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Accident Analysis for Continued Storage

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SUMMARY

This report presents the results of an analysis to determine the penetration potential of jet aircraft (both military and commercial) when striking both concrete and steel structures used for storage of commercial spent nuclear fuel (CSNF). The report also includes an estimate of the probability of an aircraft crash into above ground CSNF installations, and an analysis of the radionuclide source term resulting from the event and the resulting public consequences.

INTRODUCTION

In preparation of the Environmental Impact Statement for the Yucca Mountain high level waste repository, it was concluded that aircraft crash accidents could be an important consideration for evaluating impacts during long term storage at the generating sites. In this instance, the CSNF is stored inside concrete storage modules (CSM) in stainless steel dry storage casks (DSC). Accordingly, the ability of aircraft to penetrate concrete and steel barriers during accidental impact is of interest in the evaluations.

ANALYSIS

The analysis consists of four different but related elements: 1) an estimate of the probability of an aircraft crash onto above ground dry storage of commercial spent nuclear fuel installations, 2) an analysis of the ability of concrete and steel to resist penetration by aircraft impact, 3) the radionuclide source term estimated to result from aircraft crash onto degraded CSNF storage modules and 4) the consequences of such an event in terms of radioactive dose and resulting latent cancer fatalities to members of the public.

1. Probability of Aircraft Crash on a Commercial Spent Nuclear Fuel Installation- The probability estimate of a future air crash on one of the commercial nuclear fuel storage sites was undertaken to establish if such an event could be considered credible. Due to large uncertainties, including unknowable future aircraft operational details, the estimated probability of such an event is highly uncertain, and simplifying assumptions were made to facilitate the analysis.

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The probability of an aircraft crash on one of the commercial spent fuel storage sites was computed by considering the effective area of the 75 commercial sites, the annual number of commercial air crashes per year, and the total area of the U.S. Figure 1 shows a typical storage site and an anticipated typical arrangement of the storage modules (CSAR 1998).

The formula used to estimate the crash frequency is as follows:

$$\mathbf{F = A_{eff} \bullet N \bullet C/A_{u.s.}}$$

where:

F = frequency of aircrash onto storage sites, per year
A_{eff} = Effective area of the storage site
N = total number of sites
C= annual commercial air crash frequency
$A_{u.s.}$ = total land area of the United States

Implicit in this formulation is the assumption that the crash location is uniformly distributed over the entire U.S. It is known that airplane crashes are more probable near airports during landing and takeoff operations. For simplicity, however, this factor was ignored. This probably results in a slight underestimation of the airplane crash probability since most nuclear power plants where the spent fuel is stored are located in the vicinity of population centers and are therefore in the regional proximity of commercial airports. The estimate also does not include airplane crashes involving military aircraft which could increase the estimate.

For this analysis, it is assumed that the approximate current rate of commercial jet aircraft crashes will exist at the time of the assumed accident. This rate varies somewhat from year to year, and is assumed to be equal to four crashes per year, which is the approximate average frequency of commercial airplane crashes over the past several years (NTSB 1998). (As will be seen, if this rate were 1 per year, or even less, the crash probability would still be considered credible.)

The aircraft assumed for the analysis is a mid-sized twin engine commercial jet represented by a Boeing 757. The characteristics of this aircraft were taken from JANES 1997. The size of the aircraft has an influence on the probability of intersecting the storage installation during a crash near the installation.

The effective area of the installation depends on several factors and includes factors which acount for the possibility that the aircraft can skid into the structures or can impact directly from the side or the top. The effective area is given by the following formula from. DOE 1996:

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

Where:

A_f = effective fly-in area

and

A_s = effective skid area.

The effective fly-in area (A_f) represents the area corresponding to a direct fly-in impact and consists of two parts, the footprint area and the shadow area. The footprint is the facility area that an aircraft would hit on its descent even if the facility height were zero. This area is the roof area of the facility, which is taken as the total length times the width of the rectangular area encompassed by the storage modules. The shadow area is the facility area that an aircraft could hit on its descent, but which it would have missed if the facility height were zero. This area depends on the wingspan of the aircraft, the width and length of the facility, the height of the facility, and the angle of aircraft descent. The formula used for this area is developed in Sanzo 1996, and is given by:

$$\text{Shadow Area} = (WS+R) \bullet H\cot\phi + \frac{2 \bullet L \bullet W \bullet WS}{R}$$

Where:

WS= wingspan of the aircraft (124'10" for a Boeing 757 from Janes, 1998)
R = length of the diagonal of the facility, or $(L^2 + W^2)^{0.5}$
H = height of the storage modules (15' from Fig. 1)
cotϕ = mean of the cotangent of the aircraft impact angle, equal to 10.2 for commercial aircraft from DOE 1996.
L = length of the storage installation (470', Fig. 1)
W = width of the storage modules (106' from Fig. 1)

The skid area, As, is the wingspan of the aircraft plus the diagonal length of the facility times the skid distance of the aircraft, or

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

Where WS and R are as defined previously, and S is the skid distance of the aircraft, given as 1440 ft. for commercial aircraft in DOE 1996. The effective area then becomes:

$$A_{eff} = (WS+R) \bullet H\cot\phi + \frac{2 \bullet L \bullet W \bullet WS}{R} + L \bullet W + (WS + R) \bullet S$$

Using the values indicated for the parameters produces the following effective area:

$$A_{eff} = 1{,}040{,}099 \text{ ft.}^2 = .037 \text{ mi}^2$$

The land area of the U.S. is approximately 3.5E+6 mi^2 (Atlas, 1980).

The aircraft crash probability thus becomes:

$$\textbf{Crash probability (per yr.)} = \frac{.037\text{mi}^2\text{/site X 75 sites X 4 crashes/yr.}}{3.5\text{E+6mi}^2} = 3.2\text{E-6}$$

This probability is within the credible range, defined as greater than 1E-7/yr. by DOE (DOE 1993).

2. Concrete and Steel Penetration by Aircraft Impact- The storage modules which enclose the DSCs consist of a concrete enclosure with 40" (3.33 ft) thick concrete walls and ceiling. The DSCs are steel casks with 0.625" thick walls and end caps (CSAR 1998). For this evaluation, four types of aircraft were evaluated: 1) a mid-sized commercial jet, represented by a B-757, a commonly used aircraft by U.S. air carriers, 2) a twin engine jet fighter, represented by an F-15, 3) a single engine jet fighter, represented by an F-16, and 4) an anti-tank military jet, represented by the A-10.

The potential for aircraft to penetrate concrete is discussed in a recent DOE order (DOE 1996), and a formula is derived to estimate the penetration capability of aircraft impact. The formula is:

$$t_p = (U/V)^{0.25} (MV^2/Df_c')^{0.5}$$

where,

t_p = perforation thickness, or the concrete panel thickness that is just great enough to allow a missile to pass through the panel without any exit velocity.
U = reference velocity (200 ft/sec from DOE 1996)
V = missile impact velocity (aircraft impact velocity, ft/sec.)
M = mass of the missile, which is the weight divided by gravitational acceleration (32.2 ft./sec.^{2})
D = missile diameter (ft.)
f_c' = ultimate compressive strength of the concrete (720,000 lb/ft.^{2} from Tetra Tech NUS 1998)

For penetration of steel plate, DOE 1996 recommends the following formula:

$$T^{1.5} = 0.5MV^2/17,400K_sD^{1.5}$$

where,

T = predicted thickness to just perforate a steel plate (in.)
M = missile mass, which is the weight divided by gravitational acceleration (32.2 ft/sec.^{2})
V = missile impact velocity (ft/sec)
K_s = constant depending on the grade of the steel (usually ~ 1.0)
D = missile diameter.

The DOE standard (DOE 1998, Pg. 58) states that the bounding missile for local damage evaluation will be the aircraft engine. Table 1 provides relevant engine data for the representative spectrum or aircraft selected for the analysis.

Table 1- Aircraft Engine Characteristics

Aircraft	Weight (lb)	Engine Mass (slugs)	Engine Diameter(ft.)	Source
B-757				
Rolls Royce	7189	225	6.2	Janes, 1997
Pratt & Whitney	7300	228	7.1	Janes, 1997
F-15, F-16	3200	100	3.0	Thompson, 1998
A-10	1443	45	4.2	Thompson, 1998

The aircraft impact velocity (V) depends on the type of aircraft and the flight configuration at the time of impact. The Pantex EIS (Pantex 1996) uses 422 fps as the velocity of the impacting aircraft for evaluation of on-site facilities. The DOE Standard (DOE 1996, Pg. C-7) indicates that missile velocities from an aircraft crash event are typically less than 500 ft/sec. Both of these values were used in the penetration calculations for this assessment. Table 2 provides the results of the penetration calculations.

Table 2- Aircraft Penetration Results

Aircraft	Impact Velocity (fps)	Penetration Depth	
B-757		concrete (ft.)	steel (in.)
Rolls Royce	422	2.49	1.47
	500	2.80	1.85
Pratt & Whitney	422	2.34	1.30
	500	2.64	1.63

F-15, 16	422	2.38	1.78
	500	2.69	2.23
A-10	422	1.35	0.74
	500	1.52	0.93

Table 2 indicates that the maximum thickness of concrete penetrated by a jet engine (2.80 ft.) under the assumed conditions is considerably less than the thickness of the concrete storage modules (3.33 ft.). Thus, unless the concrete in the storage modules becomes degraded, aircraft penetration would not be expected. The aircraft engines would be expected to penetrate the 0.625" thick steel of the DSCs, however.

3. Accident Source Term- Aircraft Impact with Degraded Commercial Spent Nuclear Fuel Storage Modules. This section presents the results of an analysis to estimate the airborne release of radionuclides from aircraft impact with degraded CSNF storage modules. The section is divided into two subsections, 3a, Description of the Postulated Accidents, and 3b, Radionuclide Source Term.

3a. Description of the Postulated Accident-The accident scenario involves the impact of a mid-sized twin engine commercial jet aircraft (represented by a Boeing 757) with the CSNF storage modules. As noted previously in Sect. 2, the limiting aircraft missiles (jet engines) would not be expected to penetrate the concrete storage modules and steel CSNF storage cask while these elements are in good condition. Therefore, the accident would be expected to cause a release only after significant degradation of the concrete occurs. (The engines would be able to penetrate the steel storage cask with no degradation as indicated in Sect. 2). The extent of concrete degradation (assuming no maintenance or replacement represented by Scenario 2 in CSAR 1998) depends on location and time since construction. Based on the CSAR 1998 results, a time interval of 1000 years was selected as the nominal interval to cause degradation sufficient to allow jet engine penetration of the concrete module and steel cask. As indicated in CSAR 1998, for modules located in northern climates, the degradation interval would likely be less due to freeze-thaw cycling, on the order of 2 or 3 hundred years. For southern locations, the interval could be several thousand years. The time interval is of significance because the source term is affected by decay of the radionuclides.

The impact of each of the two jet engines is assumed to be essentially unimpeded by the degraded concrete, and would rupture two steel storage casks, and also rupture the cladding of the fuel pins contained within the cask. Each cask contains either 24 pressurized water reactor fuel assemblies or 52 boiling water reactor assemblies. However, the 24 PWR assemblies actually contain a higher inventory of radionuclides than the 52 BWR assemblies (DOE 1992). For this reason, and also because the U.S. nuclear power reactor population contains about twice as many PWRs as BWRs, the storage modules containing PWR fuel were selected for this analysis.

The aircraft impact with the degraded modules results in scattering of individual uranium dioxide fuel pellets in the immediate vicinity of the impact. Jet fuel (a hydrocarbon) is also assumed to be released during the event. This fuel is assumed to collect in pools in the immediate vicinity. This fuel ignites and burns, and heats the fuel pellets and other debris caused from the crash. It is assumed that all the fuel pellets released during the accident are heated during the fuel burn to a sufficiently high temperature (greater than 500°C) to completely oxidize the uranium dioxide to U_3O_8. (Jet fuel is a hydrocarbon, and hydrocarbon pool fires can produce temperatures up to 1100°C, NIST 1997). This oxidation process would be expected to be complete in about 1hr. under the assumed conditions. As the fuel pools burn down, increasing quantities of fuel pellets which may be immersed in the pools are exposed to air which allows the oxidation process to proceed. This chemical change is important since it converts the solid sintered fuel pellets into a powder form, more readily available for airborne release.

3b - Radionuclide Source Term- The source term of interest in this analysis is the fraction of the radionuclide materials which may become airborne during the event. There exist three potential sources of radionuclides which need to be considered for the event, as follows:

- Crud- Crud refers to activation products which are present in the cooling water of light water reactors that attaches to the external surfaces of the fuel cladding during irradiation within the reactors. During dry storage, the crud dries and forms a scale on the external surfaces of the fuel elements. It has been estimated (Seager 1994) that after a 5-yr cooling period, the radioactive isotope Co-60 would represents 92% of the PWR crud activity. The half-life of Co-60 is 5.26 years. Thus, after 1000 years of cooling, the time interval assumed to transpire before the aircraft impact accident, some 190 half lives would have elapsed, and the amount of radioactive Co-60 remaining after this interval would be negligible.

- Gap Activity- The gap activity consists of radioactive gases, cesium isotopes, and small fuel particles (fines) which have been produced by cracking of the pellets during operation. The radioactive gases are H_3 (tritium) with a half-life of 12.6 yr. and Kr-85 with a half life of 10.76 yr. Both of these isotopes would be essentially gone after the 1000 year cooling interval assumed in the accident. The fuel pellet fines in the gap would contain a small inventory including essentially all of the fission products and actinides produced during reactor operations. The total fraction of the fines which are small enough to become airborne and respirable has been estimated based on experiments (Lorenz 1988) to be 1E-8, a very small fraction. There would also be some small fraction of fines produced as a result of the mechanical energy imparted to the fuel pellets from the aircraft impact. However, this fraction is not relevant since, as discussed below, the entire inventory of fuel pellets is assumed to be oxidized to U_30_8 during the accident. The oxidation process converts all of the fuel pellets into powder which dominates the respirable release fraction.

- Fuel Pellets- Once exposed to oxygen in the air, the UO_2 can be oxidized to higher suboxides (U_4O_9, U_3O_8). Above 100°C, U_3O_8 is formed, which is a particulate material that can sluff away from the fuel pellets during formation and be suspended by the ambient air velocity (Einziger 1994). In experiments involving the heating of UO_2 fuel pellets in a furnace in the presence of air (Iwasaki 1968), it was determined that at temperatures between 500 and 700°C, the pellets would be converted to U_3O_8 in 1 hour. The particle size distribution of the resultant powder was determined, and the fraction of particles determined to be potentially small enough to become airborne was found to be 12%. Of this amount, approximately 1% (DOE 1994) is expected to become airborne and available for inhalation by downwind human receptors. Thus, the fraction of airborne fuel particles produced from the accident is estimated to be .0012.

  In addition to this release, all of the C-14 which is produced by activation of trace amounts of nitrogen in the fuel pellet matrix is assumed to be released in gaseous form.

Based on the preceding discussion, the airborne source term from the aircraft accident is represented by a release of .12% of all of the fuel pellet radionuclide inventory in 48 fuel assemblies (two DSCs each impacted by a jet aircraft engines). The inventory released is based on average PWR spent fuel as defined in DOE 1996a which lists the radionuclides produced during operation. The inventory information is given in Table 3. The table lists in the first column the radionuclides which have been found to be important contributors to health impacts (CRWMS 1996, Jackson 1984) which still have significant inventories after 1000 years, and provides in the second column the 1000yr. inventory for an individual fuel assembly. The third column lists the total inventory for 48 fuel assemblies assumed to be involved in the accident, and the fourth column gives the fraction of the radioactive material which can be breathed into the lungs (respirable airborne release), which is 0.12% of the 1000 yr. inventory as noted in the previous discussion.

Table 3- Radionuclide Inventory Data for the Aircraft Crash Accident.

Isotope	1000 yr inventory		Airborne Release (respirable)
	Curies/assembly	Curies/48 assemblies	
C-14	1.08E+1	5.18E+2	5.18E+2
Ni-59	.506	24.3	.029
Ni-63	4.54E-2	2.18	2.62E-3
Sr-90	7.16E-7	3.44E-5	4.13E-8
Y-90	7.16E-7	3.44E-5	4.13E-8
Se-79	.0883	4.24	5.1E-8

Zr-93	.455	21.84	.026
Nb-93m	.433	20.78	.025
Tc-99	2.81	135	162
Sn-126	.170	8.16	.0098
Sb-126	.0239	1.15	.00138
Sb-126m	.170	8.16	.0098
I-129	6.9E-3	.331	3.97E-4
Cs-135	.101	4.85	.0058
Cs-137	2.07E-6	9.94E-5	1.2E-7
U-234	.499	23.95	.029
Pu-238	.393	18.86	.0226
Pu-239	70.3	3.37E+3	4.04
Pu-240	96.3	4622	5.55
Pu-241	.0657	3.15	.00378
Pu-242	.39	18.72	.022
Am-241	202	9.7E+3	11.64
Am-242m	.049	2.35	.00282
Am-243	4.5	216	.259
Np-239	4.5	216	.259
Am-242	.0488	2.34	.00281
Cm-242	.0404	1.94	.00233

4. Radiological Consequences- In order to compute the public impacts from the air crash event, it is necessary to estimate the potentially exposed population out to a distance of 50 miles (the distance beyond which insignificant impacts would be expected to occur for an airborne release) For this analysis, two hypothetical sites were considered, one which represents a high population site, and a representative low population site. The average population around all of the sites in each of the five regions defined in CSAR 1998 was computed based on 1990 census data. The average ranged from a high of 329 persons/mi.^{2} in region 1 (Northeast) to a low of 77 persons/mi^2 in region 4 (Central). For the purpose of calculating consequences, both of these population densities, assumed to be uniform around the hypothetical sites, were used in the consequence calculation.

The consequences from the event were computed with the MACCS2 code (NRC 1990). This code has been used extensively by the NRC and DOE to estimate impacts from accidents involving the release of radioactive materials. The code computes radiation dose to the public due to

- direct radiation from the cloud of radioactive particles released during the accident,
- from inhaling the particles, and
- from consuming food produced from crops and grazing land which may be contaminated as the particles are deposited on the ground from the passing cloud.

The food production and consumption is based on U.S. generic values which are input to the code. The code computes the dispersion of the particles as the cloud moves downwind from the crash site. The dispersion depends on the weather conditions (atmospheric stability, precipitation rates, and wind velocity) which exist at the time of the accident. For the purpose of this calculation, the weather conditions were assumed to be identical to median conditions representative of a location near the geographic midpoint of the high and low population regions assumed in the analysis, and annual weather conditions at airports near the center of the regions were used. The results of the calculation are provided in Table 4. The latent cancer fatalities are estimated by use of a conversion factor (5E-4 latent cancer fatalities/person-rem) recommended by the International Commission on Radiological Protection (ICRP 1991)

Table 4- Consequences of Airplane Crash onto Degraded Spent Fuel Storage Modules

Impact	High Population Site	Low Population Site
Collective Population Dose (person-rem)	26,100	6,120
Latent Cancer Fatalities	13	3

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