Offsite Dose Accumulation Rates Following a Hypothetical Spent Fuel Pool Accident

Task 3 Report for the User Need NSIR-2015-001

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1.0 Introduction

In Task 3 of User Need dated 4 September 2015 (ML15168B073), the Office of Nuclear Security and Incident Response (NSIR) requested that the Office of Nuclear Regulatory Research (RES) undertake research to determine whether the offsite dose rates following a spent fuel pool accident are sufficiently low to provide any additional time margin (greater than 10 hours) before offsite exposures become excessive. In the response dated 5 October 2015 (ML15271A303), RES staff proposed to select spent fuel pool source terms developed for the consequence study in NUREG-2161 [1] to develop doses and dose rates from potential spent fuel pool accidents using MACCS to evaluate cumulative early phase acute doses to organs of interest for early health effects (red bone marrow, stomach, and lungs) as well as effective doses from early phase exposures. These doses would be provided as a function of both time and distance from the point of release.

The task analyses were performed on two different source terms examining the acute doses to organs of interest for early health effects and the lifetime committed effective doses for each type of release. The results indicate that acute fatal effects offsite appear to be unlikely from either source term provided that individuals are relocated within a reasonably short time after the release begins. For the more limiting source term analyzed, the PAG guidelines would be exceeded within the first hour of release inside 0.3 miles. Outside of 5 miles, PAG limits would be not be expected to be exceeded until more than 8 hours after release began.

2.0 Methodology

2.1 Source Term Selection

Staff used the MACCS project files developed for NUREG-2161 to conduct this analysis. Staff selected two NUREG-2161 source terms for evaluation. The base case was the source term used for a high-density pool loaded in a 1x4 arrangement with a small leak starting 37 days after reactor shutdown (OCP3.4HD). This source term was selected because it provided sufficient time for the very short lived radiological inventory to have substantially decayed. In this source term, a small release was projected to begin at approximately 41 hours after accident initiation resulting from cladding failure and gap release, with a substantial increase in the release rate at approximately 47 hours after accident initiation as a result of fire initiation due to hydrogen deflagration. Staff also selected an additional source term reflecting a sensitivity case in which a moderate leak beginning 37 days after reactor shutdown is followed by a concurrent reactor accident that initiates a fire by introducing additional oxygen to the hot fuel (OCP 3.6 RB Open 16.9 hrs). Although the base case version of this scenario with an early failure of the reactor building did not result in a substantial release due to the relatively rapid establishment of air cooling, the sensitivity case was run with an assumed reactor building failure 16.9 hours which provides a source of oxygen to the hot fuel resulting in fire initiation. This source term was selected as it does not have the low precursor gap release phase characteristic of OCP3.4HD source term, and therefore reflects a more rapidly progressing release scenario. The cumulative Cs-137 release as a function of time since accident initiation is shown in Appendix A, where the initial low gap release period for the OCP 3.4 HD release can be seen. After an initial release period, the two curves are approximately parallel for the bulk of the release, indicating a relatively similar release rate (Bq/s) for the major period of the release.

The source terms used in NUREG-2161 were for a spent fuel pool at a boiling water reactor. Source terms could be different for other fuel loading configurations, fuel inventories, or fuel types (such as PWR spent fuel pools). Staff used these source terms because they represent the most detailed, up-to-date spent fuel pool source terms available, and the inventory of the spent fuel pool is comparable to that of many operating spent fuel pools. Although staff has not analyzed SFP source terms from a PWR spent fuel pool, source terms are expected to be comparable because the factors controlling the rate of release from the damaged fuel would be similar.

2.2 MACCS Model

MACCS 3.10.0 was used to conduct the analysis. In order to provide a realistic treatment of weather, in which the wind direction and speed can vary over the course of a protracted release, the analysis used the same hourly meteorological file based on observations at the Peach Bottom Atomic Power Station that was used for the analyses in NUREG-2161. Staff used the same subset of approximately 1000 weather sequences to represent the variability in the results that could occur as a result of different weather conditions during the release. The relevant MACCS project files were executed in MACCS 3.7.0 and selected results were compared to the archives SFPS results to ensure proper source term selection. The project files were then imported into MACCS 3.10.0 and several simplifications were made to decrease the execution time and ensure the proper outputs were saved. Because only individual dose rates were needed, a uniform population density of 100 person/mi was set by assigning the variable POPFLG a value of UNIFORM and the variable POPDEN a value of 39 persons/km2). Because the network evacuation model was not used, the windshift with rotation option (IPLUME=2) was selected to increase computational efficiency. The Type A output “Peak Dose on Spatial Grid” was selected to provide the dose output. This output provides, for each sector and radial distance within the inner and outer limit, the maximum dose within the radial interval regardless of the sector in which it occurred. There is no dependence on population data. The dose is reported for phantom individuals assumed to be present at all locations. Staff selected a number of dosimetric quantities for tabulation. The lifetime committed effective dose in Sv is provided by the L-ICRP60ED output. Absorbed dose equivalents (in units of Gy-equiv) suitable for evaluation of early health effects from acute exposures are provided for red bone marrow, lungs, and stomach. The dose coefficients used to evaluate the dose from inhalation account for the effect of dose protraction by weighting dose rates over a one year period to yield an equivalent 24 hour dose. In addition, acute doses to the skin arising from external exposures, including external beta irradiation from activity deposited on exposed skin, were computed.

Staff selected two alternate approaches for evaluating the rate of dose accumulation. The first approach evaluates the dose accumulation as a function of time since the beginning of release to the environment. This approach was implemented by setting a single evacuating cohort that would immediately and instantaneously evacuate at a specified time since accident initiation. The notification time is specified by the variable OALARM, which is varied, but all subsequent evacuation delays (delay to shelter and delay to evacuation) are set at zero, and the evacuation speed was set at a value large enough to ensure that the individuals exited the evacuation grid effectively instantaneously. The effect of this approach is to evaluate the dose accumulation rate in absolute terms. Since OALARM represents the time since accident initiation and doses will be zero if evacuation is completed before the release begins, the time is adjusted by subtracting the delay time to initial release (defined by the variable PDELAY001). This eliminates the effect of different initial release times for different source terms[1].

The other approach evaluates the dose accumulation as a function of the first plume arrival at a given location (Note that the plume arrival times will generally be different at different distances and different sectors). This approach is implemented by selecting a single non-evacuating cohort and varying the relocation time specified by TIMHOT and TIMNRM. The dose thresholds for relocation were set at trivially low numbers to ensure that all exposed sectors, regardless of how low the exposure might be, were subject to relocation. Effectively, varying the relocation time varies the exposure duration of the exposed individual. This approach yields the dose that would be accumulated if the delay was measured from time since plume arrival, whenever that plume arrived.

In all cases, exposure parameters were selected to provide a best-estimate rather than a bounding estimate of the dose. Normal activity was assumed for all individuals offsite. Since on average individuals typically spend a large fraction (approximately 81%) of their time indoors, dose reduction factors based on the analyses in NUREG-2161 [1] and the State of the Art Reactor Consequence Analysis [2,3] were used to reduce the outdoor unprotected doses to account for the effects of shielding and reduced indoor air concentrations. The factors are used as multipliers on the dose that a person would receive if there was no shielding or protection; therefore, a factor of 1 represents no reduction in the dose, and a factor of 0 represents complete elimination of the dose. The values used for normal activity are provided below in Table 1. Because the effect of a seismically initiated event may also damage the structures in which an individual may be sheltered during and after passage of the cloud, the shielding and protection factors that would be assumed for outdoor activity, for example during an evacuation phase, are also provided to assist in judging the effect of the exposure parameters.

Table 1: Shielding and Protection Factors Used in the Analysis

Exposure Pathway	Shielding and Protection Factors	
	Normal Activity	Outdoors/Evacuation
Cloudshine	0.60	1.00
Inhalation	0.46	0.98
Groundshine	0.18	0.50
Skin Protection	0.46	0.98

3.0 Results

The results were generated in terms of cumulative dose received as a function of both elapsed time (either since the initial plume release or plume arrival) and distance from the site. The

[1] Although MACCS accounts for the radiological decay of the inventory as a function of time since accident initiation, the effect of different release initiation times is judged to be very small, since the initial inventory reflects 37 days of decay such that a few additional hours or days of radiological decay is not likely to have a significant effect.

received doses were evaluated out to 24 hours, which staff considers to be sufficient to evaluate the potentially slower evacuation times associated with all-hazards evacuation, and out to a distance of 20 miles, which is well beyond the 10 mile emergency planning zone such that the difference in evacuation time under a radiological emergency plan and an all hazards emergency plan is likely to be small.

The dose results represent the mean value across all weather conditions. As discussed above, approximately 1000 starting times were selected from the 8760 weather sequences available. The results in the tables below represent the frequency-weighted average across all selected weather sequences. Values associated with somewhat less likely, but potentially more consequential, weather conditions (i.e., stable, low wind speed night-time conditions or enhanced deposition due to rain) could be higher than the values shown in these tables.

The staff tabulated two dosimetric outputs. The equivalent acute bone marrow dose was evaluated to show the margin to the potentially lethal effect of hematopoietic syndrome, which is typically the most limiting fatal health effect, with a threshold judged to range between 1.1 and 5.3 Gy-eq (median value of 2.3 Gy-eq) [4]. The lifetime committed effective dose, which is analogous to the total effective dose equivalent used for protective action decision-making, was evaluated to show the combination of elapsed times and distances at which protective action guidelines could be exceeded in the event of a release.

Comparing the dose rates of the two independent approaches (time since plume arrival and time since release begins) verifies the consistency of the methods. As expected, the cumulative doses at close in distances are very close among all time intervals since the plume transit time has little impact. For evacuations that occur close to the time of release at greater distances, the dose approximations diverge. This is attributed to the fact that when using the approach that requires evacuation at defined times after release, the plume has not had sufficient time to traverse to further radial distances, yielding a small dose.   After several hours have elapsed, the dose approximations once again converge which is consistent with what one would expect allowing for all plumes to have transited these distances.

For the OCP 3.4 source term, the A-RED MARR dose would not exceed one tenth of the threshold value for hematopoietic syndrome at any distance outside of 0.1 miles within the first 16 hours. PAG guidance would be exceeded offsite at the closest distances (within 0.3 miles) three hours after release. Beyond one mile, PAG limits would not be exceeded within six hours.

For the OCP 3.6 source term, the PAG guidelines would be exceeded within the first hour of release inside 0.3 miles. Outside of 5 miles, PAG limits would be expected to be exceeded 8 hours after release. For this source term, one tenth of the threshold dose for hematopoietic syndrome would not be exceeded anywhere outside of one mile from the release within 24 hours, and within one mile would not be exceeded within fourteen hours after the release begins. At close in distances, the PAG levels are exceeded more rapidly for OCP 3.6 source term than for the OCP 3.4 source term because the initial release rate is larger for the OCP 3.6 source term.

Table 2. Time to exceed threshold dose (2.3 Gy-eq) for hematopoietic syndrome, 10% of threshold dose for hematopoietic syndrome (0.23 Gy-eq), and PAG limit (0.05 Sv TEDE)

Source Term		0.1 mi	1 mi	5 mi
OCP 3.4 HD	Red Bone Marrow Dose > 2.32 Gy-Eq	> 24 hrs	> 24 hrs	> 24 hrs
	Red Bone Marrow Dose > 0.23 Gy-Eq	16-17 hrs	> 24 hrs	> 24 hrs
	Whole Body ED > 0.05 Sv	3-4 hrs	6-7 hrs	9-10 hrs
OCP 3.6 HD (RB open at 16.9 hrs)	Red Bone Marrow Dose > 2.32 Gy-Eq	> 24 hrs	> 24 hrs	> 24 hrs
	Red Bone Marrow Dose > 0.23 Gy-Eq	14-15 hrs	> 24 hrs	> 24 hrs
	Whole Body ED > 0.05 Sv	< 1 hr	2-3 hrs	8-9 hrs

The rate of dose accumulation is shown for the more limiting source term (OCP 3.6) in Figure 2 (acute red bone marrow dose) and Figure 3 (lifetime committed effective dose) as a function of time since the release begins. The effect of distance from the site is clearly illustrated in these graphs, which the dose accumulation rate at 5 miles much less than the dose accumulate rate at very close distances (approximately a quarter mile) from the release point.

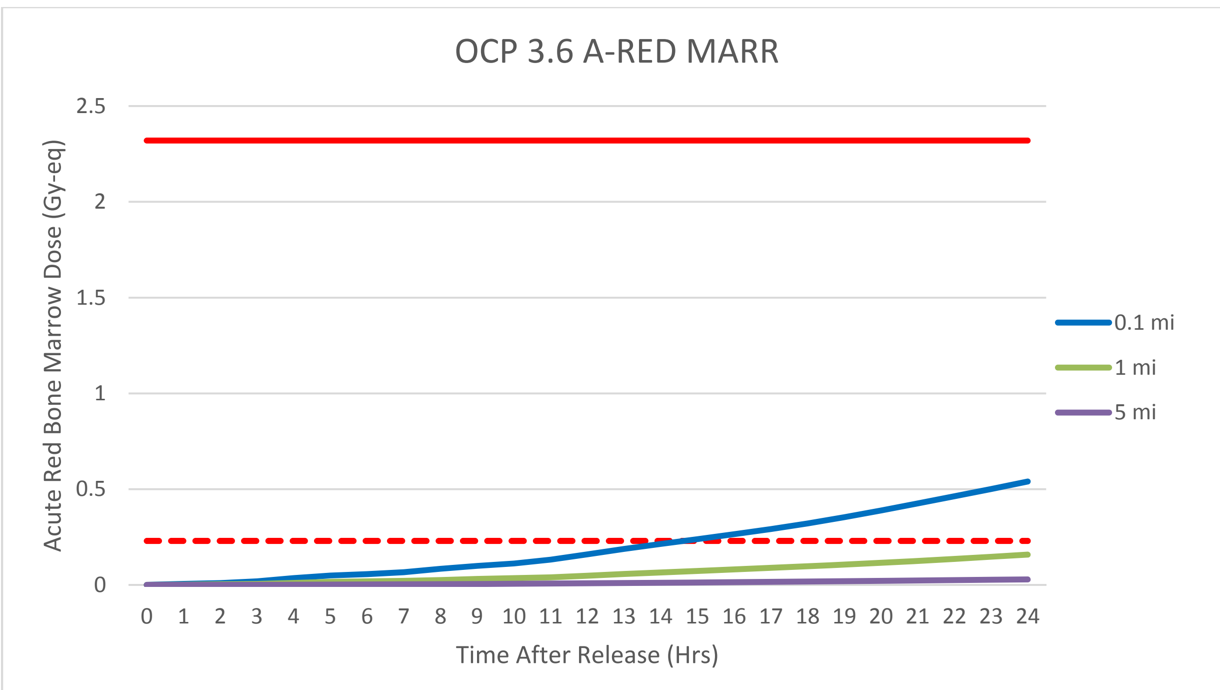


Figure 2: Cumulative acute bone marrow dose received at 0.1 mile, 1 mile, and 5 miles from the release point. Dashed line at 0.23 Gy-eq represents 1/10 of threshold dose for hematopoietic syndrome; solid line at 2.3 Gy-eq represents the threshold dose.

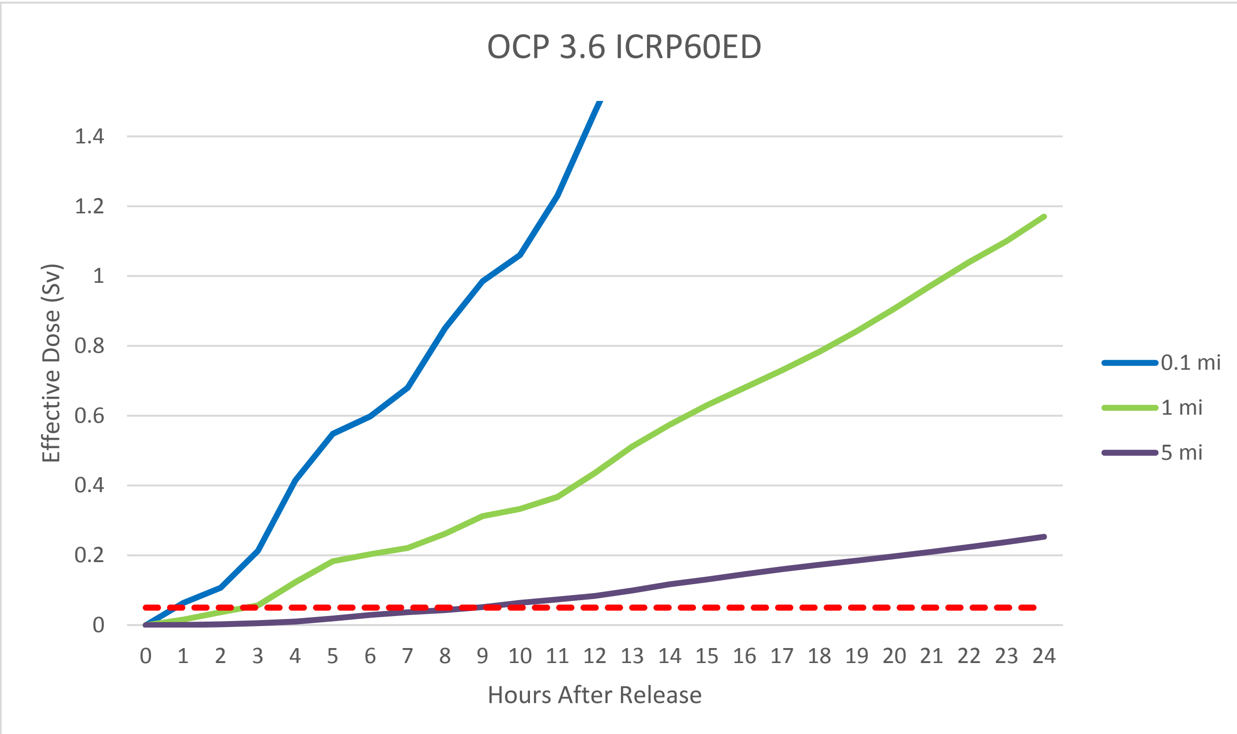


Figure 3: Cumulative lifetime committed effective doses received at 0.1 mile, 1 mile, and 5 miles from the release point. Dashed line at 0.05 Sv (5 rem) represents upper PAG limit

In addition to the whole body effective doses (used to evaluate margin to protective action guidance levels) and doses to bone marrow (used to evaluate margin to acute fatalities), doses to the lungs and stomach were also evaluated. One tenth of the threshold values for Pulmonary Syndrome and Gastrointestinal Syndrome were not exceeded anywhere outside of 0.1 miles within the first 24 hours of plume arrival. This confirmed that bone marrow dose would be the most limiting dose among those expected to result in early fatalities. Based on this analysis, acute fatal effects offsite appear to be unlikely from either source term evaluated provided that individuals are relocated within a reasonably short time after plume arrival.

The results represent the mean value across all weather trials. The MACCS code can evaluate the distribution of consequences that can result from uncertainty in predicting weather conditions at the time of a future hypothetical release by using a technique called non-uniform bin sampling was used. Weather binning is a type of importance sampling used to categorize similar sets of weather data based on wind speed, stability class, and the occurrence of precipitation. This strategy results in roughly 1,000 weather trials to represent the 8,760 hours of data in a 365-day year. A sensitivity study conducted for the Peach Bottom UA [5] showed that this sampling strategy matched the mean results that would have been obtained by choosing every hour in the weather file (8760 samples) within 3% for health risks evaluated with the linear, no-threshold (LNT) dose-response assumption and within 12% for health risks evaluated with the two non-LNT dose-response assumptions. Depending upon the weather at the time of the release, the results could be either higher or lower than the mean results presented above. For example, releases into low windspeed, stable atmospheres (typical of nighttime conditions) can result in more concentrated plumes, and rain or snow during plume transit can enhance deposition (and hence doses). Both of these conditions could lead to higher values than reported here. Conversely, releases into relatively unstable or higher windspeed environments would lead to lower releases than reported here. The mean value is presented in this analysis because it considers both the frequency and the consequences of the different possible weather conditions prevailing at the time of the release.

4.0 REFERENCES

[1] Nuclear Regulatory Commission (U.S. NRC). NUREG-2161, “Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor,” Washington D.C.: NRC, 2014

[2] Sandia National Laboratories, NUREG/CR-7009, “MACCS Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project,” Washington D.C.: NRC, 2014

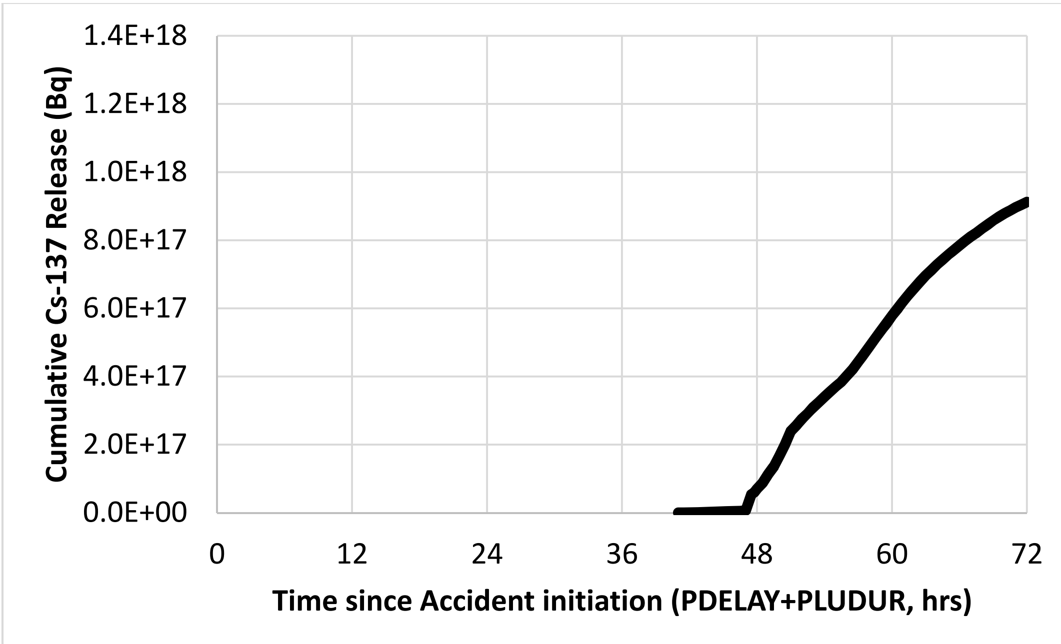
[3] Sandia National Laboratories, NUREG/CR-7155, “State-of-the-Art Reactor Consequence Analysis Project: Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station,” Nuclear Regulatory Commission, Washington, DC, draft.

[4] Sandia National Laboratories, NUREG/CR-7161, “Synthesis of Distributions Representing Important Non-Site-Specific Parameters in Off-Site Consequence Analyses,” Washington D.C.: NRC, 2013

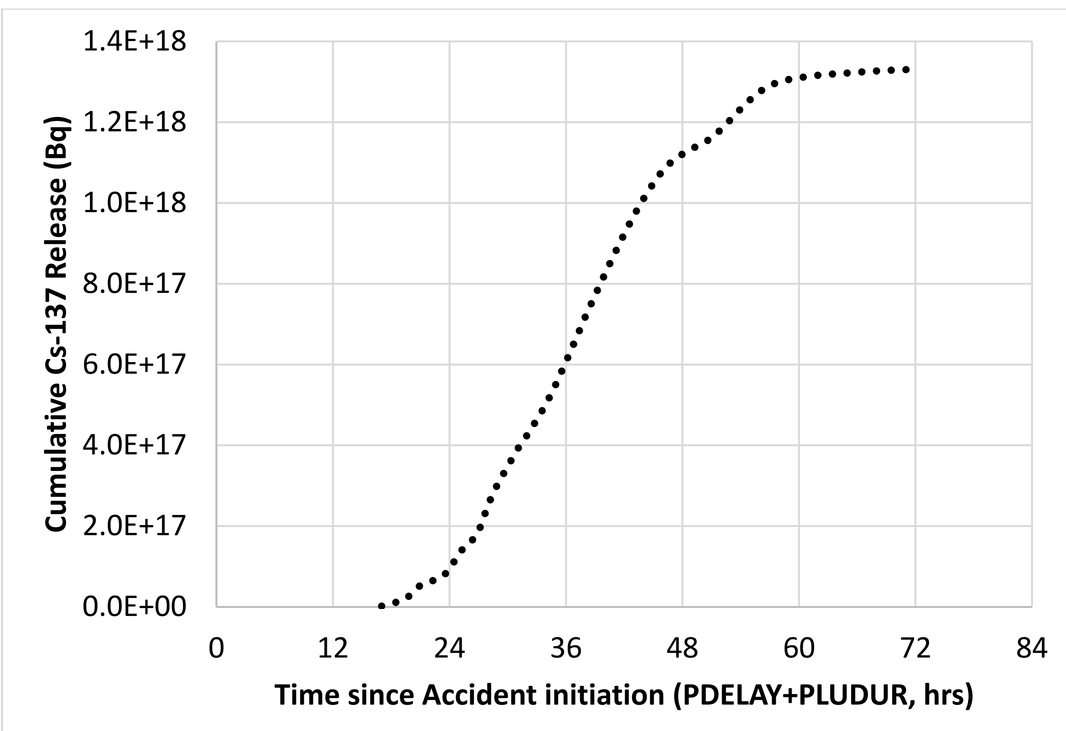
[5] Sandia National Laboratories, NUREG/CR-7155, “State-of-the-Art Reactor Consequence Analyses Project Uncertainty Analysis of the Unmitigated Long-Term Station Blackout of the Peach Bottom Atomic Power Station,” Washington D.C.: NRC, 2016

APPENDIX A: Source Terms used for analysis

Release data derived from processing of MACCS outputs



OCP 3.4



OCP 3.6