1

In 1974 the NRC issued regulatory guide 1.76 “Design-Basis Tornado and Tornado Missiles for Nuclear Power Plants.” with specific design-basis tornado specifications for new reactors [1]. The document states that nuclear power plants must be designed to withstand the wind pressure and internal pressure changes due to a design basis tornado. The NRC design basis tornado was established through a probabilistic assessment of existing tornado records (1971 &1972) and not the specific damage studies reported in this study. The NRC has specified that all new US nuclear plants are to be designed to the same estimated level of risk for each disaster known as the probability of exceedance (POE) as seen in Table 3 [22-24]. For example, the chosen NRC tornado design wind speed for all nuclear plants is to be selected based on a POE of 10^{-7} or a 10,000,000 mean recurrence interval [1]. For example, Alabama and California this POE corresponds to a tornado design wind speed of 103 m/s and 72 m/s respectively. Selecting a higher POE means the design basis disaster is of less intensity. ASCE 7-10 has chosen a POE of $5x10^{-4}$ for Cat IV buildings such as hospitals. The NRC chosen POE's reflect the relationship of normalized damage losses from natural disasters in the United States [25]. From 1950 to 2011, 56,457 tornados have caused $449 billion in normalized losses. Over the same time period, hurricanes result in $621 billion in normalized losses over 153 events. In contrast, the normalized earthquake damage over 1950 –2011 was $150 billion [25].

Each of the power plants in the damage cases from chapter 4 were constructed before the tornado design specifications were installed in 1974 and therefore were designed to meet the criteria found in GDC 2. The five case studies presented in this report did meet the criteria laid out in GDC 2 for a safe shutdown as discussed in chapter 5.

Table 4 and Table 5 summarize the characteristics of a design-basis tornado and the design-basis tornado missile spectrum used in NRC regulatory guide “DESIGN-BASIS TORNADO AND TORNADO MISSILES FOR NUCLEAR POWER PLANTS”. Figure 9 designates the regions of varying tornado intensity that the NRC has created for Nuclear Power Plant design and site location.

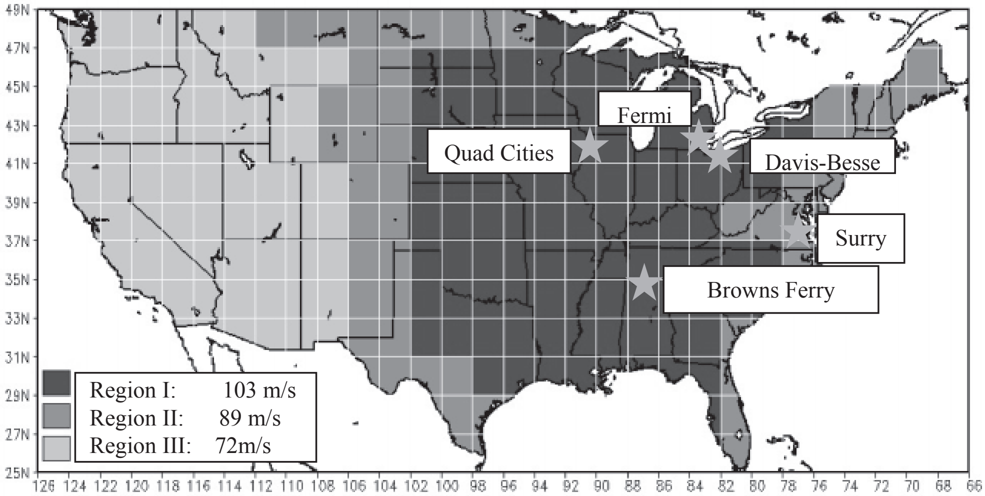

Figure 9 Tornado intensity regions for the contiguous, United States for NRC design specifications with the five damage case study locations designated

Table 3 NRC design probability of exceedance for natural disasters in US (* from Simmons et al (2013))

Disaster Type	NRC Design Probability of Exceedance	Source	# of events (1950 - 2011)	Normalized Damage Losses (1950 - 2011)* (100 Billion JPY)
Tornado	$1 x 10^{-7}$	NRC Regulatory Guide 1.76	56,457	537.27
Hurricane	$1 x 10^{-7}$	NRC Regulatory Guide 1.221	153	743.09
Flood	$1 x 10^{-6}$	NRC NUREG/CR-7046	N/A	N/A
Earthquake	$1 x 10^{-5}$	NRC Regulatory Guide 1.208	N/A	179.49

Table 4 Design-basis tornado characteristics (source: NRC (2007)1))

Region	Maximum wind speed mph (m/s)	Translational speed mph (m/s)	Maximum Rotational speed mph (m/s)	Radius of maximum rotational speed ft (m)	Pressure drop psf (hPa)	Rate of pressure drop psf/s (hPa/s)
I	230 (103)	46 (21)	184 (82)	150 (46)	172.8 (82.6)	72 (34.4)
II	200 (89)	40 (18)	160 (72)	150 (46)	129.6 (61.9)	57.6 (27.5)
III	160 (72)	32 (14)	128 (57)	150 (46)	86.4 (41.3)	28.8 (13.8)

Table 5 Design-basis tornado missile spectrum and maximum horizontal speeds (source: NRC (2007)1))

Missile Type		Schedule 40 pipe	Automobile	Solid Steel Sphere
Dimensions		6.625 in. dia x 15 ft long (0.168m dia x 4.58m long)	Region I and II 16.4 ft x 6.6 ft x 4.3 ft (5m x 2m x 1.3m)	1 in dia (2.54 cm dia)
			Region III 14.9 ft x 5.6 ft x 4.9 ft (4.5m x 1.7m x 1.5m)	
Mass		287 lb (130 kg)	Region I and II 4000 lb (1810 kg)	0.147 lb (0.0669 kg)
			Region III 2595 lb (1178 kg)	
Vm^{max}	Region I	135 ft/s (41 m/s)	135 ft/s (41 m/s)	26 ft/s (8 m/s)
	Region II	112 ft/s (34 m/s)	112 ft/s (34 m/s)	23 ft/s (7 m/s)
	Region III	79 ft/s (24 m/s)	79 ft/s (24 m/s)	20 ft/s (6 m/s)

6. SUMMARY

Nuclear Power plants in the United States are at risk of tornado strike and other natural phenomena. Incidents of damage to nuclear plants throughout the world and the US provide valuable case studies to help examine vulnerable components of a reactor. This article presents an overview of the development of nuclear power plants in the United States and damage case studies from tornado impacts on nuclear facilities. The NRC issued tornado design specifications for new reactors in 1974 based on a probabilistic risk assessment. No reactors constructed to this criterion have been struck by a tornado. Still, US plants that have been struck by a tornado have met all NRC general design criteria for safe shutdown from natural phenomena.

DEFINITIONS

- [1] Rotational Speed – the difference between the maximum tornado wind speed and the translational speed.
- [2] Hot Standby – the reactor is shut down, but system temperature and pressure are still at or near normal operating values.
- [3] Cool Shutdown – a reactor coolant system at atmospheric pressure and at a temperature below 200 degrees Fahrenheit following a reactor cool down.
- [4] Graphite Moderator – a medium that reduces the speed of neutrons, turning them into neutrons capable of sustaining a nuclear chain reaction.

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