R-008-203.1

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A BASELINE RISK ASSESSMENT FOR THE K-65 SILOS USING EPA METHODOLOGY FOR APPLICABILITY TO THE EE/CA MAY 11, 1990

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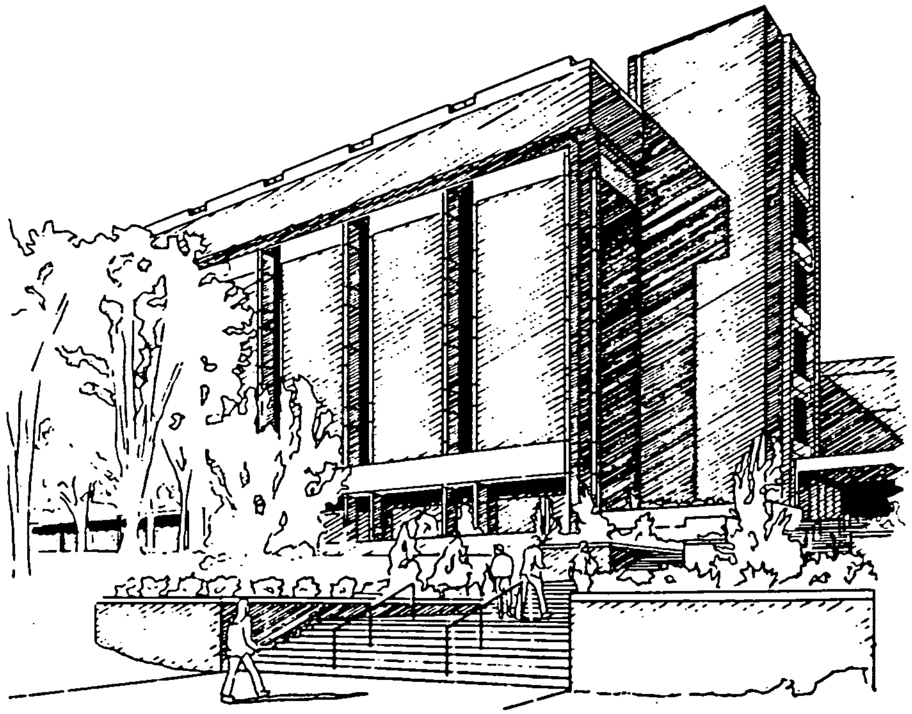

UNIVERSITY OF CINCINNATI
COLLEGE OF ENGINEERING

Revision 1

A Baseline Risk Assessment For The K-65 Silos Using EPA Methodology For Applicability To The EE/CA

May 11, 1990

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A Baseline Risk Assessment For The K-65 Silos Using EPA Methodology For Applicability To The EE/CA

Revision 1

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May 11, 1990

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Executive Summary

Introduction

The baseline risk assessment for the K-65 silos is intended to serve as a foundation for the Engineering Evaluation and Cost Analysis (EE/CA) document now being prepared by Bechtel National Incorporated. The EE/CA document is required by the Environmental Protection Agency (EPA) through 40 CFR Part 300, which is intended to provide assurances from potential threats to the public resulting from the release of hazardous or radioactive material to the environment. The EPA has published documents providing guidance for the risk assessment of hazardous substances. The methodology and procedures described in the guidance documents were utilized in the exposure assessment and risk characterization phases of this study. The probabilistic risk assessment methodologies were also utilized in the initial phase of the study, in order to quantitatively evaluate the probability and magnitude of a hypothetical release. The probabilistic methodology provides quantitative risk estimates of silo failure. In this way a variety of causes for structural failure can be compared in terms of both probability and consequence. Risks associated with tornados, the potential for increased fatal cancer incidence, and the overall impact of the K-65 silos on the public are evaluated and considered.

Using a combination of the probabilistic formalism and the conventional risk methodologies, this study provides more detail concerning the failure potential than what can be contained in a straight conventional Superfund based risk assessment. The inclusion of the additional detail is intended to provide information and perspective beneficial to the evaluation and analysis of the final disposition of the silos and the waste. Risk estimates are important in determining the critical time constraints as well as the impact from some action. The results of this study are in the form of probabilities (of some event), magnitude and distribution of potentially significant releases (of radioactive material), human exposure and dose estimates, and finally estimates of the overall risks (fatal cancers and increased cancer incidence).

Data Evaluation

The first phases of a risk assessment include the evaluation of the available data. In this facet the two risk methodologies are essentially the same. The primary difference is in the degree of evaluation. For this study the data were analyzed as thoroughly as possible using both qualitative and quantitative methods. The risk assessment analysis essentially moved from the silo structures outward. The steps of the assessment were essentially the following: 1) evaluation of the silo structure, 2) determination of the failure potential, 3) estimation of the hypothetical source term released, 4) prediction of the transport of contaminants in the environment, 5) assessment of the exposure and dose to the public, and 6) calculation of the resulting risks.

Silo Structural Integrity

The structural integrity of the silos was considered to be sufficiently degraded that the potential for a large scale release is significant. Structural analysis performed on the silos (Bechtel, 1990 and Camargo, 1986) using both destructive and non-destructive examination methods, provided ample data with which to construct failure probabilities. Detailed evaluation of the results of these previous studies provided the basis for the probability calculations. Testing of the silos provided the critical loading values and a measure of the state of quality of the structure.

Failure Probability

Using this information, basic event probabilities were developed for three primary processes leading to the continued degradation of the structure. These three processes are: 1) weathering and wear, 2) reinforcing steel corrosion, and 3) loss of concrete quality from spalling, breaking, and thinning. The rate of continued degradation of the silo dome structure was estimated using an exponential distribution. The probabilities of failure calculated from the basic event contributors is summarized in Table 1. These probabilities were then used to determine the total failure probability of the silo, also listed in Table 1. The probability per year of dome failure, due to natural degradation, was calculated to be 0.03622 for silo 1 and 0.0337 for silo 2. The probability of failure over the next five years (five year life time was assumed for this analysis) also due to natural degradation was calculated to be 0.1811 and 0.1685 for silos 1 and 2 respectively.

Tornado Effect And Probability

The next phase of the study evaluated the effect and contribution from an external event. In this case the external event considered was the occurrence of a tornado. The probability of a tornado as an initiating event was calculated and a specific risk factor was determined (based on intensity classes and wind speeds). The risk factor associated with the tornado is developed with the assumption that a single external tornado event will occur in the life of the silo (5 years was assumed). These probabilities are presented in Table 2 which lists the various probabilities by category. The failure of the structure was considered imminent for those events with wind speeds of 112 mph and greater. The range of wind speeds considered corresponds to intensity levels of F1 and greater (for detailed information on the intensity scale see Section 2.2 of the main report).

TABLE 1: BASIC EVENT CONTRIBUTORS TO DOME FAILURE

Designator	Event Description	Probability per year	
		SILO 1	SILO 2
C5e	Weathering and Wear	0.007622	0.007548
D8e	Concrete Degradation	0.014874	0.014134
D9e	Mesh Support Loss	0.013616	0.011914
D6e	Spalling Around Accessways	0.007622	0.007548
D7e	Cracking Around Accessways	0.014874	0.014134
Dome Failure Probability (DF)	Total Probability From All Basic Event Contributors	0.03622 /yr 0.1811 for 5 yrs	0.03370 /yr 0.1685 for 5 yrs

Table 2: Summary Of Probabilities Associated With The K-65 Silos

I. Silo Dome Failure Probability

A. Probability Of Failure Due To Natural Degradation

Silo 1	Silo 2	Average	
0.0361	0.0336	0.0348	per year
0.1804	0.1677	0.1741	over 5 years

B. Probability Of Failure Due To Natural Degradation Including Tornado As An External Event

Silo 1	Silo 2	Average	
0.0365	0.0339	0.0352	per year
0.1825	0.1695	0.176	over 5 years

II. Tornado Occurrence Probability (per Square Mile)

a.)

Total	per year	over 5 years
1.186 E - 3	1.248 E - 4	6.24 E - 4

b.) Probability as a function of intensity level

Intensity		
F0	1.91 E - 6	9.55 E - 6
F1	3.65 E - 5	1.83 E - 4
F2	2.83 E - 5	1.42 E - 4
F3	1.95 E - 5	9.75 E - 5
F4	1.22 E - 5	6.10 E - 5
F5	2.63 E - 5	1.32 E - 4

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Table 2: Summary Of Probabilities Associated With The K-65 Silos (continued)

III. Probability And Risk From Wind Speed Given A Single Tornado Event In A Five Year Period

wind velocity (x, mph)	probability L(x) = 1 - F(x)	risk factor r (x)
112	2.5 E - 1	3.7 E - 1
135	1.75 E - 2	4.13 E - 2
185	3.34 E - 3	5.78 E - 4
230	2.78 E - 6	6.13 E - 6
290	2.43 E - 7	7.35 E - 8

Radionuclide Inventory

The source term is the quantity of radioactive material which is available for dispersion in the environment. Several factors are important in determining the source term. These are principally; 1) the total inventory of all radionuclides contained in the waste, 2) the failure mode considered, and 3) the internal and external forces acting on the waste material in the silos.

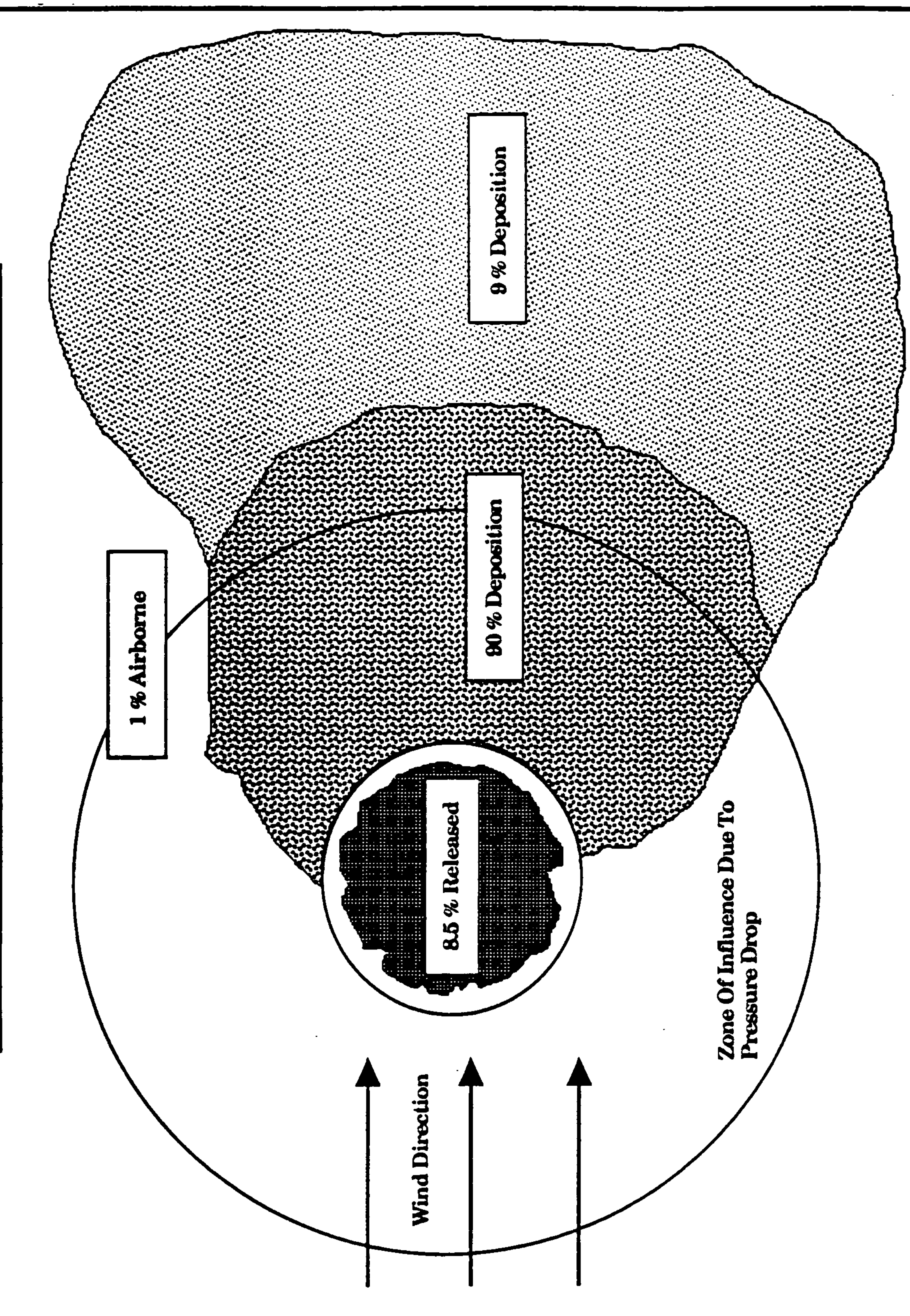
The total inventory of all the radionuclides contained in the silos is the most significant factor in determining the quantity of material that could be released to the environment. This data is typically the most difficult to obtain. After reviewing the data the best estimate for the radionuclide inventory showed the following results for silos 1 and 2 contents; 1) the radium-226 inventory is 3,300 curies (375 nCi/gr), 2) the thorium-230 inventory is 1,810 curies (265 nCi/gr), 3) the total uranium activity of 7 curies (0.41 nCi/gr for U-234 and U-238, and 0.02 nCi/gr for U -235), and 4) the total quantity of radon, available for release, is separated into 50 curies, for an acute release, and 650 curies diffusing continuously from the silos each year.

A number of silo dome failure scenarios were examined in order to realistically and accurately determine the actual quantity of material that would be dispersed in a severe weather (tornado) event. The final model for the silo failure and the resulting dispersion of radioactive contaminants considers a maximum release of a volume of residue material 1 meter in depth and 80 feet in diameter. This waste mass corresponds to approximately 8.5% of the total residue contained in both silos. The distribution in the environment was assumed to result in a large quantity of waste material being deposited within a short distance from the release point followed by a small amount being transported by the wind. The breakdown was assessed as 90% of the material released would be deposited within 300 feet of the silos. Approximately 9% would be deposited within 2,500 feet, and the remaining 1% of the waste material would be of sufficient size to be dispersed by the strong winds associated with the tornado event. Table 3 shows the quantity of each radionuclide by failure mode and by the specific transport mode (ground deposition or atmospheric dispersion). Figure 1 was included to illustrate the quantity of residue material available for release and the assumed distribution.

Table 3: Source Term Released Relative To Failuire Mode

Failure Mode	Source Term (Curies) Airborne	Ground Deposition (100 - 300 ft.)	Ground Deposition (300 - 2500 ft.)
Acute			
uranium (238, 234)	5.96 E-3	0.536	0.0536
uranium (235)	7.3 E-5	6.5 E-3	6.8 E-4
thorium-230	1.54	138.6	13.86
radium-226	2.81	252.9	25.29
radon-222	50.0	-	-
Chronic			
radon-222	650.0		

Figure 1: Magnitude And Distribution Of The Source Term



Exposure And Dose Assessment

The source term and the release mode were then used to assess the potential exposure of the public and an individual of the work force at the FMPC site. The exposure assessment process is composed of three parts: 1) the characterization of the exposure setting, 2) the identification of the exposure pathways, and 3) the determination of the exposure point doses. The characterization of the exposure setting consisted of identifying the physical characteristics of the region around the FMPC site as well as in the immediate vicinity of the K-65 silos. The identification of the significant exposure pathways and the determination of the exposure point doses required modeling of the transport of the contaminants in the environment.

The environmental transport of radionuclides (on the ground and in the air) was evaluated using standard models. AIRDOS-EPA, a Gaussian Plume model for atmospheric dispersion, was used as the principal model for determining the concentration of radionuclides in the air. The exposure point concentrations were estimated using the AIRDOS-EPA code. Table 4 lists the the exposure point concentrations calculated in this study.

The exposure pathways considered in this study were determined in part by the concentrations of contaminants in the environment. Pathways made up principally of ingestion were omitted due to the small concentrations and long time frames required. The final exposure pathways examined are made up of basically two categories: 1) external radiation doses from immersion in air and a volume source from the ground surface and 2) internal dose from inhalation of contaminated air and dust. The resultant doses at the exposure points considered are provided in the Tables 5, 6, and 7. These tables list the total doses for each release mode. The release modes depicted are separated into two acute cases, A1 and A2, and the case of chronic radon emission. Acute release A1 corresponds to the complete removal of the dome structure and the subsequent distribution of 8.5% of the total waste mass and the 50 curies of radon in the free space of the silo. Acute case A2 corresponds to the failure of the silo dome structure in a manner which will permit only the release of the radon gas (50 curies). The chronic release mode corresponds to the continuous emission of radon (approximately 650 curies of per year).

Table 5: Total Doses at each Exposure Point for the Acute Case A1

Exposure Point	Radionuclides	Dose (rem - 1 year)
Work Force (100 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**3.1×10^{1}**
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**1.5**
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**1.3×10^{-3}**

Table 6: Doses at each Exposure Point for the Acute Case A2

Exposure Point	Radionuclide	Dose (rem)
Work Force (100 meter Distance)		
Total Dose (CEDE)	Rn-222	**2.8**
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	Rn-222	**0.13**
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	Rn-222	**2.3×10^{-4}**

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Table 7: Exposure Point Doses for the Chronic Case - Radon-222 Release

Exposure Point	Dose (rem/yr)
Work Force (100 meter Distance) (CEDE)	2.57
Nearest Resident (500 meter Distance) (CEDE)	0.21
Population (14,500 meter Distance) (CEDE)	1.2×10^{-3}

Risk Characterization

The approach to this risk assessment involved both a probabilistic risk assessment methodology and a conventional Superfund based risk assessment methodology. The objective of the investigation was to quantify the risks for the baseline case and also to quantity the risks associated with the most probable cases of silo failure. In characterizing the risks for the cases of silo failure, probabilistic risk estimates were calculated as well as risk estimates for the more conventional approach which determines risk based on conditional estimates given a considerable number of assumptions about the source terms and exposure scenarios.

More specifically, risks were determined for two separate cases of silo failure: 1) the acute failure of the K-65 silos 1 and 2 due to a severe weather event (Acute Case A1) and 2) the acute failure of the K-65 silos 1 and 2 resulting from the continued structural deterioration leading to the total release of radon-222 (Acute Case A2). Risks were also determined for the baseline case of chronic radon emission. Risks were determined for the three Reasonable Maximum Exposure points for each case of silo failure and the chronic radon emission case. Two separate risk characterization methodologies were utilized in the determination of the risks for each case of silo failure and the chronic case as well. The first risk methodology analyzed was termed the risk coefficient method (RC) and was based on the effective dose equivalent risk factor of 2×10^{-4} risk per rem of exposure. The second risk method investigated was the Environmental Protection Agency's carcinogenic slope factor approach for radionuclides. Radionuclide slope factors are characterized as best estimates (maximum likelihood estimates) of the age-averaged total lifetime excess cancer incidence per unit intake or exposure.

Table 8 lists the risks determined for the acute case A1 based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 3×10^{-3} is shown in Table 8 for an individual of the work force. This means that under the exposure assumptions of the acute A1 case an individual of the work force has 3 chances in 1000 of developing cancer in his or her lifetime. Similarly a resident under the exposure assumptions of the acute A1 case has 1.4 chances in 10,000 of developing a cancer in his or her lifetime.

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Table 8: Total Risks Determined for the Acute Case A1 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	3.0×10^{-3}
Resident	1.4×10^{-4}
Population	3.0×10^{-8}

Table 9 lists the risks determined for the acute case A2 based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 2×10^{-5} is shown in Table 9 for an individual of the work force. This means that under the exposure assumptions of the acute A2 case an individual of the work force has 2 chances in 100,000 of developing cancer in his or her lifetime. Similarly, a resident under the exposure assumptions of the acute A2 case has 9.2 chances in 10 million or roughly 1 chance in 1 million of developing a cancer in his or her lifetime.

Table 9: Total Risks Determined for the Acute Case A2 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	2.0×10^{-5}
Resident	9.2×10^{-7}
Population	1.6×10^{-9}

Finally, Table 10 lists the risks determined for the chronic radon case based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 9.1×10^{-5} is shown in Table 10 for an individual of the work force. This means that under the exposure assumptions of the chronic radon-222 case an individual of the work force has 9.1 chances in 100,000 of developing cancer in his or her lifetime. Similarly, a resident under the exposure assumptions of the chronic radon case has 7.6 chances in 10 million of developing a cancer in his or her lifetime.

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Table 10: Total Risks Determined for the Chronic Radon Case Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	9.1×10^{-5}
Resident	7.6×10^{-7}
Population	4.1×10^{-8}

1.0 Introduction

The Feed Materials Production Center (FMPC) is a contractor-operated federal facility whose principal objective has been for the production of pure uranium metals for the U.S. Department of Energy (DOE). The FMPC site is located in the vicinity of the unincorporated village of Fernald, Ohio on a 1,050 acre site in a rural area about 20 miles northwest of downtown Cincinnati, Ohio. Several population centers, Ross, New Haven, and Shandon, are within several miles of the FMPC site. The production area of the FMPC site is near the center of the 1,050 acre site and occupies approximately 136 acres. The K-65 silos 1 and 2 are located on the west side of the FMPC site adjacent to Paddy's Run Creek.

The purpose of conducting this risk assessment for the K-65 silos 1 and 2 was to quantitatively estimate the risks for the baseline case of chronic radon emission and also to estimate the risks associated with most probable cases of silo failure. In characterizing the risks for the cases of silo failure, probabilistic risk estimates were calculated as well as risk estimates for the more conventional approach which determines risk based on conditional estimates given a considerable number of assumptions about the source terms and exposure scenarios.

The characterization of the failure probabilities of silos 1 and 2 was accomplished through two tasks: 1) evaluation of each silo's structure and 2) determination of their failure potentials. Two separate cases of silo failure were developed: 1) the acute case A1, which is described as a catastrophic failure of the silo resulting in the release of significant quantities of waste material and 2) the acute case A2, which is described as silo failure resulting in only the total release of radon-222 from the silo's headspace. The catastrophic failure of the silos from the acute case A1 would be caused by a severe weather event. While the acute case A2 silo failure would be caused by the continued deterioration of the silo's structure.

Risks were determined for two separate cases of silo failure: 1) the acute failure of the K-65 silos 1 and 2 due to a severe weather event (Acute Case A1) and 2) the acute failure of the K-65 silos 1 and 2 resulting from the continued structural deterioration leading to the total release of radon-222 (Acute Case A2). Risks were also determined for the baseline case of chronic radon emission. Risks were determined for three Reasonable Maximum Exposure points for each case of silo failure and the chronic radon emission case. Two separate risk characterization methodologies

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1.0 Introduction (continued)

were utilized in the determination of the risks for each case of silo failure and the chronic case as well. The first risk methodology analyzed was termed the risk coefficient method (RC) and was based on the effective dose equivalent risk factor of 2×10^{-4} risk per rem of exposure. The second risk method investigated was the Environmental Protection Agency's carcinogenic slope factor approach for radionuclides. Radionuclide slope factors are characterized as best estimates (maximum likelihood estimates) of the age-averaged total lifetime excess cancer incidence per unit intake or exposure. Figure 1 illustrates the current Environmental Protection Agency's guidance on the methodology of conducting a baseline risk assessment.

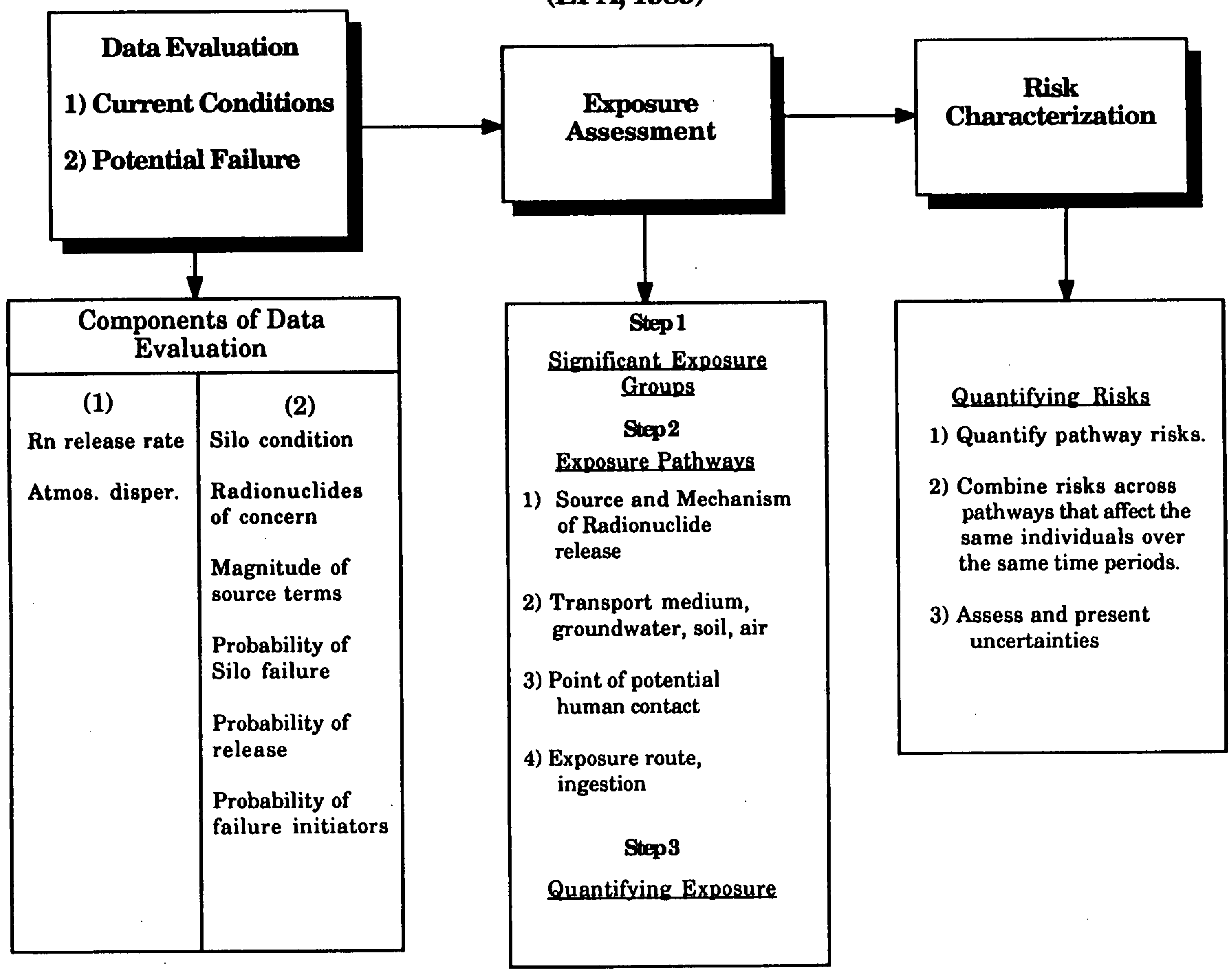
1.1 Data Evaluation

The first phases of a risk assessment include the evaluation of the available data. In this facet the two risk methodologies, risk of silo failure and lifetime cancer risk to humans given the silo failure, are essentially the same. The primary difference is in the degree of evaluation. For this study the data was analyzed as thoroughly as possible using both qualitative and quantitative methods. The risk assessment analysis essentially moved from the silo structures outward. The steps of the assessment were the following: 1) evaluation of the silo structures, 2) determination of the failure potential, 3) estimation of the source term released given the failure case, 4) prediction of the contaminant transport in the environment, 5) assessment of the exposure and doses to the maximum reasonable exposure points, and 6) calculation of the resulting health risks to an individual of each exposure point.

Structural Integrity of Silos 1 & 2

The structural integrity of the silos was considered to be sufficiently degraded that the potential for a large scale release is significant. Structural analysis performed on the silos, using both destructive and non-destructive examination methods, provided ample data with which to construct failure probabilities. Detailed evaluation of the results of these previous studies provided the basis for the probability calculations. Testing of the silos provided the critical loading values and a measure of the state of quality of the structure.

Figure 1: Baseline Risk Assessment (EPA, 1989)



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1.1 Data Evaluation (continued)

Failure Probabilities of Silos 1 & 2

Using the information from the structural integrity analysis, basic event probabilities were developed for three primary processes leading to the continued degradation of the structure. These three processes are: 1) weathering and wear, 2) reinforcing steel corrosion, and 3) loss of concrete quality from spalling, breaking, and thinning. The rate of continued degradation of the silo dome structure was estimated using an exponential distribution function. The probabilities of failure calculated from the basic event contributors are summarized in Table 1.0. These probabilities were then used to determine the total failure probability of the silo, also listed in Table 1.0. The probability per year of dome failure, due to natural degradation, was calculated to be 0.036 for silo 1 and 0.034 for silo 2. The probability of failure over the next five years (five year lifetime was assumed for this analysis) also due to natural degradation was calculated to be 0.18 and 0.17 for silos 1 and 2, respectively.

Tornado Effect and Probability

The next phase of the study evaluated the effect and contribution from an external event. In this case the external event considered was the occurrence of a tornado. The probability of a tornado as an initiating event was calculated and a specific risk factor was determined (based on intensity classes and wind speeds). The risk factor associated with the tornado is developed with the assumption that a single external tornado event will occur in the life of the silo (5 years was assumed). These probabilities are presented in Table 2 which lists the various probabilities by category. The failure of the structure was considered imminent for those events with wind speeds of 112 mph and greater. The range of wind speeds considered corresponds to intensity levels of F1 and greater (for detailed information on the intensity scale see Section 2.2 of the main report).

Radionuclide Inventory

Once the structural integrity and failure probabilities were calculated the source term had to be considered. The source term is that quantity of radioactive material which is available for dispersion in the environment. Several factors are important in determining the source term. These are principally; 1) the total inventory of all radionuclides contained in the waste, 2) the failure mode considered, and 3) the internal and external forces acting on the waste material in the silos.

TABLE 1: BASIC EVENT CONTRIBUTORS AND TOTAL DOME FAILURE PROBABILITY

Designator	Event Description	Probability per year	
		SILO 1	SILO 2
C5e	Weathering and Wear	0.007622	0.007548
D8e	Concrete Degradation	0.014874	0.014134
D9e	Mesh Support Loss	0.013616	0.011914
D6e	Spalling Around Accessways	0.007622	0.007548
D7e	Cracking Around Accessways	0.014874	0.014134
Dome Failure Probability (DF)	Total Probability From All Basic Event Contributors	0.03622 /yr 0.1811 for 5 yrs	0.03370 /yr 0.1685 for 5 yrs

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Table 2: Summary Of Probabilities Associated With The K-65 Silos

I. Silo Dome Failure Probability

A. Probability Of Failure Due To Natural Degradation

Silo 1	Silo 2	Average	
0.0361	0.0336	0.0348	per year
0.1804	0.1677	0.1741	over 5 years

B. Probability Of Failure Due To Natural Degradation Including Tornado As An External Event

Silo 1	Silo 2	Average	
0.0365	0.0339	0.0352	per year
0.1825	0.1695	0.176	over 5 years

II. Tornado Occurrence Probability (per Square Mile)

a.)

Total	per year	over 5 years
1.186 E - 3	1.248 E - 4	6.24 E - 4

b.) **Probability as a function of intensity level**

Intensity		
F0	1.91 E - 6	9.55 E - 6
F1	3.65 E - 5	1.83 E - 4
F2	2.83 E - 5	1.42 E - 4
F3	1.95 E - 5	9.75 E - 5
F4	1.22 E - 5	6.10 E - 5
F5	2.63 E - 5	1.32 E - 4

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Table 2: Summary Of Probabilities Associated With The K-65 Silos (continued)

III. Probability And Risk From Wind Speed Given A Single Tornado Event In A Five Year Period

wind velocity (x, mph)	probability $L(x) = 1 - F(x)$	risk factor r (x)
112	2.5 E - 1	3.7 E - 1
135	1.75 E - 2	4.13 E - 2
185	3.34 E - 3	5.78 E - 4
230	2.78 E - 6	6.13 E - 6
290	2.43 E - 7	7.35 E - 8

1.1 Data Evaluation (continued)

Radionuclide Inventory (continued)

The total inventory of all the radionuclides contained in the silos is the most significant factor in determining the quantity of material that could be released to the environment. These data are typically the most difficult to obtain. After reviewing the data the best estimate for the radionuclide inventory showed the following results for the contents of silos 1 and 2: 1) the radium-226 with inventory of 3,300 curies (375 nCi/gr), 2) the thorium-230 with inventory of 1,810 curies (265 nCi/gr), 3) the total uranium activity of 7 curies (0.41 nCi/gr for U-234 and U-238, and 0.02 nCi/gr for U -235), and 4) the total quantity of radon, available for release, is separated into 50 curies for an acute release and 650 curies diffusing continuously from the silos each year.

A number of silo dome failure scenarios were examined in order to realistically and accurately determine the actual quantity of material that would be dispersed in a severe weather (tornado) event. The final model for the silo failure and the resulting dispersion of radioactive contaminants considers a maximum release of a volume of residue material 1 meter in depth and 80 feet in diameter. This waste mass corresponds to approximately 8.5% of the total residue contained in both silos. The distribution of this material in the environment was assumed to result in a large quantity of waste material being deposited within a short distance from the release point followed by a small amount being transported by the wind. The breakdown was assessed as 90% of the material released would be deposited with 300 feet of the silos. Approximately 9% would be deposited within 2,500 feet, and the remaining 1% of the waste material would be of sufficient size to be dispersed by the strong winds associated with the tornado event. Table 3 shows the quantity of each radionuclide by failure mode and by the specific transport mode (ground deposition or atmospheric dispersion). Figure 2 was included to illustrate the quantity of residue material available for release and the assumed distribution.

1.2 Exposure Assessment

The exposure assessment process is composed of three parts: 1) the characterization of the exposure setting, 2) identification of the exposure pathways, and 3) the determination of the exposure point doses. The characterization of the exposure setting consisted of identifying the physical characteristics of the region around the FMPC site as well as the immediate vicinity of the K-65 silos. The identification of the significant exposure pathways and the determination of the exposure point doses requires modeling of the transport of the contaminants in the environment. Figure 3 illustrates the components of the exposure assessment process.

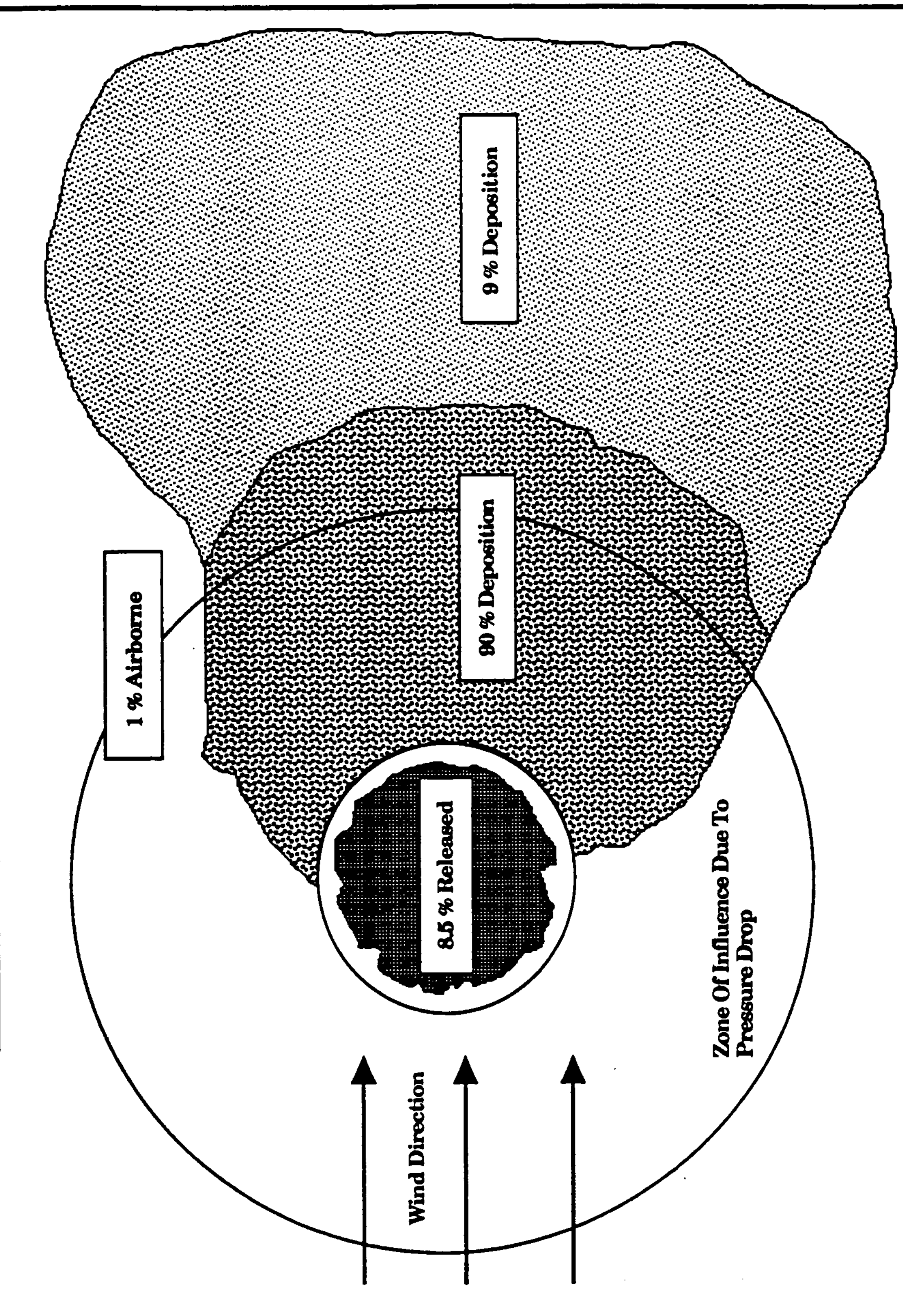

Figure 2: Magnitude And Distribution Of The Source Term

Table 3: Source Term Released Relative To Failuire Mode

Failure Mode	Source Term (Curies) Airborne	Ground Deposition (100 - 300 ft.)	Ground Deposition (300 - 2500 ft.)
Acute			
uranium (238, 234)	5.96 E-3	0.536	0.0536
uranium (235)	7.3 E-5	6.5 E-3	6.8 E-4
thorium-230	1.54	138.6	13.86
radium-226	2.81	252.9	25.29
radon-222	50.0	-	-
Chronic			
radon-222	650.0		

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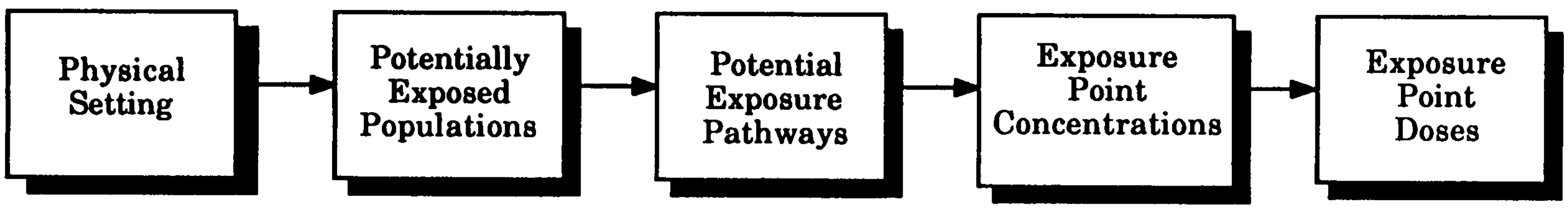
Figure 3: Components of the Exposure Assessment Process



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1.2 Exposure Assessment (continued)

Physical Setting of Silos

The K-65 silos 1 and 2 are located on the west side of the FMPC site adjacent to Paddy's Run Creek. The silos are used for the storage of radium bearing residues, a by-product of uranium ore processing. The silos are cylindrical concrete structures with a diameter of 80 feet and a height of approximately 27 feet. The silos were designed to be loaded with the metal oxides in slurry form at a maximum rate of 8000 gallons per day. The residues were allowed to settle and the water was decanted, leaving a sludge with a density of 100 pounds per cubic foot. The solid material was allowed to reach a maximum height of 23 feet.

The area surrounding the K-65 silos is primarily a rural environment. Monitoring locations were selected around the FMPC site to characterize radon concentrations and potential exposures to humans. These monitoring locations consist of the FMPC site boundaries, two schools, a local business, and two residences. These locations will serve to support the calculation of dose to the maximum exposed individual and population dose. The nearest offsite resident, in the most prominent wind direction, is 1.3 kilometers. The nearest offsite resident is 500 meters away.

For this investigation, the characterization of the physical setting around the silos primarily involves being able to predict, as a function of time and distance, the ultimate fate and distribution of the materials in the K-65 silos as a result of an accident or the continued degradation of the silos leading to the excessive release of radon. In order to perform the exposure assessment, three significant exposure points were assumed. These three exposure points represent the potentially exposed populations should a release occur from the silos.

The first significant exposure point assumed is an occupational work shift at the FMPC. This work force is assumed to be within 100 meters of the silos when the accident occurs. The second potential exposure point is the nearest resident. This person is located a distance of 500 meters from the site. The final potential exposure point is a small population, assumed to be located approximately 14.5 kilometers away.

1.2 Exposure Assessment (continued)

Identification of Potentially Exposed Populations

The identification of potentially exposed populations consists of: 1) occupational workers, 2) nearest resident, and 3) population center. The nearest resident is 500 meters away and a population center is approximately 14 kilometers from the site. This analysis focused on an individual, identified as the reasonable maximum exposure point, at each exposure location.

Identification of Exposure Pathways

The principal objective of this task is to identify those pathways by which the identified populations may be exposed. Each exposure pathway describes a mechanism by which a population (or individual) may be exposed to the contaminants originating from the silos. These exposure pathways were identified based on the consideration of the sources and mechanisms of release of the radionuclides; the most likely environmental transport route; and the location and activities of the potentially exposed populations.

An exposure pathway consists of four elements: 1) source and mechanism of radionuclide release, 2) retention or transport medium, 3) point of potential human contact with the contaminated medium (referred to as an exposure point), and 4) an exposure route (for example, inhalation) at the contact point. Table 4.0 illustrates the pathway analysis methodology.

Table 4.0: Pathway Analysis Methodology for the Acute and Chronic Cases

<u>Acute Case - Catastrophic Release (A1)</u>

Radionuclides Released:	Uranium-238, Uranium-234, Thorium-230, Radium-226, and Radon-222.
Pathways Analyzed:	Inhalation of gaseous plume (1 hour exposure). Inhalation of resuspended dust. External Exposure from radionuclides.
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

<u>Acute Case - Total Release of Radon (A2)</u>

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon plume (1 hour).
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

<u>Chronic Case - Daily Release of Radon-222</u>

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon-222
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

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1.2 Exposure Assessment (continued)

Calculation of Exposure Point Concentrations

The calculation of exposure point concentrations is dependent upon the source term available for release given either a severe weather event or the continued degradation of the silos leading to the eventual release. A number of assumptions were made in developing the source term, such as the quantity of material available for resuspension versus the quantity of material which falls out within several hundred feet of the silos. Calculations were performed using AIRDOS-EPA to determine exposure point concentrations at varying distances from the silos. These concentrations (curies per cubic meter) were then used to calculate each exposure point dose.

Calculation of Exposure Point Doses

Exposure point doses will be determined for the most significant exposure points: 1) occupational workers, 2) nearest resident, and 3) an individual of a population. Exposure point doses will be determined for three pathways of exposure: 1) an external radiation dose, 2) inhalation dose by atmospheric dispersion, and 3) inhalation dose based on resuspended dust. Exposure point doses will be determined by multiplying the results of the environmental transport calculations discussed above (calculation of exposure point concentrations) by the appropriate dose conversion factors (units of mrem per microcurie) and an inhalation rate (units of cubic meters). This will result in a dose (mrem converted to rem) for each exposure point.

1.3 Risk Characterization

This section of the investigation deals with the final step of the baseline health risk assessment process, the risk characterization phase. In this step the exposure assessments are summarized and integrated into quantitative and qualitative expressions of risk. In the following sections the risk characterization methodology is developed for each exposure point from the perspective of the acute case and the chronic case. The acute case has two subcategories which are either the catastrophic release of the silos contents from natural forces, such as a tornado, or a total release of radon resulting from the ultimate failure of the silos due to their continued structural degradation.

1.3 Risk Characterization (continued)

In the preceding draft report, "A Baseline Risk Assessment for the K-65 Silos Using EPA Methodology for Applicability to the EE/CA," the risk characterization step was performed by multiplying the ICRP risk coefficient, 2 x 10^{-4} risk per rem of exposure, by each of the particular exposure point doses in order to determine annual risks. These risks were then coupled with the probabilities associated with the two classes of failure modes which are severe weather conditions and natural degradation of the concrete structure in order to quantify the annual risks.

The following investigation presents a revision of the risk characterization methodology detailed in the draft report. Also contained in the following analysis is a risk characterization using the newly acquired Environmental Protection Agency's methodology for determining risks from radionuclides. The Office of Radiation Programs (ORP) has recently issued these radionuclide carcinogenic slope factors for the purpose of conducting health risk assessments. The "Slope Factors" were obtained directly from ORP in the form of the Health Effects Assessment Summary Table C (HEAST Table C). The methodology presented in this report for using these slope factors is contained in Chapter 10 of the Human Health Evaluation Manual (EPA, 1989) which details the EPA method for performing radiation risk assessments . Table 4.0 presented a summary of the pathway analysis methodology for the acute and chronic cases. Table 5 presents a summary of the risk characterization methodologies.

The risk characterization methodologies outlined in Table 5 are based on the effective dose equivalent risk coefficient and the EPA lifetime, age-averaged slope factors. The risk coefficient method expresses the risk as an annual risk. The annual risk can be multiplied by 70 years to give the lifetime risk. Slope factors were derived to represent the lifetime risk. Both methodologies will be presented in this investigation in order to compare the results from the draft study with the results obtained by using the updated risk information obtained from the Environmental Protection Agency.

Table 5: Risk Characterization Methodologies

Release Case	Risk Coefficient Methods	Slope Factor Methods
Acute Catastrophic Release (A1)	$\sum_p EDE_{ipq} \times RC \times P_{A1}$	$\sum_p EL_{ipq} \times SF_{ip} \times P_{A1}$
	$\sum_p EDE_{ipq} \times RC$	$\sum_p EL_{ipq} \times SF_{ip}$
Acute Total Rn-222 Release (A2)	$EDE_{ipq} \times RC \times P_{A2}$	$EL_{ipq} \times SF_{ip} \times P_{A2}$
	$EDE_{ipq} \times RC$	$EL_{ipq} \times SF_{ip}$
Chronic Rn-222 Release	$EDE_{ipq} \times RC$	$EL_{ipq} \times SF_{ip}$

Where the terms of Table 5 are defined as follows:

EDE_{ip} = Effective Dose Equivalent for pathway p, exposure point q, and radionuclide i (rem/year).

RC = Risk Coefficient, 2×10^{-4} risk per rem of exposure.

P_{A1} = Probability associated with the acute case of catastrophic release, designated by subscript A1.

EL_{ip} = Exposure Level for pathway p, exposure point q, and radionuclide i (pCi).

SF_{ip} = EPA Slope Factor for pathway p and radionuclide i with units of either $(pCi)^{-1}$ or $(pCi/m^2/yr)^{-1}$.

P_{A2} = Probability associated with the acute case of total radon release, designated by subscript A2.

2.0 Data Evaluation

This section of the report deals with the specific data used in this analysis and the general form and condition of the silos. The data evaluation section is also intended to provide the models used and the assumptions employed in the evaluation of the failure potential of the K-65 silos. The background information, concerning the silos and use, is provided here for completeness and continuity. Most of this information can be found in other reports describing the silos. Some of these additional reports were used as reference material in the preparation of this report and are cited in the reference section.

This section is divided into four parts. The first and second parts concern the silo structure with the first discussing the historical, present, and future conditions and the second dealing with the failure probabilities. Part three considers the probability of initiating events and part four provides the radionuclide inventory or source term including the release mechanism and magnitude. The majority of the available data is discussed and analyzed in this section. Some information dealing with the surrounding area and population distributions will be presented in the next section where the exposure assessment is considered.

To determine the structural condition of the silos and the probability of failure much of the analysis was dependent on the work of Camargo Associates Limited and Bechtel National Incorporated, whose reports addressed the structural integrity of the silos through both destructive and non-destructive testing techniques (Camargo, 1986) and (Bechtel, 1990). Additional data and information was supplied by WMCO and the U.S. National Oceanic and Atmospheric Administration (NOAA).

The non-destructive testing results, conducted for Camargo, provides the data that is used for the evaluation of the probability of dome failure due to natural conditions. It is important to note that significant discrepancies were found in these results. Test locations for the non-destructive testing procedures do not correspond to initial design specifications. The validity of this analysis is determined in part by the availability, quality, and accuracy of the information supplied to the University of Cincinnati.

2.1 Silo Structure

The K-65 silos are essentially large concrete waste containers. The design and use of these structures was for temporary storage of radium bearing residues remaining from uranium ore processing. The waste containment structures, silos 1 and 2, are located at the west side of the FMPC site. These silos were constructed in 1952 and have been used since then as storage facilities for the radium bearing residues from pitchblende processing. The silos are cylindrical in construction with an internal diameter of 80 feet. The corresponding cylindrical height of these silos is approximately 27 feet. A concrete dome rises to just over 9 feet above the top wall line; the thickness of the dome is 4 inches at the center and tapers to 8 inches at the wall/dome intersection.

Remedial Actions

By 1963 the exterior surface of the silos had suffered major deterioration. Large areas of the concrete walls have degraded which has lead to the exposure of the post-tensioning wires. Subsequently, patches of the wires have become severely corroded and eventually broke. Repairs to the damaged surface began in 1964, at which time a waterproof sealant was applied to the external walls. In addition, an earthen embankment was built to the top of the walls. This embankment was intended to provide an external force to counteract the internal pressure applied to the wall from the waste mass. In addition, the embankment was expected to significantly reduce radon emission. The recommendations of subsequent structural investigations, have resulted in the construction of a temporary steel and wood dome, with a 20 foot radius, to be placed on top of the existing domes. In addition, a neoprene membrane was applied over the outside of the dome to minimize radon emanation and to prevent water seepage into the silo dome cracks. Table 2.1 delineates the chronology of the construction and use, the various modifications, and major studies made on the silo structures.

Table 2.1 illustrates the various changes that have occurred to the silo from the beginning of the construction to the present. The physical processes acting on the silo have not remained constant over the life of the structure due in part to these modifications and adjustments. The addition of gunite to the exterior walls in 1963 and the earthen berm in 1964 Would have considerably reduced the wear and tear on the silos. Since no significant testing or analysis was performed during this time frame, in order to quantitatively evaluate the structural integrity, the results of the Camargo and Bechtel studies are assumed to apply to the overall life of the silos. The total age of the silos is essentially 38 years, however, since the silos were filled to capacity by 1958, the berm was added by 1964, and the Camargo study was completed by 1986 another estimate of the age of the structures for evaluating the probability of dome failure was taken to be 28 years. Both of these estimates of the life of the structure are considered in the evaluation of the potential for failure due to natural processes.

Table 2.1 K-65 Chronology Of Events

Date	Milestone or Event
1951	Construction begins
1952	Construction complete
1958	Silos filled to capacity
1963	Repairs made to the silos
1964	Earthen berm added
1979	Vents sealed
1983	Embankments enlarged
1985	Camargo non-destructive tests
1986	Protective covers added to center 20 ft.
1986	Waterproof membranes added to dome top
1987	Foam coating applied to domes
1989	DOE inspections
1989	Bechtel performs further analysis

Current Conditions

A complete structural analysis of the K-65 silos was conducted, under contract of the Westinghouse Material Company of Ohio, by Camargo Associates, Limited in 1985 and by Bechtel National Inc. in 1989. The purpose of these analyses was to determine the structural stability of the silos and to identify any potential structural problem that would require remedial action. The conclusions of the Camargo study have a direct bearing upon this present analysis; the non-destructive testing results will be used to quantify the possible mechanisms of failure.

The major conclusions of the Camargo analysis are:

1. Major portions of the domes are capable of supporting their weight plus a live load of 20 (psf). The center portion of each dome is critical for any loads. There is a general thinning of the concrete domes with sharp undulations of the interior surface. Associated with the thinned dome sections are large cracks; the interior surface exhibits various stages of deterioration. The silo dome thickness and general quality deteriorates progressively moving from the dome/wall intersect to the dome top.

2. The walls are believed to be stable as the material and berm are counteracting. The silo wall thickness, concrete quality and remaining percentage of horizontal preload wires have deteriorated progressively moving from wall top to bottom.

Current Conditions (continued)

3. The base slab (floor) was not fully investigated due to the embankment. The condition of the base slab is thought to be similar to that of the walls.

4. The walls and the base slab are considered acceptable from a structural standpoint; Camargo quotes a maximum life expectancy of between 5 to 10 years. The domes are considered to be structurally defective and are assessed to have no life expectancy.

Field Investigations

Pulse-echo techniques were used to determine concrete quality. These investigations were conducted by Muenow and Associates, Inc. on behalf of Camargo. This analysis provided quantitative results for:

1. Compressive stress of concrete.
2. Thickness of dome and walls.
3. Percentage of reinforcement remaining in dome and walls.

From this data, regions of substantial weakness can be identified. Percentage loss in compressive strength, thickness and, reinforcement will aid in substantiating failure probabilities. Initial conclusions from the analysis show that there is considerable spalling of the interior surface of the dome. There is no pattern to the thinning, however, there are significantly large areas of spalled concrete.

Considerable wall cracking and loss of post-tension wires is present in both silos. Maximum reduction in wall thickness is approximately 2 inches, however, the vast majority varies between 0.05 to 1.0 inches. A maximum of 25% of the horizontal reinforcement steel have been lost in specific areas.

Potential Failures

The modes of failure considered for this analysis cover two main initiators; 1) natural forces, specifically severe weather conditions (tornado) and 2) natural degradation of the concrete structure. These two areas were selected as they present the highest consequence in the event of failure. Relevant silo failure possibilities were developed and qualified in the status report, (February, 1990). Of the three substructures considered, (Wall, Floor slab, Dome), the silo domes present the highest probability of immediate failure and the highest risk related consequence. The wall and floor failure consequences, when compared to that for the dome, do not contribute significantly to risk. Hence only the fault tree for the dome has been evaluated at present to provide a quantitative value of risk. Information regarding the temporary dome structure is not available on which to evaluate a basic event contributor. In addition, due to the time and data limitations, some basic events have been restructured to present a simpler and more conservative evaluation.

2.2 Probability Of Failure

This section of the report considers the potential for failure of the silos to contain the radium bearing waste and the radon gas as originally intended. The potential for failure is increased by a number of different factors. These include events both internal and external to the structures themselves. The internal events are simply those corresponding to the structural integrity of the container to continue to support the static loads resulting from the mass of the waste material. The external events are considerably more difficult to quantify. These include the action of the natural environment on the structure, such as freezing, thawing, and erosion. Additional natural external events are not as evident or probable, these being seismic activities and severe weather. Seismic activity sufficient to cause structural damage is considered to be extremely remote (Camargo, 1986). The action of the wind, either from strong uniform gusts or from tornado type cyclonic turbulence is considerably more probable and devastating. This section of the risk assessment deals with the natural internal failure mode and the natural external failure mode namely tornados or severe weather.

Natural Internal Conditions

Due to the age and structural condition of the silos, it is possible that the integrity may be significantly reduced to an extent that the silos may no longer be capable of fulfilling their design intent of waste containment. These deterioration processes are time dependent and are assumed to be continuous. There are no evaluations of quality assurance during construction and hence it is not known if the design specifications were met. Therefore, the assumption was made that, at time the time of construction the silo domes were in a structurally perfect condition.

Natural Internal Conditions (continued)

Using the above assumptions and the results of the Non-Destructive Tests (NDT) performed by Muenow and Associates a model was developed to provide numerical values of the condition of the silos. The model developed was used to establish a quantitative basis for estimating the probability of dome failure due to natural degradation. A time dependent degradation rate has been developed assuming an exponential distribution function. This assumption is more accurate than using a linear model and hence compensates for the uncertainty involved with the structural stability at time of construction. Additionally, all modifications made after the Camargo report were not included in the degradation probability model. There is insufficient data available on the relationship between the current and future degradation rates. The models were developed considering only dead loads on the silo structure. Live loads such as wind, rain, or other external forces were not taken into account in the natural degradation process.

There are three primary events which are considered as the contributors to the loss of silo integrity by natural processes; these are:

1. Weathering and Wear.
2. Mesh Support Loss.
3. Concrete Quality.

These basic events are evaluated below, and produce an annual contribution to the probability of dome failure. The contribution of each of these basic events is depicted graphically in Figure 2.1. This figure shows the generalized fault tree representing the possible failure modes associated with the dome unit on the K-65 silos. The basic events are coded by letter and numeric formats. The letter represents the level at which the basic event acts and the numeral indicates the relative number of events on that specific level. The final letter in the designation indicates the type of event. The first basic event discussed is designated as C5e, where the 'C' indicates the third level of the tree, the '5' represents the fifth event, and 'e' designates the event as a basic event.

Basic Event C5e: Evaluation of Weathering and Wear

Determination of the wear of the concrete domes can be accomplished using the test values of concrete thickness. The Buckling Stability of the dome is the capacity of the dome to withstand the compressive loads without bending out of plane. Due to the general thinning of the dome, the structural integrity has been significantly reduced. The critical buckling evaluated by Camargo Associates is 284 (psf); this is valid for a thickness of 3 inches and greater. A critical buckling of 104 (psf) was similarly evaluated for concrete thickness of 2 inches.

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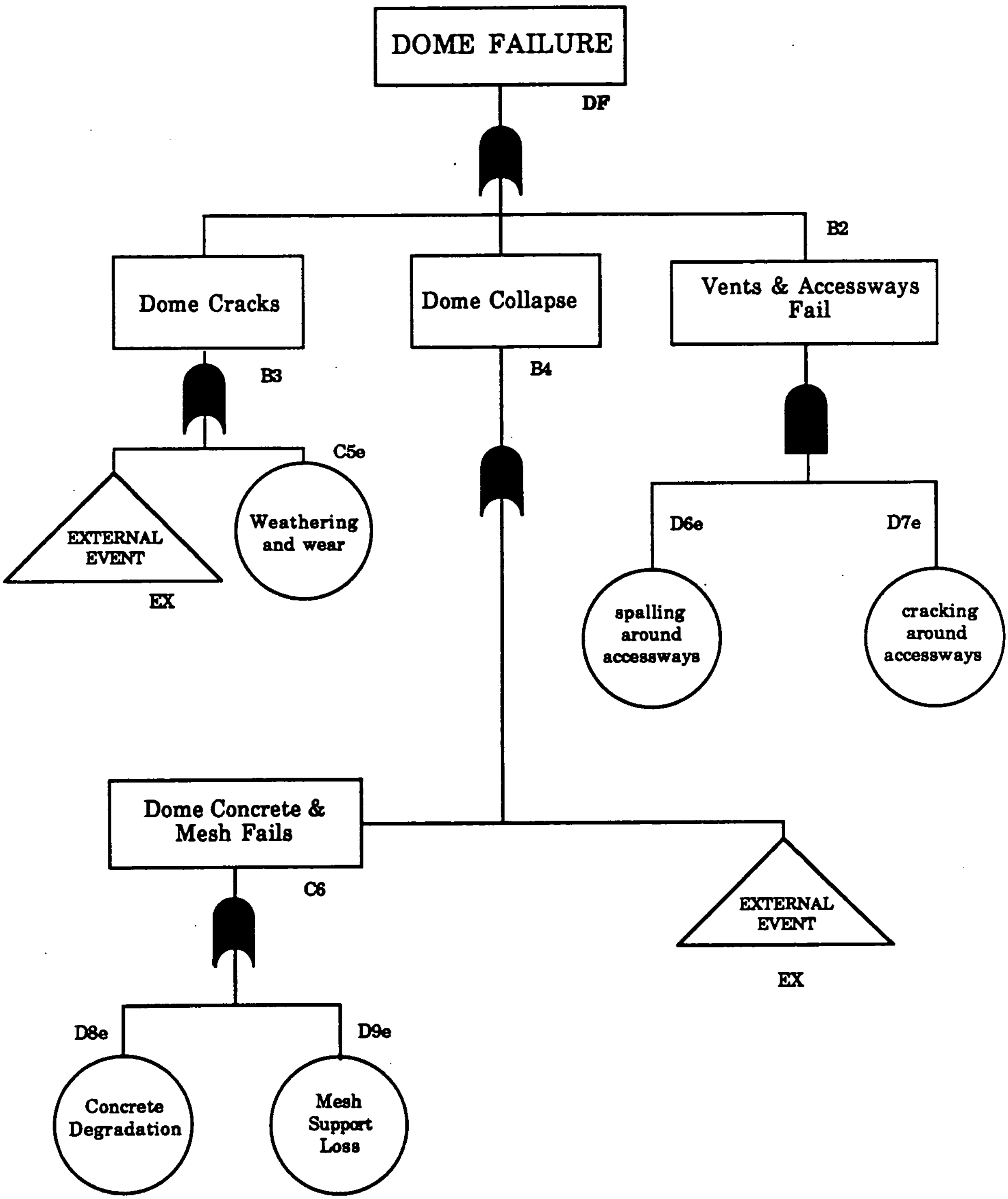
Figure 2.1: Fault Tree For Dome Failures



Basic Event C5e: Evaluation of Weathering and Wear (continued)

Using a linear relationship of critical buckling as a function of concrete thickness an extrapolated value of 1.42 inches is found to correspond to a buckling value of 0 (psf). Thus, 1.42 inches presents the lower threshold of integrity; hence any thinning resulting in a dome thickness of 1.42 inches, or less, is considered to lead to a loss of the concrete dome integrity.

The values used to compute the magnitude of thinning were taken from the testing regions towards the top of the dome (dome center) as these regions have been deemed by Camargo Associates to be critical. Areas close to the dome/wall intersection were not incorporated into the analysis as the exact testing coordinates were not provided, since it was impractical to attempt to evaluate the value of the original design specification thickness. In addition, the outer regions of the domes are not considered as critical as the inner 20-30 foot radius, thus to provide an accurate evaluation these values were omitted. From the remaining test locations, the average of the remaining concrete thicknesses for both silos were evaluated and are delineated for each silo in Table 2.2.

Table 2.2: Results Of Concrete Thinning Data

	Average Thickness Reduction (in)	Current Average Thickness (in) (1986 Camargo Report)
SILO 1	0.916	3.084
SILO 2	0.909	3.091

Assuming an exponential thinning rate of the concrete with time, and assuming that at time T=0 that the thickness was 4 inches (design specification), the thinning rates were calculated and are presented in Table 2.3. The thinning rates were developed initially for a 28 year life and were later modified using a 38 year life time. There is justification for using both of these time estimates, but since the effect of the weathering and wear processes are not fully known for the silo structure, and the various modifications, the decay rates for the 38 year life were used in the analysis. The method shown here for estimating the decay rates was based on the 28 year life.

Basic Event C5e: Evaluation of Weathering and Wear (continued)

Table 2.3: Exponential Thinning Rates (in/year)

SILO 1	$\lambda_1 = 9.29E\text{-}3$
SILO 2	$\lambda_2 = 9.21E\text{-}3$

Using these thinning rates it is possible, still using a exponential reduction rate, to predict the time taken for the dome thickness to reduce to the 1.42 inch threshold. The time to reach the critical thickness is presented for each silo in Table 2.4.

Table 2.4: Time to Reach Critical Thickness (years)

SILO 1	$T_1 = 111.48$
SILO 2	$T_2 = 112.45$

Using the fraction of functional time remaining and incorporating this value into a exponential probability density function so that the annual probability of failure, μ, can be evaluated by Equation 2.1 as follows:

$$\mu = \frac{\left[\ln\left(1 - \frac{t}{T}\right)\right]}{t} \qquad (2.1)$$

where:

t = Present age (28 and 38 years were used).
T = Time to critical thickness.
μ = Probability per year of loss of concrete thickness from weathering and wear.

Using the above relation an estimate of the basic event probability concerning the loss of structural integrity due to the thinning of the concrete in the silo dome. The estimates of the basic event C5e are then listed in Table 2.5.

Basic Event C5e: Evaluation of Weathering and Wear (continued)

Table 2.5: Probability Per Year Of Loss Of Concrete Thickness From Weathering and Wear As A Contributor To Total Dome Failure

Basic Event C5e

SILO 1	$\mu_1 = 0.0103$
SILO 2	$\mu_2 = 0.0102$

Basic Event D9e: Evaluation of Mesh Support Loss

Pulse echo techniques were employed by Muenow and Associates. To determine the quality of the reinforcement steel remaining in the domes. These tests indicate the bonding condition of the concrete to the wire mesh supports. The ability of the steel mesh to provide strength to the concrete structure relates directly to the integrity of the dome. The testing logistics used provided 252 values of steel quality at the 126 test locations. Muenow assigned a Quality Statement to each result. The quality statements are qualitative in nature and are assigned based on the general conditions inferred from the observations at a particular location.

It is important to note that the quality assignments are assigned in such a way that the better the quality the lower the number assigned. A number assignment of '1' indicates that the material is considered to be in the same condition as original design. Similarly, an assignment of quality number '4' indicates that all structural integrity has been lost. This formalism is illustrated through example in the following quality statements.

Quality Statement 1

No pulse reflections noted at reinforcement steel locations and noted depths - indicating no corrosion nor nonbonding of the steel to cement matrix.

Quality Statement 2

Minor and undefined pulse echo reflections noted at reinforcement steel locations and noted depths - indicating some possible slight corrosion and/or lack of bond between steel and cement matrix.

Quality Statement 3

Defined pulse echo reflections noted at reinforcement locations and noted depths - indicating a strong possibility of corrosion product in conjunction with a non-bond condition between steel and cement matrix.

Basic Event D9e: Evaluation of Mesh Support Loss (continued)

The 252 test results were analysed and weighted to provide a Quality Statement of the reinforced steel for the whole dome. This derived quality statement for the whole dome results in a quasi-continuous distribution. The results of the analysis for this derived quantity in connection to the steel reinforcement is depicted in Table 2.6.

Table 2.6: Reinforced Steel Quality For Entire Dome

SILO 1	$Q_1 = 1.746$
SILO 2	$Q_2 = 1.663$

It is apparent from the results in Table 2.6 that the overall quality of the steel reinforcement within the dome is less than original design, but still sufficient to provide some support. Continued degradation of the steel supports will eventually result in the total loss of support and this would be designated by a quality number of '4'.

Using similar methodology as employed to evaluate weathering and wear, an exponential decay rate of the steel quality can be determined; assuming at time t=0 the quality was 1 over the entire dome. The results of the analysis are presented in Table 2.7.

Table 2.7: Exponential Steel Quality Decay Rates ($year^{-1}$)

SILO 1	$\lambda_1 = 0.0199$
SILO 2	$\lambda_2 = 0.0180$

To determine a threshold at which the dome integrity has been compromised, a new Quality Statement 4 is introduced. It is assumed that a Quality Statement of 4 infers that total corrosion has been reached and the reinforcement steel can no longer support the dome.

The time taken to reach the critical condition 4 can be evaluated using the exponential decay rates λ_1 and λ_2 noted above. The time to reach the critical quality (where strength of the steel reinforcement is not sufficient to hold the dead loads) is determined. These results are delineated in Table 2.8.

Basic Event D9e: Evaluation of Mesh Support Loss (continued)

Table 2.8: Time to Reach Critical Quality 4 (years)

SILO 1 = 69.66

SILO 2 = 77.02

Using the exponential probability density function, with the time to critical quality, the probability of failure of the mesh support to provide strength to the silo dome can be calculated and is given in Table 2.9 for each silo.

Table 2.9: Probability Per Year Of Loss Of Mesh Support From Weathering and Wear As A Contributor To Total Dome Failure

Basic Event C9e.

SILO 1 $\mu_1 = 0.0184$

SILO 2 $\mu_2 = 0.0161$

Basic Event D8e: Evaluation of Dome Concrete Quality

Evaluation of the extent of concrete degradation can be achieved using the Concrete Quality Statement assigned by Muenow and Associates. Cracking is an inherent property of most concrete structures; the extent of such cracking would indicate the ability of the concrete to provide a compressive strength. Four Statements were specified, each of which are listed below. Each statement is set by assigning a threshold for the pulse velocity and a correlated compressive strength for a typical concrete mix.

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Basic Event D8e: Evaluation of Dome Concrete Quality (continued)

Concrete Quality Statement

1. SOLID

No Cracks; line of deterioration well defined indicating flat inside surfaces. Pulse velocity in the range of 14,000 ft./sec; compressive strength greater than 4,000 psi.

2. AVERAGE

Surface cracking; line of deterioration less well defined indicating an undulating inside surface. Pulse velocity range of 13,000 to 14,000 ft./sec; 3250 to 4,000 psi compressive strength.

3. MODERATE

Surface Cracks and full depth cracks; local sharp undulations indicating areas of deterioration. Pulse velocity range of 12,000 to 13,000 ft./sec; 3250 to 2750 psi compressive strength.

4. QUESTIONABLE

Surface cracks, full depth cracks and some crack plane offset; grouped or large areas of sharp undulation indicating areas of deterioration. Pulse velocity in the range of less than 12,000 ft./sec; less than 2750 psi compressive strength.

The methodology to be employed for this analysis has been outlined in the previous two evaluations. The results for each step are shown below. Concrete Quality 5 is the assumed to be the lower threshold for structural integrity. The average or overall quality of the dome, based on the test points is given in Table 2.10.

Table 2.10: Concrete Quality For Entire Dome

SILO 1	$Q_1 = 2.000$
SILO 2	$Q_2 = 1.948$

The results of the analysis on the dome for concrete quality are presented in Table 2.11 in the form of decay or degradation rates.

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Basic Event D8e: Evaluation of Dome Concrete Quality (continued)

Table 2.11: Exponential Degradation Rate For Concrete Quality per Year

SILO 1 $\lambda_1 = 0.0248$

SILO 2 $\lambda_2 = 0.0238$

The time to reach the critical quality is then calculated and is presented for each silo in Table 2.12.

Table 2.12: Time to Reach Critical Quality 5 (Years)

SILO 1 = 65.014

SILO 2 = 67.561

The final probabilities governing the concrete quality are listed in Table 2.13.

Table 2.13: Probability Per Year Of Loss Of Concrete Quality From Weathering and Wear As A Contributor To Total Dome Failure

Basic Event D8e.

SILO 1 $\mu_1 = 0.0201$

SILO 2 $\mu_2 = 0.0191$

Basic Events D6e & D7e: Concrete Degradation Around Accessways

The design specifications show four accessways on the surface of each dome, these inlets were the main input lines for the raffinate into the silos. Information is not available to quantify the degradation around the areas of the inlets. However, the discontinuities of the dome surface at these points will create nodes of high stress and hence there is a possibility that such stresses may lead to failure. To account for this increase in failure probability, these basic events have been assigned the same probability as those for concrete degradation (D8e) and weathering and wear (C5e), hence:

D6e = C5e

D7e = D8e

It is important to note that the evaluations for weathering and wear and for concrete degradation were performed for the whole dome surface and, in comparison, the areas affected by the degradation around the accessways is minimal. The evaluation of an accessway contribution to failure is considered to be the product of the spalling and cracking basic events. The probabilities for the spalling and cracking around the accessways are provided in Tables 2.14 and 2.15.

Table 2.14: Probability Per Year Of Accessway Failure Spalling Around Accessways

Basic Event D6e.

SILO 1	$\mu_1 = 0.0103$
SILO 2	$\mu_2 = 0.0102$

Table 2.15: Cracking Around Accessways

Basic Event D7e.

SILO 1	$\mu_1 = 0.0201$
SILO 2	$\mu_2 = 0.0191$

Basic Events D6e & D7e: Concrete Degradation Around Accessways (continued)

The probabilities for each of the basic events as well as for the total dome failure are listed in summary format in Table 2.16. This table provides a quick reference of all the probabilities associated with the loss of integrity of the silo structure.

2.3 Natural External Conditions: Tornados

This section addresses the external events of severe weather in the form of tornado type cyclonic wind action. The data evaluation, analytical methods, and the estimated probability of occurrence and associated impact of this external event, on the silos, is presented here. Considerable data was obtained from NOAA detailing the occurrence of severe weather phenomena throughout the United States. For purposes of this study only severe weather occurring in Ohio, Indiana, and Kentucky was initially considered. The data evaluated covered a time frame from January 1916 to April 1989. Some gaps in the quality and usefulness of the data existed and therefore the probabilities used in the assessment were based on the data which was the most complete and applicable.

Tornados are ranked first in number of deaths and second to tropical storms in total dollar damage in the United States, when considering atmospheric-related catastrophes (excluding air pollution). Since 1963 the average annual dollar damage resulting from tornados is approximately 200 million (Dames, 1975). The cost damage potential of a single tornado as in the Xenia, Ohio tornado of April 3, 1974 can nearly reach the 200 million dollar figure. A tornado striking one or both of the silos has a real potential for significant damage as well as possible environmental consequences. This risk assessment is centered around the probability and consequences of just such an occurrence.

To insure that a certain risk level is attained or exceeded for the K-65 silos, a statistical description of the recurrence of a given intensity of tornadic forces is desired. Since "direct" measurements of tornadic occurrence and the associated forces are generally not possible, it is important to critically examine the existing data and related meteorological information in order to understand the phenomena.

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TABLE 2.16: BASIC EVENT CONTRIBUTORS AND TOTAL DOME FAILURE PROBABILITY

Designator	Event Description	Probability per year	
		SILO 1	SILO 2
C5e	Weathering and Wear	0.007622	0.007548
D8e	Concrete Degradation	0.014874	0.014134
D9e	Mesh Support Loss	0.013616	0.011914
D6e	Spalling Around Accessways	0.007622	0.007548
D7e	Cracking Around Accessways	0.014874	0.014134
Dome Failure Probability (DF)	Total Probability From All Basic Event Contributors	0.03622 /yr 0.1811 for 5 yrs	0.03370 /yr 0.1685 for 5 yrs

2.3 Natural External Conditions: Tornados (continued)

Statistical analyses are limited by the quality and quantity of the data. The statistical approach used in this study incorporates the best data and methods available at the time of the analysis. Only tornado incidents where the location, time, date, path length and width, strength, and damage estimates were used in the study. The data collected covered the three state region of Ohio, Indiana, and Kentucky for the years from 1978 through April 1989. Due to discrepancies and obvious bias (tornado reports based solely on sightings by members of the public and generally not substantiated by radar or official observations) in the state of Indiana's tornado reports only the data for Ohio was used.

The intensity of a given tornado was found to be directly related to the path width and the track length (Pearson, 1971). The potential for destruction is directly proportional to the intensity. The length of time that the tornado is in contact with the ground also has significant contribution to the damage potential. The data used for this study included 117 tornados in Ohio over approximately a 9 and 1/4 year period from January 1980 through April 1989. The tornados were ranked according to wind speeds, intensity level, area covered, and damage. The Fujita intensity scale was used to classify the tornados and is provided in Table 2.17. The classification of the tornados for this study were taken from NOAA reports. This information was compiled by National Weather Service stations throughout Ohio, Indiana, and Kentucky.

Due to the requirements of this risk assessment, to evaluate the risk from the K-65 silos, three related analyses are needed. The first is obviously the probability of occurrence of a tornado, the second relates to the characterization of the tornado, and the third is the evaluation of the damage resulting from the atmospheric turbulence. The methodology and results of the occurrence probability will be presented first followed by the methodology used in estimating the damage or destructive potential which will include a discussion on the characterization of the tornado event.

Probability Of Occurrence

The ranking of the tornados resulted in the tabulation of the frequency of occurrence, of each tornado class, as well as the probability per unit area and per year for a tornado of a given intensity. These results are illustrated in Table 2.18. Further analysis of the data provided a relationship between a given wind speed and the wind loading. The forces resulting from a tornado are complex and extremely difficult to model. Most of the available data has come from tests performed in wind tunnels.

Table 2.17: FPP Tornado Scale

(Fujita and Pearson - May 1978)

Scale	Maximum Windspeed (miles per hour)	Path Length (miles)	Path Width (miles)
F0	40 - 72	0.4 - 0.9	0.0034 - 0.0097
F1	73 - 112	1.0 - 3.1	0.0102 - 0.0312
F2	113 - 157	3.2 - 9.9	0.0318 - 0.0994
F3	158 - 206	10 - 31	0.10 - 0.30
F4	207 - 260	32 - 99	0.40 - 0.90
F5	261 - 318	100 - 315	1.0 - 3.1

Table 2.18: Summary Results Of Tornado Data From 1980 To 1989

Intensity	Area Covered (sq. mi.)	Number of Occurrences	Probability Per Year-Per Square Mile
F0	0.74	18	1.91E - 06
F1	14.23	68	3.65E - 05
F2	11.02	23	2.83E - 05
F3	7.59	5	1.95E - 05
F4	4.77	2	1.22E - 05
F5	10.25	1	2.63E - 05
	Total	Total	Total
	48.62	117	1.25E - 04
	Total Area Of Interest (sq. mi.)		
	41,004		

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Probability Of Occurrence (continued)

The direct applicability of these results is not clearly known at this time. General empirical equations have been developed from these tests and are readily used in the nuclear power industry to evaluate the response of a given structure to tornados. The NRC Regulatory Guide 1.76 delineates the maximum wind speeds and pressures drops required to be analyzed for applicability to structural response.

Approach

It is realistic to consider tornados as random phenomena in nature as are hurricanes, earthquakes and floods. Natural phenomena may be described as either deterministic or probabilistic. The probabilistic approach is by no means vague or unreliable. Probability, like other theories, should be viewed as a conceptual structure and its conclusions rely on logic.

The risk level is defined as the probability of at least one occurrence during the life expectancy of the system considered. The risk analysis consists of collecting data on tornados with their assigned intensity classifications. A point process, Poisson, was used in modeling the tornado occurrences, thus providing the relationship between the risk level and the ratio of the return period to the life expectancy (5 years as defined in the contract). The combination of results from a best-fit density function and a best-fit point process yields the return period and thus tornado intensity (wind velocity) for the specific loads identified as critical for the K-65 silos.

Density Function

Although a discrete intensity scale is used for tornado classification, the wind speed will be the parameter ultimately used for the damage potential on the silos. Therefore, a continuous rather than a discrete density function will be used for the risk analysis. The mean wind speeds will be used to describe each intensity class. The normal or Gaussian distribution was selected to represent the tornado distribution. The X^2 test is used to compare the expected results with the data. The mean and standard deviation are estimated using the maximum likelihood method given by Equations 2.2 and 2.3.

$$\widehat{m} = \overline{x} = \frac{\sum_{i}^{n} x_i}{n} \qquad (2.2)$$

Density Function (continued)

$$\hat{\sigma}^2 = \frac{\sum_{i}^{n} (x_i - \hat{m})^2}{n - 1} \qquad (2.3)$$

where:

$\hat{m}$ = Mean value.

$\hat{\sigma}$ = Standard deviation.

n = Number of elements in the sample.

x_i = Wind speed (mph).

The point process is based on the Poisson process which assumes the rate of occurrence is constant and independent of time. Using the Poisson process allows for the relationship between the risk level and the ratio of the return period to life expectancy to be site independent.

In the Poisson process the density function for t, the time between occurrences is given by Equation 2.4:

$$f_T(t) = \mu\, e^{-\mu t} \qquad (2.4)$$

and the distribution function of t is given by Equation 2.5.

$$F_T(t) = 1 - e^{-\mu t} \qquad (2.5)$$

and the probability function for 'N' occurrences as a function of the rate of occurrence μ is given by Equation 2.6.

$$P(N = n/\mu,t) = \frac{e^{-\mu t}}{n!} (\mu t)^n\,, \quad n = 0, 1, 2, \ldots \qquad (2.6)$$

Density Function (continued)

where:

μ = Rate of occurrence.
T = Life expectancy.
t = Time of interest.
$f_T(t)$ = Probability density function.
$F_T(t)$ = Probability distribution function.
n = Number of elements in the sample.
P(N,t) = Probability of 'N' occurrences.

If the rate is assumed uniform inside the area, then the rate in a smaller area can be obtained by reducing the rate by an areal ratio. For example if 'a' and 'A' denote the reduced and original areas, respectively, then the rate inside the smaller area 'a' will be given by Equation 2.7.

$$\mu' = \mu\left(\frac{a}{A}\right) \tag{2.7}$$

The probability mass function inside the 'a' (in this analysis 'a' represents the area of influence for the silo structures) is then given by Equation 2.8.

$$P(N' = n'/\mu',t) = \frac{e^{-\mu' t}}{n'!}(\mu' t)^{n'}, \quad n' = 0, 1, 2, \ldots \tag{2.8}$$

The method of maximum likelihood is easily applied to the density function where the only parameter, μ, is given by Equation 2.9.

$$\hat{\mu} = \frac{n}{\sum_{i=1}^{n} t_i} \tag{2.9}$$

Tables 2.19 and 2.20 delineate the data and results of applying the statistical analysis to the tornado data, while the risk factor, for the Poisson process, can be represented by Equation 2.10.

$$r = 1 - e^{-L_x(x)\hat{\mu} \times T} \tag{2.10}$$

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Table 2.19: Results Of The Statistical Analysis

intensity	number of occurrences	expected value	mean wind velocity (mph)
F0	18	16.85	60.0
F1	68	71.32	95.0
F2	23	21.43	135.0
F3	5	4.79	185.0
F4	2	1.37	230.0
F5	1	0.78	290.0
	μ	σ	χ^2
	105.0	37.3	0.71

Table 2.20: Probabilities And Risk Factors

intensity	probability $L(x) = 1 - F(x)$	wind velocity (x , mph)	Column A risk factor* $r(x)$	Column B Risk Based on Probability of Tornado in Five Years
F1	2.5 E - 1	112	3.7 E - 1	2.3 E - 4
F2	1.75 E - 2	135	4.13 E - 2	2.6 E - 5
F3	3.34 E - 3	185	5.78 E - 4	3.6 E - 7
F4	2.78 E - 6	230	6.13 E - 6	3.8 E - 9
F5	2.43 E - 7	290	7.35 E - 8	4.6 E - 11

$r(x) = 1 - \exp(-L(x)\ \hat{\mu}\ T\ \ x)$ $\hat{\mu} = \frac{n}{\Sigma t_i}$

* Based On A Single Event Occurring In The 5 Year Life Time

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Density Function (continued)

The reliability function, $L_x(x)$, for wind speed x, is defined as the probability of the wind speed being at least x and is obtained by numerical integration. The risk factor is estimated assuming that there is a single tornado event in the life of the facility.

Incorporating this assumption removes the conditional probability of tornado occurrence from the calculations. In this way the damage potential of the wind and pressure forces are presented in terms of a risk estimate. The nature of risk estimates dictates that the basic constituents of the probability and consequence calculations be clearly stated and defined. When considering two different risk numbers a comparison can only be made when the basic components are similar. The greater the number of factors in a risk calculation the greater the potential for confusing and clumsy comparisons.

Certainly the ultimate consequence of any single event can be clearly seen and therefore easily compared, in this study the ultimate consequence considered is the increase in cancer fatalities (or incidence in the EPA methodology). When the consequence is more subtle, as is the case in the estimate of damage, to a structure as a result of a tornado, the basis for comparison is much less clear. For this reason the risk estimates provided in Column A of Table 2.20 were provided. The risk factor for the single tornado event in the life of the plant at first glance appear to overestimate the risk of silo failure as a result of a tornado. The intent is to illustrate the significant probabilities and risks associated with the relatively low wind speeds. The numbers provide a comparison that would be less obvious when the probability of the tornado occurring is factored in.

The obvious comparison here is that the damage potential (risk factor) is significant for average wind speeds on the order of 112 miles per hour. The probability of this wind speed occurring is quite large at 25%. The forces associated with this wind speed are 288 (psf) tension and approximately 50 (psf) compression. These forces are considered (based on the structural analysis) to be sufficient to fail the silo dome. Although these forces are not the maximum values the damage to the silo is expected to be such that a significant quantity of the radionuclide inventory could be released. The risk associated with the failure of the K-65 silos over the next five years is best represented by the risk factors in column A of Table 2.20. The risk estimates provided in column B of Table 2.20 are presented to illustrate the total probability (tornado frequency and damage potential) with the consequence of failure over the next five years factored in. These

Density Function (continued)

values are serve as an additional basis for comparison as well as to present the results when all the components, of the failure associated with a tornado as the initiator, are considered. The range of values shown in column B depict the reduction in the overall risk of silo dome failure including the relatively low probability of a tornado striking within a proximity to the silos so as to result in the expected forces and wind loadings on the structure.

The probabilities and risk factors presented in Table 2.20 were used to evaluate the maximum damage potential and therefore the maximum quantity of radioactive material that could be released to the environment. The probabilities of silo dome failure, due to natural degradation, and of a tornado occurring, per year and per square mile, were used in the final risk estimates relating the total cancer fatalities or cancer incidence as a result of human exposure to the radioactive material that hypothetically could be released. These values are delineated in Table 2.21. The central difference between the probabilities listed in Table 2.21 and those in Table 2.20 is that the net effect or consequence considered is different. The values in Table 2.21 refer to the frequency of occurrence, of a tornado, and not to the specific damage potential. The values in Table 2.21 were used in the overall risk estimates in order to form a comparative basis of the consequences. The inclusion of the specific damage potential would appear to underestimate the risk from the silo contents on the public.

Table 2.21: Probabilities Associated With Natural Degradation Of The K-65 Silos And Tornado Occurrence

Probability Of Failure Due To Natural Degradation

Silo 1	Silo 2	Average	
0.0361	0.0336	0.0348	per year
0.1804	0.1677	0.1741	over 5 years

Probability Of A Tornado Per Square Mile

per year	over 5 years
1.248 E - 4	6.24 E - 4

Characterization And Degree Of Effect

The characterization of the specific tornados of which data was available is essentially dependent on the intensity factor and the recorded wind speeds. The ideal characterization would provide pressure and velocity distributions as a function of position, corresponding to the radius of the tornado. This type of information is rarely available for actual tornados. The next best method, therefore, is to assume some realistic distributions based on the intensity factor, the area covered and the resulting damage.

The forces on a structure resulting from a tornado are of two types: 1) compressive forces and 2) tensile forces. These forces result from the high tangential and translational wind speeds and the effects of large and rapid pressure drops. The atmospheric pressure gradient at radius 'r' from the tornado axis is given by the cyclostrophic wind equation, Equation 2.11, (Long, 1958), and (Rotz, 1974).

$$dP_a(r) / dr = \rho V_t^2(r) / r \qquad (2.11)$$

where:

ρ = Mass density of air.
$V_t(r)$ = Tangential wind velocity component.
$P_a(r)$ = Pressure as a function of position.
r = Radius of the tornado measured by the wind velocity.

If the tangential velocity profile is assumed to be a Rankine vortex the velocity can be represented as a function of position as provided by Equation 2.12.

$$V_t(r) = \begin{cases} (r / R_m) V_m & (0 \le r \le R_m) \\ (R_m / r) V_m & (R_m \le r < \infty) \end{cases} \qquad (2.12)$$

The pressure distribution as a function of position is then represented by Equation 2.13.

$$P_a(r) = \begin{cases} \frac{1}{2}(-\rho V_m^2)(2 - V_{tr}^2 t^2 / R_m^2) & (0 \le r \le R_m) \\ \frac{1}{2}(-\rho V_m^2)(R_m^2 / V_{tr}^2 t^2) & (R_m \le r < \infty) \end{cases} \qquad (2.13)$$

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Characterization And Degree Of Effect (continued)

where:

V_m = Maximum tangential velocity.
V_{tr} = Translational velocity of the storm front.
R_m = Radius for the maximum tangential velocity.

The maximum forces associated with the above described pressure and velocity profiles can be obtained using the following empirical correlations, Equation 2.14 for compression, and Equation 2.15 for tension.

$$P_c = 0.5\, C_p\, C_s\, \rho\, V_{max}^2 \qquad (2.14)$$

$$P_t(0) = \rho\, V_{\theta m}^2 \qquad (2.15)$$

where:

P_c = Compression force (psf).
P_t = Tensile forces (psf).
C_p = Coefficient of lift and drag forces.
C_s = Coefficient for the shape of the structure.
V_{max}, and $V_{\theta m}$ = Maximum wind speeds.

These equations are used for the roof portion of the silo structure for both the compressive and tensile forces. The compressive forces are primarily due to the lift and drag forces of the horizontal wind components. The tensile forces are primarily due to the pressure drop associated with the storm and specifically the local depression in the vortex of the tornado itself. These correlations relate the forces of the turbulence associated with the tornado. These forces are then compared to the critical loadings of the silos to determine the damage potential. As indicated previously the critical loads on the silo dome are approximately 284 psf for the outer portions of the dome and approximately 104 psf for the center portion. Table 2.22 delineates the forces expected from the various classes of tornados as related to the mean wind speeds. The results of these calculations when compared to the critical loading on the dome show that a tornado of at least an F1 intensity or higher has the potential for failing the silo dome structure.

Table 2.22: Force Distributions As A Function Of Tornado Intensity

Intensity	Maximum Velocity (mph)	Pressure Drop ΔP (psi)	Compressive Force (psf)	Tensile Force (psf)
F1	112	2.0	49.2	288.0
F2	157	2.25	96.8	324.0
F3	206	2.5	167.0	360.0
F4	260	2.75	265.0	396.0
F5	318	3.0	397.0	432.0

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Characterization And Degree Of Effect (continued)

In the event that the dome fails, as a result of the forces from the wind and estimated pressure drop, the next major consideration is the extent of damage to the structure. In this analysis the extent of damage was postulated to range from simple cracking in the event of low wind speeds and a moderate pressure drop to the extreme case where the dome is completely removed, as a result of the maximum wind and pressure forces. The forces exerted in this extreme case would be well in excess of the critical buckling load by a factor of 2, for the outer portion of the dome, and more than a factor of 4, for the inner 20 foot section. This range of damage complicates the analysis of the release term as well as the overall risks. In order to facilitate the risk estimates the maximum damage and therefore the maximum source term released were used in the exposure assessment portion of this study. In this regard no credit was taken for parts of the silo structure falling in and thereby reducing total quantity of residues available for dispersion by the wind.

Summary Of Probabilities And Damage Potential

As a final point, all of the various probability calculations are presented in Table 2.23. This format enables the reader to view all the various calculations simultaneously. What is not able to be conveyed in a tabular format is the specific meaning for each calculation or probability estimate. This understanding or appreciation is hopefully gained through both the supporting text and the reader's own experiences. Probabilities and especially risks are difficult to grasp in terms of everyday experiences. The more complicated the probability the more difficult the understanding becomes.

It is important to note that the foam and the protective cover to the center portion of the dome were not considered to add strength to the dome structure. The additional weight these modifications impose on the dome were considered to be a detriment and tend to increase the potential for failure. For this reason the loss of the dome during a tornado event was evaluated using only the results of the force and wind loadings as applied to the silo modeled in the Camargo report. The estimated extent of damage in the event of a tornado discussed in this section was taken as a maximum and is not intended to reflect, precisely, the wide range of possibilities for the manner in which the dome structure may fail. The exposure assessment can then be broken down into fewer parts and the complexities associated with what failure mode to use is reduced to using those estimates which reflect the maximum source term and therefore the maximum consequences.

Table 2.23: Summary Of Probabilities Associated With The K-65 Silos

I. Silo Dome Failure Probability

A. Probability Of Failure Due To Natural Degradation

Silo 1	Silo 2	Average	
0.0361	0.0336	0.0348	per year
0.1804	0.1677	0.1741	over 5 years

B. Probability Of Failure Due To Natural Degradation Including Tornado As An External Event

Silo 1	Silo 2	Average	
0.0365	0.0339	0.0352	per year
0.1825	0.1695	0.176	over 5 years

II. Tornado Occurrence Probability (per Square Mile)

a.)

Total	per year	over 5 years
1.186 E - 3	1.248 E - 4	6.24 E - 4

b.) **Probability as a function of intensity level**

Intensity		
F0	1.91 E - 6	9.55 E - 6
F1	3.65 E - 5	1.83 E - 4
F2	2.83 E - 5	1.42 E - 4
F3	1.95 E - 5	9.75 E - 5
F4	1.22 E - 5	6.10 E - 5
F5	2.63 E - 5	1.32 E - 4

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Table 2.23: Summary Of Probabilities Associated With The K-65 Silos (continued)

III. Probability And Risk From Wind Speed Given A Single Tornado Event In A Five Year Period

wind velocity (x, mph)	probability L(x) = 1 - F(x)	risk factor r (x)
112	2.5 E - 1	3.7 E - 1
135	1.75 E - 2	4.13 E - 2
185	3.34 E - 3	5.78 E - 4
230	2.78 E - 6	6.13 E - 6
290	2.43 E - 7	7.35 E - 8

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2.4 Radionuclide Inventory

The ultimate consequences (exposure of the public to radioactivity) associated with the failure of the K-65 silos is totally dependent on the total radionuclide inventory or source term. The data obtained from WMCO and others clearly shows that the total quantity of radium, thorium, uranium, and radon is not precisely known. The environmental source term is directly related to the consequences associated with the failure of silos. The failure mode dictates the quantity of material released and the time frame of the release. The objective of this section is to provide the assumptions, results, and analysis for the estimates of the radionuclide inventory and the magnitude of that release.

Estimates Of The Radionuclide Inventory

The total mass of the waste material contained in the K-65 silos is approximately 19,400,000 pounds. The total amount of radionuclides residing in this mass is less than 0.12% by weight. The bulk majority of the waste mass is in the form of silicates (SiO_4), trace metals, various oxides, and residual water. The waste mass is assumed to be approximately 30 to 40 percent water with varying layers that range from hard crust like material to a powdery consistency.

A number of estimates and analyses have been conducted in order to arrive at the source term. To date the most prominent data reflects a total quantity of radium (for both silos) to be in the range of 2,300 to 4,600 curies. The best estimate within this range is on the order of 3,300 curies ($\approx$375 nCi/gr). This value was used in this risk assessment to determine the transport and dose resulting from acute releases.

The quantity of radium in the silos has a direct bearing on the production rate of radon (since radium-226 is the parent radionuclide of radon-222). The amount of radium determines in part the quantity of radon available for release. This is true in either a catastrophic failure mode or for the chronic release (radon gas leaking through the pores and cracks of the silo). Radium-226 is called the parent nuclide of radon-222 due to the fact that each time an atom of radium-226 decays an atom of radon-222 is formed. The natural decay mode for radium-226 is the emission of an alpha particle and a gamma ray. The remaining nuclide is then radon-222. The production rate of radon-222 is simply the decay rate of radium-226. There is considerable uncertainty in the radon emission rate from the

Estimates Of The Radionuclide Inventory (continued)

silos as well as the total inventory available in the free space of the dome, which is primarily due to two problems: 1) the precise quantity of radium-226 is not available and 2) the rate of diffusion of the radon gas is a nonlinear process and is not known precisely. The range of values for the inventory of radon in the upper head region range from 30 to 50 curies. The total quantity of radon released per year is also uncertain and values in the range of 167 to over 1100 curies per year have been reported. For the purposes of this study the acute release of radon was estimated to be 50 curies and the chronic yearly release rate was calculated (using best estimates and data that had more than one source) to be 650 curies. In both instances the values were taken as the maximum substantiated values in the given ranges.

Uranium in the silos is estimated (based on records and measurements) to be on the order of 0.41 nCi/gram for the 238 and 234 isotopes, with only 0.02 nCi/gram for uranium-235. The total quantity of uranium in the silos is taken to be approximately 11,200 kg. This corresponds to a total of approximately 7 curies and is assumed to be distributed uniformly throughout the solid waste material.

The existence of uranium in the silos has been known for some time, but the existence of thorium-230 in the silo residues was not expected. The concentration of thorium within the solid residues has been measured and was found to be both a significant quantity as well as non-uniformly mixed. Three samples analyzed showed a range of concentration of approximately 77 nCi/gram to 483 nCi/gram in the solid waste matrix, for a total inventory of approximately 1,810 Curies. This variation in concentration indicates the non-uniformity and leads to considerable uncertainty in the actual quantity of thorium-230.

Potential For Release

The potential for release of radionuclides to the environment is related to the physical characteristics of the waste material or residue as well as the probability of the silo failure mechanism. The probability of the failure mechanism was covered in Section 2.3. Since the total radionuclide inventory accounts for less than 1% of the total mass, the residue material must act as a carrier for the radioactive particulates. This fact then reduces the problem of determining the source term to one of estimating (qualitatively and/or quantitatively) the total mass of residue material that can be released from the silo structure. In the case of atmospheric release

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Potential For Release (continued)

the dispersion of material will be determined by the chemical form, the particle size, and the scale of turbulence in the environment. The waste material is composed predominantly of silicates (sand) and the exact water content although not known precisely has been estimated to be approximately 30 to 40 percent. The water is expected to act as a binder for the solid material thus reducing the tendency for distribution, however measurements and sampling data indicate that the upper layers of the residue material are dry and possibly easy to disperse. The transport and release therefore, of the upper layers, of the residue material from the silos after a failure was expected to be quite large.

The failure modes addressed for applicability to the release terms are: 1) catastrophic failure leading to an acute release of radon, radium, uranium, and thorium, 2) partial failure resulting in an acute release of radon, and 3) chronic failure resulting in the continuous emission of radon gas.

Magnitude of Maximum Release

The model used for evaluating the source term for an acute release where only radon-222 is released is straight forward and consists primarily of the estimation of the total quantity of radon gas in the upper free space of the silo. The model for the source term associated with an acute release where a significant amount of the residues are exposed to the atmosphere is much more difficult to evaluate. As previously stated the damage to the silo in the event of a tornado was assumed to be the complete removal of the dome structure. The total surface area of the residue material is then left exposed to the full force of the wind and pressure forces.

The total force associated with a tornado event is composed of two parts: 1) the lift and drag forces resulting from the high tangential and translational wind velocities, and 2) the uplifting forces associated with the pressure drop accompanying the funnel cloud. These forces can in many cases act in concert for the total load on an object. As a result of these two force components the dome structure is assumed to be completely removed and the residue material is allowed to experience the full effect of the wind and pressure forces. In order to estimate the effect of the wind on the removal of radioactive contaminants both the density of the residue (which is approximately 100 pounds per cubic foot) and the maximum compressive and tensile forces (which are greater than 390 pounds per square foot each) were considered. The radionuclides were assumed to be distributed homogeneously throughout the residue material and the problem of evaluating the source term released is reduced to evaluating the total quantity of residue material removed and dispersed.

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Magnitude of Maximum Release (continued)

The depth of residue material available for redistribution can be estimated by using the ratio of the pressures to the dead weight of the material. In this case the force of the wind would be capable of lifting an amount of residue material approximately 4 feet in depth and 1 foot wide. The weight of 4 cubic feet of residue material would therefore be about 400 pounds. Even though the wind forces are acting over an surface area the net effect of the continued wind and pressure forces for the duration of the tornado event is assumed to be capable of lifting nearly the 4 foot depth of material. The calculations made for this study assumed, for convenience, a total depth of 1 meter (which is approximately 3.28 feet) over the area of a single silo.

This method provides the total quantity of residue material released and therefore the magnitude of the radioactive source term, which has already been divided by radionuclide and by the specific isotope. The next phase of the analysis requires an estimate of the quantity of the released material which is airborne and the amount which is deposited on the ground near the failed silo. The best estimates on the fraction of the airborne and ground deposited material come from measurements of particle sizes and distributions resulting from explosions of sand, gravel, and other similarly related materials. In most cases the distribution of size is taken to follow a 90-9-1% ratio. The net result is that 90% of the released material is deposited within close proximity to the structure (within 300 feet of the point of release), then about 9% is deposited within about 2500 feet, and the remaining 1% is available for atmospheric dispersion. Figure 2.2 depicts the magnitude of the release and the distribution in the environment. Table 2.24 provides the magnitude and type of the source term as a function of the failure mode.

The source term estimates are based on both analytical work and references to other reports and documents concerning the K-65 silos. The calculations made include estimates of the volume of free space available in the dome portion of the silos and the approximation of the radon release rate using differential equations to relate the production and loss terms. This work was employed in an attempt to consolidate and compare the various estimates of the quantity of radium in the silos. The uncertainty of the radium concentration is considered a dominant limitation of the risk assessment.

Figure 2.2: Magnitude And Distribution Of The Source Term

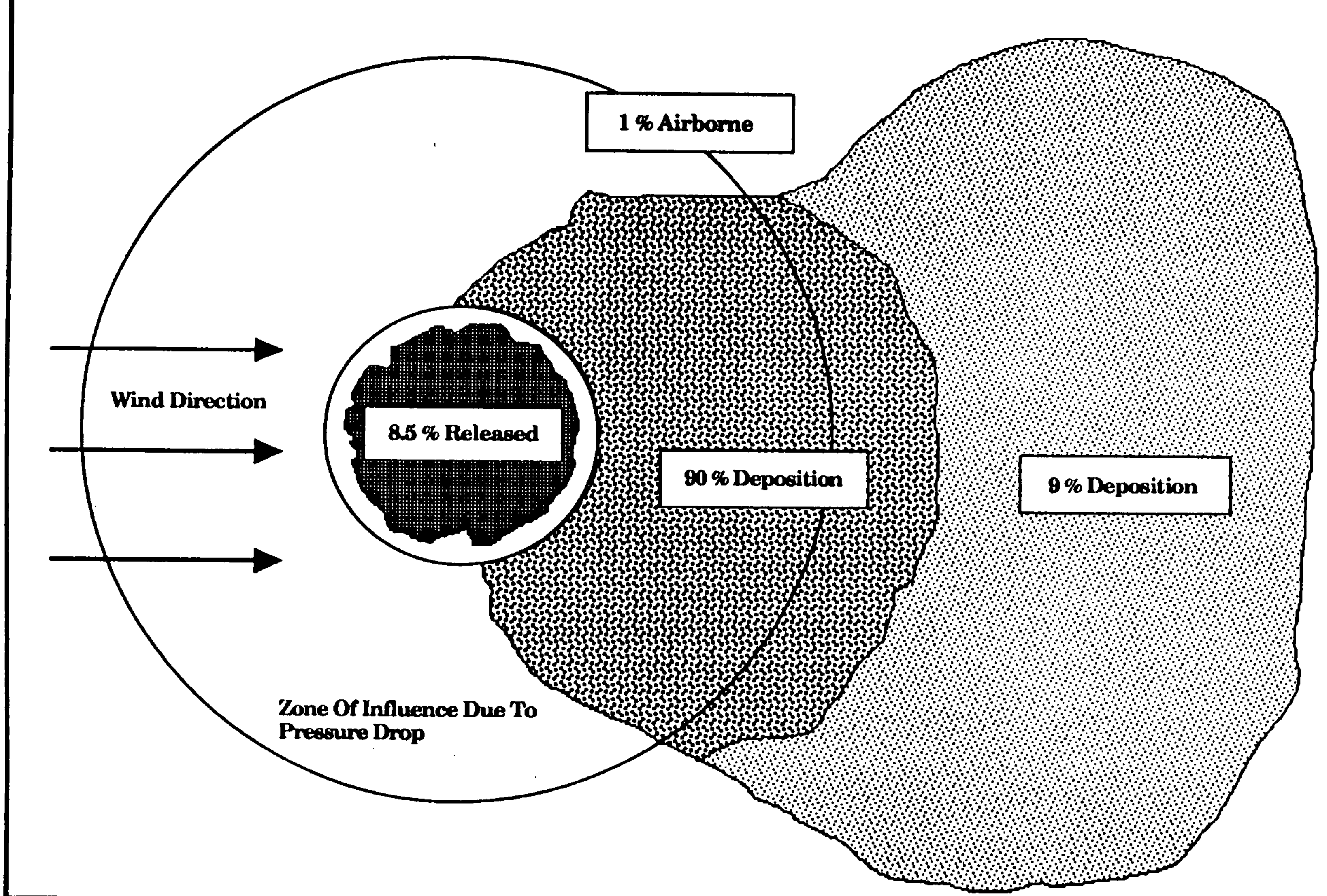

Table 2.24: Source Term Released Relative To Failuire Mode

Failure Mode	Source Term (Curies) Airborne	Ground Deposition (100 - 300 ft.)	Ground Deposition (300 - 2500 ft.)
Acute			
uranium (238, 234)	5.96 E-3	0.536	0.0536
uranium (235)	7.3 E-5	6.5 E-3	6.8 E-4
thorium-230	1.54	138.6	13.86
radium-226	2.81	252.9	25.29
radon-222	50.0	-	-
Chronic			
radon-222	650.0		

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Environmental Transport Models

The transport of the radioactive material in the environment is a component of the pathway analysis and exposure assessment phase. The details of the analysis, including the basic assumptions, will be discussed in the this section with the results (concentrations in the air and on the ground) will be presented in Section 3.

There are essentially two types of release modes considered in this analysis. These are considered as acute and chronic. This terminology refers primarily to the time frame of the release, but also to the type of failure mechanism and therefore the magnitude of the release. The chronic refers to the continuous release of radon gas, while the acute release can be either entirely radon or a combination of radon, radium, thorium, and uranium. With this convention there are a total of three exposure assessments and three source terms to be evaluated for transport in the environment.

The principal transport mechanism is atmospheric dispersion, including the ground deposition processes. Other potential transport mechanisms generally require time frames longer than a few years to assess completely. For this reason only the atmospheric transport of contaminants released from the silos was considered.

Atmospheric transport of contaminants is typically modeled using a standard Gaussian plume dispersion equation, which relates the distribution of contaminants in the atmosphere to the point of release by means of a dispersion coefficient. The dispersion coefficients are developed as a result of empirical correlations from experimental data. The best known model is that which is contained in the AIRDOS-EPA computer code. This code utilizes the Pasquill-Gifford parameter system for evaluating the dispersion coefficients.

The Gaussian plume model is applicable, in many situations, to both short term (one hour) and continuous releases and transport times. The data base containing the wind direction, velocity, and stability frequencies can be manipulated to approximate both of these release modes. For the purposes of this study the acute releases were assumed to occur over a one hour period, while the chronic release was taken as an average release rate over a one year period. The principal difference between the two modes, in terms of atmospheric transport, is the number of sectors over which the concentration calculations are made. The one hour release (acute cases) uses only one 22.5 degree sector at 100% frequency (for wind direction, velocity, and stability class) for the concentration calculations. The chronic

Environmental Transport Models (continued)

case on the other hand utilizes the time averaged wind frequency data which is accumulated over an entire year along with all 16 of the 22.5 degree sectors. Additional changes to the input data, to account for the short term release, concern the magnitude of the source provided to the code and the buildup time (for ingrowth from radioactive decay as well as scavaging and deposition processes). Depending on the specific scenario considered there are a number of options, in the input data file, that can be selected in order that the computer results best reflect the physical scenario.

The following assumptions were used to evaluate the concentrations of radionuclides in the atmosphere resulting from a hypothetical tornado event and from the continuous release of radon from the K-65 silos. As mentioned previously two types of release modes were considered: 1) acute release of radon gas and residue material, due to severe weather (tornado) and 2) the chronic release of radon gas due to the current situation of the silos. The time frames considered for the AIRDOS-EPA computer runs were taken to be 1) one hour release for the acute case and 2) one year average for the continuous case.

The continuous case was evaluated using the FMPC site specific meteorological data which includes time averaged wind speeds, stability classes, and wind directions. This method corresponds to the typical use of the AIRDOS code with the exception that the doses were evaluated with both the radionuclide data base contained in the code and by using the more recent values for dose conversion factors (DCFs) as provided by Kocher. The radionuclide data base for the DCFs contained in the AIRDOS code does not contain the most recent and accepted values. The AIRDOS code was, therefore, essentially used to evaluate the concentrations of the four radionuclide species in the atmosphere. The dose estimates provided by the AIRDOS code were useful as a reference values or for a magnitude comparison for each of the exposure scenarios considered.

The acute release was modeled using a single sector and a single stability class (F) as discussed previously. The direction considered depended on the population distribution and the predominant wind direction. The population center used in this analysis was considered to be within 14 kilometers, of the release point, and is located essentially East Northeast of the site. This would correspond to a principal wind direction from the West Southwest. Using the AIRDOS code in this manner is consistent with the basic theory of the Gaussian diffusion model since the time scale considered must be compatible with the turbulent diffusion mechanism. The translational wind speeds typically accompanying the tornado event are in the range of 30 to 70 mph and thereby providing the wind force sufficient to disperse particulates as far away as 30 miles in a one hour period.

Environmental Transport Models (continued)

The concentration in the atmosphere for both the population dose and the nearest resident were estimated using the sector average option in the AIRDOS code. Although this results in a lower dose the sector average concentration is the more realistic value and is comparable with fenceline radon measurements at the FMPC site. Table 2.25 lists several of the key input parameters and the values used in the assessment.

Table 2.25: AIRDOS-EPA Input Data

Parameter	Input Value
source height (PH)	27 feet (accounting for silo wall height)
plume height (PR)	50 meters (high winds)
lid height (LID)	1000 meters
annual rain (RR)	100 inches
average temperature (TA)	285.3 K
scavenging coefficient (SC)	1E - 5
deposition velocity (VD)	1.8E - 3

The source terms used depended on the specific release mode considered. The concentration in the atmosphere is linearly related to the source term, therefore to evaluate the concentrations resulting from greater source terms new concentrations are simple multiples of the previous concentrations. The results of the atmospheric transport models are listed and discussed in Section 3, Table 3.1.

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3.0 Exposure Assessment

Introduction

This section describes the procedures used for performing the exposure assessment as part of the baseline risk assessment process. The objective of the exposure assessment is to estimate the type and magnitude of exposures which may result due to the release of the various radionuclides present in the waste material of the K-65 silos. This information, in the form of doses and exposure levels at the significant exposure points, will be combined with the probabilities of silo failure, risk coefficients, and EPA slope factors in order to fully characterize the potential risk to each significant exposure point.

The exposure assessment process is composed of basically three steps: 1) characterizing the exposure setting, 2) identifying the exposure pathways, and 3) quantifying the exposure. The step of characterizing the exposure setting involves analyzing the physical setting around the silos and identifying the potentially exposed populations. The process of identifying the exposure pathways involves determining the source terms, defining the exposure points, and identifying the exposure routes. The final step, quantifying the exposure, involves determining the exposure point concentrations and doses.

3.1 Characterizing the Exposure Setting

For this investigation, the characterization of the physical setting around the silos primarily involves being able to predict, as a function of time and distance, the ultimate fate and distribution of the materials in the K-65 silos as a result of an accident or the continued degradation of the silos leading to the excessive release of radon. In order to perform the exposure assessment, three significant exposure points were assumed. These three exposure points represent the potentially exposed populations should a release occur from the silos.

The first significant exposure point assumed is an occupational work shift at the FMPC. This work force is assumed to be within 100 meters of the silos when the accident occurs. Furthermore, the work force is assumed to number 50 people. The second potential exposure point is the nearest resident. This person is located a distance of 500 meters from the site. The final potential exposure point is a small population, assumed to be located approximately 14.5 kilometers away.

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3.2 Identification of Exposure Pathways

The principal objective of this task is to identify those pathways by which the identified populations may be exposed. Each exposure pathway describes a mechanism by which a population (or individual) may be exposed to the contaminants originating from the silos. These exposure pathways were identified based on the consideration of the sources and mechanisms of release of the radionuclides; the most likely environmental transport route; and the location and activities of the potentially exposed populations.

An exposure pathway consists of four elements: 1) source and mechanism of radionuclide release, 2) retention or transport medium, 3) point of potential human contact with the contaminated medium (referred to as an exposure point), and 4) an exposure route (for example, inhalation) at the contact point. Table 3.0 illustrates the pathway analysis methodology.

Source And Mechanism Of Radionuclide Release

The source of the radioactive material is the K-65 silo contents. The mechanism of release is the failure of the silo structural integrity coupled with environmental processes. The source term was reviewed and estimated in Section 2.4 and will not specifically be addressed here. The mechanisms were also discussed, but on a more general level, in Section 2.4. The specific mechanism involved with the release and transport of the waste material in the silos is the wind. This study has focused on atmospheric turbulence as the primary mechanism that can lead to the catastrophic failure of the silo structures. The wind or more appropriately the weather is both the initiator and the basic phenomenon involved in the silo degradation over time.

The action of the wind and weather on the components of the structure continue to degrade the integrity through weathering, wear, freezing and thawing, and severe dynamic and static loadings. The temperature changes when water is present significantly increases the forces associated with the expansion and contraction processes. The long term affect from these forces and processes is the steady increase in the probability of failure and ultimately the release of radioactive material. As previously discussed the failure mode is directly related to the quantity and time frame of a release.

The source and mechanism can be stated simply as acute and chronic release rates and types. The acute release has the larger source term and the shorter time frame, and the chronic release is characterized by the continuous release of radon gas.

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Table 3.0: Pathway Analysis Methodology for the Acute and Chronic Cases

Acute Case - Catastrophic Release (A1)

Radionuclides Released:	Uranium-238, Uranium-234, Thorium-230, Radium-226, and Radon-222.
Pathways Analyzed:	Inhalation of gaseous plume (1 hour exposure). Inhalation of resuspended dust. External Exposure from radionuclides.
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

Acute Case - Total Release of Radon (A2)

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon plume (1 hour).
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

Chronic Case - Daily Release of Radon-222

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon-222
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

Acute Releases

The first type of acute release is designated as A1 and is characterized by the catastrophic failure of the silo structure permitting the direct link between the environment and the radionuclide inventory. The specific type of silo failure will determine the size of the release and ultimately the impact. This study characterized the acute release as resulting from the action of tornado strength wind loadings on the structure. Assuming the turbulent forces are sufficiently strong to cause complete or partial dome failure then these winds can be expected to be capable of significant dislocation and transport of the radioactive waste. In this case the total release of the available radon will be dispersed by the wind. Additionally, the solid radionuclide particulates are assumed to be distributed outside the silo structure. The quantity released was evaluated in Section 2.3.

The second type of acute release is designated as A2 and is characterized as a partial silo failure which results in the total release of radon from the head-space of each silo. The AIRDOS-EPA computer code was used to model the atmospheric dispersion of the radon and predict the exposure point concentrations. It was assumed that the exposure time for each acute case was one hour.

Chronic Release

This case is characterized by the chronic release of radon. The chronic case is caused by existing cracks or holes in the concrete. These openings will readily permit transfer of the radon gas but generally will not permit the transport or loss of significant quantities of the heavier isotopes. As indicated previously the actual mass of the radioactive waste is small and is homogeneously mixed in the bulk mass of the silo's contents which is primarily composed of silicates and water. The release of the elements of radium, thorium, and uranium would require large openings and an additional transport mechanism other than the wind.

Environmental Transport Medium

The time frame considered for this study was five years for the failure potential, the radionuclide release, and the subsequent transport in the environment. The possible transport processes available to distribute the waste material after failure of the structure are: 1) atmospheric distribution, 2) the hydrologic cycle, and 3) the distribution as a result of biotic uptake. Atmospheric distribution would involve both resuspension of contaminated dust and atmospheric distribution as a result of plume migration. Radionuclides deposited in the surface soil slowly migrate through the vadose zone where they may in turn reach the water table and travel large distances rapidly. Distribution of contaminants in the environment can also occur as a result of biotic uptake. Radionuclides can enter plants through primarily two routes: roots (root uptake) and leaves (foliar deposition). Of these three mechanisms for transport, the biotic uptake route is the least significant. The relationship between the hydrologic cycle and the atmospheric turbulence makes separation of these mechanisms difficult. The processes involved overlap and are interdependent. For purposes of this study the hydrologic cycle was not evaluated in detail due to predominantly long time frames and the large distances, to significant exposure points, involved. The exposure point discussion is addressed in a later section.

Atmospheric turbulence results in relatively rapid transport of contaminants. This transport mechanism is also characterized as having potentially significant affects or impacts over large distances. Significant concentrations can result as far away as several kilometers from the point of release.

The transport of radioactive material from the silos for both cases of the acute release and the chronic release mode was estimated using the AIRDOS-EPA computer code. This code is based on the Gaussian Plume Equation and utilizes the Pasquill-Gifford system for the evaluation of the dispersion coefficients. This formulation is not specifically applicable to the transport of contaminants as postulated in this study. The model does, however, provide a basis for estimating the possible effects from the release of the material in the K-65 silos.

The use of the AIRDOS-EPA code required data on the population distribution, agricultural production and use, and site specific meteorological conditions. The analysis, however, did not rely solely on the results from the code. The models developed were also evaluated using hand calculations and other numerical codes as supplemental material and for verification.

Environmental Transport Medium (continued)

The AIRDOS-EPA code is designed to model continuous long term releases and was assumed to be adequate in regards to the chronic release of radon. The acute releases are not as straight forward. The direction for the release was taken to be that of the most prominent wind direction. The wind speed and stability class used were also not easily determined. The result of applying the Gaussian Plume equation to atmospheric transport is that the distribution of the contaminant is averaged based on the specific input. The application to long time frames is justified based on the averaging affect of the wind direction, speed, and stability class. For those situations when the release time is short to intermediate the wind conditions are required to be nearly constant over the time frame considered. Any significant change in the wind direction, speed, or stability class will result in different results and uncertainties. The time frame for the acute releases was therefore taken to be approximately one hour. This duration is also consistent with the duration of severe weather phenomena. Table 3.1 provides the results of the atmospheric transport analysis for the radionuclides considered.

Table 3.1: Results Of Environmental Transport For Acute And Chronic Release Modes

Radionuclide	Distance (m)	Acute Conc. Air (Ci/m^3)	(pCi/g) Conc. ground	Chronic Conc. Air (Ci/m^3)
uranium	100	2.8E-09	1.069	-
	500	1.4E-10	0.049	-
	2,500	6.3E-12	0.002	-
	14,500	1.8E-15	0.0	-
thorium	100	9.8E-08	35.3	-
	500	4.6E-09	1.64	-
	2,500	2.1E-10	0.0756	-
	14,500	5.9E-14	7.56E-06	-
radium	100	1.4E-07	50.0	-
	500	6.5E-09	2.34	-
	2,500	3.0E-10	0.11	-
	14,500	8.5E-14	0.11	-
radon	100	3.3E-05	-	8.4E-09
	500	1.5E-06	-	4.8E-10
	2,500	7.3E-08	-	4.1E-11
	14,500	2.7E-09	-	2.6E-12

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Significant Exposure Points

The three potentially significant exposure points previously discussed (work force, nearest resident, and nearest population) were hypothetically established to represent three types of reasonable maximum exposure points. Detailed information on these exposure points was lacking, such as the work force population, the nearest population center and estimate of its size, and other values related to the activity patterns for each of the exposure points. Therefore, information on each exposure point was assumed.

As detailed in the previous discussion of the environmental transport medium, the primary transport route in the event of a silo failure is the wind. Therefore, atmospheric transport was assumed to be the only transport medium. Furthermore, through the atmospheric transport of the silo's material, it was determined that the principal pathways of exposure would be the inhalation of the gaseous plume, the inhalation of resuspended dust (after the source term has been spread across the surface soil), and the external radiation dose (again, due to the source material acting as a volume source from the ground). The inhalation dose from the plume release was determined using AIRDOS - EPA (EPA, 1979); while, the inhalation of resuspended dust was modeled atmospherically using AIRDOS with the dose assessment being determined using the methodology expressed in RESRAD (Gilbert, 1989). The external radiation dose to each exposure point was modeled in a similar fashion using both AIRDOS and RESRAD.

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3.3 Quantifying the Exposure Assessment

The final step in characterizing the exposure assessment process is to quantify the pathway analysis in terms of magnitude, frequency, and duration of exposure for each of the significant exposure points based on either the acute releases or the chronic release. Exposure is defined as the contact of an exposure point with the radionuclide (either by inhalation or external radiation dose). The information previously discussed detailing the atmospheric distribution of the material will be used directly to calculate the exposure point doses and exposure levels. Table 3.2 illustrates the exposure point concentrations for each radionuclide as a result of an acute release, except for radon-222 which is only used in the calculation of the plume inhalation pathway. Table 3.1 listed the concentrations for radon 222 as a result of a chronic release.

Table 3.2: Surface Soil Exposure Point Concentrations for each Radionuclide (Based on the Atmospheric Distribution of Source Material from the K-65 Silos)

Exposure Point	Radionuclide	Concentration (pCi/g of soil)
Work Force (100 meter Distance)	U-238	1.07
	U-234	1.07
	Ra-226	50.0
	Th-230	35.3
Nearest Resident (500 meter Distance)	U-238	0.049
	U-234	0.049
	Ra-226	2.34
	Th-230	1.6
Nearest Population (14,500 meter Distance)	U-238	0.002
	U-234	0.002
	Ra-226	0.1
	Th-230	7.56×10^{-6}

External Radiation Pathway

The calculation of exposure point doses for the external radiation pathway is based on the methodology contained in the RESRAD manual (Gilbert, 1989). Equation 3.1 shows the basic formula used to calculate the external radiation dose. These doses are based on the acute catastrophic release, as may occur in a severe weather event.

$$Dose_{i1} = \frac{Conc._i\,(\frac{pCi}{g}) \times DCF_{i1}\,(\frac{mrem/yr}{pCi/g}) \times \rho_b\,(\frac{g}{cm^3}) \times FO_1}{1000\ mrem/rem} \qquad (3.1)$$

$Dose_{i1}$ = Dose from the i^{th} radionuclide over the external radiation pathway, 1, in units of rem per year.

$Conc._i$ = Concentration of the i^{th} radionuclide in units of picocurie per gram of soil.

DCF_{i1} = Dose Conversion Factor of the i^{th} radionuclide with units of millirem per year per picocurie per gram of soil.

ρ_b = Bulk density of soil with units of grams per cubic centimeter.

FO_1 = Occupancy factor for direct radiation pathway, 0.6.

This pathway is based on an accidental release of material from the silos during a severe weather event. During a tornado, for instance, a certain percentage of material will be blown from the silos and will remain suspended in air as fine particulate matter and result in a plume inhalation dose, while the majority of the material will settle in decreasing quantities with the increasing distance from the silos. The dose calculated in Equation 3.1 is the annual effective dose equivalent for external radiation from this deposited material. The concentration refers to the radionuclide concentration in the surface soil with units of picocuries per gram of soil. The bulk density of the soil is given by ρ with units of grams per cubic centimeter. The final term of Equation 3.1 is the occupancy and shielding factor, defined as 0.6 in RESRAD. Table 3.3 lists the doses calculated for the exposure points from the external radiation pathway. In Table 3.3 the total dose, abbreviated EDE for effective dose equivalent, refers to the summation of all four radionuclides for each exposure point.

Table 3.3: Exposure Point Doses for the External Radiation Dose (Acute Case A1) (Based on the Atmospheric Distribution of Source Material from the K-65 Silos)

Exposure Point	Radionuclide	Dose (rem/yr)
Work Force (100 meter Distance)	U-238	8.1×10^{-5}
	U-234	8.1×10^{-7}
	Ra-226	0.46
	Th-230	4.0×10^{-5}
Total Dose (EDE)		**0.46**
Nearest Resident (500 meter Distance)	U-238	3.7×10^{-6}
	U-234	3.7×10^{-8}
	Ra-226	0.022
	Th-230	1.8×10^{-6}
Total Dose (EDE)		**0.022**
Population (14,500 meter Distance)	U-238	1.5×10^{-7}
	U-234	1.5×10^{-9}
	Ra-226	1.0×10^{-3}
	Th-230	8.4×10^{-12}
Total Dose (EDE)		**1×10^{-3}**

Inhalation of Resuspended Dust (Acute Release)

The inhalation of resuspended dust pathway also follows the methodology contained in the Gilbert manual. This pathway is also based on the release of material from the silos during a severe weather event. During a tornado a certain percentage of material will be blown from the silos and will remain suspended in air as fine particulate and result in a plume inhalation dose, while the majority of the material will settle in decreasing quantities with the increasing distance from the silos. This deposited material, whose distribution was determined by the AIRDOS-EPA code, was used to calculate the inhalation of resuspended dust dose.

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Inhalation of Resuspended Dust (Acute Release A1) continued

Equation 3.2 illustrates the dose calculation for the inhalation of resuspended dust pathway. The term ASR refers to the air-to-soil concentration ratio (dust loading), a RESRAD default value of 2 x 10^{-4} g/m^3 was used. The term FI refers to the annual inhalation rate (7300 m^3 per year). The value of 0.6 is used as an occupancy factor (Gilbert, 1989). Table 3.4 lists the exposure point doses for this pathway.

$$Dose_{i21} = Conc._i \left(\frac{pCi}{g}\right) \times DCF_{i2} \left(\frac{mrem}{pCi}\right) \times FI_2 \left(\frac{m^3}{yr}\right) \times FO_2\ (0.6) \times ASR \left(\frac{g}{m^3}\right) \quad (3.2)$$

$Dose_{i21}$ = Dose to an individual at each significant exposure point from the i^{th} radionuclide over the inhalation pathway, 2, and subpathway of resuspended dust, 1, with units of mrem per year (converted to rem/yr).

$Conc._i$ = Concentration of the i^{th} radionuclide in the surface soil, with units of picocuries per gram of soil (pCi/g).

DCF_{i2} = Dose Conversion Factor for the i^{th} radionuclide with units of millirem per picocurie.

FI_2 = Inhalation rate of 7300 cubic meters per year (20 m^3/day).

FO_2 = Occupancy Factor for the inhalation pathway, 0.6.

ASR = Air-to-Soil Concentration Ratio or dust loading factor, with units of grams per cubic meter (g/m^3).

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Table 3.4: Exposure Point Doses for the Inhalation of Resuspended Dust Pathway (Acute Case A1) (Based on the Atmospheric Distribution of Source Material from the K- 65 Silos)

Exposure Point	Radionuclide	Dose (rem/yr)
Work Force	U-238	7.7 x 10^{-5}
(100 meter Distance)	U-234	8.3 x 10^{-5}
	Ra-226	2.4 x 10^{-4}
	Th-230	6.8 x 10^{-3}
Total Dose (CEDE)		**7.2 x 10^{-3}**
Nearest Resident	U-238	5.2 x 10^{-6}
(500 meter Distance)	U-234	5.6 x 10^{-6}
	Ra-226	1.6 x 10^{-5}
	Th-230	4.6 x 10^{-4}
Total Dose (CEDE)		**4.9 x 10^{-4}**
Population	U-238	2.1 x 10^{-7}
(14,500 meter Distance)	U-234	2.3 x 10^{-7}
	Ra-226	7.6 x 10^{-7}
	Th-230	2.1 x 10^{-9}
Total Dose (CEDE)		**1.2 x 10^{-6}**

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Inhalation of Gaseous Plume Pathway

The plume inhalation pathway is based on the quantity of suspended particulates resulting from a severe weather event disrupting the silo's integrity. As with the other two pathways, this pathway's results are based on the release of four significant radionuclides: uranium-238, uranium-234, radium-226, thorium-230, and radon-222. The calculations for this pathway were determined using AIRDOS EPA to model the atmospheric transport of the puff release and the methodology described by Gilbert to calculate the dose. The models utilized in the AIRDOS code were previously described. Equation 3.3 illustrates the calculation of the plume inhalation dose. Table 3.5 lists the doses at each exposure point which were determined for this pathway. The total dose refers to the summation of doses for each of the five radionuclides, with the abbreviation of CEDE referring to the annual committed effective dose equivalent.

$$Dose_{i22} = \text{Air Conc.} \left(\frac{pCi}{m^3}\right) \times FI_2 \times ED \times \left(\frac{10^{-6}\mu Ci}{pCi}\right) \times DCF_{i2} \qquad (3.3)$$

where the terms of Equation 3.3 are defined as follows:

$Dose_{i22}$ = Dose from the i^{th} radionuclide to an individual at a significant exposure point over the inhalation pathway, 2, and the subpathway of the gaseous plume release, 2, with units of rem per year.

Air Conc. = Air Concentration of i^{th} radionuclide at significant exposure point with units of picocuries per cubic meter. Modeled using the AIRDOS-EPA code.

FI_2 = Inhalation intake rate for individual at significant exposure point with units of cubic meters per hour (0.833 m^3/hr).

ED = Exposure Duration for an individual at each significant exposure point (1 hour).

DCF_{i2} = Dose Conversion Factor for the i^{th} radionuclide with with units of (rem/μCi) or (rem/pCi).

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Table 3.5: Exposure Point Doses for the Inhalation of an Acute Atmospheric Release of Material from the K-65 Silos (Acute Case A1) (Based on 1 Hour Exposure Period)

Exposure Point	Radionuclide	Dose (rem/yr)
Work Force (100 meter Distance)	U-238	2.8×10^{-1}
	U-234	3.0×10^{-1}
	Ra-226	9.2×10^{-1}
	Th-230	2.6×10^{1}
	Rn-222	2.8
Total Dose (CEDE)		**3.05×10^{1}**
Nearest Resident (500 meter Distance)	U-238	1.4×10^{-2}
	U-234	1.5×10^{-2}
	Ra-226	4.3×10^{-2}
	Th-230	1.2×10^{0}
	Rn-222	1.3×10^{-1}
Total Dose (CEDE)		**1.43**
Population (14,500 meter Distance)	U-238	1.8×10^{-7}
	U-234	2.0×10^{-7}
	Ra-226	5.6×10^{-7}
	Th-230	1.6×10^{-5}
	Rn-222	2.3×10^{-4}
Total Dose (CEDE)		**2.5×10^{-4}**

Summation of Doses for each Exposure Point (Acute Case A1)

The final task of the exposure assessment phase for the acute release case A1 is to determine the total dose to each exposure point based on the summation of the applicable pathways. The three pathways analyzed for the dose assessment, external radiation, inhalation of plume release, and inhalation of resuspended dust, are complete pathways given silo failure for each of the exposure points. Table 3.6 lists the total doses for each exposure point based on the acute release of uranium-238, 234, radium-226, thorium-230, and radon-222.

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Table 3.6: Total Doses at each Exposure Point - for the Acute Case A1 (Based on the Plume Inhalation Dose, Inhalation of Resuspended Dust, and External Radiation Dose)

Exposure Point	Radionuclides	Dose (rem - 1 year)
Work Force (100 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**3.1×10^{1}**
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**1.5**
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	**1.3×10^{-3}**

Exposure Assessment of the Acute Total Release of Radon-222 - Case A2

The exposure assessment of the acute total release of radon-222, designated as case A2, is a subset of the gaseous plume inhalation dose which is designated as case A1. Therefore, the methodology used to determine the acute radon-222 dose at each exposure point is the same as that which was previously discussed in Equation 3.3. This pathway is based on the partial failure of the silo's structure to the extent that only radon-222 can escape. Table 3.7 lists the doses determined for the acute case A2, the total release of radon-222.

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Table 3.7: Doses at each Exposure Point for the Acute Case A2 (Based on the Total Release of Radon-222)

Exposure Point	Radionuclide	Dose (rem)
Work Force (100 meter Distance)		
Total Dose (CEDE)	Rn-222	2.8
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	Rn-222	0.13
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	Rn-222	2.3×10^{-4}

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Exposure Assessment of the Chronic Release

Exposure to individuals at each of the significant exposure points from radon-222 occurs on a daily basis. The details of the chronic case were previously described. The environmental transport modeling, the exposure points, and the pathways are the same as the acute cases and as a result will not be discussed here. The primary difference is in the source term available, since only radon will be available for the chronic case. Table 3.8 lists the exposure point doses for the chronic case.

Table 3.8: Exposure Point Doses for the Chronic Case - Radon-222 Release

Exposure Point	Dose (rem/yr)
Work Force (100 meter Distance) (CEDE)	2.57
Nearest Resident (500 meter Distance) (CEDE)	0.21
Population (14,500 meter Distance) (CEDE)	1.2×10^{-3}

Summary of Exposure Assessment

The exposure assessment process is composed of three components: 1) the characterization of the exposure setting, 2) the identification of the exposure pathways, and 3) the determination of exposure point doses. The characterization of the exposure setting consisted of identifying the physical characteristics of the region around the K-65 silos which would lead to the transport of contaminants from the silos to the potential exposure points. Three significant exposure points were identified as reasonable maximum exposure points. The principal contaminant transport route identified was that of atmospheric transport. The atmospheric distribution of radionuclides from the silos to the surrounding region results in three pathways which contribute to the dose assessment of each significant exposure point. The three exposure pathways are inhalation of the puff release, inhalation of the resuspended dust after radionuclides have been deposited on the surface soil, and the external radiation resulting from the atmospherically deposited radionuclides. Quantifying the exposure assessment consisted of determining the exposure point concentrations for each radionuclide in the air and surface soil. The principal radionuclides which were investigated: uranium-238, uranium-234, radium-226, thorium-230, and radon-222. Dose conversion factors from the Department of Energy (DOE, 1988) and the AIRDOS EPA computer code were used to calculate the doses to an individual at each exposure point.

Table 3.6 lists the total doses to an individual at each exposure point for the acute case A1. These doses reflect an individual's total dose, given the assumptions of the A1 case of silo failure, for the first year. Table 3.7 lists the doses for the acute A2 case of silo failure. These doses represent both the first year dose and the five year dose since the probability of silo failure is based on one occurrence in the next five years. Table 3.8 lists the doses for the chronic radon-222 case at each of the exposure points. These doses are in units of rem per year since they represent the annual dose that an individual at each of the three exposure points could receive, given the assumptions, each year.

Summary of Exposure Assessment (continued)

Table 3.6: Total Doses at each Exposure Point for the Acute Case A1

Exposure Point	Radionuclides	Dose (rem - 1 year)
Work Force (100 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	3.1×10^{1}
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	1.5
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	U-238, 234, Ra-226, Th-230 Rn-222	1.3×10^{-3}

Table 3.7: Doses at each Exposure Point for the Acute Case A2

Exposure Point	Radionuclide	Dose (rem)
Work Force (100 meter Distance)		
Total Dose (CEDE)	Rn-222	2.8
Nearest Resident (500 meter Distance)		
Total Dose (CEDE)	Rn-222	0.13
Population (14,500 meter Distance) (individual of Population)		
Total Dose (CEDE)	Rn-222	2.3×10^{-4}

Summary of Exposure Assessment (continued)

Table 3.8: Exposure Point Doses for the Chronic Case - Radon-222 Release

Exposure Point	Dose (rem/yr)
Work Force (100 meter Distance) (CEDE)	2.57
Nearest Resident (500 meter Distance) (CEDE)	0.21
Population (14,500 meter Distance) (CEDE)	1.2×10^{-3}

4.0 Risk Characterization

Introduction

This section of the investigation deals with the final step of the baseline health risk assessment process, the risk characterization phase. In this step the exposure assessments are summarized and integrated into quantitative and qualitative expressions of risk. In the following sections the risk characterization methodology is developed for each exposure point from the perspective of the acute case and the chronic case. The acute case has two subcategories which are either the catastrophic release of the silos contents from natural forces, such as a tornado, or a total release of radon resulting from the ultimate failure of the silos due to their continued structural degradation.

In the preceding draft report, "A Baseline Risk Assessment for the K-65 Silos Using EPA Methodology for Applicability to the EE/CA," the risk characterization step was performed by multiplying the ICRP risk coefficient, 2×10^{-4} risk per rem of exposure, by each of the particular exposure point doses in order to determine annual risks. These risks were then coupled with the probabilities associated with the two classes of failure modes which are severe weather conditions and natural degradation of the concrete structure in order to quantify the annual risks.

The following paragraphs present a revision of the risk characterization methodology detailed in the draft report. Also contained in the following discussion is a risk characterization using the newly acquired Environmental Protection Agency's methodology for determining risks from radionuclides. The Office of Radiation Programs (ORP) has recently issued these radionuclide carcinogenic slope factors for the purpose of conducting health risk assessments. The "Slope Factors" were obtained directly from ORP in the form of the Health Effects Assessment Summary Table C (HEAST Table C). The methodology presented in this report for using these slope factors is contained in Chapter 10 of the Human Health Evaluation Manual (EPA, 1989) which details the EPA method for performing radiation risk assessments . Table 4.0 presents a summary of the pathway analysis methodology for the acute and chronic cases. Table 4.1 presents a summary of the risk characterization methodologies.

The risk characterization methodologies outlined in Table 4.1 are based on the effective dose equivalent risk coefficient and the EPA lifetime, age-averaged slope factors. The risk coefficient method expresses the risk as an annual risk. The annual risk can be multiplied by 70 years to give the lifetime risk. Slope factors were derived to represent the lifetime risk. Both methodologies will be presented in this investigation in order to compare the results from the draft study with the results obtained by using the updated risk information obtained from the Environmental Protection Agency.

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Table 4.0: Pathway Analysis Methodology for the Acute and Chronic Cases

<u>Acute Case - Catastrophic Release (A1)</u>

Radionuclides Released:	Uranium-238, Uranium-234, Thorium-230, Radium-226, and Radon-222.
Pathways Analyzed:	Inhalation of gaseous plume (1 hour exposure). Inhalation of resuspended dust. External Exposure from radionuclides.
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

<u>Acute Case - Total Release of Radon (A2)</u>

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon plume (1 hour).
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

<u>Chronic Case - Daily Release of Radon-222</u>

Radionuclide Released:	Radon-222
Pathway Analyzed:	Inhalation of radon-222
Exposure Points:	Worker (100 meters). Nearest Resident (500 meters). Population Center (14.5 kilometers)

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Table 4.1: Risk Characterization Methodologies

Release Case	Risk Coefficient Methods	Slope Factor Methods
Acute Catastrophic Release (A1)	$\sum_p EDE_{ipq} \times RC \times P_{A1}$	$\sum_p EL_{ipq} \times SF_{ip} \times P_{A1}$
	$\sum_p EDE_{ipq} \times RC$	$\sum_p EL_{ipq} \times SF_{ip}$
Acute Total Rn-222 Release (A2)	$EDE_{ipq} \times RC \times P_{A2}$	$EL_{ipq} \times SF_{ip} \times P_{A2}$
	$EDE_{ipq} \times RC$	$EL_{ipq} \times SF_{ip}$
Chronic Rn-222 Release	$EDE_{ipq} \times RC$	$EL_{ipq} \times SF_{ip}$

Where the terms of Table 4.1 are defined as follows:

EDE_{ip} = Effective Dose Equivalent for pathway p, exposure point q, and radionuclide i (rem/year).

RC = Risk Coefficient, 2×10^{-4} risk per rem of exposure.

P_{A1} = Probability associated with the acute case of catastrophic release, designated by subscript A1.

EL_{ip} = Exposure Level for pathway p, exposure point q, and radionuclide i (pCi).

SF_{ip} = EPA Slope Factor for pathway p and radionuclide i with units of either $(pCi)^{-1}$ or $(pCi/m^2/yr)^{-1}$.

P_{A2} = Probability associated with the acute case of total radon release, designated by subscript A2.

Defining the Risk Coefficient, RC

Risk is synonymous with a hazard or peril and appears as a loss or injury. Risk analysis addresses the probability related to this loss or injury. This view of risk, although simplified, provides a measure of the hazard. In everyday life risk is often expressed as a probability. This probability is often stated in very general terms. For example, the risk of being killed in a car accident is 1 in 4000. The EPA recently issued warnings regarding radon gas in the home. The EPA established an action level at 4 pCi/liter of air. This was based on the risk to individuals breathing this air. The risk to individuals from radon gas (its daughter products) is lung cancer incidence. EPA radon data indicates that radon gas at a level of 4 picocuries per liter would result in 13-50 lung cancer deaths per 1000 people exposed over their lifetime. This would be considered a lifetime risk of 50/1000 or 5×10^{-2}.

Evaluating the risk from chronic low level exposure to ionizing radiation has been the subject of countless research papers and prestigious scientific committee evaluations. Excellent discussions of the effect of low level ionizing radiation on humans can be found in the United Nations Scientific Committee on the Effects of Atomic Radiation (UN, 1977) and National Academy of Sciences / National Research Council Advisory Committee on the Biological Effects of Ionizing Radiation (known as BEIR III)(NAS, 1972). Both reports contain risk estimates for exposure to chronic low level ionizing radiation. These risk estimates vary and are the subject of much scientific discussion.

It is now widely acknowledged that the "risk" from low level exposure to ionizing radiation is the risk of a fatal cancer. Thus, the current discussion focuses on the risk coefficient associated with the induction of a fatal cancer. Most scientists (BEIR III, ICRP, and NCRP) now use a risk coefficient of 2×10^{-4} per rem of exposure. This means that if 10,000 people were exposed to 1 rem of radiation, there is a probability that 2 fatal cancers would be induced. Since the national cancer rate is about 21%, a cohort of 10,000 people will have 2100 "natural" cancer deaths.

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Defining the EPA Slope Factors, SF_{ip}

In the draft investigation the risk characterization step was performed by multiplying the dose equivalents for each exposure point by the ICRP risk coefficient of 2×10^{-4} risk per rem of exposure. This method yielded an estimate of risk but was not completely applicable for members of the general public. A better estimate of risk can be determined by using age averaged coefficients for individual organs receiving the radiation doses (EPA, 1989). This EPA method uses organ-specific dose conversion factors to derive slope factors that represent the age-averaged lifetime excess cancer incidence per unit intake for the radionuclides of concern. The Integrated Risk Information System (IRIS) is currently being updated to include these slope factors for various radionuclides over the principal pathways of exposure (EPA, 1989). At the time of the draft report, the IRIS network could not be accessed which is why the conventional method of using dose equivalent risk coefficients was used. Since the draft report carcinogenic slope factors for the radionuclides of concern have been obtained from the Office of Radiation Programs in Washington, D.C (EPA, 1990). The following sections define the equations associated with both the EPA slope factor method and the risk coefficient method.

Risk Characterization of Acute Case A1

The risk assessment methodology for the acute case A1 was outlined in Table 4.1. The two methodologies for characterizing risk which are described in Table 4.1 are the risk coefficient method and slope factor method. The results of the risk coefficient method will be illustrated first.

Risk Coefficient Method

Table 4.2 lists the total doses to an individual of each exposure point for the acute case A1. The doses are in units of rem per year and represent the annual contribution to the 50 year committed effective dose equivalent from a one year intake. If the exposure duration for each exposure point were a lifetime, a lifetime dose could be determined by multiplying these total doses by a lifetime of 50 or 70 years. The Environmental Protection Agency assumes a lifetime is 70 years. However, this assessment assumed exposure over the inhalation of resuspended dust and the external radiation pathways would occur for the period of one-to-five years. The puff release pathway was assumed to have an exposure period of one hour. Therefore, the doses from the inhalation of resuspended dust and the external irradiation pathways are multiplied by 5 years to represent their total dose contribution to each exposure point over the five year exposure duration.

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Risk Characterization of Acute Case A1 (continued)

Table 4.2: Total Doses to an Individual of each Exposure Point for the Acute Case A1

Exposure Point	Total Dose (first year) (rem)	Total Dose (five year) (rem)
Work Force	30.9	32.8
Nearest Resident	1.45	1.54
Population	1.3×10^{-3}	5.3×10^{-3}

Risk Coefficient Method (continued)

The risk coefficient methodology is expressed in Equation 4.0. The risk coefficient (RC) is 2×10^{-4} risk per rem of exposure and the dose ($D_{case,EP}$) is the total dose for each particular case and exposure point.

$$\mathbf{Risk_{case,EP} = RC \times D_{case,EP}} \qquad (4.0)$$

Table 4.3 lists the risks determined using the risk coefficient method for first year exposure and also the risk for the total five year exposure duration.

Table 4.3: Risks to an Individual of each Exposure Point for the Acute Case A1 Based on the Risk Coefficient Method

Exposure Point	Risk (first year)	Risk (five year)
Work Force	6.2×10^{-3}	6.6×10^{-3}
Nearest Resident	2.9×10^{-4}	3.1×10^{-4}
Population	2.5×10^{-7}	1.1×10^{-6}

Risk Characterization of Acute Case A1 (continued)

Risk Coefficient Method (continued)

Risks were also developed using the risk coefficient method and the probability of silo failure for the acute case A1. The general formula for determining risk by incorporating the probability of silo failure is shown in Equation 4.1, where P defines the probability associated with the particular case. Table 4.4 lists the risks as reflected by including the probability of silo failure for the acute case A1. This probabilistic risk assessment methodology is included since it reflects a more realistic assessment of the risk associated with the failure of the silos by a severe weather event. The development of the probabilities was discussed in Section 2.0 and Table 4.4a lists the probabilities for the acute case A1: probability per year and probability over the 5 year exposure duration.

$$Risk_{case,EP} = RC \times D_{case,EP} \times P_{case} \quad (4.1)$$

Table 4.4a: Probabilities for the Acute Case A1 - Severe Weather Event

Probability Description	Silo 1	Silo 2	Average
Probability per year	1.25×10^{-4}	1.25×10^{-4}	1.25×10^{-4}
Probability over 5 years	6.25×10^{-4}	6.25×10^{-4}	6.25×10^{-4}

Table 4.4: Risks to an Individual of each Exposure Point for the Acute Case A1
Based on the Risk Coefficient Method and the Associated Probability

Exposure Point	Risk (five year)	Risk (Probability)
Work Force	6.6×10^{-3}	4.1×10^{-6}
Nearest Resident	3.1×10^{-4}	1.9×10^{-7}
Population	1.1×10^{-6}	6.7×10^{-10}

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method

The carcinogenic slope factor method is based on the United States Environmental Protection Agency's risk assessment methodology for radionuclides (EPA, 1989). The EPA classifies all radionuclides as Group A carcinogens based on their property of emitting ionizing radiation and on the extensive weight of evidence provided by epidemiological studies of ionizing radiation induced cancers in humans (EPA, 1990). The U.S. EPA use data derived from both human epidemiological studies and animal experiments to construct mathematical models of exposure, dose, and risk in order to estimate radionuclide slope factor values. The complex models utilized by the EPA consider pathways of exposure, the distinct metabolic behavior of each element by compound and the radiological characteristics of each nuclide of concern, the time and duration of exposure, the radiosensitivity of each target organ in the body, the latency period for cancer expression in these organs, and the age and sex of individuals in the exposed population. The radiation risk models extrapolate cancer risks due to low dose exposures from risks observed at higher doses using linear, dose-response relationships.

Slope factors for radionuclides are characterized as best estimates (maximum likelihood estimates) of the age-averaged total lifetime excess cancer incidence, total cancers, per unit intake or exposure. Quantitative carcinogenic slope factors for radionuclides estimate the risk per unit intake or exposure. More specifically, they represent the risk per picocurie inhaled or ingested or as the risk per picocurie per square meter per year due to external exposure.

The acute case A1 is based on an individual at each exposure point receiving a dose of radiation from three pathways: 1) external radiation pathway, 2) inhalation of resuspended dust pathway, and 3) inhalation of gaseous plume pathway. The following paragraphs detail each of these pathways as they are developed using the EPA's radionuclide slope factors.

External Radiation Pathway

The EPA derived risk associated with the external radiation pathway is defined by Equation 4.2.

$$\mathbf{Risk_{ipq} = Conc_{is} \times FO_1 \times \rho_b \times 1000\ g/kg \times SF_{ip} \times ED} \qquad (4.2)$$

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

External Radiation Pathway (continued)

The terms of Equation 4.2 are described as follows:

$Risk_{ipq}$ = EPA based age-averaged, lifetime risk for i^{th} radionuclide, pathway p, and exposure point q.

$Conc_{is}$ = Concentration of i^{th} radionuclide in surface soil with units of pCi/g of soil.

FO_1 = Occupancy Factor for the direct radiation pathway.

ρ_b = Bulk Surface Density of contaminated soil with units of kg/m^2.

ED = Exposure Duration, 5 years.

SF_{ip} = Slope Factor for radionuclide i and pathway p with units of $(pCi)^{-1}$ or $(pCi/m^2/yr)^{-1}$.

Table 4.5 lists the risks determined for the external radiation pathway using the EPA methodology of the carcinogenic slope factors. As one would expect the highest risk exists for an individual of the work force exposed to radium-226, since it emits a high energy gamma-ray.

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

Table 4.5: Risks Determined for the External Radiation Pathway of the Acute Case A1 - Based on the EPA Slope Factor Methodology

Exposure Point	Radionuclide	Risk
Work Force	Uranium-238	2.7×10^{-8}
	Uranium-234	3.3×10^{-8}
	Radium-226	1.1×10^{-5}
	Thorium-230	1.1×10^{-6}
Total Risk		**1.3×10^{-5}**
Resident	Uranium-238	1.2×10^{-9}
	Uranium-234	1.5×10^{-9}
	Radium-226	5.3×10^{-7}
	Thorium-230	5.2×10^{-8}
Total Risk		**5.9×10^{-7}**
Population	Uranium-238	5.0×10^{-11}
	Uranium-234	6.2×10^{-11}
	Radium-226	2.5×10^{-8}
	Thorium-230	2.4×10^{-13}
Total Risk		**2.5×10^{-8}**

Inhalation of Resuspended Dust Pathway

The inhalation of resuspended dust pathway is based on the same environmental transport properties as those discussed in Section 3 which characterized the dose assessment. Equation 4.3 illustrates the methodology used to characterize the inhalation of resuspended dust pathway using the EPA based risk techniques.

$$\mathbf{Risk_{ipq} = Conc_{is} \times FO_2 \times ASR \times FI_2 \times ED \times EF \times SF_{ip}} \quad (4.3)$$

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

Inhalation of Resuspended Dust Pathway (continued)

The terms of Equation 4.3 are defined as follows:

$Risk_{ipq}$ = EPA based age-averaged, lifetime risk for i^{th} radionuclide, pathway p, and exposure point q.

$Conc_{is}$ = Concentration of radionuclide i in surface soil with units of pCi/g of soil.

FO_2 = Occupancy Factor for the inhalation pathway, 0.6.

ASR = Air-to-Soil Concentration Ratio, 2 x 10^{-4} g/m^3.

FI_2 = Air Intake Rate, 20 m^3/day.

ED = Exposure Duration, 5 years.

EF = Exposure Frequency, 365 days/year or 250 days/year.

SF_{ip} = Slope Factor for radionuclide i for the inhalation pathway p, with units of $(pCi)^{-1}$.

Table 4.6 lists the risks for the inhalation of resuspended dust pathway determined using the EPA based methodology. The highest risk for this pathway is contributed by thorium-230.

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

Table 4.6: Risks Determined for the Inhalation of Resuspended Dust Pathway of the Acute Case A1 - Based on the EPA Slope Factor Methodology

Exposure Point	Radionuclide	Risk
Work Force	Uranium-238	7.7×10^{-8}
	Uranium-234	8.7×10^{-8}
	Radium-226	4.5×10^{-7}
	Thorium-230	3.3×10^{-6}
Total Risk		**3.9×10^{-6}**
Resident	Uranium-238	5.2×10^{-9}
	Uranium-234	5.8×10^{-9}
	Radium-226	3.1×10^{-8}
	Thorium-230	2.2×10^{-7}
Total Risk		**2.6×10^{-7}**
Population	Uranium-238	2.1×10^{-10}
	Uranium-234	2.4×10^{-10}
	Radium-226	1.5×10^{-9}
	Thorium-230	1.0×10^{-12}
Total Risk		**1.9×10^{-9}**

Inhalation of Gaseous Plume Release

The inhalation of the gaseous plume release is characterized by Equation 4.4. This pathway is based on a puff release from the silos, which is initiated by a severe weather event, with the exposure period at each exposure point being one hour.

$$\mathbf{Risk_{ipq} = Conc_{ia} \times FI_2 \times ED \times 1 \times 10^{12}\ pCi/Ci \times SF_{ip}} \qquad (4.4)$$

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

Inhalation of Gaseous Plume Release Pathway (continued)

The terms of Equation 4.4 are defined as follows:

$Risk_{ipq}$ = EPA based age-averaged, lifetime risk for i^{th} radionuclide, pathway p, and exposure point q.

$Conc_{ia}$ = Concentration of radionuclide i in air with units of Ci/m^3 of air (modeled using AIRDOS).

FI_2 = Air Intake Rate, 0.833 m^3/hour.

ED = Exposure Duration, 1 hour.

SF_{ip} = Slope Factor for radionuclide i for the inhalation pathway p, with units of $(pCi)^{-1}$.

Table 4.7 lists the risks determined for the acute case A1 of the gaseous plume release pathway. Observe that the exposure duration for this pathway is one hour, based on the estimated length of time of the severe weather event. The most critical radionuclide is the thorium-230.

Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

Table 4.7: Risks Determined for the Inhalation of Gaseous Plume Release Pathway of the Acute Case A1 - Based on the EPA Slope Factor Methodology

Exposure Point	Radionuclide	Risk
Work Force	Uranium-238	5.6×10^{-5}
	Uranium-234	5.6×10^{-5}
	Radium-226	3.5×10^{-4}
	Thorium-230	2.5×10^{-3}
	Radon-222	2.0×10^{-5}
Total Risk		**3.0×10^{-3}**
Resident	Uranium-238	2.8×10^{-6}
	Uranium-234	2.8×10^{-6}
	Radium-226	1.6×10^{-5}
	Thorium-230	1.2×10^{-4}
	Radon-222	9.2×10^{-7}
Total Risk		**1.4×10^{-4}**
Population	Uranium-238	3.6×10^{-11}
	Uranium-234	3.6×10^{-11}
	Radium-226	2.1×10^{-10}
	Thorium-230	1.5×10^{-9}
	Radon-222	1.6×10^{-9}
Total Risk		**3.5×10^{-9}**

The Total Risk for each Exposure Point - Acute Case A1

The total risk for each exposure point is defined by Equation 4.5. Each exposure point, under the acute case A1, is assumed to be exposed through the three previously discussed pathways.

$$\mathbf{Risk_q = \Sigma_{ip}\, EL_{ipq} \times SF_{ip}} \qquad (4.5)$$

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Risk Characterization of Acute Case A1 (continued)

Carcinogenic Slope Factor Method (continued)

The Total Risk for each Exposure Point - Acute Case A1 (continued)

Table 4.8 lists the total risks for each exposure point for the acute case A1. These risks represent the Environmental Protection Agency's methodology for determining the lifetime cancer risk from the intake or exposure to radionuclides.

Table 4.8: Total Risks Determined for the Acute Case A1 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	3.0×10^{-3}
Resident	1.4×10^{-4}
Population	3.0×10^{-8}

In a similar fashion, the total risks for the acute case A1, expressed above, can be modified to reflect the probability of silo failure under the acute case A1 and in the process present a more realistic estimate of the risk associated with the failure of the K-65 silos. These enhanced risks are listed in Table 4.9. The average probability of silo failure over the 5 year exposure duration was used to determine the risks in Table 4.9. The probabilities for the acute case A1 are listed in Table 4.4a.

Table 4.9: Total Risks Determined for the Acute Case A1 - Based on the EPA Slope Factor Methodology and the Probability of Silo Failure

Exposure Point	Risk
Work Force	2.0×10^{-6}
Resident	8.9×10^{-8}
Population	1.9×10^{-11}

Risk Characterization of Acute Case A2

Risk Coefficient Method

Table 4.10 lists the doses from radon-222 for the acute case A2 at each exposure point. The acute case A2 is similar to the acute case A1. The difference is manifested in the type of event which leads to the silo failure. The failure of the silos for the acute case A2 is based on the natural or continued degradation of the silo's structure. The risks for this case were developed in a similar fashion as for the acute case A1. First, the risks at each exposure point will be estimated using the risk coefficient method and then the risks at each exposure point will be estimated again but with the additional influence of the acute case A1 probability. Equation 4.6 illustrates the risk calculation for the conventional method of simply multiplying the risk coefficient by the dose equivalent. Equation 4.7 illustrates the risk calculation for the risk coefficient method using the probability of silo failure given the natural degradation case.

$$\mathbf{Risk_q = \Sigma_{ip}\, Dose_{ipq} \times RC} \qquad (4.6)$$

$$\mathbf{Risk_{qp} = \Sigma_{ip}\, Dose_{ipq} \times RC \times P_{A2}} \qquad (4.7)$$

The terms of Equations 4.6 and 4.7 are defined as follows:

$\mathbf{Risk_q}$ = Risk to Exposure Point q based on the risk coefficient method.

$\mathbf{Risk_{qp}}$ = Risk to Exposure Point q based on risk coefficient method and Probability A2.

$\mathbf{Dose_{ipq}}$ = Dose for radionuclide i, pathway p, and exposure point q.

RC = Risk Coefficient, 2×10^{-4} risk per rem of exposure.

Table 4.11 illustrates the risks determined from the doses in Table 4.10 using the risk coefficient value.

Risk Characterization of Acute Case A2

Risk Coefficient Method (continued)

Table 4.10: Doses at each Exposure Point for the Acute Case A2

Exposure Point	Dose (rem)
Work Force (100 meter Distance)	2.8
Nearest Resident (500 meter Distance)	0.13
Population (14,500 meter Distance) (Individual of Population)	2.3×10^{-4}

Table 4.11: Risks at each Exposure Point for the Acute Case A2 Based on the Risk Coefficient Method

Exposure Point	Risk
Work Force (100 meter Distance)	5.7×10^{-4}
Nearest Resident (500 meter Distance)	2.6×10^{-5}
Population (14,500 meter Distance) (Individual of Population)	4.6×10^{-8}

The risks in Table 4.11 can be enhanced by multiplying by the probability of silo failure for the acute case A2. These modified risks are listed in Table 4.12. Table 4.12a lists the probabilities for the acute case A2.

Risk Characterization of Acute Case A2 (continued)

Risk Coefficient Method (continued)

Table 4.12a: Probabilities for the Acute Case A2 - Natural Degradation

Probability Description	Silo 1	Silo 2	Average
Probability per year	0.036	0.0336	0.0348
Probability over 5 years	0.180	0.168	0.174

Table 4.12: Risks at each Exposure Point for the Acute Case A2 Based on the Risk Coefficient Method and the Probability of Silo Failure

Exposure Point	Risk
Work Force (100 meter Distance)	1.0×10^{-4}
Nearest Resident (500 meter Distance)	4.5×10^{-6}
Population (14,500 meter Distance) (Individual of Population)	8.1×10^{-9}

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Risk Characterization of Acute Case A2 (continued)

Slope Factor Method

The slope factor risk method for the acute case A2 is similar to the risk coefficient method, except instead of determining the exposure point dose one determines an *Exposure Level* . The exposure level is then multiplied by the pathway and radionuclide specific slope factor in order to characterize the lifetime, age-averaged cancer risk for an individual at each exposure point. Equation 4.8 describes the risk determined by using the slope factor methodology. Equation 4.9 illustrates the slope factor risk but with the addition of the acute case A2 probability of silo failure.

$$\mathbf{Risk_q = \Sigma_{ip}\, EL_{ipq} \times SF_{ip}} \qquad (4.8)$$

$$\mathbf{Risk_{qp} = \Sigma_{ip}\, EL_{ipq} \times SF_{ip} \times P_{A2}} \qquad (4.9)$$

The terms of Equations 4.8 and 4.9 are defined below.

$Risk_q$ = Slope Factor Risk for exposure point q.

EL_{ipq} = Exposure Level for radionuclide i, pathway p, and slope factor of radionuclide i and pathway p. This case is only for radon-222 and the inhalation pathway.

SF_{ip} = Slope Factor for radionuclide i and pathway p with units of $(pCi)^{-1}$ or $(pCi/m^2/yr)^{-1}$.

$Risk_{qp}$ = Slope Factor Risk for exposure point q with the Probability (A2) of silo failure included.

P_{A2} = Probability of Silo Failure for the natural degradation case.

The exposure Level, $EL_{radon\text{-}222q}$, is defined by Equation 4.10.

$$\mathbf{EL_{radon\text{-}222q} = Conc_{air} \times FI_2 \times ED \times CF} \qquad (4.10)$$

Risk Characterization of Acute Case A2 (continued)

Slope Factor Method (continued)

The terms of Equation 4.10 are defined as follows:

$EL_{radon\text{-}222q}$ = Exposure Level for the acute A2 case considering radon-222 over the inhalation pathway.

$Conc_{air}$ = Air Concentration modeled using AIRDOS EPA, Ci/m^3.

FI_2 = Inhalation Rate, 0.833 m^3/hr.

ED = Exposure Duration for acute case A2, 1 hour.

CF = Conversion Factor, pCi/Ci.

Table 4.13 lists the risks at each exposure point for the acute case A2 determined by using the slope factor methodology. Table 4.14 lists the slope factor risks at each exposure point for the acute case A2 with the addition of the probability of silo failure, P_{A2}. These probabilities were listed in Table 4.12a.

Table 4.13: Total Risks Determined for the Acute Case A2 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	2.0×10^{-5}
Resident	9.2×10^{-7}
Population	1.6×10^{-9}

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Risk Characterization of Acute Case A2 (continued)

Slope Factor Method (continued)

Table 4.14: Total Risks Determined for the Acute Case A2 - Based on the EPA Slope Factor Methodology and the Probability of Silo Failure

Exposure Point	Risk
Work Force	3.5×10^{-6}
Resident	1.6×10^{-7}
Population	2.9×10^{-10}

Risk Characterization for the Chronic Radon-222 Case

Risk Coefficient Method

The final case examined in this investigation are the risks associated with the ongoing radon emissions from the K-65 silos. This case is not based on silo failure, but rather on the fact that radon-222 is emanating from the silos, primarily the dome, on a daily basis. Equation 4.11 illustrates the risk calculation for the chronic case using the risk coefficient method. The subscript q refers to the exposure point.

$$\mathbf{Risk_q = Dose_{Rn\text{-}222q} \times RC} \qquad (4.11)$$

Table 4.15 lists the doses for the chronic radon case. Also listed in Table 4.15 are the risks at each exposure point for the chronic case. Note that the risks illustrated are annual risks and total risks which were determined by multiplying the annual risks by the 5 year exposure period.

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Risk Characterization for the Chronic Radon-222 Case (continued)

Risk Coefficient Method (continued)

Table 4.15: Doses and Risks at each Exposure Point for the Chronic Radon Case Based on the Risk Coefficient Method

Exposure Point	Annual Dose (rem/year)	Total Dose (rem)	Annual Risk	Total Risk
Worker	2.57	12.9	5.14×10^{-4}	2.57×10^{-3}
Resident	0.21	1.07	4.29×10^{-5}	2.14×10^{-4}
Population	1.16×10^{-3}	5.81×10^{-3}	2.37×10^{-7}	1.16×10^{-6}

Slope Factor Method

The risk characterization of the chronic radon case using the slope factor methodology is described by Equation 4.12. The subscript q refers to the exposure point and the EL refers to the exposure level. The exposure level for the chronic case is defined by Equation 4.13.

$$\mathbf{Risk_q = EL_{Rn\text{-}222q} \times SF_{inhalation}} \quad (4.12)$$

$$\mathbf{EL_{Rn\text{-}222q} = Conc_{air} \times FI_2 \times ED \times EF \times FO} \quad (4.13)$$

The terms of Equation 4.13 are defined as follows:

$\mathbf{EL_{Rn\text{-}222q}}$ = Exposure Level, pCi.

$\mathbf{FI_2}$ = Air Intake Rate, 20 m^3/d.

ED = Exposure Duration, 5 years.

EF = Exposure Frequency, 250 days/year or 365 days per year.

FO = Occupancy Factor, outdoors 60% of time, 0.6.

Risk Characterization for the Chronic Radon-222 Case (continued)

Slope Factor Method (continued)

Table 4.16 lists the risk at each exposure point for the chronic radon case using the slope factor methodology. These risks represent the EPA's risk characterization methodology for determining the age-averaged, lifetime cancer risk from the chronic release of radon over the five year exposure period.

Table 4.16: Total Risks Determined for the Chronic Radon Case Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	9.1×10^{-5}
Resident	7.6×10^{-7}
Population	4.1×10^{-8}

Summary of the Risk Characterization Results

The approach to this risk assessment involved both a probabilistic risk assessment methodology and a conventional Superfund based risk assessment methodology. The objective of the investigation was to quantify the risks for the baseline case and also to quantity the risks associated with the most probable cases of silo failure. In characterizing the risks for the cases of silo failure, probabilistic risk estimates were calculated as well as risk estimates for the more conventional approach which determines risk based on conditional estimates given a considerable number of assumptions about the source terms and exposure scenarios.

More specifically, risks were determined for two separate cases of silo failure: 1) the acute failure of the K-65 silos 1 and 2 due to a severe weather event (Acute Case A1) and 2) the acute failure of the K-65 silos 1 and 2 resulting from the continued structural deterioration leading to the total release of radon-222 (Acute Case A2). Risks were also determined for the baseline case of chronic radon emission. Risks were determined for the three Reasonable Maximum Exposure points for each case of silo failure and the chronic radon emission case. Two separate risk characterization methodologies were utilized in the determination of the risks for each case of silo failure and the chronic case as well. The first risk methodology analyzed was termed the risk coefficient method (RC) and was based on the effective dose equivalent risk factor of 2×10^{-4} risk per rem of exposure. The second risk method investigated was the Environmental Protection Agency's carcinogenic slope factor approach for radionuclides. Radionuclide slope factors are characterized as best estimates (maximum likelihood estimates) of the age-averaged total lifetime excess cancer incidence per unit intake or exposure.

Table 4.8 lists the risks determined for the acute case A1 based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 3×10^{-3} is shown in Table 4.8 for an individual of the work force. This means that under the exposure assumptions of the acute A1 case an individual of the work force has 3 chances in 1000 of developing cancer in his or her lifetime. Similarly a resident under the exposure assumptions of the acute A1 case has 1.4 chances in 10,000 of developing a cancer in his or her lifetime.

Summary of the Risk Characterization Results (continued)

Table 4.8: Total Risks Determined for the Acute Case A1 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	3.0×10^{-3}
Resident	1.4×10^{-4}
Population	3.0×10^{-8}

Table 4.13 lists the risks determined for the acute case A2 based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 2×10^{-5} is shown in Table 4.13 for an individual of the work force. This means that under the exposure assumptions of the acute A2 case an individual of the work force has 2 chances in 100,000 of developing cancer in his or her lifetime. Similarly, a resident under the exposure assumptions of the acute A2 case has 9.2 chances in 10 million or roughly 1 chance in 1 million of developing a cancer in his or her lifetime.

Summary of the Risk Characterization Results (continued)

Table 4.13: Total Risks Determined for the Acute Case A2 Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	2.0×10^{-5}
Resident	9.2×10^{-7}
Population	1.6×10^{-9}

Finally, Table 4.16 lists the risks determined for the chronic radon case based on the EPA slope factor methodology. A lifetime excess cancer incidence risk of 9.1×10^{-5} is shown in Table 4.16 for an individual of the work force. This means that under the exposure assumptions of the chronic radon-222 case an individual of the work force has 9.1 chances in 100,000 of developing cancer in his or her lifetime. Similarly, a resident under the exposure assumptions of the chronic radon case has 7.6 chances in 10 million of developing a cancer in his or her lifetime.

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Summary of the Risk Characterization Results (continued)

Table 4.16: Total Risks Determined for the Chronic Radon Case Based on the EPA Slope Factor Methodology

Exposure Point	Risk
Work Force	9.1×10^{-5}
Resident	7.6×10^{-7}
Population	4.1×10^{-8}

5.0 Uncertainty Analysis

This section discusses the inherent problems and limitations with the data and models used in the risk assessment. The problems and limitations are due to difficulties in data collection, record keeping, modeling, and any number of other areas. These limitations lead directly to a lack of confidence in the final results. The evaluation of these limitations and confidence problems is covered by the more general topic of uncertainty analysis. This analysis should be performed on both a qualitative and quantitative level. The ability to conduct the uncertainty analysis is also in part limited by the limitations and problems that created the uncertainties in the first place. In the situations where little or no data is available the uncertainty in the results is quite large and furthermore the ability to evaluate the uncertainty on a quantitative level is limited.

The uncertainty analysis associated with this risk assessment is primarily on a qualitative level. The uncertainties in the data and analysis associated with the probability calculations are much easier to quantify than for instance the uncertainties in the source term estimates. The intent of this section is to present the general qualitative uncertainties of this study. These uncertainties are presented for each phase of the risk assessment project from the evaluation of the structural integrity and calculation of failure probabilities to the final stages of the risk estimates.

Uncertainty In Silo Structural Integrity

The structural integrity of the silos was evaluated using previous reports, of studies performed on the silos, by Both Camargo Associates Limited and Bechtel National Incorporated. The data available from these previous studies was derived from both destructive and non-destructive testing. The use of this data has induced a certain amount of uncertainty in the probability of failure due to a number of factors. The Camargo study, which provided the data used for determining the decay rates, was finished prior to the addition of the foam cover or the wood and steel protective covering in the center of each silo. These additions therefore could not be considered in the probability estimates of dome failure. The uncertainty imposed by the omission of these additions can be evaluated on a qualitative level by addressing the physical nature of the degradation process and the critical loadings of the silo structure.

The results of both the Bechtel report and the Camargo study showed that the structural integrity of the silo dome structure was not sufficient to provide any estimate of life expectancy. The results also showed that the dead load capacity of the dome was small and was subject to failure from any significant additional dead or live loads. Taking this information into account the additional protective measures made to the silo domes can be considered to have a negligible affect on the structural integrity. The ability for these modifications to prohibit or at least retard the weathering process however is more difficult to address.

Clearly there is a degree of uncertainty in this area, however, the magnitude of the effect on the probabilities is expected to be small due in part to the time frame with which the modifications were made. The silos were nearly 30 years old by the time the foam covering and the protective wood and steel section was added. Considerable weathering and wear had taken place by this time. The additional modifications will only retard the weathering processes on the outside of the structure. Since the silo is not an airtight structure air is permitted to be exchanged between the inside and the outside. This exchange process will continue to degrade the dome from the inside. Given the above discussion the magnitude of the uncertainty in the probability of failure, due to natural degradation, is considered to be small.

Uncertainty In Tornado Related Probabilities

The uncertainty analysis associated with the probability of the external 'tornado' event can be evaluated on both a quantitative and qualitative level. The errors and uncertainties are basically quantified when the statistical analysis is performed on the data. The probability distributions used to represent the data have confidence intervals (as defined by the standard deviation) and the goodness of fit tests, to determine just how well the data used fits the assumed distribution, reflect the uncertainty in the raw data. Additionally much of the uncertainty in the raw data is removed in the initial investigation stages by only considering data which is substantiated and quantified (recall data on tornados was omitted for these reasons). The net effect of performing the detailed statistical analysis is to reduce or at least qualify the uncertainties. The impact of the remaining uncertainties, in the probability of occurrence and damage of a tornado, had on the final results was considered to be less than an order of magnitude and is therefore a 'low' degree of effect.

Uncertainty In The Source Term (release and magnitude)

This part of the risk assessment was considered to contain the dominate degree of uncertainty. The variation in the data concerning the concentrations and total inventory of the radionuclides produced a significant uncertainty. The variation in the total quantity of radium-226 was approximately 36% above and below the best estimate value used in this study. The other radionuclides had similar ranges of uncertainty. This level of uncertainty corresponds to an impact of approximately one order of magnitude in the results (in terms of the exposure).

The impact from these uncertainties, on the risk assessment, is expected to be in the range of a single order of magnitude. The determination of this impact must wait until after the exposure and dose assessment has been made. Uncertainty in a single radionuclide or a group of contaminants does not affect the risk in the same way since the dose received from exposure is dependent on the impact from the contaminant and the pathway considered.

The model and analysis techniques used to evaluate the magnitude of the source term released also resulted in significant uncertainties. The model used postulated a maximum credible release term. The total quantity of residue material released to the environment was assumed to be approximately 8.5% of the total volume of waste mass contained in both silos. This corresponds to approximately 1.65 x 10^6 pounds of residue material (including the radioactive contaminants).

The model used to determine this magnitude of release assumed that a single silo failed catastrophically with the dispersion of a volume of waste material 1 meter deep (3.28 feet) and 80 feet in diameter. Due to the large source term and the fact that no credit was taken for inhibitors to the ability of the wind to distribute the material the overall effect of these uncertainties is an over prediction of the resulting dose. The effect of the uncertainties was considered to also be approximately one order of magnitude.

Uncertainty In The Dose Assessment

The total dose received by an individual or a population is the sum of dose from each pathway and for each radionuclide. The result of the dose assessment, presented in Section 3.0, clearly indicates that the dominate contributor to the total dose is via the inhalation pathway and from thorium-230. The impact of the uncertainties of the source term as well as the uncertainties in the dose calculations on the overall risk can be summarized by addressing the variation in the dose from thorium-230. Since the uncertainty in the magnitude of the thorium-230 source term was essentially the same as that of radium-226 (approximately 36%) then the impact on the risk is also expected to about one order of magnitude (probably over estimating the dose and therefore the risk).

Uncertainty In The Risk Estimates

The final impact of the error or uncertainty in the basic data, the modeling, and the analytical techniques eventually alters or produces a confidence interval for the risks. The impact from each of the stages of the risk assessment were clearly shown to be non-linear, meaning that the sum of the uncertainties does not directly affect the risk estimates. Through the uncertainty analysis (primarily qualitative) performed for this study the net impact on the risk estimates was considered to be about one order of magnitude. Additionally the dominate contributor to the uncertainty was in the magnitude and release estimates of the radioactive contaminant inventory.

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