Appendix 6

Structural Integrity of Spent Fuel Pool Structures Subject to Aircraft Crashes

The generic data provided in DOE-STD-3014-96, "Accident Analysis for Aircraft Crash Into Hazardous Facilities," U.S. Department of Energy (DOE), October 1996, was used to assess the likelihood of an aircraft crash into or near a decommissioned spent fuel pool. Aircraft damage can affect the structural integrity of the spent fuel pool or affect the availability of nearby support systems, such as power supplies, heat exchangers and water makeup sources, and may also affect recovery actions.

The frequency of an aircraft crashing into a site, F, was obtained from the four-factor formula in DOE-STD-3014-96, and is referred to as the effective aircraft target area model:

$$F = \sum_{i,j,k} N_{ijk} \cdot P_{ijk} \cdot f_{ijk}(x, y) \cdot A_{ij} \qquad \text{Equation 1}$$

where:

N_{ijk}	=	estimated annual number of site-specific aircraft operations (no./yr)
P_{ijk}	=	aircraft crash rate (per takeoff and landing for near-airport phases) and per flight for in-flight (nonairport) phase of operation
$f_{ijk}(x,y)$	=	aircraft crash location probability (per square mile)
A_{ij}	=	site-specific effective area for the facility of interest including skid and fly-in effective areas (square miles)
i	=	(index for flight phase): i=1,2, and 3 (takeoff, in-flight, landing)
j	=	(index for aircraft category, or subcategory)
k	=	(index for flight source): there could be multiple runways and nonairport operations

The site-specific area is shown in Figure 1 and is further defined as:

$$A_{eff} = A_f + A_s$$

where:

$$A_f = (WS + R) \cdot (H \cdot \cot\theta) + \frac{2 \cdot L \cdot W \cdot WS}{R} + L \cdot W \qquad \text{Equation 2}$$

$$A_s = (WS + R) \cdot S$$

and where:

A_{eff}	= total effective target area	H	= height of facility
A_f	= effective fly-in area	L	= length of facility
A_s	= effective skid area	W	= width of facility
WS	= wing span	S	= aircraft skid distance
cotθ	= mean of cotangent of aircraft impact angle	R	= length of facility diagonal

Alternatively, a point target area model was defined as just the area (length times width) of the facility in question.

Table 1 summarizes the generic aircraft data and crash frequency values for five aircraft types (from Tables B-14 through B-18 of DOE-STD-3014-96).

The data presented in Table 1 was used to determine the frequency of aircrafts hits per year for various building sizes (length, width, and height) for the minimum, average and maximum crash rates. The resulting frequencies are presented in Table 2. The product $N_{ijk}*P_{ijk}*f_{ijk}(x,y)$ for Equation 1 was taken from the crashes per mi^2-yr and A_{ij} was obtained from Equation 2 based on the aircraft characteristics. Two sets of data were generated: one included the wing and skid lengths using the effective aircraft target area model and a second case which considered only the area (length times width) of the site using the point target area model.

The building or facility characteristics were chosen to cover a range typical of a spent fuel pool to that of the PWR auxiliary building or the BWR secondary containment structure.

The results from the DOE effective aircraft target area model, using the generic data in Table 1, were compared to the results of two evaluations reported in "Probabilistic Safety Assessment and Management," A. Mosleh and R.A. Bari (Eds), PSAM 4, Volume 3, Proceedings of the 4-th International Conference on Probabilistic Safety Assessment and Management, 13-18 September 1998, New Your City, USA.

The first evaluation of aircraft crash hits was summarized by C.T. Kimura, et al., in "Aircraft Crash Hit Analysis of the Decontamination and Waste Treatment Facility (DWTF) at the Lawrence Livermore National Laboratory (LLNL)." DWTF Building 696 was assessed. It was a 254 feet long by 80 feet wide, 1-story, 39 feet high structure. The results of Kimura's study are shown in Table 3.

Applying the DOE generic data to the DWTF resulted in a frequency range of 6.6×10^{-5} hits per year to 6.5×10^{-9} hits per year, with an average value of 4.4×10^{-6} per year, for the effective aircraft target area model. For the point target area model, the range was 4.4×10^{-10} to 2.2×10^{-6} per year, with an average value of 1.5×10^{-7} per year.

The second evaluation was presented in a paper by K. Jamali, et al., "Application of Aircraft Crash Hazard Assessment Methods to Various Facilities in the Nuclear Industry," in which additional facility evaluations were summarized. For the Seabrook Nuclear Power Station, Jamali's application of the DOE effective aircraft target area model to the Final Safety Analysis

Report (FSAR) data resulted in an impact frequency 2.38×10^{-5} per year. The Millstone 3 plant area was reported as 9.5×10^{-3} square miles and the FSAR aircraft crash frequency was reported to be 1.6×10^{-6} per year. Jamali applied the DOE effective aircraft target area model to information found in the Millstone 3 FSAR. Jamali reported an impact frequency of 2.74×10^{-6} per year using the areas published in the FSAR and 2.31×10^{-5} per year using the effective area calculated the effective aircraft target area model.

When the generic DOE data in Table 1 was used (for a 514x514x100 foot site), the estimated impact frequency range was 2.9×10^{-5} to 6.3×10^{-9} per year, with an average of 1.9×10^{-6} per year, for the point target area model. The effective aircraft target area model resulted in estimated range between 2.4×10^{-4} to 3.1×10^{-8} per year, with an average of 1.6×10^{-5} per year.

A site-specific evaluation for Three-Mile Island Units 1 and 2 was documented in NUREG/CR-5042, "Evaluation of External Hazards to Nuclear Power Plants in the United States," Lawrence Livermore National Laboratory, December 1987. The NUREG estimated the aircraft crash frequency to be 2.3×10^{-4} accidents per year, about the same value as would be predicted with the DOE data set for the maximum crash rate for a site area of 0.01 square miles.

NUREG/CR-5042 summarized a study of a power plant response to aviation accidents. The results are presented in Table 4. The probability of the penetration of an aircraft through reinforced concrete was taken from that study.

There is reasonable assurance that the DOE model and generic data provides a range of aircraft crash hit frequencies that would be consistent with plant-specific evaluations. At this level of effort, the resulting damage from an aircraft crash cannot be fully evaluated on a plant-specific bases.

A detailed structural evaluation is beyond the scope of this effort. In general, PWR spent fuel pools are located on, or below grade, and BWR spent fuel pools, while generally elevated about 100 feet above grade, are located inside a secondary containment structure. The vulnerability of support systems (power supplies, heat exchanges and makeup water supplies) requires a knowledge of the size and location of these systems, information not readily available.

Calculated values for risk-informed assessment of spent fuel pool

Significant pool damage

PWR The value for significant PWR spent fuel pool damage resulting from a direct hit was estimated based on the point target model for a 100x50 foot pool with a conditional probability of 0.32 (large aircraft penetrating 6-ft of reinforced concrete) that the crash resulted in significant damage. If 1-of-2 aircraft are large and 1-of-2 crashes result in spent fuel uncovery, then the estimated range is 4.3×10^{-8} to 9.6×10^{-12} per year. The average value was estimated to be 2.9×10^{-9} per year.

BWR The value for significant BWR spent fuel pool damage resulting from a direct hit was estimated to be the same as that for the PWR, 4.3×10^{-8} to 9.6×10^{-12} per year. The average value was estimated to be 2.9×10^{-9} per year. Mark-I and Mark-II secondary containments do not appear to offer any significant structures to reduce the likelihood of penetration, although on one side there may be a reduced likelihood due to other structures. Mark-III secondary containments may reduce the likelihood of penetration as the spent fuel pool may be considered to be protected by additional structures.

Support system availability

The value for loss of a support system (power supply, heat exchanger or makeup water supply) was estimated based on the DOE model including wing and skid area for a 400x200x30 foot area with a conditional probability of 0.01 that one of these systems is hit. The estimated value range was 1.0×10^{-6} to 1.0×10^{-10} per year. The average value was estimated to be 7.0×10^{-8} per year.

Alternatively, the value for loss of a support system (power supply, heat exchanger or makeup water supply) was estimated based on the DOE model including wing and skid area for a 10x10x10 foot structure. The estimated value range was 1.1×10^{-5} to 1.1×10^{-9} per year with the wing and skid area modeled, with the average estimated to be 7.3×10^{-7} per year. Using the point model, the estimated value range was 1.1×10^{-8} to 2.4×10^{-12} per year without the wing and skid area modeled, with the average estimated to be 7.4×10^{-10} per year.

Table 1 - Generic aircraft data

Aircraft	Wingspan (ft)	Skid distance (ft)	cotθ	Crashes per mi²-yr			Notes:
				Min	Ave	Max	
General aviation	50	1440	10.2	1×10^{-7}	2×10^{-4}	3×10^{-3}	
Air carrier	98	60	8.2	7×10^{-8}	4×10^{-7}	2×10^{-6}	
Air taxi	58	60	8.2	4×10^{-7}	1×10^{-6}	8×10^{-6}	
Large military	223	780	7.4	6×10^{-8}	2×10^{-7}	7×10^{-7}	takeoff
Small military	100	447	10.4	4×10^{-8}	4×10^{-6}	6×10^{-8}	landing

Table 2 - Aircraft hits per year

Building (L x W x H) (ft)	Average effective area (mi²)	Minimum hits (per year)	Average hits (per year)	Maximum hits (per year)
With the DOE effective aircraft target area model				
100 x 50 x 30	6.9×10^{-3}	3.2×10^{-9}	2.1×10^{-6}	3.1×10^{-5}
200 x 100 x 30	1.1×10^{-2}	5.3×10^{-9}	3.7×10^{-6}	5.5×10^{-5}
400 x 200 x 30	2.1×10^{-2}	1.0×10^{-8}	7.0×10^{-6}	1.0×10^{-4}
200 x 100 x 100	1.8×10^{-2}	9.6×10^{-9}	5.1×10^{-6}	7.6×10^{-5}

Building (L x W x H) (ft)	Average effective area (mi^2)	Minimum hits (per year)	Average hits (per year)	Maximum hits (per year)
400 x 200 x 100	$3.3x10^{-2}$	$1.8x10^{-8}$	$9.6x10^{-6}$	$1.4x10^{-4}$
80 x 40 x 30	$6.1x10^{-3}$	$2.8x10^{-9}$	$1.8x10^{-6}$	$2.7x10^{-5}$
10 x 10 x 10	$2.9x10^{-3}$	$1.1x10^{-9}$	$7.3x10^{-7}$	$1.1x10^{-5}$
With the point target area model				
100 x 50 x 0	$1.8x10^{-4}$	$1.2x10^{-10}$	$3.7x10^{-8}$	$5.4x10^{-7}$
200 x 100 x 0	$7.2x10^{-4}$	$4.8x10^{-10}$	$1.5x10^{-7}$	$2.2x10^{-6}$
400 x 200 x 0	$2.9x10^{-3}$	$1.9x10^{-9}$	$5.9x10^{-7}$	$8.6x10^{-6}$
80 x 40 x 0	$1.1x10^{-4}$	$1.1x10^{-11}$	$2.4x10^{-8}$	$3.5x10^{-7}$
10 x 10	$3.6x10^{-6}$	$2.4x10^{-12}$	$7.4x10^{-10}$	$1.1x10^{-8}$

Table 3 - DWTF aircraft crash hit frequency (per year)

Period	Air Carriers	Air Taxes	General Aviation	Military Aviation	Total[1]
1995	$1.72x10^{-7}$	$2.47x10^{-6}$	$2.45x10^{-5}$	$5.03x10^{-7}$	$2.76x10^{-5}$
1993-1995	$1.60x10^{-7}$	$2.64x10^{-6}$	$2.82x10^{-5}$	$6.47x10^{-7}$	$3.16x10^{-5}$
1991-1995	$1.57x10^{-7}$	$2.58x10^{-6}$	$2.89x19^{-5}$	$7.23x10^{-7}$	$3.23x10^{-5}$
1986-1995	$1.52x10^{-7}$	$2.41x10^{-6}$	$2.89x10^{-5}$	$8.96x10^{-7}$	$3.23x10^{-5}$

Note (1): Various periods were studied to assess variations in air field operations.

Table 4 - Probability of penetration as a function of location and concrete thickness

		Probability of penetration			
		Thickness of reinforced concrete			
Plant location	Aircraft type	1 foot	1.5 feet	2 feet	6 feet
≤ 5 miles from airport	Small ≤ 12,000 lbs	0.003	0	0	0
	Large > 12,000 lbs	0.96	0.52	0.28	0
> 5 miles from airport	Small ≤ 12,000 lbs	0.28	0.06	0.01	0
	Large > 12,000 lbs	1.0	1.0	0.83	0.32

Figure 1 - Rectangular facility effective target area elements