Risk Assessment of Additional Metal Casks

PSA Reference: PSA-R-T15-08
Alternate Reference: FA-0099
Revision: 4

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LIST OF ABBREVIATIONS

ALARA	As Low As Reasonably Achievable
ARF	Airborne Release Fraction
ASME	American Society of Mechanical Engineers
BOC	Beginning of Cycle
BWR	Boiling Water Reactor
CFR	United States of America: Code of Federal Regulations
CSB	Cask Storage Building
DOE	Department of Energy
DR	Damage Ratio
EFPD	Effective Full Power Days
EOC	End of Cycle
EPRI	Electric Power Research Institute
FA	Fuel Assembly
FHA	Fuel Handling Accident
HEP	Human Error Probability
HM	Heavy Metal
HI-STAR 100	Holtec International Storage, Transport and Repository Cask System
HI-STORM 100	Holtec International Storage and Transfer Operation Reinforced Module
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
ISFSI	Independent Spent Fuel Storage Installation
KNPS	Koeberg Nuclear Power Station
LLW	Low Level Waste
LOCA	Loss of Coolant Accident
LOSP	Loss of Off-Site Power
LPF	Leak Path Factor
MAAP	Modular Accident Analysis Program
MPC	Multi-Purpose Canister
NIL	Nuclear Installation License
NNR	National Nuclear Regulator
NPO	Nuclear Plant Operator
NUREG	U.S. NRC reports or brochures on regulatory decisions, results of research, results of incident investigations and other technical and administrative information
ORIGEN-S	SCALE System Module to Calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Term

PC COSYMA	PC Version of Code System from MARIA
PCR	Paul C. Rizzo
PGA	Peak Ground Acceleration
PMC	Fuel Handling System
PRA/PSA	Probabilistic Risk Assessment / Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RAR	Risk Assessment Report
RFE	Reactor Fuel Engineering
RP	Radiation Protection
SAR	Safety Analysis Report
SF	Spent Fuel
SFSC	Spent Fuel Storage Cask
SFP	Spent Fuel Pool
SME	Subject Matter Expert
SNF	Spent Nuclear Fuel
S/O	Stretch Out
SPAR-H	Standardized Plant Analysis Risk Human Reliability Analysis
TISF	Transient Interim Storage Facility
TPU	Thermal Power Uprate
U.S. NRC	United States Nuclear Regulatory Commission

1 INTRODUCTION

1.1 Objective

There will be a shortage of wet storage as Koeberg Nuclear Power Station's (KNPS) spent fuel pools reach capacity and hence the need for spent Fuel Assemblies (FAs) to be moved into dry storage systems has been identified. The spent fuel storage project requires a risk assessment for the storage of spent fuel assembly dry storage casks at the Koeberg site.

The objective of this report is to identify and quantify the risks associated with the spent fuel assembly dry cask storage system using Probabilistic Safety Assessment (PSA) techniques.

The site personnel and public radiological risk associated with the cask loading, transport and storage and monitoring will be quantified and compared to the National Nuclear Regulator (NNR) licensing criteria. The full details of these criteria are presented in RD-0024 [1]. The allowable annual risks are summarised below in Table 1.

Table 1: NNR Licensing Criteria for Plant Personnel and Public Risk

PERSONNEL RISK	ACCIDENTS
Average	1E-5 Fatalities / Year
Peak	5E-5 Fatalities / Year
PUBLIC RISK	**ACCIDENTS**
Average	1E-8 Fatalities / Year
Peak	5E-6 Fatalities / Year

1.2 Scope

The scope of this report is to assess the risk to site personnel and the public associated with accidents involving spent fuel assembly metal casks. Such accidents could occur during the cask loading, transfer or storage phase at the Koeberg site. The cask PSA does not include an assessment of the risks associated with the transportation of the casks to a permanent off-site facility. Risks associated with the normal operation of the casks are outside the scope of this document.

Sabotage has been excluded from consideration as this challenge is addressed by separate and more confidential studies as recommended by Electric Power Research Institute (EPRI) and is normally carried out by the regulatory authority [2].

To the extent practical, the assessment is based on recent studies performed by EPRI [2] and [3].

1.3 Key Assumptions Used in the Risk Assessment

1.3.1 Number of Fuel Assemblies

The number of spent (FAs) that are required to be stored in casks were taken from the 60 year plant life scenario with thermal power uprating (TPU) developed by Reactor Fuel Engineering (RFE). This scenario estimates 5115 spent FAs will be generated until 2045 (See Appendix E). Since 112 spent FAs are already stored in 4 casks on Koeberg site, this leaves the remaining 5003 spent FAs that must be stored in casks.

There are other proposals on the number of spent FAs that must be stored that can be considered for analysis. However, the above numbers are considered bounding from a PSA perspective and therefore will be used in this risk assessment.

1.3.2 Fuel Data

The spent FAs to be loaded into casks will be assumed to be scoped by the fuel management strategy presented in Section 4.1.1.

1.3.3 Number of Casks

Koeberg Nuclear Power Station currently stores 4 CASTOR X/28F type casks in the Cask Storage Building (CSB) within the Low Level Waste (LLW) Complex onsite. These are metal casks with a bolted double lid system that stores 28 spent FAs.

Additional casks are being procured to allow the station to operate so that the spent fuel pools do not reach their maximum capacity. The chosen design for the new casks are HOLTEC HI-STAR 100. These are metal casks with a multi-purpose container (MPC) and an overpack system that stores 32 spent FAs.

It will further be assumed that the remaining metal casks will store 32 spent FAs and accommodate all fuel assemblies generated by Koeberg for the 60 year plant life scenario with TPU. The chosen design of the remaining metal casks is not known and could be of a different design than the HOLTEC HI-STAR 100.

The total number of casks to be considered in this analysis is displayed in Table 2.

Table 2: Number of Casks

CASK DESCRIPTON	NUMBER OF CASKS
112 spent FAs stored in existing 4 casks	4
5003 spent FAs will be loaded into casks by the year 2045 (32 fuel assemblies per cask) [See Appendix E]	157
Total	**161**

1.3.4 Location and Size of the Temporary Interim Storage Facility (TISF)

There are six locations that were identified for possible development of the Temporary Interim Storage Facility (TISF) and are displayed in Figure 1. An evaluation was performed [45] and the preferred site was determined to be the Cask Storage Building site. The CSB site is located adjacent to the Low-Level Waste complex on the northern boundary of the KNPS. The second location for the development of the TISF is Ekhaya site which is located along the southern boundary of the KNPS.

Figure 1: KNPS layout of proposed location alternatives

The proposed TISF will consist of a concrete slab that will be surrounded with security fencing and will cover an area of approximately 12800 m^2. The concrete slab will be reinforced and designed to support the mass of the fully loaded casks and transfer equipment. It will further be designed to withstand the effects of any extreme natural site phenomena, including a seismic event, soil liquefaction, storm water, etc. The proposed design of the concrete slab is based on the Paul C. Rizzo (PCR) 0.5g response spectra for beyond design basis and a Peak Ground Acceleration (PGA) = 0.5g was used as an input for the seismic loading calculations [65].

The facility will be designed to accommodate storage of the casks for spent fuel generated at Koeberg up to the end of the operational life of the plant and development will take place in a modular manner.

The risk assessment will assume that all casks stored in the TISF are exposed directly to the surrounding environment and no credit for any building effects is taken in this analysis.

1.3.5 Number of Cask Loadings per Year

The fuel management strategy according to the 60 year plant life scenario with TPU estimates that 68 spent fuel assemblies can be unloaded from the core. Therefore, 3 casks

(68 spent FAs / 32 FAs per cask) will cover the fuel assemblies removed from the spent fuel pool during a refuelling outage. It is also possible that 2 refuelling outages could happen in 12 month window (one outage per unit), resulting in a possible 6 casks (3 cask loadings per outage multiplied by 2 outages per 12 month rolling window) that need to be loaded per year.

The Koeberg spent fuel project envisages that at most 7 cask movements may take place per year and the assumption used in this report is 7 cask movements per year. A sensitivity analysis for varying the number of cask movements per year is contained in Section 6.3.

From previous cask risk assessments [18] and [19] and to reduce the risk of incorrect cask loading, the fuel assemblies in the spent fuel pool building must have had at least 90 days decay since criticality before they can be loaded into casks. According to the Safety Analysis Report (SAR) [20] all cask loading operations take place at least 90 days after a core unload. This reduces the risk on an incorrect loading accident by an order of magnitude.

1.4 Methodology

1.4.1 Approach Used for Dry Cask Storage PSA

The approach used to perform the PSA for the dry cask storage will be aligned with the EPRI guidelines provided in the following documents which define appropriate and key elements for performing a dry cask storage PSA:

- EPRI 1003011, "Dry Cask Storage Probabilistic Risk Assessment Scoping Study" [2], and
- EPRI 1009691, "Probabilistic Risk Assessment (PRA) of Bolted Storage Casks" [3].

The following NUREG developed by the United States Nuclear Regulatory Commission (U.S. NRC) for a pilot PRA was also referred to:

- NUREG-1864 "A Pilot Probabilistic Risk Assessment of a Dry Cask Storage System at a Nuclear Power Plant" [4].

1.4.2 Methodology for Calculating Risk

The purpose of this section is to present the methodology and standards used for performing the necessary dose calculations in order to determine mortality risks for both the public and site personnel. With regard to standards, RD-0024 [1] is the primary requirement that will be met but where RD-0024 does not give instruction, the American Society for Mechanical Engineers (ASME) PSA standards will be used as guides in the development of this risk assessment with the intent that this risk assessment should meet the "Capability Category II" classification in the areas impacting risk informed decisions.

Where no specific PSA standard exists, the following ASME standards will be used to the extent practical:

- ASME/ANS RA-Sb–2013, "Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications" [50],
- ANSI/ANS-58.22 (2009), "Low Power and Shutdown PRA Methodology, Draft"

[51],

- ANSI/ANS/ASME-58.24 (2010), "Severe Accident Progression and Radiological Release (Level 2) PRA Methodology to Support Nuclear Installation Applications, Draft" [52], and
- ASME/ANS-58.25 (2010), "Radiological Accident Offsite Consequence Analysis (Level 3 PRA) to Support Nuclear Installation Applications, Draft" [53].

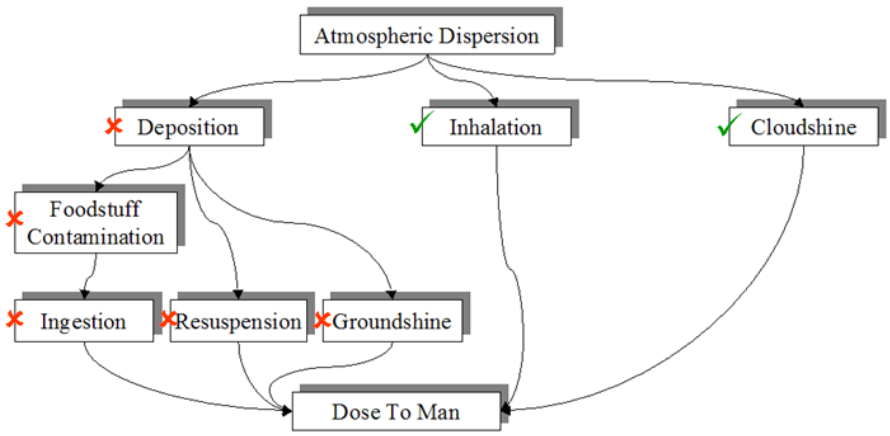
There are two methods to determine the mortality risk to site personnel. The usual method is described in detail in the following paragraphs and is used in situations where the dose is received by a person standing in the building when the accident occurs. The release is localised and should not result in any significant off-site doses. This method will be used to calculate the peak and average site personnel risk due to cask seal leaks, cask loading errors and cask drop accidents involving the failure of the integrity of the cask. The calculations performed are based on the process described in "Site Personnel Risk Methodology" [5] and is also described in more detail in Section 1.4.2.1.

The second method, which is usually used to determine the mortality risk to the public, can be used to determine site personnel risks when it is expected that the building will be vacant at the time of the accident, but that the release will affect site personnel located elsewhere on site. This method uses PC COSYMA and will be used to calculate the peak and average mortality risks to site personnel in the event of a cask drop resulting in failure of the SFP liner and cask storage accidents from external events (e.g., aircraft crash induced fire). PC COSYMA is also used to determine the peak and average public mortality risks, explained in more detail in Section 1.4.2.2.4.

1.4.2.1 Site Personnel Risks

When determining the Total Effective Dose all the different pathways of human radiation exposure should be considered. The pathways for atmospheric and ground releases are shown in Figure 1. The deposition pathway, for an atmospheric release is not considered when calculating site personnel risk; since in accident conditions this pathway will not dominate (this pathway takes time to come into effect and in the event of an accident, the site personnel will evacuate as soon as possible).

Atmospheric Release



Ground Release

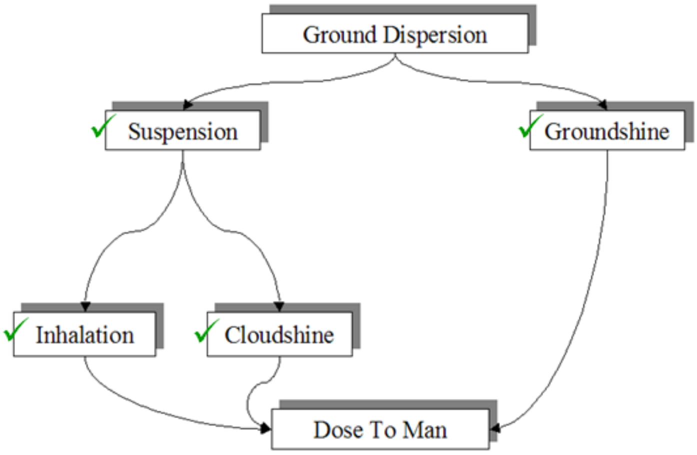


Figure 2: Main Environmental Pathways of Human Radiation Exposures from Atmospheric and Ground Releases

The cask is a dry storage cask system and does not result in ground releases (i.e., contaminated liquid on the ground). Therefore, the effective dose from ground releases will not be considered.

The committed effective dose from the inhalation and the effective dose from the cloudshine pathways should be combined to obtain the total effective dose before calculating the stochastic risk for cask accidents. For the deterministic risk, a normalised sum of the considered pathways for each organ is determined and the absorbed doses to the organs are then combined to calculate the deterministic risk.

Cloudshine is known as external exposure since the radiation arises outside the body. This is in contrast to the intake of radionuclides by inhalation, where the radiation is emitted inside the body.

Radioisotopes emit alpha particles, beta particles or gamma rays or some combination of these. Since alpha particles are rapidly absorbed within a few centimetres of air, they do not travel far and even if originating from close to the body does not usually penetrate the outside layers of dead skin. Therefore, external radiation due to alpha particles is ignored. Beta particles, however, travel several centimetres in air and have a limited range in tissue, which are a few centimetres at most, before being completely absorbed. Therefore, external radiation due to beta particles represents a radiation hazard only to the skin. Gamma rays travel typically hundreds of metres in air and their highly penetrating radiation leads to exposure of the whole body and its organs. The exposure due to gamma rays is generally found to be the most significant source of external exposure. For inhalation, internal exposure due to alpha, beta and gamma radiation to the whole body and its organs (bone marrow, lungs and gastro-intestinal tract) are considered. The figure below shows the different pathways, doses and radiation exposures considered in the analysis of site personnel risk due to accidents.

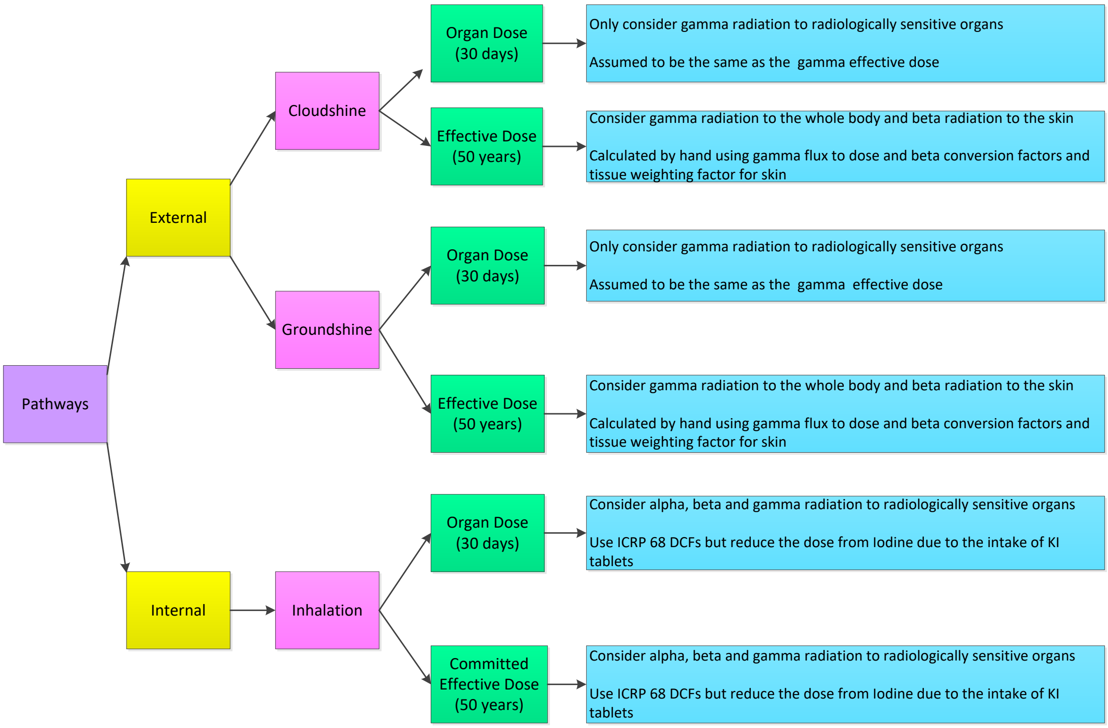


Figure 3: The Relationship between the Different Pathways, Doses and Radiation Types

1.4.2.1.1 The Total Effective Dose Due To External Radiation

For determining the effective dose due to cloudshine, only gamma irradiation is considered since alpha particles do not penetrate the skin and beta particles only penetrate a few centimetres in tissue. The cloudshine dose should be combined with the skin dose due to beta radiation from cloudshine as described later in this section, to obtain the total effective dose.

What follows is the derivation of the equations used to calculate the effective dose due to cloudshine. The beta skin dose calculation is also discussed.

Derivation of Cloudshine Effective Dose

First, it is shown that gamma air attenuation and build-up inside a building is negligible.

The linear absorption coefficient for gamma energy in air STP (μ_{en}) is given by the expression μ_{en} / ρ = 2.75E-03 m^2/kg, ρ for air at STP being 1.293 kg/m^3 ([6], pg. 58 – valid for gamma energies from 0.07 to 2 MeV). The halving distance for γ energy flux in air is therefore approximately 0.693 / (2.75E-03 $\times$ 1.293) = 195 meters. Inside a building with dimensions measured in several meters, therefore, there would be negligible γ air attenuation or build-up. Scatter from solid surfaces would also be negligible. It should be noted that the use of the above assumption leads to an overestimation of the effective dose due to cloudshine for important radionuclides.

Gamma Ray Energy Flux from a Hemispherical Cloud

It will generally be necessary to calculate the gamma effective dose to an individual immersed for a short period of time, T in hours, in an atmosphere containing a mixture of radioactive isotopes.

It is common practice to assume that the release of radioactivity can be approximated by a hemispherical cloud of gas of radius R meters and specific activity $b_{c,i}$ Bq/m^3 (disintegrations per m^{3}s) of a certain isotope. Further assume that a fraction f_i of disintegrations emit a γ photon of energy E MeV. It is also assumed that the γ air attenuation or build-up inside a building is negligible, as shown above.

The following equation is defined:

$$\Psi_{c,j} := \frac{b_{c,j} \cdot f_j .E.R}{4} \text{ MeV } m^{-2} s^{-1} = 2.5 \times 10^{-5}\, b_{c,j} \cdot f_j .E.R \text{ MeV } cm^{-2} s^{-1} \qquad (1)$$

Gamma Effective Dose Due To Cloudshine

The gamma effective dose rate (H) is then obtained by replacing the gamma energies by the appropriate flux / dose-rate conversion factors (f_E) taken from Table 2.3.1.1 in the "The Koeberg Site Personnel Risk Assessment", [5] and reproduced in Table 3. Care must be taken to include all significant gamma energies for each isotope. This replacement is done using the following equation:

$$H = f_E \times (\Psi / E) \qquad (2)$$

Table 3: Flux / Dose-Rate Conversion Factor f_E

Bin Number	Energy Range (MeV)	Flux / Dose Conversion Factor (f_E) (Sv/h) / (1/cm^{2}s)
1	10 - 8	8.77E-05
2	8 - 6.5	7.48E-05
3	6.5 - 5	6.37E-05
4	5 - 4	5.41E-05
5	4 - 3	4.62E-05
6	3 - 2.5	3.96E-05
7	2.5 - 2	3.47E-05
8	2 - 1.66	3.02E-05
9	1.66 - 1.33	2.63E-05
10	1.33 - 1	2.21E-05
11	1 - 0.8	1.83E-05
12	0.8 - 0.6	1.52E-05
13	0.6 - 0.4	1.17E-05
14	0.4 - 0.3	8.76E-06
15	0.3 - 0.2	6.31E-06
16	0.2 - 0.1	3.83E-06
17	0.1 - 0.05	2.67E-06
18	0.05 - 0.01	9.35E-06

Where H is the gamma effective dose rate, f_E the flux / dose-rate conversion factor, Ψ the γ energy flux and E the energy of the emitted γ photon.

The gamma effective dose rate as the dose point is approaching the release point/ the centre of the hemispherical cloud of radius R due to a specific isotope is therefore (including all significant gamma energies for each isotope):

$$H_{c,i} = 2.5 \times 10^{-8} \times \sum (f_i \times f_E) \times b_{c,i} \times R \quad \text{Sv/h} \qquad (3)$$

And the gamma effective dose rate at a height h above a plate of radius R due to a specific isotope is therefore:

$$H_{g,i} = 2.5 \times 10^{-8} \times \sum (f_i \times f_E) \times b_{g,i} \times \ln \left[(R^2 + h^2) / h^2 \right] \quad \text{Sv/h} \qquad (4)$$

Thus, to calculate the gamma effective dose, determine the values of all the parameters and multiply the above dose-rate equations by the exposure time, T, in hours (that is $D = H \times T$).

The gamma effective dose due to cloudshine for a specific radioactive isotope is therefore calculated as follow:

$$D_{c,i} = 2.5 \times 10^{-8} \times \sum (f_i \times f_E) \times b_{c,i} \times R \times T \quad \text{Sv} \qquad (5)$$

Where $\sum(f_i \times f_E)$ is the flux to dose conversion factor for the specific radioactive isotope. The sum of the gamma effective doses due to each radioactive isotope gives the gamma effective dose, D_c due to cloudshine. Details for the calculation of the isotopic concentration in the atmosphere for each accident type can be found in “Site Personnel Risk Methodology – A Koeberg PSA Procedure”. Table 4 presents the values of $\sum(f_i \text{ x } f_E)$ for commonly used isotopes.

Table 4: Sum $\sum(f_i \text{ x } f_E)$ for commonly used isotopes

Isotope	$\sum(f_i \text{ x } f_E)$ (Sv/h) / (1/cm^{2}s)	Isotope	$\sum(f_i \text{ x } f_E)$ (Sv/h) / (1/cm^{2}s)
Ag-110	7.04E-07	Nd-147	7.77E-06
Ag-110m	5.67E-05	Ni-59	3.23E-06
Ag-111	6.73E-07	Ni-63	N/A
Am-241	7.17E-06	Np-237	7.38E-06
Am-242	5.31E-06	Np-239	1.01E-05
Am-242m	2.56E-06	Pm-147	8.65E-10
Am-243	4.06E-06	Pm-148	1.10E-05
Ba-140	6.26E-06	Pm-148m	4.51E-05
Ce-141	3.43E-06	Pr-143	3.20E-14
Ce-144	1.67E-06	Pu-236	1.20E-06
Cm-242	1.01E-06	Pu-238	1.04E-06
Cm-243	8.87E-06	Pu-239	9.96E-06
Cm-244	9.36E-07	Pu-240	9.96E-07
Cm-245	8.38E-06	Pu-241	6.29E-10
Cm-246	8.33E-07	Pu-242	8.28E-07

Isotope	$\sum(f_i \times f_E)$ (Sv/h) / (1/cm²s)	Isotope	$\sum(f_i \times f_E)$ (Sv/h) / (1/cm²s)
Co-58	2.34E-05	Rb-86	1.94E-06
Co-60	4.84E-05	Re-188	1.61E-06
Cr-51	1.07E-05	Rh-103m	1.07E-06
Cs-134	3.38E-05	Ru-103	1.11E-05
Cs-135	N/A	Ru-106	N/A
Cs-136	4.76E-05	Sb-124	3.72E-05
Cs-137	1.42E-05	Sb-125	1.53E-05
Cs-138	4.32E-05	Sb-126	6.40E-05
Eu-152	2.98E-05	Sr-89	1.70E-09
Eu-154	2.63E-05	Sr-90	N/A
Eu-155	4.47E-06	Ta-182	2.60E-05
Eu-156	2.50E-05	Tc-99	N/A
Fe-55	2.67E-06	Te-125m	1.25E-05
Fe-59	2.22E-05	Te-127	1.17E-07
H-3	N/A	Te-127m	4.07E-06
Hf-175	1.25E-05	Te-129	3.26E-06
Hf-181	1.49E-05	Te-129m	3.67E-06
I-129	7.86E-06	U-234	9.90E-07
I-131	9.42E-06	U-238	8.18E-07
I-132	4.68E-05	W-181	3.72E-06
Kr-85	5.03E-08	W-185	3.28E-09
La-140	4.22E-05	Xe-131m	5.84E-06
Mn-54	1.83E-05	Xe-133	5.95E-06
Nb-93m	1.22E-06	Y-90	1.02E-09
Nb-94	3.35E-05	Y-91	6.63E-08
Nb-95	1.52E-05	Zr-93	N/A
Nb-95m	5.80E-06	Zr-95	1.51E-05

Note: For Cs-137 the gammas associated with the secular equilibrium daughter products Ba-137m have been considered.

In deriving Table 4 the energies and abundances (f_i) of gammas for the isotopes were taken from the radionuclide database of LUDEP [8]. The f_E values for each gamma energy were taken from the previous Table 3. Note that N/A (not applicable) in Table 4 refers to the fact that the particular isotope is not a gamma emitter.

The Beta Skin Dose

When an individual is immersed for a short period of time in an atmosphere containing a mixture of radioactive isotopes or standing in a puddle of contaminated liquid, the skin is exposed to beta radiation. This beta skin dose due to external radiation multiplied by the relevant weighting factor should be added to the gamma effective dose due to cloudshine to obtain the total effective dose. This is discussed in the paragraphs below.

The beta skin dose due to external radiation from a specific radioactive isotope i is calculated using the following equation:

$$D_{s,i} = BCF \times b_i \times T \quad (6)$$

Where, BCF is the beta conversion factor for a specific radioactive isotope, b_i is the isotopic concentration in the atmosphere or on the ground of a specific radioactive isotope and T is the exposure time in hours. The sum of the beta skin doses due to each radioactive isotope gives the total beta skin dose, D_s, due to external radiation. Table 5 provides the beta conversion factors for commonly used isotopes for cloudshine.

The beta conversion factor values were obtained from Table 13.13 and Table 13.15 in the "Handbook of Health Physics and Radiological Health" [6] and Table III.3 in Federal Guidance Report No. 12 [7] and the highest value was selected.

Table 5: Beta Conversion Factors for Cloudshine

Isotope	Beta Conversion Factor ($Sv.m^3/Bq.hr$)	Isotope	Beta Conversion Factor ($Sv.m^3/Bq.hr$)
Ag-110	2.96E-10	Nd-147	7.02E-11
Ag-110m	5.65E-10	Ni-59	0.00E+00
Ag-111	7.88E-11	Ni-63	0.00E+00
Am-241	9.86E-12	Np-237	5.54E-12
Am-242	2.95E-11	Np-239	5.76E-11
Am-242m	4.90E-13	Pm-147	2.92E-12
Am-243	9.86E-12	Pm-148	2.87E-10
Ba-140	9.07E-11	Pm-148m	4.25E-10
Ce-141	3.67E-11	Pr-143	6.34E-11
Ce-144	1.05E-11	Pu-236	1.74E-13
Cm-242	1.54E-13	Pu-238	1.47E-13
Cm-243	3.52E-11	Pu-239	6.70E-14
Cm-244	1.41E-13	Pu-240	1.41E-13
Cm-245	1.93E-11	Pu-241	4.21E-16
Cm-246	1.26E-13	Pu-242	1.18E-13
Co-58	2.01E-10	Rb-86	1.75E-10
Co-60	5.22E-10	Re-188	1.93E-10
Cr-51	6.30E-12	Rh-103m	1.62E-13
Cs-134	3.40E-10	Ru-103	9.97E-11
Cs-135	3.26E-12	Ru-106	0.00E+00
Cs-136	4.50E-10	Sb-124	4.54E-10
Cs-137	3.11E-11	Sb-125	9.54E-11
Eu-152	2.48E-10	Sb-126	6.23E-10
Eu-154	2.98E-10	Sr-89	1.33E-10
Eu-155	1.22E-11	Sr-90	3.31E-11
Eu-156	3.59E-10	Ta-182	N/A
Fe-55	0.00E+00	Tc-99	9.86E-12
Fe-59	2.57E-10	Te-125m	6.98E-12
H-3	0.00E+00	Te-127	4.10E-11
Hf-175	7.74E-11	Te-127m	3.06E-12
Hf-181	1.30E-10	Te-129	1.29E-10
I-129	3.96E-12	Te-129m	5.36E-11
I-130	4.90E-10	U-234	1.53E-13
I-131	1.07E-10	U-238	1.05E-13
I-132	5.69E-10	W-181	6.62E-12

Isotope	Beta Conversion Factor (Sv.m^3/Bq.hr)	Isotope	Beta Conversion Factor (Sv.m^3/Bq.hr)
Kr-85	4.75E-11	W-185	1.63E-11
La-140	5.98E-10	Xe-131m	1.74E-11
Mn-54	1.68E-10	Xe-133	1.79E-11
Nb-93m	1.54E-13	Y-90	2.28E-10
Nb-94	3.43E-10	Y-91	1.39E-10
Nb-95	1.55E-10	Zr-93	0.00E+00
Nb-95m	4.03E-11	Zr-95	1.62E-10

N/A (not applicable) in the above table means that the particular isotope is not a beta emitter. In general, the beta skin dose rates are comparable with the gamma immersion dose rates in an infinite atmosphere. Therefore, after application of a tissue weighting factor of 0.01 they can generally be ignored. In the confined space case on the other hand, the total beta skin dose multiplied by a tissue weighting factor of 0.01 is comparable with the gamma effective dose from immersion and must be added to it for risk calculations. It is questionable whether doses to the skin can contribute to cancer risk and cause fatality since skin cancer can be relatively easily removed. However, cancerous cells in the skin can spread to and invade the rest of the human body by the process of metastasis and cause the appearance of second malignant tumours. Metastasis, the spread of cancer to distant sites in the body, is what makes cancer so lethal. Therefore, doses to the skin due to beta radiation will be conservatively included in risk determinations.

1.4.2.1.2 Organ Dose Due To External Exposure

The absorbed dose to organs of the body (organ dose) due to external radiation is used for deterministic risk calculations. The kinds of radiation of concern are those sufficiently penetrating to traverse the overlying tissues of the body and deposit ionising energy in radiosensitive organs and tissues. Penetrating radiations are limited to gamma rays for which the relative biological effectiveness $RBE_{T,R} = w_R = 1$ for all organs of the body. Furthermore, since the organs of the body are weighted such that the tissue weighting factor (w_T) all add up to 1 (i.e., $\sum_T w_T = 1$), it follows that the absorbed dose to organs of the body (organ dose) in Gy due to external radiation is the same as the gamma effective dose in Sv due to external exposure from cloudshine and / or groundshine. The beta skin dose is not included in the calculation of the organ dose due to external radiation because it is not considered as a fatal organ since skin cancer can be relatively easily removed. Metastasis, the spread of cancer to distant sites in the body, is also ignored in the calculation of organ doses.

1.4.2.1.3 Committed Effective Dose and Committed Equivalent Organ Doses Due To Inhalation

For radioactive isotopes, the committed effective dose and committed equivalent organ doses due to inhalation should be calculated using the database of International Commission on Radiological Protection (ICRP) Publication 68 dose conversion factors from Radiological Toolbox, Version 3.0.0 [59]. The committed effective dose for a 50 year period is calculated as well as the 30 day committed equivalent doses to specific organs. The following equation was used to calculate the committed effective dose and committed equivalent organ doses due to inhalation:

$$D_{o,i} = DCF_{o,i} \times b_i \times B \times T \quad \text{Sv} \qquad (7)$$

Where:

$D_{o,i}$	is the committed effective dose equivalent organ dose in Sv due to inhalation of radioactive isotope *i,*
$DCF_{o,i}$	is the committed effective dose or equivalent organ dose conversion factor (maximum value over all chemical forms from [59]) for the specific radioactive isotope *i*,
b_i	is the isotopic concentration in the atmosphere in Bq/m^3 of the specific radioactive isotope,
B	is the breathing rate in m^3/hr, and
T	is the exposure time in hours.

The deposition of gases and vapours in the respiratory tract is material specific. Virtually all inhaled gas molecules contact airway surfaces, but are usually re-entrained in the air unless they dissolve in, or react with, the surface lining. Noble gases are generally insoluble and not very reactive, and will, therefore, be exhaled with no or little absorption or deposition taking place. Therefore, for noble gases, the inhalation dose is insignificant compared to the immersion dose and no attempt needs to be made to calculate the inhalation dose due to noble gases.

The stomach wall dose is conservatively used for the GI Tract. The stomach wall is the next highest after the thyroid and the lungs for inhaled radioactive iodine isotopes.

Where justifiable, iodine tablets are assumed to be taken within 30 minutes of the accident by the personnel who received the dose. These tablets prevent 87% [5] of the accumulated committed effective dose from the inhalation of iodine.

Although the breathing rate should be justified for each accident scenario, a conservative breathing rate of 1.5 m^3/h (4.17E-4 m^3/s) is used, which is slightly higher than the breathing rate of an active person as recommended in PC COSYMA for off-site releases. Within LUDEP, this corresponds to an adult male (user defined exposure) undergoing light exercise 100% of the time.

1.4.2.1.4 Stochastic Risk Conversion

The method adopted for stochastic risk is to calculate the total effective dose being the total effective dose due to external irradiation (cloudshine and beta skin radiation) for the duration of the exposure plus the 50 year committed effective dose due to inhalation (internal irradiation) of the isotopes of interest. Since the exposure is received over a relatively short period, a risk conversion factor of 5% per Sv is recommended.

1.4.2.1.5 Deterministic Risk Conversion

The method adopted for calculating deterministic (non-stochastic) risk is based on [5]. It is assumed (following a suggestion made by the NNR) that only the committed equivalent organ dose accumulated during the first 30 days following the inhalation is relevant.

To calculate deterministic mortality risk, it is necessary to consider separately the absorbed doses to the bone marrow, lungs and gastro-intestinal tract, since these organs are the most radio-sensitive but have different degrees of radiosensitivity. The thyroid has not been included in the calculation since damage can be reduced by the prompt administration of stable iodine and because, with adequate medical intervention, destruction of the thyroid should not be fatal.

The deterministic risk is given by a sigmoid function of the form:

$$R = 1 - e^{-H} \quad (8)$$

Where:

$$H = \ln 2 \left(\frac{D_i}{D_{50}} \right)^S \quad (9)$$

$$D_{50} = D_\infty + \frac{D_0}{(D_i / t_i)} \quad (10)$$

The function H is known as the hazard function and D_{50} is the absorbed dose at which the effect is detected in 50% of the population. It is a generalised term. In practice, LD_{50} for lethal effects and ED_{50} for morbidity effects are used when applying the above equation. D_i is the absorbed dose received due to cloudshine, groundshine or inhalation (Gy), D_∞ (Gy) is the value of D_{50} at high dose rates, D_0 (Gy^2/h) describe the increase in D_{50} with decrease in dose rate, and t_i in hours is the exposure duration. The parameter S describes the steepness of the risk function.

When different exposure pathways are considered for the same organ, i.e., when the organ is exposed to doses from groundshine, cloudshine and inhalation, the principle is to sum normalised doses before calculating the hazard function. This is expressed mathematically as follows:

$$\left(\frac{D_i}{D_{50}} \right) = \left(\frac{D_i}{D_{50}} \right)_{Inhalation} + \left(\frac{D_i}{D_{50}} \right)_{Groundshine} + \left(\frac{D_i}{D_{50}} \right)_{Cloudshine} \quad (11)$$

Where D_i refers to the absorbed dose applicable to the exposure considered.

When fatality can arise from different causes, i.e., from internal irradiation of the lungs, bone marrow or GI tract, the individual values of the hazard function for each organ are summed before calculating the risk, that is:

$$H = H_{lungs} + H_{bone\ marrow} + H_{GI\ tract} \quad (12)$$

In essence, this means that the different causes are assumed to act independently.

Table 6 lists the recommended values for parameters to use when calculating the fatal effects to the bone marrow, lungs and GI tract. These values were taken from Reference [5].

Table 6: Recommended Values of Parameters to Use When Determining Fatal Effects

Organ	Mortality Effect	Shape S	D_∞ (Gy)	D_0 (Gy^2/h)
Lungs	Pulmonary syndrome	7	10	30
Red bone marrow	Haematopoietic syndrome	6	4.5	0.1
Remainder	Gastro-intestinal syndrome	10	15	0
Ovaries	Pre- and neo natal death	3	1.5	0

1.4.2.1.6 The Peak and Average Site Personnel Risks

To determine the risk to site personnel involved in a particular accident, one needs to determine the initiating event frequency of the accident and the mortality consequence to the site personnel. The mortality consequence refers to the sum of the stochastic and deterministic risk and should include doses from all the released radioactive isotopes and all the different pathways of exposure.

In most cases, the deterministic risk will contribute insignificantly to the overall risk when the dose rates are relatively low and the short-term (30 day) committed equivalent doses to the specified organs are all well below 4 Sv. Only when the short-term (30 day) committed equivalent dose to the specified organs is considerably above 4 Sv does the deterministic risk dominate. Therefore, in most cases the stochastic risk will dominate and only this risk will then be considered in site personnel risk calculations.

The risk to an operator involved in an accident is calculated as follows:

$$\textit{Risk} = \textit{Initiating Event Frequency} \times \textit{Mortality Consequence} \quad (13)$$

In order to compare the site personnel risk due to all the considered accidents to the NNR criteria for site personnel risk, it is necessary to calculate an overall peak and average site personnel risks. It is generally assumed that different site personnel would be exposed in the event of cask accidents occurring at the TISF (i.e., cask seal failure accident) and inside the Spent Fuel (SF) Building (i.e., cask drop and cask loading error accidents) and that all site personnel are exposed in the event of cask drop with Spent Fuel Pool (SFP) liner break and aircraft crash induced fire impacting TISF. The peak and average site personnel risks are determined as shown in Table 7. For the peak risk, the highest risk value of either cask seal failure or the sum of the cask drop and cask loading error accidents are added to the risks from cask drop with SFP liner break and aircraft crash induced fire impacting the TISF.

Table 7: Determination of Overall Peak and Average Site Personnel Risks

Peak Site Personnel Risk	Average Site Personnel Risk
The overall peak site personnel risk is determined as follows: The highest risk value of either: (i) the cask seal failure accident (occurs at TISF) (ii) the sum of cask drop accident / 4 and cask loading error accident / 4 (occurs in SF Building) + Cask drop inside SF Building with SFP liner break (expose all personnel on site) + Cask failure due to aircraft crash-fire (expose all personnel on site)	The overall average site personnel risk is determined as the sum of : + cask loading error accident × (4 × 15) / 1000 + cask drop accident (no SFP liner break) × (4 × 15) / 1000 + cask drop with SFP liner break accident (expose all personnel on site) + cask seal failure accident x 2 / 1000 + cask failure due to aircraft crash-fire (expose all personnel on site)

For cask loading error and cask drop accidents, a fuel handler/supervisor is only involved in cask handling activities for a maximum of 6 hours per 24 hour period [70], that is, ¼ (= 6 hr / 24 hr) of the cask handling activities over 24 hours. Therefore, the peak site personnel risk is divided by a factor of 4 since the individuals present during these cask handling accidents will all have the same peak risk. The maximum number of personnel present during the 6 hours exposure period is 15.

For seal failure accidents it is assumed that 2 personnel can be exposed in the TISF.

The average risk is the sum of all the accidents, taking into account the number of site personnel involved in each accident relative to the total number of on-site personnel, which is assumed to be 1000.

The overall peak and average site personnel risk are then expressed as a percentage of the NNR criteria for site personnel risk due to accidents.

1.4.2.2 Public Mortality Risks

1.4.2.2.1 PC COSYMA

In this study the radiological consequences are evaluated using PC COSYMA Version 2.02. PC COSYMA describes consequences of accidental releases as endpoints. The major endpoints, which can be calculated by the system, are:

- Air concentration or deposition of particular nuclides;
- Doses received by members of the population;
- Individual or collective risks of health effects in the exposed population;
- The extent and duration of countermeasures which might be imposed to reduce health effects; and
- Economic costs of the countermeasures and health effects.

The first endpoint provides information on the air concentration and deposition of nuclides at various selected distances. Information on doses accumulated by different organs can also be obtained at each distance considered. The doses can be short term or long term. Short term doses in this analysis are doses accumulated over a maximum of 30 days while long term doses assume an exposure period of 50 years. Detailed information on contributions to doses by different nuclides and different exposure pathways can also be obtained. Numbers of health effects, both long term and short term, can also be determined.

Health effects due to exposure to radiation are of two types, namely, deterministic health effects and stochastic health effects. Some health effects are fatal while others are not. Deterministic health effects are those which appear within a few weeks after the accident. They typically occur following very large releases. Deterministic health effects can be fatal but largely include loss or impairment of various vital organs. Stochastic health effects, on the other hand, can surface even years after the accident has occurred. They are largely cancers, fatal and non-fatal, and also include hereditary effects in the descendants of the exposed population. Further information on health effects can be obtained in terms of the risks of such effects. There are two types of risks of health effects, namely, individual risk of early and late health effects at various distances from site.

In case of a severe accident, information on amounts of food produced in the area near site that may be banned from consumption can also be obtained. Also, after an accidental release, protective measures are generally taken to mitigate the release. These measures are referred to as countermeasures. These vary from distribution of stable iodine to relocation of the affected population. All forms of countermeasures have been excluded from the present study except for a total ban on consumption of food produced in the area near site.

PC COSYMA can be used for deterministic or probabilistic calculations. Deterministic calculations consider the consequences in a single set of atmospheric conditions. Probabilistic calculations consider the consequences in a wide range of atmospheric conditions. The results are presented in different ways for the two types of calculation. The results of deterministic calculations can be presented in terms of the value of each of the endpoints at each grid points considered in the calculation. Information on average values as a function of distance from the release can also be presented. The results of probabilistic calculations are most easily presented in terms of the probability distributions of the different endpoints. However, for some endpoints, detailed information on the values at each grid location in each of the sequences of atmospheric conditions considered can also be presented. In this analysis, only probabilistic calculations will be performed. The results of PC COSYMA do not take into account the frequency of occurrence of a particular accident. To obtain actual probabilities of consequences the conditional probabilities must be multiplied by the frequency of occurrence of the particular release category.

Models Used to Perform Calculations in PC COSYMA:

Below is a list of models used in PC COSYMA to calculate doses and risks in the absence of countermeasures:

- Atmospheric Dispersion Model
- Plume Rise Model
- Radioactive Decay Model
- Dry Deposition Model
- Wet Deposition Model
- Meteorological Sampling Scheme
- Dose Calculation Models
- Health Effects Models

General Assumptions Used in PC COSYMA:

Three major assumptions have been made in this analysis, namely:

- Further irradiation of the exposed population through ingestion of foodstuffs is not considered.
- No emergency plan (countermeasures), other than the food ban, to mitigate the accident has been assumed.
- Population projections for the end of plant life are also not considered.

The exclusion of the ingestion dose is reasonable due to the following (also see Section 5.2 in the Koeberg Level 3 Risk Assessment [10]):

- It is assumed that a total ban on food products grown locally will be imposed immediately following an accident. This is feasible since a significant fraction of the food consumed in the Western Cape is not grown locally.
- Food countermeasures are easy to implement given the well-developed infrastructure and supply system in South Africa. In addition, the implementation of a food ban and the control of foodstuffs is adequately procedurised in Section 5.7 of the Koeberg emergency planning procedure, KEP 024 [48], and in the Integrated Koeberg Nuclear Emergency Plan, KAA-811 [49].

No other countermeasures were considered, leading to a conservative estimation. The main reason for not including countermeasures is to implement a “defence-in-depth” approach. The risk should be kept as low as possible and within the NNR limits without placing an onerous burden on the public. Countermeasures such as evacuation and relocation are addressed in the Emergency Plan. Sheltering – although one of the simplest countermeasures – was not considered in dose calculations as protection against irradiation may be inadequate in buildings near the site.

PC COSYMA Input Deck:

PC COSYMA uses various data files to perform calculations of radiological consequences caused by accidental releases of radiation into the atmosphere. Specification of site-specific and other relevant data required for each run of PC COSYMA. The site-specific data used in the analysis include the population distribution, meteorological conditions and the source term details.

Meteorological Data

Probabilistic runs of PC COSYMA require a data file containing hourly atmospheric conditions for one or two years. The meteorological conditions attributed to the site were obtained from 2 years of hourly measurements taken at the meteorological station at Koeberg. Excel files containing these measurements (supplied by the Koeberg Weather Station) were converted to a meteorological data text file in the format used by PC COSYMA.

The meteorological sampling scheme used is the stratified sampling scheme. The years for which the data is applicable are 2006 and 2007. The files containing the meteorological conditions used in this analysis are called **\PCCOSYM2\DATA\MET-0607a.mh2** and **MET-0607a.inp**.

Population Data

The population data was obtained from the "QA Model Document: Update of PC COSYMA Population Data File to 2008 Baseline" [11]. The PC COSYMA population data file is named "pop2008a.gr2" and represents the 2008 projected cumulative population (i.e., sum of the permanent resident and tourist populations) as documented in the latest demography section of the Duynefontein Site Safety Report. It is used to obtain the peak public risks for all accident scenarios as well as the peak site personnel risks due to cask drop accidents leading to failure of the SFP liner and aircraft crash induced fire.

The spatial distribution of the population data specified for the purposes of this risk assessment is for an area within a 60 km radius around the Duynefontein site comprising 25 distance bands and 72 sectors at 5 degree intervals. The distance bands used are: 0 to 1 km, 1 to 2.5 km, 2.5 to 5 km, 5 to 7.5 km, 7.5 to 10 km, 10 to 12.5 km, 12.5 to 15 km, 15 to 17.5 km, 17.5 to 20 km, 20 to 22.5 km, 22.5 to 25 km, 25 to 27.5 km, 27.5 to 30 km, 30 to 32.5 km, 32.5 to 35 km, 35 to 37.5 km, 37.5 to 40 km, 40 to 42.5 km, 42.5 to 45 km, 45 to 47.5 km, 47.5 to 50 km, 50 to 52.5 km, 52.5 to 55 km, 55 to 57.5 km, 57.5 to 60 km.

Source Term

Source term details used as an input into PC COSYMA to calculate the radiological risk associated with the casks can be found in Section 4.

For further details on required inputs to PC COSYMA, the reader is referred to the Koeberg Level 3 Risk Assessment [10].

1.4.2.2.2 Peak Public Risks

The peak individual risk refers to the highest risk that a member of the public may be subjected to as a result of a nuclear accident. The risk will be greatest closest to the plant. In the case of Koeberg, the point closest to the site at which the public may be found is the site boundary. The site boundary at Koeberg extends from 1.3 km to 2.5 km from site. Therefore the peak public risk will be calculated at the distance band from 1 km to 2.5 km. Thus, the risk at 1.75 km is given as annual fatalities at 1.75 km divided by the number of people in that distance band. The number of people in the 1.75 km distance band is determined as 2076 from the 2008 baseline [11].

If $D_{i(1.75\ km)}$ is the total mean number of fatalities at 1.75 km due to Release Category RC_i, f_i is the frequency of the Release Category (RC_i) and $P_{(1.75\ km)}$ is the total population at 1.75 km then the peak public risk is given by:

$$\text{Peak public risk} = \frac{\sum_{i=1}^{8}(D_{i(1.75\,km)} \times f_i)}{P_{(1.75\,km)}} \quad (14)$$

1.4.2.2.3 Average Public Risks

The average public risk to an individual in the national population is defined as the number of annual fatalities divided by the total national population. The national population figure is

48687000 from the 2008 census data [10]. PC COSYMA only calculates consequences in an area described by a 60 km radius.

Therefore, if D_i is the total mean number of fatalities summed over all distances due to Release Category RC_i and f_i is the frequency of the Release Category (RC_i), then the average risk to the public is given by:

$$Average\ Public\ Risk = \frac{\sum_{i=1}^{8}(D_i \times f_i)}{Total\ National\ Population} \quad (15)$$

Lastly, as per the NNR's acceptance communicated in letter k27823N [76] of the interim arrangement for addressing the use of outdated population data in PSA Level 3 studies proposed in Section 5 of the report titled: “Impact Evaluation of Outdated Population Data Used in PSA Studies”, Number: PSA-R-T16-22, Revision 4 [77] and described in memo PSA21-0001 [72], the average public risk determined for the year 2008 (using the above equation) is also determined for the year 2025 by applying an additional scaling by a factor of 2.3.

1.4.2.2.4 Peak and Average Site Personnel Risks Using PC COSYMA Results

The PC COSYMA results are used to approximate the peak and average site personnel risk of mortality for the cask drop with SFP liner break accident and an aircraft crash induced fire impacting the TISF accident.

The sum of the short-term and long-term conditional individual risk of mortality is used to define the maximum risk inside the 1 km radius. Since all the personnel are exposed to this risk, this corresponds to the peak and average site personnel risks due to severe accidents.

Using PC COSYMA to estimate doses on site (e.g., close to the site of the accident) can lead to considerable uncertainty. Therefore, the site personnel risks from severe accidents can therefore only be regarded as a poor approximation but that this approximation is far from the allowable limits that a considerable factor of increase could be imposed without effecting the conclusions of the report.

In this regard Eskom acknowledges the NNR’s acceptance communicated in letter k27997N [74] of the proposed application of a scaling (or risk increase) factor of 10.0 derived in the report entitled “Comparison of PC Cosyma and ARCON2 Near-Field Atmospheric Dispersion Factors”, Number: PSA-R-T18-03, Revision 2 [73], to be applied to the PC Cosyma results at 500 m that are used to approximate the peak and average risks to site personnel from accidents related to releases from core damage, the spent fuel pool and casks accidents, in order to appropriately adjust the PC Cosyma results at 500 m to be more representative and bounding of the results expected at a distance of 100 m. Accordingly, the peak and average risks to site personnel from accidents related to releases from cask drop with SPF liner break and aircraft crash induced fire accidents were adjusted / scaled by a factor of 10.

Further; by far the majority of severe accidents take several hours to develop into a release from the spent fuel building. This will allow for the implementation of our Emergency Plan which involves the evacuation of non-essential personnel and the sheltering of the rest, including the administration of stable iodine tablets for sheltered personnel. Given these protective actions; the site personnel doses should be limited.

1.5 Description of the Cask Storage System

This section gives a general description of the known chosen cask designs

1.5.1 General Description of the CASTOR X/28F

The CASTOR X/28F cask is designed to transport and to store 28 Pressurised Water Reactor (PWR) spent fuel assemblies. For transport the cask is designed under consideration of the Eskom technical specifications for storage of spent fuel [12], according to the International Atomic Energy Agency (IAEA) Regulations for Safe Transport of Radioactive Material [13] as a type B(U)F package.

The basic design requirements under normal handling, transportation and storage operations are:

- The fuel cladding must be protected against degradation and gross ruptures.
- Appropriate surveillance equipment must be provided to ensure that limiting conditions are not exceeded.
- There shall be adequate protection of the health and safety of the public and operating staff.
- Safe removal of the contents of the cask must be possible after at least 50 years of storage by use of suitable handling equipment.

Figure 4 shows the four CASTOR X/28F casks currently stored at the Koeberg site and Figure 5 shows the main components of the CASTOR X/28F cask. The CASTOR X/28F cask body is made of a thick-walled cylindrical ductile iron casting. This material exhibits high resistance to corrosion. The cask has two lids, primary and secondary, both made of stainless steel, each lid with separate metallic O-rings to secure leak tightness. The thickness of the lids is 258 mm and 80 mm and they are fastened to the body with 56 and 70 bolts, respectively. The lid system is monitored by a pressure sensing device mounted in the secondary lid. Helium gas provides the internal heat transfer and this inert gas serves to prevent corrosion [14].

The stainless steel basket provides assembly support, criticality control and heat conduction path. The ductile cast iron cask body together with the lids and the seals is used as the confinement system. It also provides the gamma and neutron shielding. For improved neutron shielding, one row of axial hole in the wall of the cask body is filled with polyethylene rods as moderator material. Also a plate of polyethylene is inserted in the bottom section. Bottom steel plugs are inserted in the axial holes to improve gamma shielding.

For handling operations four trunnions, two each at the top and bottom ends, are mounted.

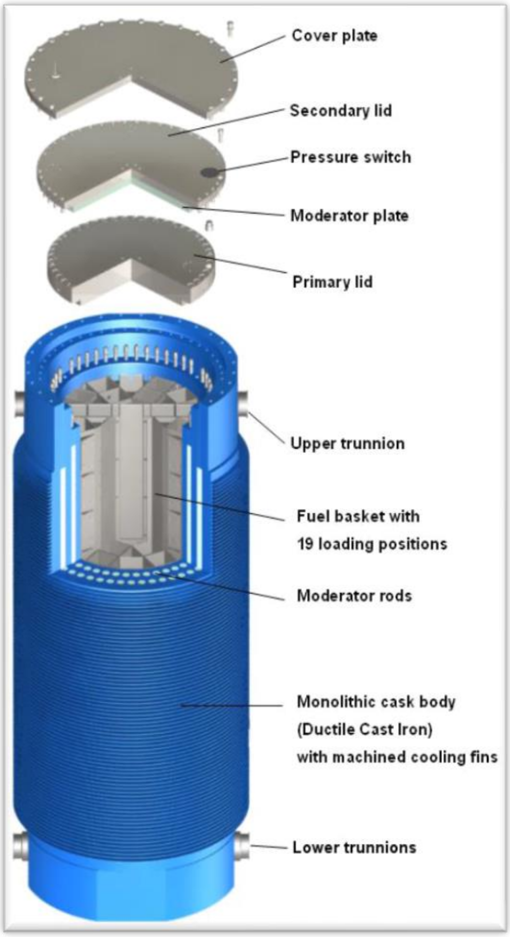


Figure 4: Four casks currently stored at Koeberg

Figure 5: Main Components of the CASTOR X/28F

During dry storage in the spent fuel casks, decay heat is taken up by the casks and transferred to the surrounding air by natural convection and radiation. In the TISF, heat removal also takes place by natural convection.

1.5.1.1 Special Safety Features

- Cask tightness and barrier against activity release and loss of internal heat transfer medium (helium).
- Structural integrity and stability as a safe confinement against external impacts and cask handling failures.
- Criticality safety to assure that the fuel inside the cask remains sub-critical.
- Radiation protection based on sufficient gamma and neutron shielding.
- Passive heat removal of the decay produces heat by natural convection.

The principal design criteria of the CASTOR X/28F casks are provided below:

Table 8: CASTOR X/28F Design Criteria

CASK FEATURES	DESIGN VALUES
Containment general the standard leak rate of each lid cavity atmosphere pressure	 double lids, each lid with metal seal, monitored containment ≤ 10^{-6} mbar l/s (at 1 bar, 293 K) helium, 0.8 bar
Shielding maximum total dose rate at surface at 2m distance	 < 2000 µSv/h < 100 µSv/h
Thermal Design peak temperature of the hottest rod Criticality general multiplication factor (k_{eff})	 < 340˚C fresh fuel, optimal reflection < 0.95
Cask capacity	28 FAs
Moderator material (polyethylene)	70 rods in sidewall (70 mm diameter) Plate in bottom (50 mm thickness)
Cask cavity atmosphere gas maximum gauge pressure	 helium 7 bar
Interlid atmosphere gas maximum gauge pressure	 helium 7 bar
Cask overall length Cask outer diameter	4849 mm 2506 mm
Cask maximum heat load	17.1 kW

1.5.1.2 Advantages of the CASTOR® Cask Concept

- All safety-related aspects are guaranteed by the casks themselves, also in case of accidents.
- The radioactive materials are sealed leak-tight in monolithic cask body with a double-lid system; very low release of radioactive materials will occur, even after an unlikely accident such as drop or severe earthquake.
- Decay heat is removed by inherently safe natural convection; no exhaust air or other active cooling media are necessary.
- Due to the high level of safety, greater acceptance from authorities and the public.

1.5.2 General Description of the HOLTEC HI-STAR 100

The HI-STAR 100 System is a canister system comprising a Multi-Purpose Canister (MPC) inside of an overpack designed for both storage and transportation (with impact limiters) of irradiated nuclear fuel (See Figures 6, 7 & 8). The HI-STAR 100 System consists of interchangeable MPCs that house the spent nuclear fuel and an overpack that provides the containment boundary, helium retention boundary, gamma and neutron radiation shielding, and heat rejection capability. Figure 6 depicts the HI-STAR 100 with its two major components, the MPC and the overpack.

The HI-STAR 100 overpack is a multi-layer steel cylinder with a welded baseplate and bolted lid (closure plate) (See Figure 8). The inner shell of the overpack forms an internal cylindrical cavity for housing the MPC. The outer surface of the overpack inner shell is buttressed with intermediate steel shells for radiation shielding. The overpack closure plate incorporates a dual O-ring design to ensure its containment function. The containment system consists of the overpack inner shell, bottom plate, top flange, top closure plate, top closure inner O-ring seal, vent port plug and seal, and drain port plug and seal.

The HI-STAR 100 overpack is fitted with two impact limiters fabricated of aluminium honeycomb completely enclosed by an all-welded austenitic stainless steel skin. The two impact limiters are attached to the overpack with 20 and 16 bolts at the top and bottom.

The HI-STAR 100 system is designed for both storage and transport. The multi-purpose design reduces spent fuel handling operations and thereby enhances radiological protection. Once the spent fuel is loaded and the MPC and overpack are sealed, the HI-STAR 100 system can be positioned on site for temporary or long term storage or transported directly offsite. More detailed information on the HI-STAR 100 design can be found in [46].

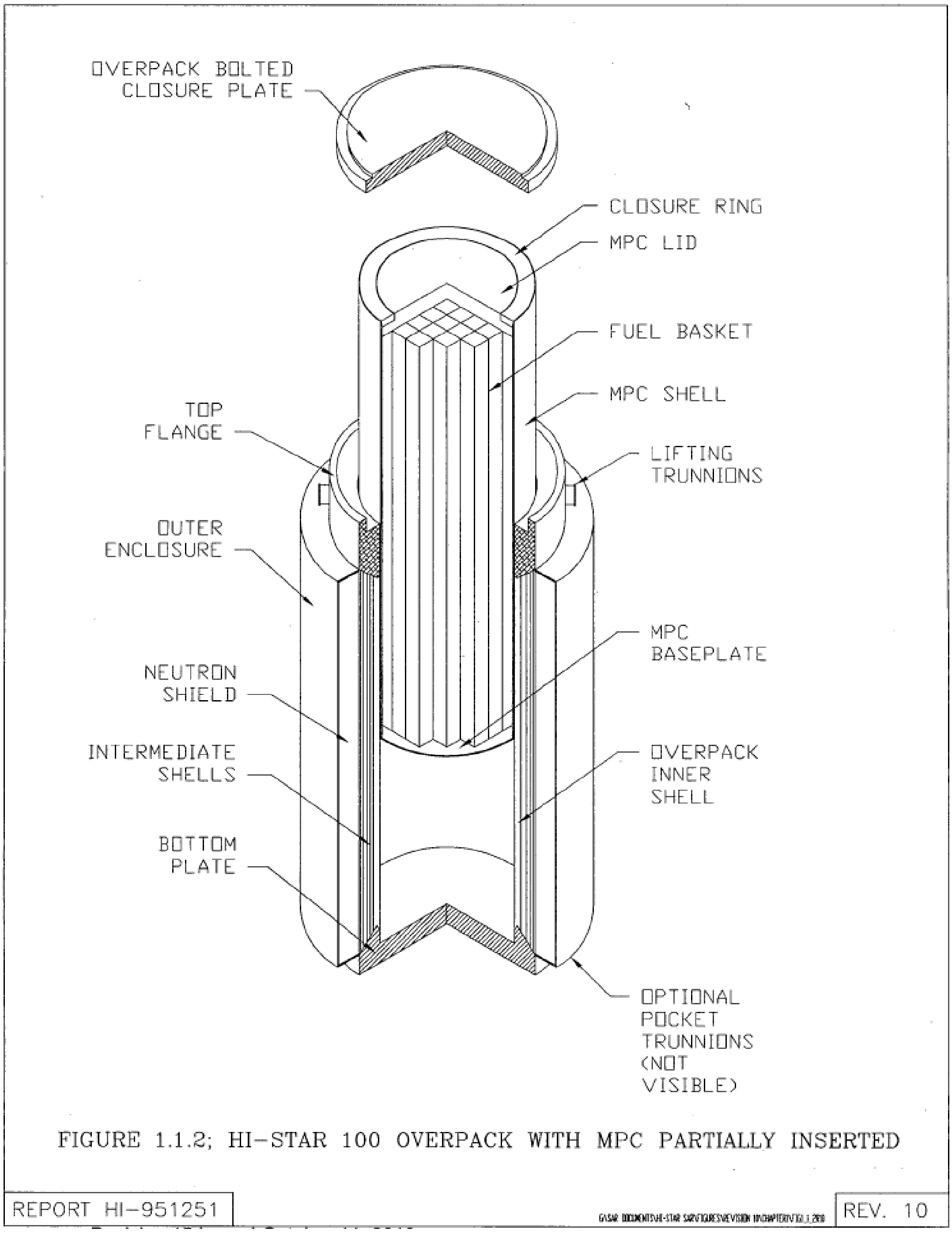


Figure 6: HI-STAR 100 Overpack and MPC

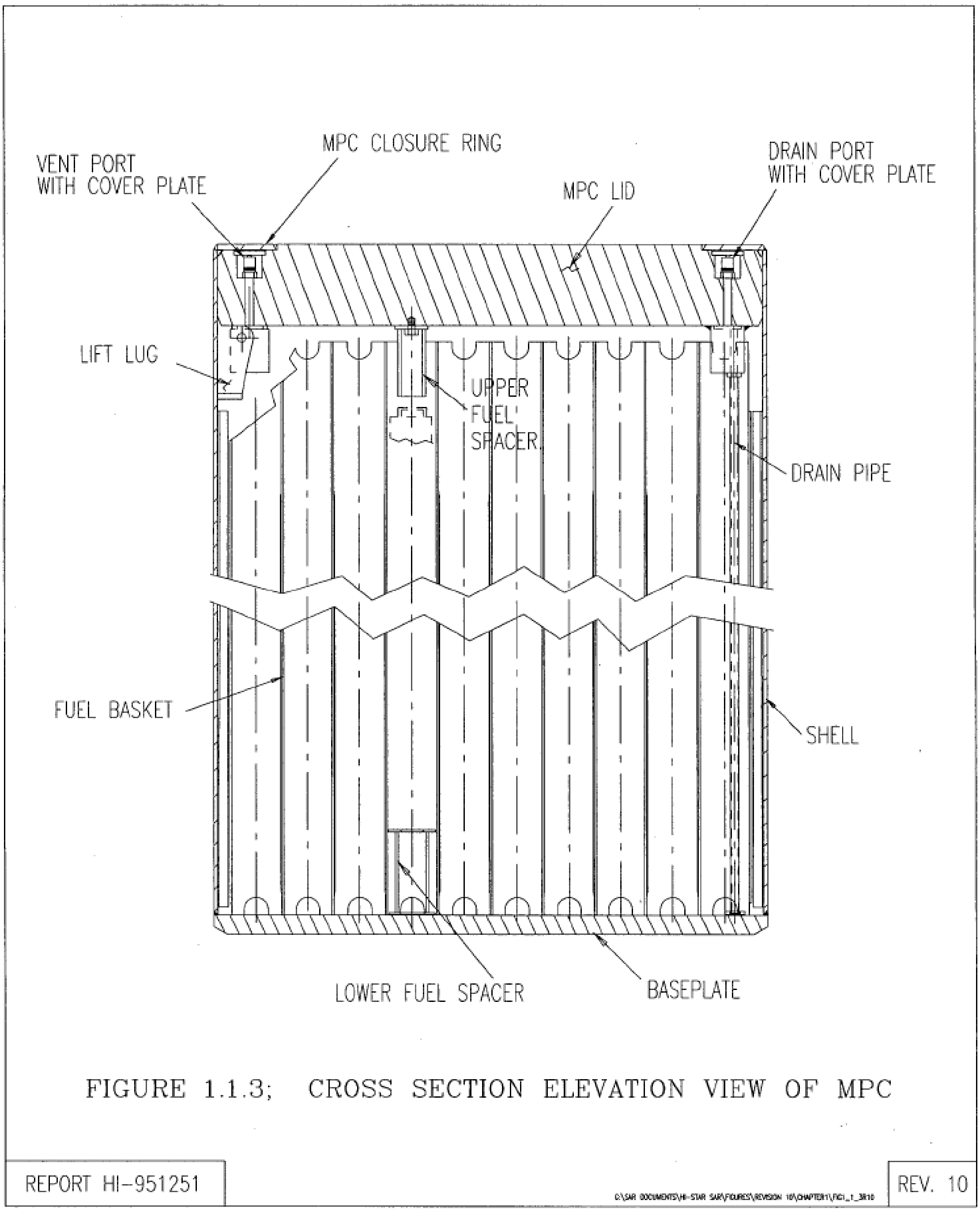


Figure 7: Cross Section Elevation View of MPC

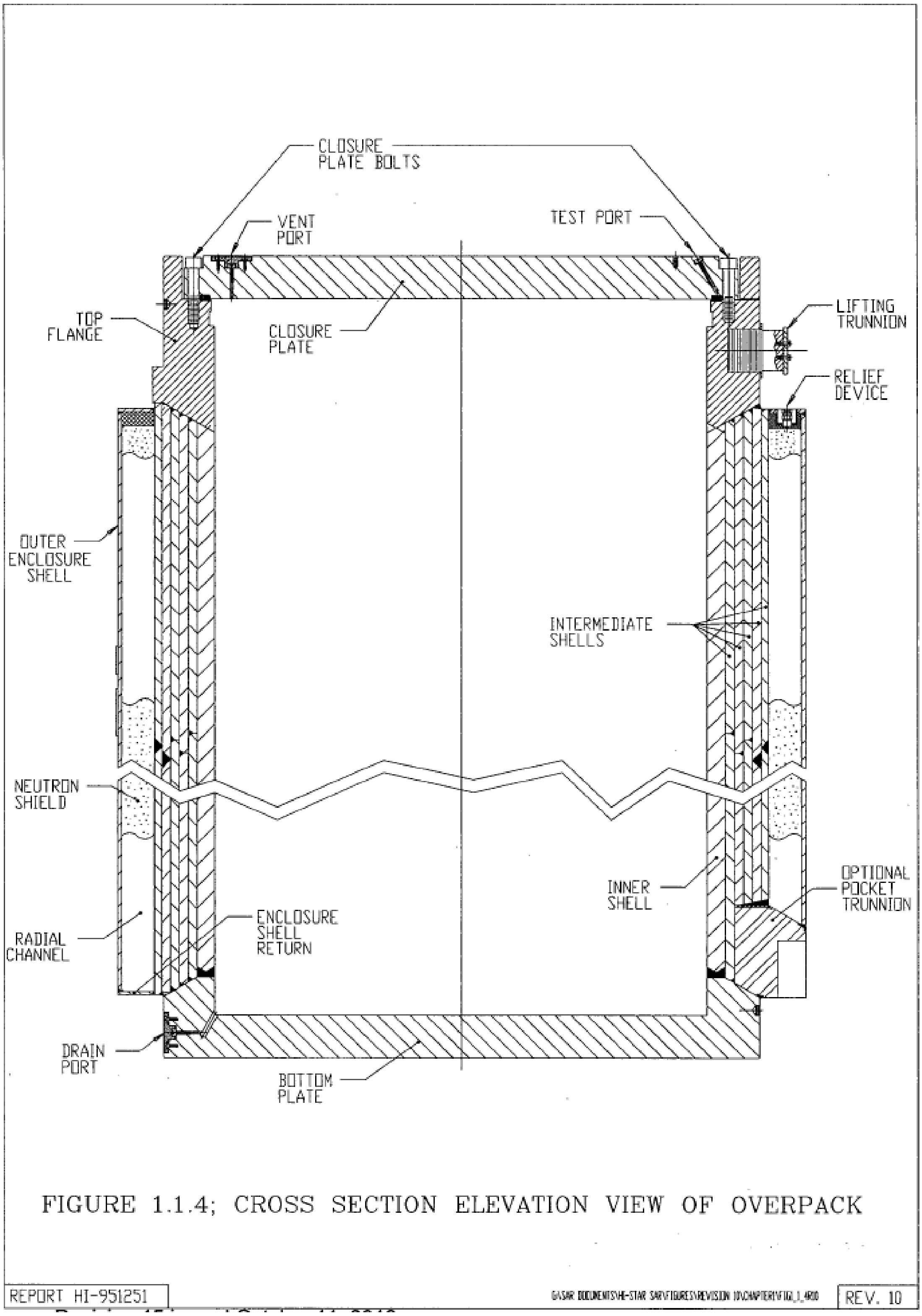


Figure 8: Cross Section Elevation View of Overpack

Table 9: HI-STAR 100 Design Criteria

CASK FEATURES	DESIGN VALUES
Containment general standard air leak tested	Multi-purpose canister MPC and overpack system, 1 lid with a double seal and bolts 4.3×10^{-6} atm cm^3/s (helium)
Cask capacity	32 FAs
Maximum permissible reactivity including all uncertainty and biases (k_{eff})	< 0.95
Minimum Metamic neutron absorber ^{10}B loading (g/cm^2)	0.0310
Cask overall length Cask outer diameter	5086.35 mm 2438.4 mm
Cask maximum heat load	20 kW

Table 10: HI-STAR 100 Design Pressure

Pressure Location	Condition	Pressure (psig)
MPC Internal Pressure	Normal Condition of Transport	100 (6.9 bar)
	Hypothetical Accident	200 (13.8 bar) *
MPC External Pressure	Normal Condition of Transport	40 (2.8 bar)
	Hypothetical Accident	60 (4.1 bar) **
Overpack External Pressure	Normal Condition of Transport	(0) Ambient
	Hypothetical Accident	300 (20.7 bar)
Overpack Internal Pressure	Normal Condition of Transport	-Same as MPC Internal Pressure
	Hypothetical Accident	-Same as MPC Internal Pressure
Overpack Enclosure Shell Internal Pressure	Normal Condition of Transport	30 (2.1 bar)
	Hypothetical Accident	30 (2.1 bar)

* This pressure is only associated with the hypothetical accident where 100% rod rupture is assumed to occur. For all other accident events, such as a 30-ft (9 m) drop, the applicable MPC internal pressure is the design pressure under normal conditions of transport.
** For transport, this represents the differential pressure limit for elastic/plastic stability calculations.

For conservatism, the design value is set equal to the MPC internal pressure under normal conditions of transport. The HI-STAR 100 packaging does not have a maximum normal operating pressure greater than 700 kPa [46].

2 INITIATING EVENTS

An initiating event is a disturbance in the normal operation of the spent fuel cask storage system, which could potentially lead to a release of radioactive material to the environment. A dry cask storage system is designed around passive features and does not include normal running operating systems and emergency safeguard systems as does a nuclear power plant. As such many internal initiating events that are modelled in the "at power" PSA (e.g., turbine trip, loss of all feedwater, small break Loss of Coolant Accident (LOCA), etc.) are not applicable to a dry cask storage system. The external initiating events applicable to a dry cask storage system are similar to those considered for the "at-power" PSA.

2.1 Initiating Event Identification

This aspect of the spent fuel cask risk assessment involves the identification and discussion of a spectrum of potential challenges to the dry cask storage system design during the loading, transfer and storage processes. This process involved information gathering and review of the industry guidance. A comprehensive list of initiating events was developed by EPRI which was constructed from a review of various risk assessment reports for dry cask spent fuel processing and storage [3]. This listing has both internal and external events, process related and cause related. Internal events occur within the process, such as an operational error, equipment failure, or loss of a protective system. External events are initiated outside the process or facility. Thus, an operational error or a failure of a piece of equipment is an internal event, while earthquakes, fires, floods, or aircraft impacts are external events. This list is presented in Table 11 and is comprehensive and generic. It should be noted that the initiating event list may appear to be unorganised and seem to overlap. This is due to the nature of the literature search that determines initiating event descriptions from multiple sources.

Table 11: Complete List of Initiating Events from EPRI Report 1009691

INTERNAL EVENTS	EXTERNAL EVENTS
1 Drop into spent fuel pool	1 Tip-over due to high wind
2 Drop while moving to preparation area	2 Tip-over due to high water
3 Tip-over before sealing	3 Tip-over due to Tsunami
4 Drop while moving to equipment hatch	4 Tip-over due to soil settling/erosion
5 Drop while moving through containment to transport area	5 Seismic events
6 Drop while moving from preparation area to containment boundary	6 Volcanic activity
7 Drop from poor rigging	7 Ground vehicle impact on storage vault
8 Drop from performing minor maintenance while load in motion	8 Strikes from heavy objects
9 Drop from operating crane without proper authorization or signals	9 Wind/flood driven objects
10 Drop from failure of defective boom, cable or sheaves	10 Meteorite
11 Drop from crane failure due to over loading	11 Hail
12 Drop from handling load near stationary equipment	12 Flying vehicles impact cask

INTERNAL EVENTS	EXTERNAL EVENTS
13 Drop from other causes (control systems failure, skipped maintenance inspections)	13 Light aircraft
14 Storage building structural failure	14 Heavy aircraft
15 Refueling building structural failure	15 Fire/explosion (Storage tanks)
16 Drop on to concrete at storage building	16 Fire/explosions (Transformers)
17 Drop onto asphalt, gravel, soil	17 Fire/explosions (Nearby barge or ship)
18 Tip-over while moving	18 Fire/explosions (Nearby trucks or railcars)
19 Tip-over while moving due to impact on transporter	19 Fire/explosions (Military missile)
20 Long term corrosion of storage building	20 Fire/explosions (Other facilities)
21 Long term corrosion of cask	21 Vent blockage - loss of cooling
22 Tip-over when placing additional cask	22 Wind carrying dirt and debris
23 Loading error - wrong assemblies placed into cask	23 Intense precipitation
24 Loading error - wrong poison	24 Accumulation of snow, dirt or ice on vents
25 Loading error - high burnup or short storage	25 Dirt from landslide / heavy rain
26 Transfer events	26 Dirt from volcano ash deposits
27 Loss of shielding integrity	27 Biological intrusion into vents
28 Fire from transport vehicle fuel	28 Flood water over vent below storage building
29 Equipment failure in fuel pool	29 Flood water cover storage vault
30 Fire causes pressurization and differential heating	30 Flood water partially covering the storage vault
31 Fire and tip-over from on-site transportation accident causes	31 High ambient temperature causes pressurization
	32 Lightning
	33 Fire (external) causes pressurization and differential heating
	34 Fire from a gas main
	35 Forest fire

2.2 Initiating Event Screening

A formal screening process was developed for the Koeberg Cask PSA to identify those events in Table 11 that will be retained for further analysis and those that can be eliminated from further evaluation. For the initiating events that are retained, estimates of frequencies, probability of cask failure, and consequences are developed.

2.2.1 Initiating Event Screening Criteria

The screening process considered the following screening criteria which are based on ASME PSA Standard [15] and NUREG/CR-4550 [16]. An event was screened out if:

1) The event is of equal or lesser damage potential than the events for which the cask or Independent Spent Fuel Storage Installation (ISFSI) has been designed. This requires an evaluation of cask design bases in order to estimate the resistance of structures and systems to a particular external hazard.

2) The event has a significantly lower mean frequency of occurrence than another event, taking into account the uncertainties in the estimates of both frequencies, and the event could not result in worse consequences than the consequences from the other event.

3) The event cannot occur close enough to the cask ISFSI to affect it. This criterion must be applied taking into account the range of magnitudes of the event for the recurrence frequencies of interest.

4) The event is included in the definition of another event.

5) The event is slow in developing, and it can be demonstrated that there is sufficient time to eliminate the source of the threat or to provide an adequate response.

6) The event has an initiating event frequency less than 1.00E-08 per reactor year.

A screening analysis was performed on all the events listed in Table 11 based on the above criteria. The results of the screening analyses are shown in Tables A1 and A2 in Appendix A. Note that the numerical value in Table A1 column titled “Exclusion Criteria” refers to the above 6 screening criteria and are numbered accordingly. Criteria 6 may be used to perform a second screening after further analysis has been completed on the events not screened out.

2.2.2 Initiating Events Excluded From Further Consideration in EPRI 1009691

Fuel handling accidents that involve dropping a single fuel assembly during cask loading inside the Spent Fuel Building are discussed in the EPRI Guide [3] and screened out from further analysis as fuel handling accidents are scoped in the site safety assessment report and is not within the scope of the EPRI cask risk assessment report.

Although this accident was screened out by EPRI an investigation was done into the impact of fuel handling accidents during cask loading inside the Spent Fuel Building on the cask risk assessment.

Fuel handling accidents do not result in significant consequences off-site and therefore have no impact on the peak and average public risk. Only the peak and average site personnel risks needs to be assessed. The Koeberg Site Personnel Risk Assessment Study [5] determined the probability of a fuel assembly drop accident per assembly movement as 5.76E-08 per FA movement. The number of fuel assemblies to be loaded into casks per year is 224 per year (32 FAs x 7 cask loadings per year). Thus, the frequency of fuel handling accidents during cask loading is 1.29E-05 per year. The consequence of a fuel handling accident during cask loading was calculated and the analysis results show that fuel handling accident involving dropping a single fuel assembly contributes less than 0.1% to the overall peak and average site personnel risk results. Detailed results supporting this conclusion are presented in Appendix G.

Based on the above risk results, fuel handling accidents involving dropping a single fuel assembly during cask loading inside the Spent Fuel Building will not be considered further in this report.

2.2.3 Initiating Events Not Screened Out

Table 12 presents the initiating events not screened out by the six screening criteria listed in Section 2.2.1.

Table 12: Initiating Events Not Screened Out

INITIATING EVENT	REMARKS
Loading error - wrong assemblies placed into cask	Requires further consideration
Overall Cask Drop	Requires further consideration
Seal Leaks	Requires further consideration
Heavy Aircraft Crash Induced Fire	Requires further consideration

A brief description of the events that have not been screened out is described below. Additional analysis of the events is presented in other sections of the report.

2.2.3.1 Cask Loading Error – Wrong Assemblies Placed Into Cask

Fuel loading errors considered in this initiator are the loading of spent fuel assemblies with higher burnup fuel or shorter cooling time. These loading errors can lead to elevated temperatures within the spent fuel assemblies inside the cask causing the cladding to fail and release fission products into the inert cover gas (helium). These increased temperatures in the cask can eventually lead to seal leakage and loss of integrity of the cask resulting in release of fission products into the environment. For the Holtec cask design, elevated temperatures can result in multi-purpose container failure followed by failure of the overpack top flange’s dual seals. The main contributor to this initiating event is human error associated with developing the cask loading plan for spent fuel assemblies.

2.2.3.2 Overall Cask Drop

Overall cask drop initiator examines the various modes of cask drop which includes drops at various heights, different angles and under different conditions.

The casks are designed to withstand a drop from a height of up to 9 m without loss of integrity to the cask or the seal. The only time a cask is raised above 9 m is in the spent fuel building, where a drop could damage the integrity of the SFP liner. Cask drops during loading or unloading of the cask transporter need not be considered as the cask is raised to a maximum height of 2 m. This analysis will therefore only consider cask drops in the spent fuel building, and will conservatively assume that any drop will lead to loss of integrity of the cask and subsequent release of radioactivity.

EPRI methodology ([9] and [75]) was used to calculate the conditional probability of spent fuel pool integrity failure and further details can be found in Section 3.2.3).

The cask drop accident where the lid is not welded on and the cask is dropped into the loading cell with the potential spill of spent fuel is scoped under the Cask Drop with SFP liner break accident. A lid retention system is not credited for the above accident in the current cask PSA. Note that when the cask is lifted out of the loading cell and moved to the cleaning cell, failure of the MPC weld is not an issue because the MPC is unsealed (loose lid). Also, since the MPC is filled with water, for any fuel cladding failure that may occur during these stages, the fuel particulates would be scrubbed since the gap release passes through the water in the MPC [4].

2.2.3.3 Seal Leaks or Failures

Manufacturing defects, seal degradation, or human errors in inspecting, handling and sealing the cask can cause seal leaks or failures and loss of integrity of the cask and subsequent release of radioactivity. For example, the cask is not sealed properly if water is left in the bolt holes, because the initial torque readings would read falsely high and the seal could leak especially after the water slowly evaporated through the threads. A pressure test with inert gas is conducted after the seal is set out to verify that the seal is effective and to detect leaks.

The frequency of cask seal failure is based on one slow leak that was experienced in 2005 since the four CASTOR X28/F casks were introduced in 2000. The root cause was due to retention of moisture within the inter-lid space after the initial loading of the casks. The SAR indicates that following secondary lid seal leakage confirmation, the leaking cask should be returned to the fuel building for the seal to be replaced within 6 months [20]. A corrective action to replace all secondary seals on the four casks was implemented as a result. To date, the leak tightness on the four casks has been maintained.

2.2.3.4 Heavy Aircraft Crash Induced Fire

Various categories and subcategories of aircraft are considered in the Koeberg Aircraft Crash Risk Assessment [21]. These are general aviation, commercial aviation and military aviation. These three categories are subdivided as follows. General aviation is comprised of rotary wing (helicopters), fixed wing (piston/turbojet) and fixed wing (turboprop). Commercial aviation is comprised of air taxis and air carriers. Military aviation is comprised of military helicopters, small military aircraft, and large military aircraft.

The only types of aircraft that are considered massive enough to affect the integrity of the casks and cause cask failure are air taxis, air carriers and large military aircraft. These will be referred to as heavy aircraft with all other aircrafts types being grouped as light aircraft for the purposes of this report. Table 13 shows this grouping.

Table 13: Grouping of Various Categories of Aircraft

<table>
<tr><th>Aircraft Category</th><th colspan="8">Aircraft Sub-Category</th></tr>
<tr><td>General</td><td rowspan="2">Light</td><td colspan="2">Rotary Wing</td><td colspan="2">Piston/Turbojet</td><td colspan="2">Turboprop</td><td></td></tr>
<tr><td>Military</td><td colspan="2">Helicopters</td><td colspan="2">Small</td><td colspan="2">Large</td><td rowspan="2">Heavy</td></tr>
<tr><td>Commercial</td><td></td><td colspan="3">Taxis</td><td colspan="3">Carriers</td></tr>
</table>

3 DATA ANALYSIS

In this section, the data with respect to the initiating events, human actions and component failures are analysed. In the evaluation of the spent fuel cask, the data analysis includes calculations of the occurrence of events, such as crane failure and load drop.

3.1 Cask Loading Error

The probability of loading a cask incorrectly is calculated below. It is assumed that incorrect loading results in assemblies with a higher than allowable decay heat are loaded which results in the failure of the cask seals.

3.1.1 Analysis of Human Error Probability

The procedure for loading and unloading of casks is documented in Koeberg procedure KWF-023 [22]. The following main steps for loading spent fuel assemblies have been extracted from this procedure and are listed below:

- Fuel handling team must possess valid qualification and supervisor must be qualified and authorised.
- Fuel assembly serial numbers must be independently verified before being loaded into casks.
- An authorised cask loading plan and sequence must be used.
- All fuel assemblies for cask loading must comply with the relevant restrictions on enrichment, cooldown time and burnup specified in the Koeberg Nuclear Installation License NIL-01.
- The fuel handler loads the fuel assembly into the cask according to paragraphs 7.1.3 to 7.1.9 in procedure KWF-023 [22].
- Fuel assemblies must be visually inspected and leak tested with data analysed before final loading into casks.
- Fuel assembly serial numbers must be verified independently using binoculars before being loaded into the cask. If required the underwater camera with video recording can be utilised to record the cask and fuel assembly serial number with the date and time.
- Fuel assembly orientation must be maintained and logged in conjunction with the cask orientation and pool orientation.
- The control room is informed prior to and after each fuel assembly movement in accordance with the loading plan and sequence for sign-offs.
- On completion of loading irradiated fuel into the cask, the sign off procedures must be kept at RFE for record.

A reactor fuel engineering (RFE) subject matter expert (SME) develops a loading sequence which is independently reviewed by another RFE SME. The loading sequence is programmed into the PMC computer prior to fuel handling operations. Once the fuel loading plan has been loaded onto the PMC computer the likelihood of a human error by way of the operator selecting an incorrect fuel assembly is insignificant (the crane has interlocks, it will only move according to the programmed loading sequence). In addition, the crane operators will note and record assembly identities to ensure compliance to the prescribed loading plan.

Operators have been instructed not use the manual override function of the PMC during fuel movements.

The human error for the initiating event is then only the error associated with the development of the cask loading plan.

Assumptions used in the analysis:

- If an error occurs during the development of the cask loading plan, it will be assumed to affect multiple spent fuel assemblies such that the maximum heat load design limit of the cask may be exceeded.
- In practice the checks performed during fuel handling operations are against the loading plan. Thus, if the loading plan is incorrect, this is unlikely to be resolved during fuel handling operations. Therefore, no credit is given to fuel handling personnel mitigating loading plan errors.

The cognitive part of the SPAR-H calculation [54] will not be quantified because this task does not contain any diagnosis activity.

The Human Error Probability (HEP) analysis is presented in Appendix C where the probability of loading a cask incorrectly is calculated as 1.30E-05 per cask.

3.1.2 Thermal Analysis

The calculation further considers cases where errors in loading FAs with less than 2 years cooling time in the SFP can occur by applying the binomial distribution methodology described further in NUREG-1864 [4].

The thermal analysis investigates the number of incorrectly loaded FAs that are required to cause temperatures high enough to damage the fuel and result in the heat capacity of the cask being exceeded. Reference [2] states that the scenario of a gross series of errors that result in every FA loaded into the MPC being a FA that is incorrect/insufficiently cooled is not considered credible, but useful for the purposes of exploring the impact of such an event.

In these scenarios the heat load in the MPC was increased from 21 kW to 33 kW, 66 kW, and 126 kW. These heat loads correspond to fuel that has cooled in the spent fuel pool for 5, 2.5, 1, and 0.5 years respectively.

Even if every single FA loaded into the MPC were incorrect, no MPC failures are predicted for heat loads of 21 kW, 33 kW, and 66 kW. But if the heat load was 126 kW, the MPC could be expected to fail from creep rupture. No fuel failures are expected for heat loads of 21 kW and 33 kW. In these extremely unlikely scenarios, fuel failure could be expected to occur when the heat load is 66 kW and 126 kW. For the 66 kW heat load the fuel temperature is expected to reach 543ºC when the cask reaches thermal equilibrium, but the fuel rods are unlikely to fail at this temperature.

For the purposes of this assessment is it was conservatively assumed that MPC failure followed by cask overpack failure will occur for cask heat loads exceeding 66 kW due to cask loading errors. A combination analysis was performed to determine what number of low and high decay heat (incorrect/insufficient cooling time) FAs that are required to exceed the heat capacity of 66 kW. The decay heat for the 0.4, 1.7 and 19 year old FAs considered in the combination analysis is presented in Table 14. The decay heat values for the FAs with less than 2 years of cooling time (i.e., the incorrectly loaded FAs with high decay heat) were calculated using ORIGEN-S and are presented in Appendix C. The decay heat value for the 19 year old FA is representative of the FA with the shortest cooling time that can actually physically be loaded into the cask and was taken from information available in Reference [3]. The number of FAs with less than 2 years of cooling time was confirmed by Reactor Fuel Engineering (RFE) staff at Koeberg [66].

Table 14: Decay Heat for FAs Used in the Combination Analysis

Decay Period (years)	Decay Heat of FA (W)	No. of FAs < 2 Years
19	5.38E+02	N/A
1.7	3.51E+03	61
0.4	8.80E+03	61
Total		**122**

The results of this combination analysis are presented in Table 15 and show the different number of incorrectly loaded 1.7 and 0.4 year old FAs that can potentially be combined with correctly loaded 19 year old FAs to result in the decay heat of the cask of 66 kW being exceeded. Appendix C presents an example of the detailed combination analysis calculation that was performed for the case where zero 1.7 year old FA is incorrectly loaded into the cask. A similar combination analysis calculation was performed to derive the results presented in Table 15 for the cases of 1 up to a maximum of 32 incorrectly loaded 1.7 year old FAs [67].

Table 15: Number of 1.7 and 0.4 Year Old FA Combinations Required to Exceed 66 kW

No. of 1.7 Year Old FAs Loaded Incorrectly	Minimum No. of Incorrectly Loaded 0.4 Year Old FAs Required to Exceed 66 kW
0	6
1	6
2	6
3	5
4	5
5	5
6	4
7	4
8	4
9	3
10	3
11	2
12	2
13	2
14	1
15	1
16	1
17	0
18	0

No. of 1.7 Year Old FAs Loaded Incorrectly	Minimum No. of Incorrectly Loaded 0.4 Year Old FAs Required to Exceed 66 kW
19	0
20	0
21	0
22	0
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0

I. Binomial Calculation

From EPRI 1009691 [3], the binomial distribution function can be used to estimate the cask loading error probability based on the number of cases that result in selecting and incorrectly loading possible combinations of 1.7 and 0.4 year old FAs given that the fraction of FAs with less than 2 years of cooling time in the SFP is approximately 10% (= 122 / 1158 FAs) based on information received from RFE staff [66]. Of this 10% of FAs that have decayed for less than 2 years, 50% (i.e., 61 out of 122 FAs) has decayed for 1.7 and 0.4 years respectively.

The binomial distribution function can be used to assess the probabilities for situations "k out of n" ($k_{out\_of\_n}$) type through various applications of the formula and is defined as follows:

$$P(k_{out\_of\_n}) = \frac{n!}{k!(n-k)!}\,(p^k)(q^{(n-k)} \qquad (16)$$

where:

n = number of opportunities for event x (selecting a FA with less than two years cooling) to occur;
k = number of times that event x is stipulated to occur to cause seal damage;
p = probability that event x will occur on any particular spent FA selection randomly; and
q = probability that event x will not occur on any particular spent FA selection.

Taking into consideration that the spent FAs with less than 2 years cooling which can potentially be loaded incorrectly comprises of both 1.7 and 0.4 year old FAs, the binomial distribution function formula was applied twice; first to calculate the probability for each of the possible cases of incorrectly loading 1.7 year old FAs (i.e., 0 to a maximum of 32) which, for each 1.7 year old FA cases, was then combined with another binomial distribution function calculation considering the minimum number of incorrectly loaded 0.4 year old FAs required as presented in Table 14. For differentiation purposes, the 1.7 year old spent FAs binomial distribution function parameters are defined as n1, k1, p1 and q1 and the 0.4 year old spent FAs binomial distribution function parameters are defined as n2, k2, p2 and q2 respectively.

The probability that an incorrectly loaded 1.7 and 0.4 year old FA will occur (i.e., p1 and p2 respectively) and will not occur (i.e., q1 and q2 respectively) are presented in Table 16. These probabilities are based on the fact that 10% of FAs in the SFP has decayed for less than 2 years and of this 10%, 50% (i.e., 61 out of 122 FAs) has decayed for 1.7 and 0.4 years respectively.

Table 16: Probability Input Parameter Values for the Binomial Distribution Function Probability

Probability			
1.7 Year Old FAs		**0.4 Year Old FAs**	
p1	0.05	p2	0.05
q1 = (1 - p1)	0.95	q2 = (1 - p2)	0.95

Since the maximum capacity of the HOLTEC type casks procured for Koeberg is 32 spent FAs per cask, the number of opportunities n1 that exists for incorrectly selecting and loading 1.7 year old FAs is 32. Given the case that n1 1.7 year old FAs have been incorrectly selected and loaded, the number of opportunities n2 that exists for further incorrectly selecting and loading 0.4 year old FAs is then defined as 32 - n1.

The number of times k1 that a 1.7 year old FA can be selected and loaded incorrectly can vary from 0 to a maximum of 32 (see Table 15). Given the case that k1 × 1.7 year old FAs are considered to be incorrectly selected and loaded, the minimum number of times k2 that a 0.4 year old FA can then be incorrectly selected and loaded is as presented in Table 15.

Table 17 presents the final results of the binomial distribution function calculation used to determine the cask loading error probability of 1.12E-02 for incorrectly loading k1 × 1.7 year old and > k2 × 0.4 year old FA combinations out of a maximum of 32 FAs. The detailed intermediate binomial distribution function calculations for the > k2 × 0.4 year old FA cases are contained in Reference [67].

Table 17: Binomial Distribution Function Calculation to Determine Cask Loading Error Probability for Incorrectly Loading k1 × 1.7 and > k2 × 0.4 Year Old FA Combinations Out of 32 FAs

No. of opportunities for incorrectly loading a 1.7 year old FA (n1)	No. of times k1 incorrectly loaded 1.7 year old FA can cause fuel damage (k1)	Probability that an incorrectly loaded 1.7 year old FA will occur on any FA selected randomly (p1)	Probability that an incorrectly loaded 1.7 year old FA will not occur on any FA selected randomly (q1)	Probability for 1.7 year old FA cases (k1 out of n1)	Minimum No. of incorrectly loaded 0.4 year old FAs (k2) required to exceed 66 kW given k2 x 1.7 year old FAs loaded incorrectly	Probability of the Total of ALL 0.4 year old FA cases for k2 (> k2 out of n2)	Probability for (k1 out of n1) 1.7 year old FA cases and (> k2 out of n2) 0.4 year old FA cases
32	0	n/a	n/a	n/a	6	5.30E-03	5.30E-03
32	1	0.051476793	0.948523207	3.20E-01	6	4.50E-03	1.44E-03
32	2	0.051476793	0.948523207	2.69E-01	6	3.79E-03	1.02E-03
32	3	0.051476793	0.948523207	1.46E-01	5	1.52E-02	2.23E-03
32	4	0.051476793	0.948523207	5.75E-02	5	1.32E-02	7.57E-04
32	5	0.051476793	0.948523207	1.75E-02	5	1.13E-02	1.97E-04
32	6	0.051476793	0.948523207	4.27E-03	4	4.24E-02	1.81E-04
32	7	0.051476793	0.948523207	8.60E-04	4	3.74E-02	3.21E-05
32	8	0.051476793	0.948523207	1.46E-04	4	3.27E-02	4.77E-06
32	9	0.051476793	0.948523207	2.11E-05	3	1.12E-01	2.37E-06
32	10	0.051476793	0.948523207	2.64E-06	3	1.01E-01	2.67E-07
32	11	0.051476793	0.948523207	2.86E-07	2	2.95E-01	8.43E-08
32	12	0.051476793	0.948523207	2.72E-08	2	2.75E-01	7.48E-09
32	13	0.051476793	0.948523207	2.27E-09	2	2.56E-01	5.80E-10
32	14	0.051476793	0.948523207	1.67E-10	1	6.14E-01	1.03E-10
32	15	0.051476793	0.948523207	1.09E-11	1	5.93E-01	6.45E-12
32	16	0.051476793	0.948523207	6.27E-13	1	5.71E-01	3.58E-13
32	17	0.051476793	0.948523207	3.20E-14	0	n/a	3.20E-14
32	18	0.051476793	0.948523207	1.45E-15	0	n/a	1.45E-15
32	19	0.051476793	0.948523207	5.79E-17	0	n/a	5.79E-17
32	20	0.051476793	0.948523207	2.04E-18	0	n/a	2.04E-18
32	21	0.051476793	0.948523207	6.34E-20	0	n/a	6.34E-20
32	22	0.051476793	0.948523207	1.72E-21	0	n/a	1.72E-21
32	23	0.051476793	0.948523207	4.06E-23	0	n/a	4.06E-23
32	24	0.051476793	0.948523207	8.26E-25	0	n/a	8.26E-25
32	25	0.051476793	0.948523207	1.43E-26	0	n/a	1.43E-26
32	26	0.051476793	0.948523207	2.10E-28	0	n/a	2.10E-28
32	27	0.051476793	0.948523207	2.53E-30	0	n/a	2.53E-30
32	28	0.051476793	0.948523207	2.45E-32	0	n/a	2.45E-32
32	29	0.051476793	0.948523207	1.83E-34	0	n/a	1.83E-34
32	30	0.051476793	0.948523207	9.95E-37	0	n/a	9.95E-37
32	31	0.051476793	0.948523207	3.48E-39	0	n/a	3.48E-39
32	32	0.051476793	0.948523207	5.91E-42	0	n/a	5.91E-42
	Probability of the Total of ALL (k1 out of n1) 1.7 year old cases and (> k2 out of n2) 0.4 year old cases =						1.12E-02

3.1.3 Cask Loading Error Probability

The determine the probability of the cask exceeding its design heat capacity, the probability of incorrectly loading spent FAs with less than 2 years cooling time of 1.12E-02 (see Table 17) is combined with the human error probability associated with the cask loading activity.

The cask loading error probability is then calculated as follows:
P(heat up) = P(greater than × FAs with < 2 years cooling) × P(error in cask loading plan)

Table 18: Evaluation of Cask Loading Error Probability Fraction of fuel

Fraction of Fuel < 2 Years in SFP	Binomial Function Cases Greater Than x of 32	Error in Cask Loading Plan	Probability of Potential Over Heating
0.10	1.12E-02	1.30E-05	1.45E-07

From

Table 18, the probability of incorrectly loading a cask with FAs with cooling times of less than 2 years that result in the design heat capacity of the cask being exceeded is 1.45E-07 per cask.

The cask loading error probability has to be multiplied by the number of cask loadings per year to determine the overall annual cask loading error frequency.

The number of cask movements considered in the analysis is 7 cask movements per year. Therefore, the annual frequency of a cask loading error is 1.02E-06 (7 × 1.45E-07) per year for the station.

The cask loading error probability presented in this section assumes that 'incorrect' FAs can be randomly selected from the Region I and Region II racks in the spent fuel pool. This probability can be significantly reduced through modifying the software on the fuel building PMC crane to restrict movement over the Region I racks during cask loading operations. Since most of the recently discharged FAs remain in the Region I racks until shortly before the next outage, this software modification would exclude a large number of high decay heat FAs from possible incorrect loading into the MPC, thereby reducing the value of the binomial function calculated in Table 17.

3.2 Overall Cask Drop

3.2.1 Probability of a Cask Drop

The probability of a cask drop accident was assessed by various independent analyses which are discussed in the following paragraphs.

It is important to discuss the specific design conditions for the fuel building with regards to cask drop accidents under high and low fuel drop conditions.

A high drop of a fuel cask (between 20.50 and the bottom of the cells) is not considered as a design load due to the safety features in the design of the cask handling crane [68]. In fact the probability study carried out for the cask handling crane for the Reference Stations shows that the probability of a fuel cask drop is too low to take such an event into account [23]. The following design features which aim to reduce the consequences of a cask drop accident have been maintained at Koeberg:

- The cask handling crane layout is such that the cask cannot move over the spent fuel pool.
- The spent fuel pool is structurally separated from the structures served by the cask handling crane by means of an expansion joint above the 0.00 m level.
- The bottom of the cask loading and cask cleaning cells have been designed to withstand a high drop of the cask based on the following information:
    - Cask = mass 110 T – base section: 2 m × 2 m
    - Heights of fall:
        - Cleaning cell: 20.50 – 14.25 = 6.25 m
        - Loading cell: 20.50 – 7. 25 = 13.25 m
    - Shock absorbing material
    - Thickness of material:
        - Cleaning cell: 1.00 m
        - Loading cell: 2.00 m
    - Reinforced concrete
- Below the cask handling shaft and under the floor at the 0.00 m level, shock absorbing material has proved to withstand the drop of the cask (after it has penetrated the 0.00 m slab):
    - Height of fall = 20.50 – (-3.40) = 23.90 m
    - Thickness of Siporex (shock absorbing material) = 3.00 m

Whenever the distance from the bottom of the cask to a floor is less than 0.50 m there is a risk of low level impact if there is a failure in the hoisting mechanism and prior to the application of the safety brakes and stoppage of the cask. This risk is addressed in the following way:

- Cleaning and loading cells are designed to take this impact;
- Concrete slab at the 0.00 m level under the handling shaft: this slab is not designed to withstand a direct impact. For this reason the cask transporter shall be kept under the cask during low handling phases (distance from the bottom of cask to platform of transporter is less than 0.50 m) and the maximum energy of the cask following a drop will be absorbed by the transporter.

3.2.1.1 Framatome Cask Handling Crane Risk Analysis

The cask handling crane risk assessment performed by Framatome [23] was used to assess the probability of a cask drop for the various cask handling stages in a cask movement operation. The results are shown in Table 19.

Table 19: Probability of a Cask Drop during the Various Handling Phases

Handling Phases	Lower Bound *[per year]*	Remarks	Upper Bound *[per year]*	Remarks
Hoisting-lowering without start-stop transients	*5.00E-10*	Without lifting beam failures	*5.00E-07*	With lifting beam failures
Start-stop transient	*1.00E-10*		*1.00E-10*	
Low level approaches	*6.40E-05*		*6.40E-05*	
Hoisting-lowering Phase	6.40E-05		6.45E-05	
Transfer Phase	1.00E-07	If safety brakes locked on	8.50E-07	If safety brakes not locked on
Loss of Electrical Power	negligible		negligible	
Overall	6.41E-05		6.54E-05	
Final Cask Drop Probability	**1.00E-07**	Without low level approaches	**1.35E-06**	Without low level approaches

In this analysis, the probability of a cask drop is dominated by low level approaches (i.e., where the bottom of the cask is less than 0.50 m above a floor) during which the overhead crane safety devices are ineffective. However, since the fuel building was designed with shock absorbing material at the base of the cask cells and handling shaft, a cask drop at this time would be of no consequence. Similarly, the cask transporter is designed to cushion a low level drop at the handling shaft [23]. Therefore, when low level approaches are discounted the cask drop probability becomes 1.35E-06. Since the Framatome analysis conservatively assumed 5 cask handlings per year, the overall cask drop probability per cask handling operation is therefore 2.70E-07 (1.35E-06 / 5).

3.2.1.2 NUREG-1774: U.S. Crane Operating Experience

A recent study was conducted on the frequency of heavy load drops and very heavy load drops [25]. This study was based on actual crane operating experience from 74 U.S. Nuclear Power Plants over 34 years. It was reported that out of the estimated 54 000 very heavy (over 30 tons) load lifts, 3 load drops occurred. This results in a drop probability of 5.60E-05 per operation (~ 3 in 54 000).

3.2.1.3 EPRI-1009691: Crane Failure

The EPRI report for spent fuel cask PRA [3] uses a generic crane example in the development of models to quantify the frequency of load drops associated with crane failure. The base case model uses the crane reliability data model developed in NUREG-0612, “Control of Heavy Loads at Nuclear Power Plants” which was based on data from the Navy on crane accidents and modified to reflect better quality training of the nuclear plant crane operators. The EPRI model also uses the procedures and process observed at Peach Bottom in report “Trip Report on Observation of Spent Fuel Cask Loading and Transport”.

A fault tree model was developed by EPRI and the overall probability of load drop from crane equipment failure was calculated to be 5.30E-06 per lift. Table C-8 in the EPRI report [3] lists the dominant cutsets that contribute to the overall drop probability of 5.30E-06. In Table 20, the first 7 cutsets (with probabilities per lift > 1.0E-07) are screened for applicability to Koeberg, and justifications are given below as to why they can be screened out (note that for cable failures, Koeberg takes credit for regular cable inspections). The result is that the EPRI crane failure probability reduces to 1.0E-7 (5.3E-06 – 5.2E-06) per lift when adjusted for Koeberg’s case. Assuming 4 lifts per cask operation for the different stages of cask handling in the spent fuel building, the result is a cask drop probability of 4.0E-7 per operation.

Table 20: Basic Crane Failure Cutsets Listing

IE No.	Inputs	Description	Event Probability	Cutset Probability per lift *
1	CCFROPES	Common cause failure of cables	2.0E-06	2.0E-06
2	DGGBF	Broken teeth in gear box	1.0E-06	1.0E-06
3	CCFBRK	CCF of mechanical brakes	8.0E-07	8.0E-07
4	DSBKIF	Gear box shaft brake coupling shear	8.0E-07	8.0E-07
5	DGBRXF	Failure of drum gear box shaft	2.0E-07	2.0E-07
6	GBIBSF	Gear box brake shear	2.0E-07	2.0E-07
7	GRBXSF	Failure of drum gear box coupling	2.0E-07	2.0E-07
8	DOPBF	Failure of drum bearings or pedestals	4.0E-08	4.0E-08
9	ROPEDF	Cable rope drum fracture due to mis-reeving	4.0E-08	4.0E-08
10	OPEREO	Operator error in operation	3.0E-08	3.0E-08
11	CFHOOK	Catastrophic failure of the lifting rig or hook	2.0E-09	2.0E-09

1) CCFROPES
Discounted because at Koeberg inspection of ropes are performed very frequently, e.g. before every cask lift.

2) DGGBF (gearbox tooth)
N/A – For the Koeberg crane, gearbox failure will not result in a cask drop because of the emergency brakes mounted on the drum.

3) CCFBRK (CCF of mechanical brakes)
N/A – For the Koeberg crane, there are two different sets of brakes, viz.,

- On the motor shaft, a service brake and auxilliary service brake, electromechanically actuated on loss of power (in normal use, auxilliary brake has a brief delay); and
- On the hoist drums, spring actuated brakes held open in normal use by a hydraulic system, actuated on loss of power to hydraulic pack.

Thus, the Koeberg crane has a redundant and diverse braking systems, so CCF failure of both sets is not considered.

4) DSBKIF (Gear box shaft brake coupling shear)
N/A – This feature is not relevant to the Koeberg crane. In any event, failure of the motor shaft or shafts linking gearbox to half-couplers to pinions cannot result in a load drop because even if the hoist drums are completely dissociated from the motor shaft (as would occur in gearbox failure), this will not result in a load-drop because the emergency brakes on the hoist drums will arrest the fall upon overspeed actuation.

5) DGBRXF (Failure of drum gear box shaft)
As above. Complete disconnection of the gearbox from the hoist drums will not result in a cask drop.

6) GBIBSF (Gear box brake shear)
As above. Complete disconnection of the gearbox from the hoist drums will not result in a cask drop.

7) GRBXSF Failure of drum gear box coupling
As above. Complete disconnection of the gearbox from the hoist drums will not result in a cask drop.

Lastly, it must be noted that cask drops < 0.5 m are excluded from the above justifications.

3.2.2 Summary of Cask Drop Accident Probabilities

The cask drop probabilities from the different sources considered are listed below.

Table 21: Cask Drop Probabilities Obtained from Different Sources

Source	Drop Probability Per Operation
Framatome (1979) [23]	2.70E-07
NUREG-1774 (2003) [25]	5.60E-05
EPRI-1009691 (2004) (adjusted for Koeberg) [3]	4.00E-07

The NUREG source is not deemed to be realistic enough as it considers all heavy load drops and this analysis focuses on cask drops into the SFP. The Framatome source is regarded as a very early study and requires some additional work. The EPRI Study uses generic crane failure data based on Navy crane accidents but has been modified for nuclear cask operations and is the most recent source of information. The aim of this cask assessment is to align with EPRI as far as possible and hence a Koeberg adjusted value of 4.0E-07 will be used for the probability of cask drop accidents.

The number of cask movements considered in the analysis will be 7 cask movements per year.

Thus, a frequency of 2.80E-06 (4.0E-07 × 7) cask drops per year is obtained. As already mentioned, a cask drop accident can result in either failure of the seal integrity or, if the cask is dropped in the spent fuel building, a loss of integrity to the SFP liner.

3.2.3 Conditional Probability of Spent Fuel Pool Integrity Failure

EPRI 3002000498 [9] and EPRI 3002002691 [75] assumes that the probability the drop occurs over the spent fuel pool is 0.13 (i.e., 13% of the duration of the movement occurs over the pool) and the probability that a drop results in structural damage to the spent fuel pool is 0.16 (i.e., 16% of all drops in the pool result in pool failures). An overall failure rate of 2.08E-02 (0.13 × 0.16) pool failures per cask handling is applied in the report.

WASH-1400 [41] assumed that only for a fraction of the duration of the cask movement 1.67E-02 (1 in 60), would the cask be in a position where a drop could cause gross structural damage to the pool wall if a crane failure occurred, i.e., a probability of 1.67E-02. It was further assumed in this study that 100% of cask drops in this location would result in gross structural damage to the pool wall, i.e., all cask drops in the location will result in pool failures. Therefore, there is an overall failure rate of 1.67E-02 (1.67E-02 × 1.00E+00) pool failures per cask handling.

NUREG/CR-4982 [17] refined the WASH-1400 assessment. This assessment considered that the section of the pool where the cask is set down has an impact pad to absorb the impulse of a dropped cask. Thus, only horizontal movements of the cask near a structurally critical section of the pool (e.g., the vertical wall of the pool) would pose a threat of structural damage. NUREG/CR-4982 states that the assumption that all load drops in this vicinity lead to loss of pool wall integrity is too conservative for the following reasons:

- Many “load drops” would be partially attenuated by crane mechanisms which limit descent rates and so reduce impact energy,
- In case of some “off-centre” hits, the full potential impact energy would not be absorbed by the pool edge (cask tilted, one end strikes floor first), and
- Account should be taken of exterior cask fittings (e.g., cooling vanes) which absorb some impact energy.

NUREG/CR-4982 further notes that most steps in the crane operation do not jeopardise the structural integrity of the pool. Only steps that could lead to the cask striking the pool edge with sufficient force to damage its integrity. NUREG/CR-4982 estimates this as 1% of the total cask movement operation. Therefore 1.00E-02 refers to the fraction of steps in crane operation per cask handling that the crane spends in the vicinity of the pool edge that could potentially cause a cask drop.

NUREG/CR-4982 goes on to estimate the conditional probability of structural damage to the SFP liner given a cask drop in the vicinity of the pool edge as 1 in 10, i.e., 1.00E-01, per cask drop.

Thus, the overall probability of a loss of SFP liner integrity given a cask drop is 1.00E-03 pool failures per cask handling operation (1.00E-02 × 1.00E-01).

Electrowatt, “Probabilistic Analysis of Spent Fuel Pit Accidents”, [40] considered catastrophic pit liner failure but due to the low probability of this event it did not contribute significantly to the overall risk.

WCAP-17763-P [35] excludes cask drops damaging the integrity of the pool liner based on plant design features.

EPRI 1009691 [3] does not consider cask drop damaging the spent fuel pool liner as credible because of design features such as the floor of the cask loading cell being made to absorb the impact of a dropped cask.

At Koeberg the duration of cask movements in close proximity to the spent fuel pool was calculated from the total duration of time taken to complete a cask handling activity in the SFP building (96 hours) [69]. It is assumed that the cask is in close proximity to the SPF at the stage when the cask is hoisted out of the CCC and moved to the CLC up to the stage when the cask returns to the CCC. Note that the time spent (9 hours) loading the FAs into the cask has been excluded as this activity does not involve movement of the cask itself. The duration of cask movements in close proximity to the SPF is therefore 0.16 (15 / 96 hours).

For drops from greater heights it is probable that the structural separation would be effective up to a certain height. For drops from maximum height, it is not certain that the spent fuel pool concrete would not crack since there would be significant energy transmitted through the foundation raft. It is not certain that the spent fuel pool liner would tear; nevertheless, to remain conservative it is postulated that it does so because of differential movements of the liner and concrete. The leakage of water from the spent fuel pool would uncover the fuel and allow it to melt before corrective actions could be undertaken.

Accordingly, the Koeberg PSA assumes a 50% probability that a cask-drop (excluding the 0.5 m low cask drop) within the fuel building will cause complete failure of the SFP liner and result in SFP uncovery [57]. This value is considered conservative, compared to the generic value of 0.16 for the probability that a drop results in structural damage to the spent fuel pool used in References [9] and [75].

Therefore, the conditional probability of SFP integrity failure by applying the EPRI methodology is 0.08 (0.16 duration in close proximity of pool × 0.5 drop probability resulting in SFP liner damage).

This information is summarised in the table below.

Table 22: Conditional Probability of Pool Integrity Failure per Cask Handling Operation

Source	Conditional probability assuming a cask is dropped during its transfer	Reference
EPRI (PWR & BWR)	2.08E-02	[9], [75]
WASH-1400	1.67E-02	[41]
NUREG/CR-4982	1.00E-03	[17]
Electrowatt	Insignificant risk	[40]
Westinghouse	Excluded	[35]
EPRI	Not considered	[3]
Koeberg	8.00E-02	[69], [57]

Using the Koeberg specific value, the probability per cask handling operation that a cask drop results in loss of integrity of the SFP liner is 3.20E-08 (4.00E-07 × 8.00E-02)

Considering that 7 cask movements per year can occur, the frequency of a cask drop with SFP liner break is 2.24E-07 (7 × 3.20E-08) per year. Consequences of damage to the SFP liner will be discussed in Section 5.

3.3 Cask Seal Leaks and Failures

Since the introduction of the 4 CASTOR X/28F casks for spent fuel storage at Koeberg in March 2000, 1 slow seal leak (with a seal leak rate of approximately 1.19 kPa per day) has been detected [26]. The frequency of a slow seal leak can therefore be calculated to be 5.73E-03 slow leaks per seal per year (1 slow leak detected out of 8 seals over 21.80 years i.e., 1 ÷ 8 ÷ 21.80).

The SAR indicates that following secondary lid seal leakage confirmation, the leaking cask should be returned to the fuel building for the seal to be replaced within 6 months [20]. Thus, a value of 6 months will be used for calculation purposes. The frequency of both seals failing can be calculated, using a constant failure rate model [27] and taking into account common cause failure (CCF), to be:

Frequency (cask failure) = Frequency (1 seal) × Probability (2nd seal failure in 6 months) + CCF

$$= \lambda \times \left[1 - e^{(-\lambda t)}\right] + \beta\lambda \quad (17)$$

Where: λ = the failure rate of a seal (5.73E-03 slow seal failures per year)
t = the time period given to implement corrective actions (6 months)
β = the common cause beta factor

The β value of 4.70E-02 was obtained from the generic CCF data contained in Table 5-11 of NUREG/CR-5485 [27]. Using this method, the frequency that both seals on a cask will develop slow leaks leading to a possible radioactive release is 2.86E-04 per cask per year or 4.60E-02 per year for the station (161 × 2.86E-04). It must be noted that cask seal failure accidents have been conservatively assessed for 161 casks; however, cask seal failure accidents have been screened out or excluded from the Koeberg Spent Fuel Storage Cask Risk Assessment – Additional Casks [56]. Since the design of the remaining casks is unknown and Eskom may procure a different cask design in the future, a decision was made to conservatively assess seal failure accidents for 161 casks.

No catastrophic seal leak leading to immediate depressurization of the inter-lid space has been recorded to date and the SAR indicates that the probability of double catastrophic seal failures is negligible [20]. The frequency of such a catastrophic leak, in the event of a common cause failure, can be calculated using the same method as above.

Even though no recorded failures have occurred, zero (0) will not be used. Instead, 0.5 failures will be conservatively used. The period of experience is 174.4 seal years (i.e., 8 × 21.80). The detailed calculation is shown below:

Slow Seal Failure Rate (λ) = 2.87E-03 Failures per year (0.5 failure / 174.4 seal years)
Time (t) = 0.5 yrs
CCF Factor (β) = 4.70E-02

Frequency (cask failure) = Frequency (1 seal) × Probability (2nd seal failure in 6 months) + CCF
$= \lambda \times \left[1 - e^{(-\lambda t)}\right] + \beta\lambda$
$= 2.87\text{E-}03 \times \left[1 - e^{(-2.87\text{E-}03 \times 0.5)}\right] + 4.70\text{E-}02 \times 2.87\text{E-}03$
$= 1.39\text{E-}04$

Thus, the frequency of two seal ruptures is 1.39E-04 per cask per year or 2.24E-02 per year for the station (i.e., 161 × 1.39E-04).
The 4 CASTOR X/28F type casks are stored in the Cask Storage Building within the Low Level Waste Complex onsite and these are radiological zones. Due to Radiological Protection (RP) and ALARA concerns, access is restricted to the Cask Storage Building and Low Level Waste Complex as these are radiological zones. Consequently, the only normal daily activity in the CSB is the monitoring [55] of the cask parameters (temperature, pressure, etc.) by Operating during the morning shift by the Outside Plant NPO (Nuclear Plant Operator).

The occupancy factor is the time spent by the NPO performing the monitoring activity in the CSB. This is a radiological zone/restricted area and therefore the NPO cannot be present in the area throughout the day. Hence the only time the NPO will be directly exposed to radiation hazard from a cask seal failure will be during the monitoring activity when he/she is in the vicinity of the cask and thus the occupancy factor is considered in the calculation of the frequency to account for this. Should a cask seal failure occur while the NPO is not in the vicinity of the cask performing the monitoring activity, then no risk from cask seal failure will exist as there will be no radiation exposure to the NPO.

The Koeberg procedure for CSB monitoring [55] does not stipulate the time spent on the monitoring activity; hence it was required to interview the staff to establish timelines for input into the calculations to determine the exposure time taking into consideration that ALARA principle must be respected. Statements from Operating and RP staff indicated that the duration of the monitoring activity is a maximum of 5 minutes per day which results in an occupancy factor of 3.47E-03 (5 minutes / (60 × 24) minutes).

Since the TISF will be a similar radiological zone as the CSB or LLW complex, the same occupancy factor will be applied. Therefore, the frequency of cask seal failure is 7.76E-05 per year for the station (i.e., 2.24E-02 × 3.47E-03) and is applicable to the site personnel frequency only.

3.3.1 Seal Leak Timing

A number of calculations have been performed to determine the time period for the inter-lid space pressure to decrease to such a pressure that would allow a radioactive release from the primary space in the event of a primary seal leak [28]. The results are outlined below:

- The inter-lid space would have to be re-pressurized 226 times before a pressure of 400 kPa is reached in the primary space assuming that re-pressurization to 700 kPa occurs when the inner-lid space pressure decreases to the alarm point of 400 kPa.
- If the inter-lid space pressure is lost to the primary space and no re-pressurization occurs, the primary space will remain in a vacuum (82.82 kPa) and any further leakage will still be towards the primary space.
- If a leak of up to 10 kPa/day on the primary seal occurs, it would take 30 days for the inter-lid pressure to reach 400 kPa. The primary space pressure would reach 400 kPa after 18 years if re-pressurization to 700 kPa of the inter-lid space occurs.
- Assuming a primary seal leak of 10 kPa/day and that re-pressurization occurs at 101.3 kPa, the primary space would reach atmospheric pressure after 1.3 years.
- It was found that, at a leak rate of 10 kPa/day, it would take 30 days for the inter-lid space pressure to reach 400 kPa. Assuming re-pressurization of the inter-lid space to 700 kPa every time the alarm set point is reached, the primary space pressure would reach 100 kPa after 1.2 years.

From the above information it is improbable that any release from the primary space could occur in the 6 month time period by when the seal is required to be fixed. Therefore, only catastrophic leaks on both seals will be considered as an accident resulting in a radioactive release.

3.4 Heavy Aircraft Crash

In general the Koeberg Aircraft Crash Risk Assessment [21] deems that none of the sensitive buildings would be impacted by a light aircraft or helicopter crash, but all other aircraft categories are liable to penetrate any building at the time of the impact.

In addition, the casks can withstand very heavy loads and high temperatures and the casks may withstand the impact.

An aircraft crash risk assessment for the casks and the proposed cask storage facility was performed [29]. The results from consequence assessment for light aircraft crash indicate that scabbing poses the greatest risk if an aircraft were to crash into the casks. However, the casks wall thickness is greater than 110% of the scabbing thickness and 120% of the perforation thickness. Furthermore, the casks are designed to prevent scabbing and perforation following a light aircraft crash [61].

From Reference [30], the consequence results for the heavy aircraft crash further affirm that scabbing poses the greatest risk if an aircraft were to crash into the casks. The scabbing thickness is larger than 110% of the wall thickness and the perforation thickness is larger than 120% of the wall thickness. It can be conservatively assumed that the casks are not designed to prevent scabbing and perforation following a direct impact from a heavy aircraft. In both cases, a heavy aircraft travelling between 500 km/h and 600 km/h would most likely penetrate the casks.

From the above results it is concluded that only heavy aircrafts have a significant potential for breaching the seals.

Figure 9 indicates the location of the preferred new cask storage facility (TISF) to north-northwest border of the site. The aircraft cash risk assessment conservatively assumes that the TISF is isolated without shielding.

Figure 9: Satellite Image of Eskom's Preferred TISF site

The building dimensions assumed in the Koeberg Aircraft Crash Risk Assessment for the Casks Project [29] were for the proposed storage facility that stores 6 casks along its breadth and 14 casks along its length. Reference [29] noted however that these were only proposed dimensions and subject to change when the TISF building dimensions were finalised.

However, the proposed TISF will not consist of a building as previously analysed in Revision 1 of this report [47]. Latest information [45] indicate that the TISF will consist of a concrete slab that will be surrounded with security fencing and will cover an area of approximately 12800 m^2 and the casks will be exposed directly to the surrounding environment.

In the absence of a building, the heavy aircraft crash frequency calculations only considers the ground area of the TISF which is 12800 m^2 filled with casks of 5.086 m in height. These new dimensions were used to update the calculations in Reference [29]. Details of the updated calculations are presented in Appendix D.

The results of the assessment for the frequency of heavy aircraft crash into the cask storage facility, which includes commercial aviation (air carriers and air taxis) and large military aircraft, is displayed in the Table 23.

Table 23: Overall Annual Aircraft Crash Frequency for Commercial Aviation (Air Carriers and Air Taxis) and Large Military Aircraft

	Overall Annual Aircraft Crash Frequency (Per Year)			Total Overall Annual Aircraft Crash Frequency (Per Year)
	Air Carriers	**Air Taxis**	**Large Military Aircraft**	
	Kobayashi Method	**Only Background Crash Rate**	**Gliding DOE**	
Cask Storage Facility (TISF)	3.62E-08	9.56E-09	4.34E-08	8.91E-08

The total probability of heavy aircraft crash induced fire impacting the cask storage facility is approximately 8.91E-08 per year (i.e., 3.62E-08 + 9.56E-09 + 4.34E-08).

4 RADIONUCLIDE RELEASE

The calculations to determine mortality risks require a description of the characteristics of the radionuclide release, including the quantity of each radionuclide released to the environment, the amount of energy associated with the release, the time of the release after accident initiation, the height of release and the frequency of occurrence predicted for the accident. This information is referred to as the accident source term. It is conservatively assumed that the time of release is 0 hours after accident initiation, as the less time allowed for radionuclide decay, the less the radionuclide concentrations and the lower the dose and health effects risk.

The purpose of the radionuclide grouping scheme used as input in PC COSYMA calculations is simply to assign release fractions to radionuclides and to determine the fraction of each relevant isotope released to the environment. Thus, radionuclides with the same release fractions are grouped together and this grouping by release fractions may not be the same for each accident and is independent of and does not influence other groupings considered internally in PC COSYMA (i.e., grouping by deposition).

The radiological consequence analysis using PC COSYMA uses a radionuclide selection cut-off since it is not possible to consider all nuclides in the PC COSYMA nuclide library because of the CPU time and disk storage which would be required. In this study, the nuclide selection cut-off used for each of the exposure pathways for the cask related accidents is as follows:

Table 24: Nuclide Selection Cut-Off Used In PC COSYMA Calculations

Pathway	Radionuclide Selection Cut-off in %				
	MC_LOAD[1]	MC_SFB[2]	MC_SFPL[3]	MC_SEAL[4]	MC_FIRE[5]
Cloudshine	0.01	0.01	0.01	0.01	0.01
Groundshine	0.02	0.01	0.01	0.01	0.01
Inhalation	0.02	0.01	0.01	0.01	0.01
Skin and Clothing	0.01	0.01	0.01	0.01	0.01
Ingestion	100	100	100	100	100

[1] Cask Loading Error
[2] Cask Drop
[3] Cask Drop with SFP Liner Break
[4] Cask Seal Failure
[5] Heavy Aircraft Crash Induced Fire impacting TISF

4.1 Cask Source Term for Cask Seal Failure and Cask Drop (No SFP Liner Break) Accidents

In this section, the concentration of each isotope in a cask is calculated and used to determine the radionuclide release to the atmosphere in the event of failure of the cask integrity.

4.1.1 Cask Initial Inventory for Seal Failure and Cask Drop (No SFP Liner Break) Accidents

The radionuclide inventory and decay heat for the fuel assemblies with 4.4% enrichment was calculated with the ORIGEN-S code. The input parameters for the ORIGEN-S analysis were taken from the Reactor Fuel Engineering Report [31] and are displayed in Table 25.

Table 25 : Inputs for ORIGEN-S Analysis of Spent Fuel Assemblies

FA Cycle	Cumulative Burnup at BOC* (MWd/tU)	Cumulative Burnup at EOC (MWd/tU)	Burnup during cycle (MWd/tU)	Nominal Power (P_n) / FA (MW/FA)	Cycle length incl. S/O (EFPD)	Number of feed FAs
Cycle 1	0	20 991	20 991	22.4	433	56
Cycle 2	20 990	35 056	14 066	15.0	433	56
Cycle 3	33 623	47 799	14 176	15.1	433	45

* BOC – beginning of cycle

Natural cycle length: 418.8 effective full power days (EFPDs)
Cycle length including stretch out (S/O): 433 EFPDs
Relative Power at end of cycle (EOC): 0.905
Gadolinium weight: 84.58 kg
Core Mass: 72 524 kg heavy metal (HM)

The number of outage days for the fuel cycle was assumed to be zero. The initial inventory for a cask loaded after 3600 days was then calculated [32] with the ORIGEN-S code using the above input parameters. The radionuclide inventory and decay heat is displayed in Appendix B, Table B1.1 considering a cask capacity of 32 spent FAs for all casks. The results presented in Appendix B, Table B1.1 were produced by multiplying the ORIGEN results presented in [32] for a single assembly by 32.

The above inputs bound the assemblies currently stored in the pool that would be moved to dry storage.

Radionuclides contained in the cask include: fission and activation products contained in crud material adhering to the outside of fuel rods, and actinides, fission products and activation products contained inside the fuel rods. Crud is referred to as the radioactive flaky material that is formed on the outside of a fuel rod due to the radioactive and corrosive environment of a PWR. Some of this material is loosely bound to the fuel rod and can be dislodged in some circumstances such as vibration and flowing gas. Although crud contains a number of radionuclides, only cobalt-60 (Co-60), is a major contributor to the radiation exposure.

Using EPRI 1009691 [3] guidance, the amount of Co-60 in the crud per fuel assembly is estimated to be 49.1 curies at the time of discharge from reactor. This was derived assuming a Westinghouse 17x17 standard fuel assembly with surface area of 1.21E+03 cm^2/rod and an initial crud surface concentration of 140 μCi/cm^2 of Co-60 at the time of discharge. Each assembly has 25 guide tubes. Assuming each guide tube to have the same surface area as that of a fuel rod, then each assembly could have a total of 49.1 curies of Co-60 in the crud.

After 10 years of cooling, the crud could contain about 13.2 curies of Co-60 per assembly (using the radioactive decay equation). However, recent observations indicate that; "PWR fuel rods should typically be considered crud free by the time they are loaded into a cask. The technical basis for this recommendation is the solubility of metal oxides typical of PWR fuel deposits in acidic spent-fuel pool water," [3]. Therefore, we assumed a 100-fold reduction of Co-60 within the crud from the removal of crud by the acidic fuel pool environment, leaving 0.132 curies per assembly. This equates to 1.56E+11 Bq of Co-60 per cask (0.132 Ci × 3.7E+10 Bq/Ci × 32 spent fuel assemblies per cask). This value of crud will be added to the Co-60 initial inventory in Appendix B, Table B1.1.

The activity of Co-60 in the cask (32 spent fuel assemblies) has been calculated to be 1.61E+14 Bq, as displayed Appendix B, Table B1.1 [Ref. 32]. Adding the activity of crud results in a total Co-60 activity of 1.61E+14 Bq (1.56E+11 Bq + 1.61E+14 Bq) per cask. Hence adding the activity of crud does not change the activity of Co-60 calculated for the cask and this dominates the results.

4.1.2 Release Fractions for Cask Seal Failure and Cask Drop (No SFP Liner Break)

The assessment of release fractions for the cask drop accident and cask seal failure takes into account the following factors as described in EPRI 1009691, Appendix H [3]:

- Estimation of the degree of damage or damage ratio (DR) of the fuel inside the cask (i.e., the fraction of fuel rods assumed to be damaged).
- Estimation of the amount of airborne material within the cask, i.e., the fraction of materials released into the cask that is airborne and is expressed as the airborne release fraction (ARF).
- Determination of the transport of material within the cask to the environment. This is known as the leak path factor (LPF).

For the cask drop accident, the degree of damage within a cask is a function of the impact force experienced by the cask during a cask drop accident. The NRC and the industry have performed studies relating to potential fuel failure and this is documented in NUREG-0170 [62], Modal Study, SAND-90-2406 (Sanders Report) [63] and NUREG/CR-6672 [64].

The analysis in EPRI 1009691 for cask drop accident considers a cask drop from a height of 9 m. The 9 m drop used by EPRI is based on various other studies done by NRC on a "hypothetical cask accident". EPRI 1009691 references the report "A Method for Determining the Spent Fuel Contribution to Transport Cask Containment Requirements", SAND-90-2406, also known as the Sanders Report [63] as the basis for the 9 m drop scenario. The Sanders Report [63] states that the 9 m drop is a regulatory accident condition that must be analysed. The basis for the regulatory accident condition comes from 10 CFR 71 - PACKAGING AND TRANSPORTATION OF RADIOACTIVE MATERIAL.

10 CFR 71 requires the analysis of the following hypothetical accident condition:

Free Drop: A free drop of the specimen through a distance of 9 m (30 foot) onto a flat, essentially unyielding, horizontal surface, striking the surface in a position for which maximum damage is expected.

Further, the EPRI report also makes mention of other NRC reports such as NUREG-0170 and NUREG/CR-4829 which also quote the regulatory accident condition of a 9 m drop.

Hence, it can be concluded that 10 CFR 71 regulations is the ultimate basis for the 9 m drop cask drop accident and EPRI have adopted this regulatory position for assessment in their cask report.

The analysis in the Sanders Report [63] provides an estimate of the fuel failure probability per rod resulting from a 9 m drop under various orientations. The fuel rod failure probability resulting from all fuel failure modes (pinhole, rupture, rod breakage and longitudinal split) and specific angles (side, corner and end drops) is 2.00E-04 under all drop orientations. The EPRI report assumes a TN32 cask with W 17x17 fuel assemblies (264 fuel rods per assembly; 8448 fuel rods total) and this leads to about 2 fuel rod failures per drop. The EPRI report conservatively assumed that casks drop from height of 9 m can lead to 0.02% fuel failure.

Applying the same methodology to HOLTEC HI-STAR 100 cask with W 17x17 fuel assemblies (264 rods per assembly; 8448 fuel rods total), also leads to approximately 2 fuel rod failures per drop. This assessment will also assume 0.02% fuel failure for cask drop accidents which is referred to as the damage ratio (DR).

For cask seal failure accidents, it is expected that a certain percentage of the fuel rods within a dry storage cask will have cladding pinhole and hairline crack and this is an accepted NRC policy [3]. The percentage of cladding failure however will be less than that experienced from a cask drop accident. This study will conservatively assume 0.02% cladding failure (damage ratio) for cask seal failure accidents as this represents the bounding case.

Suggested release fractions for various isotopes have been obtained from NUREG-1536 [33] and NUREG-1567 [34], and are shown in Table 26. These values represent the fraction of materials that is released into the cask that is airborne (i.e., ARF).

The release fraction for crud is not listed Table 26 as the activity of crud has been calculated and compared to the activity of Co-60 inside the fuel assembly and assessed to have no significant impact.

Table 26: Radionuclide Grouping and Airborne Release Fractions (ARF)

Radionuclide Group	Nuclides	Airborne Release Fraction
1 Gases	H, Kr, Xe	3.00E-01
2 Gases	I	1.00E-01
3 Volatiles	Cs, Ru, Sr	2.00E-04
4 Fuel Fines (particulates)	All remaining nuclides	3.00E-05

The assessment of release fractions for the cask drop and seal failure accidents also takes into account the assessment of the LPF. The gaseous and particulate fission products within the cask would be forced out when a cask confinement breach occurs. The driving force is the cask internal pressurization from the cask helium backfill and the gaseous fission products within the cask. The amount of gaseous fission product is proportional to the fuel failure fraction within the cask. From EPRI 1009691 [3], the leak path factor for cask drop and cask seal failure accidents can be approximated by the following equation:

$$\text{LPF} = \left(1 - f_{dep}\right) * \left(1 - \frac{P_0}{P_{in}}\right) \quad (18)$$

Where:

f_{dep} = fraction of vapours and particulates that rapidly deposits onto cask interior surface; this fraction may also be called the retention factor.

P_0 = ambient pressure

P_{in}= cask internal pressure

EPRI 1009691, Table H-5 [3] provides a summary of values for retention fraction for different accident scenarios. For seal failure accidents, a small leak area is assumed and the corresponding f_{dep} is used in the release fraction calculation. For the cask drop accident, a large leak area is assumed as a weld crack or bolted movement could occur and f_{dep} for impact only with large leak area is used in the release fraction calculation.

The f_{dep} for cask seal failure and cask drop accidents was taken from EPRI 1009691, Table H-5 [3].

Table 27: f_{dep} for Cask Seal Failure and Cask Drop Accidents

Accident Scenario	f_{dep}				
	Crud	Noble Gases & Tritium	Caesium	Particulates	Ruthenium
Cask Seal Failure	0.98	0	0.999	0.98	0.98
Cask Drop	0.45	0	0.60	0.45	0.45

Using:

P_0 = 101.325 kPa (ambient pressure)

P_{in}= 700 kPa (cask internal pressure)

$\left(1 - \frac{P_0}{P_{in}}\right)$ = 0.855

The Leak Path Factor (LPF) was determined below using f_{dep} from Table 27 above.

Table 28: LPF for Cask Seal Failure and Cask Drop Accidents

Accident Scenario	LPF				
	Crud	Noble Gases & Tritium	Caesium	Particulates	Ruthenium
Cask Seal Failure	1.71E-02	8.55E-01	8.55E-04	1.71E-02	1.71E-02
Cask Drop	4.70E-01	8.55E-01	3.42E-01	4.70E-01	4.70E-01

The total release fraction is then the product of the damage ratio, the airborne release fraction and the leak path factor, i.e.,:

$$RF_{total} = DR * ARF * LPF \quad (19)$$

The RF_{total} results for all nuclide groups are displayed in Table 29.

Table 29: Cask Releases for Seal Failure and Cask Drop (No SFP Liner Break)

Radionuclide Group No.	Nuclide	Cask Initial Inventory for 10 Year Old Fuel (Bq)	Total Release Fraction		Total Activity Released to Atmosphere (Bq)	
			Seal Failure: 0.02% Cladding Failure (Pre-existing Condition)	Cask Drop: 0.02% Cladding Failure	Seal Failure: 0.02% Cladding Failure	Cask Drop: 0.02% Cladding Failure
1	H-3	2.19E+14	5.13E-05	5.13E-05	1.12E+10	1.12E+10
	Kr-85	3.63E+15			1.86E+11	1.86E+11
2	I-129	2.56E+10	3.42E-07	9.40E-06	8.75E+03	2.40E+05
3	Cs-134	5.30E+15	3.42E-11	1.37E-08	1.81E+05	7.26E+07
	Cs-135	4.22E+11			1.44E+01	5.77E+03
	Cs-137	6.88E+16			2.35E+06	9.41E+08
4	Ag-108m	8.49E+09	1.03E-10	2.82E-09	8.71E-01	2.39E+01
	Ag-110	2.15E+09			2.21E-01	6.08E+00
	Ag-110m	1.59E+11			1.63E+01	4.47E+02
	Am-241	1.63E+15			1.68E+05	4.61E+06
	Am-242	1.37E+13			1.41E+03	3.87E+04
	Am-242m	1.37E+13			1.41E+03	3.87E+04
	Am-243	2.77E+13			2.84E+03	7.81E+04
	Be-10	4.45E+06			4.57E-04	1.26E-02
	Ce-144	1.04E+14			1.07E+04	2.93E+05
	Cm-242	1.13E+13			1.16E+03	3.20E+04
	Cm-243	2.53E+13			2.60E+03	7.15E+04
	Cm-244	2.88E+15			2.95E+05	8.11E+06
	Cm-245	4.82E+11			4.94E+01	1.36E+03
	Cm-246	1.31E+11			1.35E+01	3.71E+02
	Cm-247	8.71E+05			8.94E-05	2.46E-03
	Cm-248	4.98E+06			5.11E-04	1.41E-02
	Co-58	2.68E-01			2.75E-11	7.55E-10
	Co-60	1.61E+14			1.65E+04	4.54E+05
	Eu-152	4.05E+12			4.15E+02	1.14E+04
	Eu-154	4.78E+15			4.90E+05	1.35E+07
	Eu-155	1.86E+15			1.91E+05	5.24E+06
	Fe-55	1.87E+13			1.92E+03	5.28E+04
	Hf-175	2.33E-03			2.39E-13	6.58E-12
	Hf-182	4.38E+05			4.49E-05	1.24E-03
	Mn-54	1.85E+10			1.90E+00	5.21E+01
	Mo-93	3.69E+09			3.79E-01	1.04E+01
	Na-22	2.78E-05			2.85E-15	7.85E-14
	Nb-92	1.26E+05			1.29E-05	3.54E-04
	Nb-93m	3.42E+12			3.51E+02	9.64E+03
	Nb-94	1.04E+11			1.07E+01	2.95E+02
	Nb-95	2.02E+01			2.08E-09	5.71E-08
	Nb-95m	1.08E-01			1.11E-11	3.05E-10
	Ni-59	2.26E+11			2.32E+01	6.38E+02

Radionuclide Group No.	Nuclide	Cask Initial Inventory for 10 Year Old Fuel (Bq)	Total Release Fraction		Total Activity Released to Atmosphere (Bq)	
			Seal Failure: 0.02% Cladding Failure (Pre-existing Condition)	Cask Drop: 0.02% Cladding Failure	Seal Failure: 0.02% Cladding Failure	Cask Drop: 0.02% Cladding Failure
	Ni-63	3.02E+13			3.10E+03	8.51E+04
	Np-237	3.37E+11			3.46E+01	9.52E+02
	Np-238	6.18E+10			6.34E+00	1.74E+02
	Np-239	2.77E+13			2.84E+03	7.81E+04
	P-32	1.46E+03			1.49E-07	4.11E-06
	Pm-147	7.48E+15			7.68E+05	2.11E+07
	Po-210	3.12E+04			3.20E-06	8.79E-05
	Pu-236	1.75E+11			1.80E+01	4.94E+02
	Pu-238	3.54E+15			3.63E+05	9.98E+06
	Pu-239	2.30E+14			2.36E+04	6.48E+05
	Pu-240	2.63E+14			2.70E+04	7.41E+05
	Pu-241	7.40E+16			7.59E+06	2.09E+08
	Pu-242	1.72E+12			1.76E+02	4.84E+03
	Ra-226	2.08E+05			2.14E-05	5.88E-04
	Re-188	1.47E-03			1.51E-13	4.14E-12
	Sb-124	5.89E-04			6.04E-14	1.66E-12
	Sb-125	5.22E+14			5.36E+04	1.47E+06
	Sb-126	6.14E+10			6.30E+00	1.73E+02
	Sc-46	7.40E-02			7.59E-12	2.09E-10
	Si-32	1.46E+03			1.49E-07	4.11E-06
	Ta-182	5.01E+05			5.14E-05	1.41E-03
	Tc-99	1.03E+13			1.06E+03	2.90E+04
	Te-125m	1.28E+14			1.31E+04	3.60E+05
	Te-127	8.67E+05			8.89E-05	2.44E-03
	Te-127m	8.84E+05			9.07E-05	2.49E-03
	U-234	7.65E+11			7.85E+01	2.16E+03
	U-235	1.10E+10			1.13E+00	3.12E+01
	U-238	1.69E+11			1.74E+01	4.77E+02
	W-181	4.40E+03			4.52E-07	1.24E-05
	W-185	3.77E-01			3.86E-11	1.06E-09
	Y-90	4.72E+16			4.85E+06	1.33E+08
	Y-91	1.55E-01			1.59E-11	4.37E-10
	Zn-65	8.57E+06			8.80E-04	2.42E-02
	Zr-93	1.05E+12			1.07E+02	2.95E+03
	Zr-95	9.19E+00			9.43E-10	2.59E-08
5	Ru-106	4.46E+14	6.84E-10	1.88E-08	3.05E+05	8.39E+06
	Sr-89	1.41E-04			9.64E-14	2.65E-12
	Sr-90	4.72E+16			3.23E+07	8.88E+08

In later chapters these atmospheric release amounts will be used to determine the specific activity for each isotope, which in turn is used to calculate site personnel mortality risks. The atmospheric releases are also used by PC COSYMA to calculate the public mortality risks.

4.1.3 Building Dimensions, Energy and Height of Release

For off-site consequence assessment the release is assumed to occur in one phase for the cask drop and cask seal failure accidents with zero time delay.

The decay heat from the ORIGEN-S analysis [32] for a decay time of 3600 days was determined to be 28.5 kW (32 × 0.89 kW). The radionuclide inventory and decay heat for the fuel assemblies with 4.4% enrichment was calculated with the ORIGEN-S code which is a conservative assessment The casks are loaded with spent fuel assemblies that have been cooled for a minimum of 10 years and will therefore consist of fuel assemblies with lower enrichments than 4.4% that are currently in the core. The decay heat of these assemblies will also be checked and verified before cask loading takes place.

It has been decided that using the cask maximum heat load of 20 kW as the energy of the release will be more conservative (due to the lower effective release height that results from the lower energy of the release) for the radiological analysis. The fraction of energy released is 0.24 from previous analysis documented in Reference [16]. Therefore the energy of release is (20 kW × 0.24) 4.8E-03 MW. This is input into PC COSYMA as 0.005 MW (considering 3 significant figures).

The height of the release was set to 10 m as PC COSYMA uses a minimum release height of 10 metres. If the user sets a height of less than 10 m, the system automatically corrects it to 10 metres during the calculations. This can be found in the PC COSYMA Source Code. The higher the release height, the greater the spread of the fission products and the lower the dose concentration near the vicinity of the accident.

PC COSYMA requires the height and the width of the building to model mixing in the building wake. Sensitivity analyses were performed that found the most conservative building width option to use in PC COSYMA is to select the largest of the building length and building width values.

The cask drop accident occurs inside the Spent Fuel (SF) building which has a height of 38.5 m, a length of 30 m and a width of 17 m (i.e., a width of 30 m was used in PC COSYMA).

The cask seal failure accident is assumed to occur at the TISF. The TISF is a concrete pad surrounded by security fencing and the casks are exposed directly to the surrounding environment and therefore no building is considered in the PC COSYMA calculations for this accident.

4.2 Spent Fuel Pool Source Term for Cask Drop with SFP Liner Break

The isotopic concentration for the SFP is calculated in this section for the event of a cask drop with SFP liner break.

4.2.1 Spent Fuel Pool Initial Inventory

A cask drop accident in the spent fuel building resulting in failure of the integrity of the cask loading cell and the SFP liner is assumed to result in the consequent melting of all spent fuel assemblies in the pool as make-up activities would be insufficient to prevent complete SFP assembly uncovery.

The initial isotopic inventory in the Spent Fuel Pool was taken from the Spent Fuel Pool PSA Report [36]. The inventory used is for the 15 days after criticality case and relates to the decay heat of 4.06 MW being present during normal operation. The 15 days SFP inventory is conservative as cask loading can only take place 90 days after core unload as explained earlier in Section 1.3.5.

Table 30: Initial Inventory in Spent Fuel Pool

Radionuclide Group No.	Nuclides	15 Days – Normal Mode (Bq)
1	Kr-85	1.93E+17
	Xe-129m	4.81E+13
	Xe-131m	8.05E+15
	Xe-133m	8.44E+14
	Xe-133	3.16E+17
	Xe-135m	1.11E+01
	Xe-135	5.95E+06
	I-129	1.63E+12
	I-131	2.72E+17
	I-132	5.73E+16
	I-133	1.17E+13
	I-135	6.95E+01
	Cs-134	1.03E+18
	Cs-137	3.92E+18
2	Te-132	5.56E+16
3	Sr-89	5.39E+17
	Sr-90	2.57E+18
	Ba-140	6.83E+17
4	Sb-127	7.40E+15
	Mo-99	3.83E+16
	La-140	7.86E+17
	Ce-141	1.09E+18
	Ce-144	1.54E+18
	Np-239	2.76E+17
	Pu-238	2.36E+17
	Cm-242	1.09E+17
	Cm-244	3.24E+17

4.2.2 Release Fractions for Cask Drop with SFP liner break

NUREG/CR-4982 [17] provides fission product release fractions for a severe SFP accident. These fission product release fractions are shown in Table 31. However, NUREG/CR-6451 [37] provided an updated estimate of these fission product release fractions. The release fractions in NUREG/CR-6451 (also shown in Table 31) are the same as those in NUREG/CR-4982, with the exception of lanthanum and cerium. NUREG/CR-6451 stated that the release fraction of lanthanum and cerium should be increased from 1.0E-06 in NUREG/CR-4982 to 6.0E-06, because fuel fines (particulates) could be released off-site from fuel with high burnup. While the EPRI staff believe that it is unlikely that fuel fines would be released off-site in any substantial amount, a sensitivity analysis was performed using a release fraction of 6.0E-06 for lanthanum and cerium to determine whether such an increase could even impact off-site consequences. The results of the sensitivity analysis showed that even if it were possible for fuel fines to be released offsite, there would be no change in off-site consequences as a result.

Based on the above analysis by EPRI, the NUREG/CR-6451 release fractions will be used for the cask drop accident with spent fuel pool liner break.

Table 31: Radionuclide Grouping and Release Fractions for Cask Drop with SFP Liner Break used in PC COSYMA

Radionuclide Group No.	Radionuclides	Total Release Fraction	
		NUREG/CR-4982	NUREG/CR-6451
1	Noble gases, Iodine, Caesium	1.00E+00	1.00E+00
2	Tellurium	2.00E-02	2.00E-02
3	Strontium, Barium	2.00E-03	2.00E-03
4*	Lanthanum, Cerium	1.00E-06	6.00E-06

* For all other particulates, the total Release Fraction is the same as that that defined for Group 4.

4.2.3 Building Dimensions, Energy and Height of Release

For off-site consequence assessment the release is assumed to occur in one phase for the SFP accident with zero time delay. The following information regarding the energy of the release was determined with MAAP analyses and is used in conjunction with the MAAP release fractions in PC COSYMA to calculate mortality risks [16]. MAAP runs performed indicate that the fraction of energy released is 0.24, resulting in the energy of the release being:

- 0.974 MW (determined as 4.06 MW × 0.24) for the 15 day case.

The height of the release was set to 10 m as PC COSYMA uses a minimum release height of 10 metres. If the user sets a height of less than 10 m, the system automatically corrects it to 10 metres during the calculations. This can be found in the PC COSYMA Source Code. The higher the release height, the greater the spread of the fission products and the lower the dose concentration near the vicinity of the accident.

PC COSYMA requires the height and the width of the building to model mixing in the building wake. Sensitivity analyses were performed that found the most conservative building width option to use in PC COSYMA is to select the largest of the building length and building width values.

The cask drop accident with SFP liner break accident occurs inside the SF building. The SF building has a height of 38.5 m, a length of 30 m and a width of 17 m (i.e., a width of 30 m was used in PC COSYMA).

4.3 Source Term for Cask Loading Error - Loading Incorrect Fuel Assembly

Since the cask basket design ensures sub-criticality (k_{eff} < 0.95) even for un-irradiated fuel assemblies [14], criticality due to incorrect loading is not credible.

It is however conceivable that temperature limits may be exceeded in the event of loading a number of 'hot' assemblies into the cask. The thermal power of an assembly was determined from the nuclide thermal power results produced by the ORIGEN-S code [32], and are given in Table 32 below.

Table 32: Assembly Thermal Power

Assembly Age	Thermal Power (kW)
90 Days	14.46
10 Years	0.89

In a worst case scenario, assemblies which have last been unloaded from the core - corresponding to a decay time of 90 days - may be loaded into the cask. As can be seen above, the thermal power of an assembly with a 90 day decay time is orders of magnitude higher than an assembly with a 10 year decay time, and if a sufficient number of these assemblies are incorrectly loaded the heat generated will exceed the cask maximum heat load which is assumed to be 20 kW.

4.3.1 Cask Initial Inventory for Cask Loading Error

The initial inventory for accidents involving loading incorrect fuel assemblies into the cask is presented in Appendix B, Table B2.1. This inventory conservatively assumes that the cask is loaded with 32 spent fuel assemblies that have only decayed for 90 days rather than the 10 years decay that should be applicable if the cask is loaded correctly.

The radionuclide inventory and decay heat for the fuel assemblies with 4.4% enrichment was calculated with the ORIGEN-S code. The input parameters for the ORIGEN-S analysis were taken from the Reactor Fuel Engineering Report [31] and are displayed in Table 33.

Table 33: Inputs for ORIGEN-S Analysis of Spent Fuel Assemblies

FA Cycle	Cumulative Burnup at BOC (MWd/tU)	Cumulative Burnup at EOC (MWd/tU)	Burnup during cycle (MWd/tU)	P_n / FA (MW/FA)	Cycle length incl. S/O (EFPD)	Number of feed FAs
Cycle 1	0	20 991	20 991	22.4	433	56
Cycle 2	20 990	35 056	14 066	15.0	433	56
Cycle 3	33 623	47 799	14 176	15.1	433	45

Natural cycle length: 418.8 EFPDs
Cycle length including S/O: 433 EFPDs
Relative Power at EOC: 0.905
Gadolinium weight: 84.58 kg
Core Mass: 72 524 kg HM

The number of outage days for the fuel cycle was assumed to be zero. The initial inventory for a cask loaded after 90 days was then calculated [32] with the ORIGEN-S code using the above input parameters.

4.3.2 Release Fractions for Cask Loading Error

The assessment of release fractions for the cask loading error accidents also takes into account the damage ratio (DR), the airborne release fraction (ARF) and the leak path factor (LPF) as described in Section 4.1.2 from Appendix H of Reference [3].

The fuel rod response to high thermal loads has shown that up to 100% of the fuel rods can be breached or ruptured and the associated damage ratio will be 1.

The airborne release fractions have been taken from NUREG/CR-4829 [38] and NUREG/CR-0722 [39] and are presented in Table 34 below. The release fractions represent the radioactive material released from the fuel rods into the cask. It is presumed to be released from the spent fuel cask if a leak path exists in the containment vessel (cask).

Table 34: Radionuclide Grouping and Airborne Release Fractions[6] for a Single Assembly with 100% of the Fuel Rods Ruptured Due To High Temperature

Radionuclide Group No.	Radionuclides	Airborne Release Fraction
1	Noble gases, Tritium	3.90E-01
2	Iodine	4.30E-03
3	Caesium	2.00E-04
4	All other nuclides	2.00E-06
5	Ruthenium	4.80E-05

From EPRI 1009691 [3], the leak path factor for cask loading error accidents can be approximated by the following equation:

$$\mathrm{LPF} = \left(1 - f_{dep}\right) * \left(1 - \frac{P_0}{P_{in}}\right) \quad (20)$$

[6] The release fraction for Xe was assumed to be the same as that for Kr - based on similar chemical characteristics.

The f_{dep} for cask loading error accidents was taken from EPRI 1009691, Table H-5, Impact only – small area [3]. A small area is assumed in the calculation of the LPF for cask loading error as it assumed that the cask seals will fail first due to the high temperatures in the cask. According to EPRI 100961 [3] cask loading errors can increase the temperatures of the spent FAs within the cask and result in fuel cladding failure and fission products are released into the inert cover gas. The increased temperatures and pressures inside the cask can result in leaks through the cask seal system and the seals are the point of failure. Failure of the seal is defined as a small area.

Table 35: f_{dep} for Cask Loading Error Accidents

Accident Scenario	f_{dep}				
	Crud	Noble Gases & Tritium	Caesium	Particulates	Ruthenium
Cask Loading Error	0.98	0	0.999	0.98	0.98

Using:
P_0 = 101.325 kPa (ambient pressure)
P_{in}= 700 kPa (cask internal pressure)

$(1 - \frac{P_0}{P_{in}}) = 0.855$

The Leak Path Factor (LPF) was determined below using f_{dep} from Table 35above.

Table 36: LPF for Cask Loading Error Accidents

Accident Scenario	LPF				
	Crud	Noble Gases & Tritium	Caesium	Particulates	Ruthenium
Cask Loading Error	1.71E-02	8.55E-01	8.55E-04	1.71E-02	1.71E-02

The total release fraction is then the product of the damage ratio, the airborne release fraction and the leak path factor, i.e.,:

$$RF_{total} = DR * ARF * LPF \quad (21)$$

The RF_{total} results for all nuclide groups are displayed in Table 37.

Table 37: Total Release Fractions for Cask Loading Error Accidents

Radionuclide Group No.	Radionuclides	Total Release Fraction (RF_{total})
1	Noble gases, Tritium	3.33E-01
2	Iodine	7.35E-05
3	Caesium	1.71E-07
4	All other nuclides	3.42E-08
5	Ruthenium	8.21E-07

4.3.3 Building Dimensions, Energy and Height of Release

The decay heat obtained from the ORIGEN-S analysis [32] for a decay time of 90 days is 463 kW (32 × 14.46 kW). It has been decided that using the cask maximum heat load of 20 kW as the energy of the release will be more conservative (due to the lower effective release height that results from the lower energy of the release) for the radiological analysis.

From the Koeberg Level 3 Risk Assessment, the fraction of energy released with the fission products ranges from 0.23 to 0.25 regardless of the accident scenario. It can therefore be seen that the fraction of energy released is not a value which varies greatly. The off-site consequences are themselves relatively independent of the fraction of energy released. This energy slightly impacts on the spread on the isotopic deposition and not the overall magnitude.

This analysis will therefore assume the fraction of energy released with the fission products is 0.24. This is in line with the MAAP analysis carried out for the accident scenario for severe accidents in the spent fuel building, the details of which can be obtained from Reference [16]. Therefore, the energy of release is (20 kW × 0.24) 4.8E-03 MW. This is input into PC COSYMA as 0.005 MW (considering 3 significant figures).

The height of the release was assumed to be 10 meters as PC COSYMA uses a minimum release height of 10 metres. If the user sets a height of less than 10 m, the system automatically corrects it to 10 metres during the calculations. This can be found in the PC COSYMA Source Code. The higher the release height, the greater the spread of the fission products and the lower the dose concentration near the vicinity of the accident.

PC COSYMA requires the height and the width of the building to model mixing in the building wake. Sensitivity analyses were performed that found the most conservative building width option to use in PC COSYMA is to select the largest of the building length and building width values.

The cask loading error accident is assumed to occur inside the SF building. The SF building has a height of 38.5 m, a length of 30 m and a width of 17 m (i.e., a width of 30 m was used in PC COSYMA).

4.4 Source Term for an Aircraft Crash Induced Fire Impacting the Temporary Interim Cask Storage Facility (TISF)

The isotopic concentration for the TISF is calculated in this section for the event of an aircraft crash induced fire accident impacting the TISF and the casks stored within the facility.

4.4.1 Initial Inventory for TISF

The initial inventory for the TISF is based on the assumption that the TISF can store a maximum of 161 casks, i.e., the analysis assumes that when the aircraft crash happens the TISF contains 161 casks. The initial inventory for a cask loaded after 3600 days as presented in Appendix B, Table B1.1 considering a cask capacity of 32 spent FAs was used (see Section 4.1.1 for more details on the ORIGEN-S code calculation that this cask inventory is based on).

4.4.2 Release Fractions for TISF

The release fractions presented in this section are referenced from EPRI 1009691 and are applicable to an aircraft crash event where there is severe impact resulting in a large fire and subsequent breach of the casks' integrity. There are four categories of releases defined for this analysis:
1) crud (Co-60),
2) gases (nobles and tritium),
3) volatiles (Cs), and
4) particulates (fuel fines and intact fuel pellets).

Since aircraft crash event involves a high temperature fire, Ruthenium would be considered as a different category from particulates, because if it is exposed to oxygen while at elevated temperature, the non-volatile RuO_2 can be converted to RuO_3 and RuO_4, which are more easily vapourised. A large area breach of the casks is assumed for aircraft crash with a severe impact followed by a fire.

The release fraction for crud (Co-60) is not listed Table 38 as the activity of crud has been calculated in Section 4.1.1 and compared to the activity of Co-60 inside the fuel assembly and assessed to have no significant impact.

Table 38 presents the release fractions for an aircraft crash induced fire impacting the cask storage facility (TISF). Since the aircraft crash impacting the cask and inducing a fire represents an extreme event it is conservatively assumed that no deposition of nuclides onto cask interior surface occurs.

Table 38: Radionuclide Grouping and Release Fractions for an Aircraft Crash Induced Fire Impacting the Casks inside the TISF

Radionuclide Group	Nuclides	Release Fraction
1 Gases (Nobles and Tritium)	H, Kr, Xe, H-3	3.00E-01
2 Gases	I	1.00E-01
3 Volatiles	Cs	1.50E-04
4 Fuel Fines (particulates)	All remaining nuclides	3.00E-05
5 Fuel Fines (particulates)	Ru	1.30E-04

4.4.3 Building Dimensions, Energy and Height of Release

For off-site consequence assessment the release is assumed to occur in one phase for the aircraft crash induced fire accident with zero time delay.

The decay heat from the ORIGEN-S analysis [32] for a decay time of 3600 days was determined to be 28.5 kW (32 × 0.89 kW). The TISF will contain 161 casks with a total decay heat of 4.59 MW.

It has been decided that using the cask maximum heat load of 20 kW will be more conservative for the radiological analysis. The decay heat for the TISF will then be 3.22 MW. The fraction of energy released is 0.24 from previous analysis. Therefore, the energy of release is 0.7728 MW (3.22 MW × 0.24). This is input into PC COSYMA as 0.773 MW (considering 3 significant figures).

The height of the release was set to 10 m as PC COSYMA uses a minimum release height of 10 metres. If the user sets a height of less than 10 m, the system automatically corrects it to 10 metres during the calculations. This can be found in the PC COSYMA Source Code. The higher the release height, the greater the spread of the fission products and the lower the dose concentration near the vicinity of the accident.

The TISF is a concrete pad and the casks are exposed directly to the surrounding environment and therefore no building will be credited in the PC COSYMA calculations for this accident.

5 CONSEQUENCE ASSESSMENT

5.1 Cask Loading Error Accident

5.1.1 Peak and Average Site Personnel Risks

Mortality risks to site personnel require the computation of doses received from cloudshine and inhalation. The first step is to calculate the atmospheric concentration of each isotope in the radioactive release. The table below presents the atmospheric concentrations for the cask loading error accident using the cask initial inventory for a 90 days decay period presented in Appendix B, Table B2.1, and the total release fractions from Section 4.3.2. The radionuclides with atmospheric concentrations below 20 Bq/m^3 are not presented and included in the atmospheric concentration tables for cask accidents. This provides a reasonable estimate of the dose since some radioactive isotopes have a concentration greater than 1.00E+06 Bq/m^3.

Table 39: Atmospheric Concentration for the Cask Loading Error Accident

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (100% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[7] (Bq/m^3)
Ag-110	3.66E+13	3.42E-08	1.25E+06	5.96E+02
Ag-110m	2.70E+15	3.42E-08	9.23E+07	4.40E+04
Ag-111	7.57E+12	3.42E-08	2.59E+05	1.23E+02
Am-241	1.92E+14	3.42E-08	6.56E+06	3.12E+03
Am-242	1.43E+13	3.42E-08	4.90E+05	2.33E+02
Am-242m	1.44E+13	3.42E-08	4.94E+05	2.35E+02
Am-243	2.77E+13	3.42E-08	9.48E+05	4.51E+02
Ba-140	6.04E+15	3.42E-08	2.07E+08	9.83E+04
Ce-141	1.11E+17	3.42E-08	3.81E+09	1.81E+06
Ce-144	5.30E+17	3.42E-08	1.81E+10	8.64E+06
Cm-242	3.43E+16	3.42E-08	1.17E+09	5.59E+05
Cm-243	3.20E+13	3.42E-08	1.09E+06	5.21E+02
Cm-244	4.16E+15	3.42E-08	1.42E+08	6.77E+04
Co-58	2.12E+14	3.42E-08	7.25E+06	3.45E+03
Co-60	5.70E+14	3.42E-08	1.95E+07	9.27E+03
Cr-51	1.44E+14	3.42E-08	4.94E+06	2.35E+03
Cs-134	1.34E+17	1.71E-07	2.29E+10	1.09E+07
Cs-135	4.22E+11	1.71E-07	7.21E+04	3.43E+01
Cs-136	3.23E+14	1.71E-07	5.53E+07	2.63E+04
Cs-137	8.60E+16	1.71E-07	1.47E+10	7.00E+06
Eu-152	6.67E+12	3.42E-08	2.28E+05	1.09E+02
Eu-154	1.04E+16	3.42E-08	3.55E+08	1.69E+05
Eu-155	7.70E+15	3.42E-08	2.63E+08	1.25E+05
Eu-156	2.24E+15	3.42E-08	7.66E+07	3.65E+04
Fe-55	2.14E+14	3.42E-08	7.33E+06	3.49E+03
Fe-59	3.93E+12	3.42E-08	1.34E+05	6.40E+01

[7] Atmospheric Concentration = Released to Atmosphere / 2100 m^3 [5].

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (100% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[7] (Bq/m^3)
H-3	3.76E+14	3.33E-01	1.25E+14	5.96E+10
Hf-175	2.88E+12	3.42E-08	9.84E+04	4.69E+01
Hf-181	1.56E+14	3.42E-08	5.35E+06	2.55E+03
I-129	2.56E+10	7.35E-05	1.88E+06	8.95E+02
I-131	1.98E+14	7.35E-05	1.45E+10	6.92E+06
I-132	3.10E+09	7.35E-05	2.28E+05	1.09E+02
Kr-85	6.77E+15	3.33E-01	2.26E+15	1.07E+12
La-140	6.96E+15	3.42E-08	2.38E+08	1.13E+05
Mn-54	4.49E+13	3.42E-08	1.53E+06	7.31E+02
Nb-93m	4.62E+12	3.42E-08	1.58E+05	7.53E+01
Nb-95	4.93E+17	3.42E-08	1.69E+10	8.03E+06
Nb-95m	3.46E+15	3.42E-08	1.18E+08	5.63E+04
Nd-147	1.02E+15	3.42E-08	3.49E+07	1.66E+04
Ni-63	3.22E+13	3.42E-08	1.10E+06	5.24E+02
Np-239	2.77E+13	3.42E-08	9.48E+05	4.51E+02
Pm-147	9.48E+16	3.42E-08	3.24E+09	1.54E+06
Pm-148	2.06E+14	3.42E-08	7.05E+06	3.36E+03
Pm-148m	3.88E+15	3.42E-08	1.33E+08	6.32E+04
Pr-143	7.31E+15	3.42E-08	2.50E+08	1.19E+05
Pu-236	1.74E+12	3.42E-08	5.95E+04	2.83E+01
Pu-238	3.63E+15	3.42E-08	1.24E+08	5.92E+04
Pu-239	2.30E+14	3.42E-08	7.86E+06	3.74E+03
Pu-240	2.60E+14	3.42E-08	8.91E+06	4.24E+03
Pu-241	1.18E+17	3.42E-08	4.03E+09	1.92E+06
Pu-242	1.72E+12	3.42E-08	5.87E+04	2.80E+01
Re-188	4.08E+13	3.42E-08	1.40E+06	6.65E+02
Rb-86	2.42E+12	3.42E-08	8.26E+04	3.93E+01
Rh-103m	1.61E+17	3.42E-08	5.51E+09	2.62E+06
Ru-103	1.61E+17	8.21E-07	1.32E+11	6.30E+07
Ru-106	3.11E+17	8.21E-07	2.56E+11	1.22E+08
Sb-124	2.11E+14	3.42E-08	7.22E+06	3.44E+03
Sb-125	5.99E+15	3.42E-08	2.05E+08	9.76E+04
Sb-126	1.53E+12	3.42E-08	5.25E+04	2.50E+01
Sr-89	1.12E+17	3.42E-08	3.82E+09	1.82E+06
Sr-90	5.99E+16	3.42E-08	2.05E+09	9.76E+05
Ta-182	9.71E+13	3.42E-08	3.32E+06	1.58E+03
Tc-99	1.03E+13	3.42E-08	3.52E+05	1.68E+02
Te-125M	1.41E+15	3.42E-08	4.81E+07	2.29E+04
Te-127	4.27E+15	3.42E-08	1.46E+08	6.96E+04
Te-127m	4.37E+15	3.42E-08	1.49E+08	7.12E+04
Te-129	3.00E+15	3.42E-08	1.02E+08	4.88E+04
Te-129m	4.66E+15	3.42E-08	1.60E+08	7.60E+04
W-181	2.31E+12	3.42E-08	7.90E+04	3.76E+01
W-185	4.42E+13	3.42E-08	1.51E+06	7.19E+02
Xe-131m	7.86E+13	3.33E-01	2.62E+13	1.25E+10
Xe-133	7.23E+12	3.33E-01	2.41E+12	1.15E+09

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (100% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[7] (Bq/m^3)
Y-90	5.99E+16	3.42E-08	2.05E+09	9.76E+05
Y-91	1.78E+17	3.42E-08	6.08E+09	2.89E+06
Zr-95	2.94E+17	3.42E-08	1.01E+10	4.80E+06

From the atmospheric concentration, the gamma effective dose due to cloudshine and beta skin dose presented in Table 40 below were calculated for an exposure time of 10 minutes as follows:

$$\text{Gamma effective dose} = 2.5\times10^{-8} \times \Sigma(f_i \times f_E) \times b_c \times R \times T \quad (22)$$

$$\text{Beta Skin Dose} = \text{Beta Conversion Factor} \times b_c \times T \quad (23)$$

Where: b_c = Atmospheric Concentration (Bq.m^{-3})
R = Radius of the hemispherical cloud (m)
T = Duration of the exposure (hrs)

Table 40: Doses for Immersion for the Cask Loading Error Accident

Nuclide	$\Sigma(f_i \times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m^3/Bq.hr)	Beta Skin Dose (Sv)
Ag-110	7.04E-07	1.75E-11	2.96E-10	2.94E-08
Ag-110m	5.67E-05	1.04E-07	5.65E-10	4.14E-06
Ag-111	6.73E-07	3.46E-12	7.88E-11	1.62E-09
Am-241	7.17E-06	9.33E-10	9.86E-12	5.13E-09
Am-242	5.31E-06	5.16E-11	2.95E-11	1.15E-09
Am-242m	2.56E-06	2.51E-11	4.90E-13	1.92E-11
Am-243	4.06E-06	7.63E-11	9.86E-12	7.41E-10
Ba-140	6.26E-06	2.57E-08	9.07E-11	1.49E-06
Ce-141	3.43E-06	2.59E-07	3.67E-11	1.11E-05
Ce-144	1.67E-06	6.01E-07	1.05E-11	1.51E-05
Cm-242	1.01E-06	2.35E-08	1.54E-13	1.44E-08
Cm-243	8.87E-06	1.92E-10	3.52E-11	3.05E-09
Cm-244	9.36E-07	2.64E-09	1.41E-13	1.59E-09
Co-58	2.34E-05	3.37E-09	2.01E-10	1.16E-07
Co-60	4.84E-05	1.87E-08	5.22E-10	8.07E-07
Cr-51	1.07E-05	1.05E-09	6.30E-12	2.47E-09
Cs-134	3.38E-05	1.53E-05	3.40E-10	6.17E-04
Cs-135	N/A	N/A	3.26E-12	1.86E-11
Cs-136	4.76E-05	5.22E-08	4.50E-10	1.97E-06
Cs-137	1.42E-05	4.14E-06	3.11E-11	3.63E-05
Eu-152	2.98E-05	1.35E-10	2.48E-10	4.49E-09
Eu-154	2.63E-05	1.85E-07	2.98E-10	8.39E-06
Eu-155	4.47E-06	2.33E-08	1.22E-11	2.55E-07
Eu-156	2.50E-05	3.80E-08	3.59E-10	2.18E-06
Fe-55	2.67E-06	3.88E-10	0.00E+00	0.00E+00
Fe-59	2.22E-05	5.92E-11	2.57E-10	2.74E-09
H-3	N/A	N/A	0.00E+00	0.00E+00

Nuclide	$\Sigma(f_i \times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m^3/Bq.hr)	Beta Skin Dose (Sv)
Hf-175	1.25E-05	2.44E-11	7.74E-11	6.04E-10
Hf-181	1.49E-05	1.58E-09	1.30E-10	5.51E-08
I-129	7.86E-06	2.93E-10	3.96E-12	5.91E-10
I-131	9.42E-06	2.72E-06	1.07E-10	1.23E-04
I-132	4.68E-05	2.12E-10	5.69E-10	1.03E-08
Kr-85	5.03E-08	2.25E-03	4.75E-11	8.50E+00
La-140	4.22E-05	1.99E-07	5.98E-10	1.13E-05
Mn-54	1.83E-05	5.57E-10	1.68E-10	2.05E-08
Nb-93m	1.22E-06	3.83E-12	1.54E-13	1.93E-12
Nb-95	1.52E-05	5.09E-06	1.55E-10	2.07E-04
Nb-95m	5.80E-06	1.36E-08	4.03E-11	3.78E-07
Nd-147	7.77E-06	5.37E-09	7.02E-11	1.94E-07
Ni-63	N/A	N/A	0.00E+00	0.00E+00
Np-239	1.01E-05	1.90E-10	5.76E-11	4.33E-09
Pm-147	8.65E-10	5.57E-11	2.92E-12	7.52E-07
Pm-148	1.10E-05	1.54E-09	2.87E-10	1.60E-07
Pm-148m	4.51E-05	1.19E-07	4.25E-10	4.48E-06
Pr-143	3.20E-14	1.59E-16	6.34E-11	1.26E-06
Pu-236	1.20E-06	1.42E-12	1.74E-13	8.22E-13
Pu-238	1.04E-06	2.57E-09	1.47E-13	1.45E-09
Pu-239	9.96E-06	1.55E-09	6.70E-14	4.18E-11
Pu-240	9.96E-07	1.76E-10	1.41E-13	9.97E-11
Pu-241	6.29E-10	5.03E-11	4.21E-16	1.35E-10
Pu-242	8.28E-07	9.65E-13	1.18E-13	5.50E-13
Re-188	1.61E-06	4.46E-11	1.93E-10	2.14E-08
Rb-86	1.94E-06	3.18E-12	1.75E-10	1.15E-09
Rh-103m	1.07E-06	1.17E-07	1.62E-13	7.08E-08
Ru-103	1.11E-05	2.91E-05	9.97E-11	1.05E-03
Ru-106	N/A	N/A	0.00E+00	0.00E+00
Sb-124	3.72E-05	5.33E-09	4.54E-10	2.60E-07
Sb-125	1.53E-05	6.22E-08	9.54E-11	1.55E-06
Sb-126	6.40E-05	6.67E-11	6.23E-10	2.60E-09
Sr-89	1.70E-09	1.29E-10	1.33E-10	4.04E-05
Sr-90	N/A	N/A	3.31E-11	5.38E-06
Ta-182	2.60E-05	1.71E-09	N/A	N/A
Tc-99	N/A	N/A	9.86E-12	2.76E-10
Te-125M	1.25E-05	1.19E-08	6.98E-12	2.67E-08
Te-127	1.17E-07	3.39E-10	4.10E-11	4.76E-07
Te-127m	4.07E-06	1.21E-08	3.06E-12	3.63E-08
Te-129	3.26E-06	6.63E-09	1.29E-10	1.05E-06
Te-129m	3.67E-06	1.16E-08	5.36E-11	6.79E-07
W-181	3.72E-06	5.83E-12	6.62E-12	4.15E-11
W-185	3.28E-09	9.83E-14	1.63E-11	1.95E-09
Xe-131m	5.84E-06	3.03E-03	1.74E-11	3.62E-02
Xe-133	5.95E-06	2.84E-04	1.79E-11	3.42E-03
Y-90	1.02E-09	4.15E-11	2.28E-10	3.71E-05
Y-91	6.63E-08	7.99E-09	1.39E-10	6.70E-05

Nuclide	$\Sigma(f_i \times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m^3/Bq.hr)	Beta Skin Dose (Sv)
Zr-95	1.51E-05	3.02E-06	1.62E-10	1.29E-04
Totals		**5.63E-03**		**8.54E+00**

The committed effective dose and committed equivalent doses to specific organs from inhalation and a summary of the total effective and normalised doses for the cask loading error accident are presented in Table 41. The committed effective dose and committed equivalent organ doses from inhalation were calculated using the database of ICRP Publication 68 dose conversion factors from Radiological Toolbox.

Table 41: Doses for Inhalation and a Summary of Total Effective and Normalised Organ Doses for the Cask Loading Error Accident

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
H-3	6.10E-01	6.10E-01	6.10E-01	6.10E-01
I-129	2.15E-05	2.91E-08	7.83E-08	2.69E-08
I-131	3.46E-02	1.61E-04	1.19E-03	1.63E-04
I-132	8.41E-09	7.33E-10	1.63E-08	4.07E-09
Cs-134	2.61E-02	2.45E-02	2.32E-02	2.45E-02
Cs-135	8.49E-09	7.98E-09	8.07E-09	8.07E-09
Cs-136	1.25E-05	9.21E-06	9.21E-06	9.87E-06
Cs-137	1.17E-02	1.10E-02	1.07E-02	1.10E-02
Ag-110	N/A	N/A	N/A	N/A
Ag-110m	8.02E-05	4.62E-05	4.18E-04	5.61E-05
Ag-111	4.93E-08	3.39E-09	2.83E-07	5.85E-09
Am-241	2.11E-02	2.97E-02	1.87E-02	1.41E-03
Am-242	7.00E-07	2.62E-07	4.78E-06	9.33E-09
Am-242m	1.41E-03	2.12E-03	3.23E-04	1.06E-04
Am-243	3.05E-03	4.17E-03	2.48E-03	2.14E-04
Ba-140	3.93E-05	4.18E-05	4.43E-06	6.39E-06
Ce-141	1.40E-03	1.13E-04	1.09E-02	5.44E-05
Ce-144	6.26E-02	4.10E-02	4.75E-01	3.89E-03
Cm-242	5.17E-01	1.82E-01	3.49E+00	3.36E-03
Cm-243	2.60E-03	3.77E-03	3.51E-03	1.43E-04
Cm-244	2.88E-01	4.23E-01	4.40E-01	1.40E-02
Co-58	1.47E-06	3.71E-07	6.73E-06	3.97E-07
Co-60	3.94E-05	1.46E-05	2.23E-04	1.51E-05
Cr-51	2.12E-08	1.06E-08	5.18E-08	9.41E-09
Eu-152	7.33E-07	1.25E-06	1.09E-06	2.99E-07
Eu-154	1.48E-03	2.53E-03	2.74E-03	4.22E-04
Eu-155	1.47E-04	2.13E-04	4.07E-04	1.35E-05
Eu-156	2.73E-05	5.29E-06	1.46E-04	4.28E-06
Fe-55	8.03E-07	2.88E-06	2.27E-07	2.27E-07
Fe-59	5.12E-08	6.72E-08	2.72E-07	3.36E-08
Hf-175	1.03E-08	3.28E-08	5.27E-08	3.63E-09
Hf-181	2.61E-06	3.31E-06	1.78E-05	2.55E-07

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
La-140	4.25E-05	1.08E-05	7.94E-05	1.33E-05
Mn-54	2.19E-07	2.56E-07	5.66E-07	1.21E-07
Nb-93m	1.62E-08	1.75E-09	1.26E-07	7.15E-10
Nb-95	2.61E-03	6.42E-04	1.63E-02	5.42E-04
Nb-95m	1.20E-05	7.89E-07	7.04E-05	1.55E-06
Nd-147	8.72E-06	9.13E-07	5.40E-05	6.64E-07
Ni-63	2.62E-07	2.23E-07	3.67E-07	2.23E-07
Np-239	1.24E-07	5.41E-09	5.75E-07	1.58E-08
Pm-147	1.35E-03	1.58E-03	9.65E-03	1.27E-05
Pm-148	1.85E-06	2.10E-07	7.38E-06	3.61E-07
Pm-148m	6.80E-05	2.53E-05	4.27E-04	1.41E-05
Pr-143	6.54E-05	3.27E-06	4.16E-04	4.46E-06
Pu-236	9.21E-05	1.28E-04	3.12E-04	3.97E-06
Pu-238	4.44E-01	6.66E-01	7.55E-01	2.37E-02
Pu-239	2.99E-02	4.49E-02	4.40E-02	1.59E-03
Pu-240	3.39E-02	5.09E-02	4.98E-02	1.80E-03
Pu-241	2.78E-01	3.84E-01	1.01E-01	1.73E-02
Pu-242	2.17E-04	3.22E-04	3.01E-04	1.19E-05
Rb-86	1.28E-08	1.97E-08	1.08E-08	1.18E-08
Re-188	1.23E-07	7.65E-09	2.49E-07	3.99E-07
Rh-103m	1.64E-06	7.21E-08	6.56E-06	5.77E-06
Sb-124	4.04E-06	2.41E-06	2.41E-05	6.70E-07
Sb-125	8.05E-05	1.03E-04	5.37E-04	1.98E-05
Sb-126	2.00E-08	8.75E-09	7.50E-08	4.19E-09
Sr-89	2.55E-03	2.46E-03	1.73E-02	1.64E-04
Sr-90	1.88E-02	4.88E-02	1.54E-01	1.95E-04
Ta-182	2.93E-06	3.91E-07	2.10E-05	3.36E-07
Tc-99	1.34E-07	1.43E-09	1.01E-06	7.55E-08
Te-125m	1.66E-05	2.64E-05	1.20E-04	9.17E-07
Te-127	3.13E-06	5.92E-07	1.15E-05	1.64E-06
Te-127m	1.10E-04	4.09E-04	7.29E-04	6.23E-06
Te-129	6.95E-07	7.81E-08	1.95E-06	1.59E-06
Te-129m	1.03E-04	2.85E-04	6.46E-04	1.20E-05
W-181	4.04E-10	1.97E-10	5.17E-11	1.13E-10
W-185	3.96E-08	1.02E-08	4.32E-09	5.75E-09
Y-90	4.15E-04	2.68E-05	1.24E-03	1.07E-04
Y-91	4.41E-03	1.74E-03	3.04E-02	2.39E-04
Zr-95	5.03E-03	1.11E-02	3.48E-02	1.16E-03
Ru-103	3.46E-02	1.20E-02	2.36E-01	1.29E-02
Ru-106	1.07E+00	4.57E-01	7.91E+00	4.87E-01
Total[a]	3.50E+00	3.02E+00	1.45E+01	1.22E+00
Total[b]	3.47E+00	N/A	N/A	N/A
Total[c]	**3.56E+00**	**N/A**	**N/A**	**N/A**
Total[d]	**N/A**	**1.04E-06**	**5.30E-15**	**8.95E-12**

[a] Assumes no iodine tablets are administered to victims.
[b] Assumes iodine tablets are administered to victims within 30 minutes of the accident.

[c] Is the total effective dose over 50 years and include the committed effective, gamma effective and beta skin doses.
[d] Is the 30 day normalised dose to the relevant organs from internal (i.e., inhalation) and external (i.e., gamma immersion) exposure pathways.
Total[c] = 50 year committed effective dose (Total[b]) + gamma effective dose + beta skin dose × tissue weighting factor.
Total[d] = 30 day normalised organ dose from inhalation (Total[a]) + normalised organ dose from gamma exposure.

Since the dose rates are relatively low and the short-term (30 day) committed equivalent doses to the specified organs are all less than 1 Sv (see Total[d] in Table 41), the deterministic risk contributes insignificantly to the overall risk. Only once the short-term (30 day) committed equivalent dose to the specified organs is above 4 Sv does the deterministic risk become significant. Therefore, since the stochastic risk dominates, only this risk will be calculated.

Table 42 presents the peak and average site personnel conditional risks used to determine the overall peak and average site personnel risk. The stochastic risk conversion factor of 5% per Sv is applied (see Section 1.4.2.1.3) resulting in an individual risk of mortality of 1.78E-01 (3.56 × 0.05).

For cask loading error accident, a fuel handler/supervisor involved only involved in cask loading activities for a maximum of 6 hours per 24 hour period [70], that is ¼ (= 6hr / 24 hr) of the cask loading activities over 24 hours. Therefore, the peak site personnel risk is divided by a factor of 4 since the individuals present during a cask loading error accident will all have the same peak risk. The maximum number of personnel present during the 6 hours exposure period is 15. The total number of site personnel is assumed to be 1000.

Table 42: Peak and Average Site Personnel Conditional Risks for the Cask Loading Error Accident

Frequency (/yr)	Consequence (Sv)	Consequence (Ind. Risk of Mortality)	Number of Site Personnel Exposed	Peak Station Risk (/yr)	Average Station Risk (/yr)	Average Site Personnel Conditional Risk*	Peak Site Personnel Conditional Risk*
1.02E-06	3.56E+00	1.78E-01	60	4.54E-08	2.73E-09	2.67E-03	4.46E-02

* The average and peak site personnel conditional risks are determined as the respective average and peak station risk divided by the frequency.

5.1.2 Peak and Average Public Risks

The peak and average public risks for the cask loading error (wrong assemblies loaded into cask) accident were calculated using the PC COSYMA results given in Appendix F, Table F33 (based on the release inputs described in Sections 4.3.1 to 4.3.3) and the public risk methodology presented in Section 1.4.2.2. The results for the peak and average public risks are presented in Table 43.

Table 43: Peak and Average Public Risks for the Cask Loading Error Accident

Accident	Frequency (Per Year)	Average Public Conditional Risk	Average Public Risk (Per Year)	Peak Public Conditional Risk	Peak Public Risk (Per Year)
Cask Loading Error (2008 National Population)	1.02E-06	3.97E-10	4.05E-16	1.78E-07	1.82E-13

5.2 Overall Cask Drop

5.2.1 Cask Drop Accident (No SFP Liner Break)

5.2.1.1 Peak and Average Site Personnel Risks

Mortality risks to site personnel require the computation of doses received from cloudshine and inhalation. The first step is to calculate the atmospheric concentration of each isotope in the radioactive release. The table below presents the atmospheric concentrations for the cask drop accident using the cask initial inventory for a 3600 days decay period presented in Appendix B, Table B2.1, and the total release fractions from Table 29 in Section 4.1.2. The radionuclides with atmospheric concentrations below 0.1 Bq/m^3 are not presented and included in the atmospheric concentration tables for cask drop accidents. This provides a reasonable estimate of the dose since some radioactive isotopes have a concentration greater than 1.00E+03 Bq/m^3.

Table 44: Atmospheric Concentration for the Cask Drop Accident (No SFP Liner Break)

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (0.02% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[8] (Bq/m^3)
Ag-110m	1.59E+11	2.82E-09	4.47E+02	2.13E-01
Am-241	1.63E+15	2.82E-09	4.61E+06	2.19E+03
Am-242	1.37E+13	2.82E-09	3.87E+04	1.84E+01
Am-242m	1.37E+13	2.82E-09	3.87E+04	1.84E+01
Am-243	2.77E+13	2.82E-09	7.81E+04	3.72E+01
Ce-144	1.04E+14	2.82E-09	2.93E+05	1.40E+02
Cm-242	1.13E+13	2.82E-09	3.20E+04	1.52E+01
Cm-243	2.53E+13	2.82E-09	7.15E+04	3.40E+01
Cm-244	2.88E+15	2.82E-09	8.11E+06	3.86E+03
Cm-245	4.82E+11	2.82E-09	1.36E+03	6.47E-01
Cm-246	1.31E+11	2.82E-09	3.71E+02	1.76E-01
Co-60	1.61E+14	2.82E-09	4.54E+05	2.16E+02
Cs-134	5.30E+15	1.37E-08	7.27E+07	3.46E+04
Cs-135	4.22E+11	1.37E-08	5.77E+03	2.75E+00
Cs-137	6.88E+16	1.37E-08	9.42E+08	4.49E+05
Eu-152	4.05E+12	2.82E-09	1.14E+04	5.44E+00

[8] Atmospheric Concentration = Released to Atmosphere / 2100 m^3 [5].

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (0.02% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[8] (Bq/m^3)
Eu-154	4.78E+15	2.82E-09	1.35E+07	6.41E+03
Eu-155	1.86E+15	2.82E-09	5.24E+06	2.50E+03
Fe-55	1.87E+13	2.82E-09	5.28E+04	2.51E+01
H-3	2.19E+14	5.13E-05	1.12E+10	5.35E+06
I-129	2.56E+10	9.40E-06	2.40E+05	1.14E+02
Kr-85	3.63E+15	5.13E-05	1.86E+11	8.88E+07
Nb-93m	3.42E+12	2.82E-09	9.64E+03	4.59E+00
Nb-94	1.04E+11	2.82E-09	2.95E+02	1.40E-01
Ni-59	2.26E+11	2.82E-09	6.38E+02	3.04E-01
Ni-63	3.02E+13	2.82E-09	8.51E+04	4.05E+01
Np-237	3.37E+11	2.82E-09	9.52E+02	4.53E-01
Np-239	2.77E+13	2.82E-09	7.81E+04	3.72E+01
Pm-147	7.48E+15	2.82E-09	2.11E+07	1.00E+04
Pu-236	1.75E+11	2.82E-09	4.94E+02	2.35E-01
Pu-238	3.54E+15	2.82E-09	9.98E+06	4.75E+03
Pu-239	2.30E+14	2.82E-09	6.48E+05	3.08E+02
Pu-240	2.63E+14	2.82E-09	7.41E+05	3.53E+02
PU-241	7.40E+16	2.82E-09	2.09E+08	9.94E+04
Pu-242	1.72E+12	2.82E-09	4.84E+03	2.31E+00
Ru-106	4.46E+14	1.88E-08	8.39E+06	4.00E+03
Sb-125	5.22E+14	2.82E-09	1.47E+06	7.01E+02
Sr-90	4.72E+16	1.88E-08	8.88E+08	4.23E+05
Tc-99	1.03E+13	2.82E-09	2.90E+04	1.38E+01
Te-125m	1.28E+14	2.82E-09	3.60E+05	1.71E+02
U-234	7.65E+11	2.82E-09	2.16E+03	1.03E+00
U-238	1.69E+11	2.82E-09	4.77E+02	2.27E-01
Y-90	4.72E+16	2.82E-09	1.33E+08	6.34E+04
Zr-93	1.05E+12	2.82E-09	2.95E+03	1.40E+00

From the atmospheric concentration, the gamma effective dose due to cloudshine and beta skin dose as presented in Table 45 below were calculated for an exposure time of 10 minutes as follows:

$$\text{Gamma effective dose} = 2.5\times10^{-8} \times \Sigma(f_i\times f_E) \times b_c \times R \times T \qquad (24)$$

$$\text{Beta Skin Dose} = \text{Beta Conversion Factor} \times b_c \times T \qquad (25)$$

Where: b_c = Atmospheric Concentration (Bq.m^{-3})
R = Radius of the hemispherical cloud (m)
T = Duration of the exposure (hrs)

Table 45: Doses for Immersion for the Cask Drop Accident (No SFP Liner Break)

Nuclide	$\Sigma(f_i \times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m^3/Bq.hr)	Beta Skin Dose (Sv)
Ag-110m	5.67E-05	5.03E-13	5.65E-10	2.01E-11
Am-241	7.17E-06	6.55E-10	9.86E-12	3.61E-09
Am-242	5.31E-06	4.08E-12	2.95E-11	9.07E-11
Am-242m	2.56E-06	1.97E-12	4.90E-13	1.51E-12
Am-243	4.06E-06	6.29E-12	9.86E-12	6.11E-11
Ce-144	1.67E-06	9.71E-12	1.05E-11	2.44E-10
Cm-242	1.01E-06	6.40E-13	1.54E-13	3.91E-13
Cm-243	8.87E-06	1.26E-11	3.52E-11	2.00E-10
Cm-244	9.36E-07	1.51E-10	1.41E-13	9.08E-11
Cm-245	8.38E-06	2.26E-13	1.93E-11	2.08E-12
Cm-246	8.33E-07	6.13E-15	1.26E-13	3.71E-15
Co-60	4.84E-05	4.36E-10	5.22E-10	1.88E-08
Cs-134	3.38E-05	4.87E-08	3.40E-10	1.96E-06
Cs-135	N/A	N/A	3.26E-12	1.49E-12
Cs-137	1.42E-05	2.66E-07	3.11E-11	2.33E-06
Eu-152	2.98E-05	6.75E-12	2.48E-10	2.25E-10
Eu-154	2.63E-05	7.03E-09	2.98E-10	3.18E-07
Eu-155	4.47E-06	4.65E-10	1.22E-11	5.07E-09
Fe-55	2.67E-06	2.79E-12	0.00E+00	0.00E+00
H-3	N/A	N/A	0.00E+00	0.00E+00
I-129	7.86E-06	3.75E-11	3.96E-12	7.56E-11
Kr-85	5.03E-08	1.86E-07	4.75E-11	7.03E-04
Nb-93m	1.22E-06	2.33E-13	1.54E-13	1.18E-13
Nb-94	3.35E-05	1.96E-13	3.43E-10	8.02E-12
Ni-59	3.23E-06	4.09E-14	0.00E+00	0.00E+00
Ni-63	N/A	N/A	0.00E+00	0.00E+00
Np-237	7.38E-06	1.39E-13	5.54E-12	4.18E-13
Np-239	1.01E-05	1.57E-11	5.76E-11	3.57E-10
Pm-147	8.65E-10	3.62E-13	2.92E-12	4.89E-09
Pu-236	1.20E-06	1.18E-14	1.74E-13	6.82E-15
Pu-238	1.04E-06	2.06E-10	1.47E-13	1.16E-10
Pu-239	9.96E-06	1.28E-10	6.70E-14	3.44E-12
Pu-240	9.96E-07	1.46E-11	1.41E-13	8.29E-12
PU-241	6.29E-10	2.60E-12	4.21E-16	6.97E-12
Pu-242	8.28E-07	7.95E-14	1.18E-13	4.53E-14
Ru-106	N/A	N/A	0.00E+00	0.00E+00
Sb-125	1.53E-05	4.47E-10	9.54E-11	1.11E-08
Sr-90	N/A	N/A	3.31E-11	2.33E-06
Tc-99	N/A	N/A	9.86E-12	2.27E-11
Te-125m	1.25E-05	8.93E-11	6.98E-12	1.99E-10
U-234	9.90E-07	4.24E-14	1.53E-13	2.62E-14
U-238	8.18E-07	7.75E-15	1.05E-13	3.98E-15
Y-90	1.02E-09	2.70E-12	2.28E-10	2.41E-06
Zr-93	N/A	N/A	0.00E+00	0.00E+00
Totals		**5.10E-07**		**7.12E-04**

The committed effective dose and committed equivalent doses to specific organs from inhalation and a summary of the total effective and normalised organ doses for cask drop accidents are presented in Table 46. The committed effective dose and committed equivalent organ doses from inhalation were calculated using the database of ICRP Publication 68 dose conversion factors from Radiological Toolbox.

Table 46: Doses for Inhalation and Summary of Total Effective and Normalised Organ Doses

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
H-3	5.49E-05	5.49E-05	5.49E-05	5.49E-05
I-129	2.75E-06	3.72E-09	1.00E-08	3.43E-09
Cs-134	8.31E-05	7.79E-05	7.35E-05	7.79E-05
Cs-135	6.81E-10	6.39E-10	6.46E-10	6.46E-10
Cs-137	7.52E-04	7.07E-04	6.84E-04	7.07E-04
Ru-106	3.50E-05	1.50E-05	2.60E-04	1.60E-05
Sr-90	8.14E-03	2.11E-02	6.66E-02	8.46E-05
Ag-110m	3.89E-10	2.24E-10	2.02E-09	2.72E-10
Am-241	1.48E-02	2.08E-02	1.32E-02	9.87E-04
Am-242	5.53E-08	2.07E-08	3.78E-07	7.38E-10
Am-242m	1.11E-04	1.66E-04	2.54E-05	8.30E-06
Am-243	2.51E-04	3.44E-04	2.05E-04	1.77E-05
Ce-144	1.01E-06	6.63E-07	7.68E-06	6.28E-08
Cm-242	1.41E-05	4.95E-06	9.51E-05	9.13E-08
Cm-243	1.70E-04	2.47E-04	2.30E-04	9.36E-06
Cm-244	1.64E-02	2.41E-02	2.51E-02	8.02E-04
Cm-245	4.37E-06	6.15E-06	3.72E-06	3.07E-07
Cm-246	1.19E-06	1.68E-06	1.01E-06	8.38E-08
Co-60	9.19E-07	3.41E-07	5.19E-06	3.51E-07
Eu-152	3.67E-08	6.25E-08	5.44E-08	1.50E-08
Eu-154	5.61E-05	9.62E-05	1.04E-04	1.60E-05
Eu-155	2.93E-06	4.24E-06	8.11E-06	2.68E-07
Fe-55	5.78E-09	2.07E-08	1.63E-09	1.63E-09
Nb-93m	9.87E-10	1.07E-10	7.69E-09	4.36E-11
Nb-94	8.77E-10	2.60E-10	5.61E-09	2.46E-10
Ni-59	1.21E-10	5.54E-11	1.82E-10	5.54E-11
Ni-63	2.03E-08	1.72E-08	2.84E-08	1.72E-08
Np-237	1.70E-06	2.83E-06	1.93E-06	9.74E-08
Np-239	1.02E-08	4.46E-10	4.74E-08	1.30E-09
Pm-147	8.79E-06	1.03E-05	6.28E-05	8.29E-08
Pu-236	7.65E-07	1.06E-06	2.59E-06	3.29E-08
Pu-238	3.57E-02	5.35E-02	6.06E-02	1.90E-03
Pu-239	2.47E-03	3.70E-03	3.62E-03	1.31E-04
Pu-240	2.82E-03	4.24E-03	4.15E-03	1.50E-04
Pu-241	1.44E-02	1.99E-02	5.22E-03	8.94E-04
Pu-242	1.79E-05	2.65E-05	2.48E-05	9.80E-07
Sb-125	5.78E-07	7.36E-07	3.86E-06	1.42E-07
Tc-99	1.11E-08	1.18E-10	8.30E-08	6.22E-09
Te-125m	1.24E-07	1.97E-07	9.00E-07	6.86E-09

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
U-234	1.75E-06	2.82E-07	1.05E-05	1.00E-07
U-238	3.24E-07	6.25E-08	1.93E-06	1.93E-08
Y-90	2.70E-05	1.74E-06	8.09E-05	6.98E-06
Zr-93	1.02E-08	4.21E-08	2.77E-09	5.27E-12
Total[a]	9.63E-02	1.49E-01	1.80E-01	5.87E-03
Total[b]	9.63E-02	N/A	N/A	N/A
Total[c]	**9.63E-02**	**N/A**	**N/A**	**N/A**
Total[d]	**N/A**	**5.73E-22**	**1.22E-41**	**5.82E-35**

[a] Assumes no iodine tablets are administered to victims.

[b] Assumes iodine tablets are administered to victims within 30 minutes of the accident.

[c] Is the total effective dose over 50 years and include the committed effective, gamma effective and beta skin doses.
[d] Is the 30 day normalised dose to the relevant organs from internal (i.e., inhalation) and external (i.e., gamma immersion) exposure pathways.

Total[c] = 50 year committed effective dose (Total[b]) + gamma effective dose + beta skin dose × tissue weighting factor.

Total[d] = 30 day normalised organ dose from inhalation (Total[a]) + normalised organ dose from gamma exposure.

Since the dose rates are relatively low and the short-term (30 day) committed equivalent doses to the specified organs are all less than 1 Sv (see Total[d] in Table 46), the deterministic risk contributes insignificantly to the overall risk. Only once the short-term (30 day) committed equivalent dose to the specified organs is above 4 Sv does the deterministic risk become significant. Therefore, since the stochastic risk dominates, only this risk will be calculated.

Table 47 below presents the peak and average site personnel conditional risks used to determine the overall site personnel risk. The stochastic risk conversion factor of 5% per Sv is applied to the stochastic dose (see Section 1.4.2.1.3) resulting in an individual risk of mortality of 4.82E-03 (9.63E-02 × 0.05). For cask drop accidents, a fuel handler/supervisor is only involved in cask handling activities for a maximum of 6 hours per 24 hour period [70], that is ¼ (= 6 hr / 24 hr) of the cask handling activities. Therefore, the peak site personnel risk is divided by a factor of 4 since the individuals present during a cask handling accident will all have the same peak risk. The maximum number of personnel present during the 6 hours exposure period is 15. The total number of site personnel is assumed to be 1000.

Table 47: Peak and Average Site Personnel Conditional Risks for the Cask Drop Accident (No SFP Liner Break)

Frequency (/yr)	Consequence (Sv)	Consequence (Ind. Risk of Mortality)	Number of Site Personnel Exposed	Peak Station Risk (/yr)	Average Station Risk (/yr)	Average Site Personnel Conditional Risk*	Peak Site Personnel Conditional Risk*
2.80E-06	9.63E-02	4.82E-03	60	3.37E-09	2.02E-10	7.22E-05	1.20E-03

* The average and peak site personnel conditional risks are determined as the respective average and peak station risk divided by the frequency.

5.2.1.2 Peak and Average Public Risks

The peak and average public risks for a cask drop accident (no SFP Liner Break) were calculated using the PC COSYMA results given in Appendix F, Table F33 (based on the release inputs described in Sections 4.1.1 to 4.1.3) and the public risk methodology presented in Section 1.4.2.2. The results for the peak and average public risks are presented in Table 48.

Table 48: Peak and Average Public Risks for the Cask Drop Accident (No SFP Liner Break)

Accident	Frequency (Per Year)	Average Public Conditional Risk	Average Public Risk (Per Year)	Peak Public Conditional Risk	Peak Public Risk (Per Year)
Cask Drop (no SFP Liner Break) (2008 National Population)	2.80E-06	6.54E-12	1.83E-17	2.91E-09	8.14E-15

5.2.2 Cask Drop with SFP Liner Break Accident

5.2.2.1 Peak and Average Site Personnel Risks

The peak and average site personnel risks were calculated using PC COSYMA and the results presented in Appendix F, Table F37, and the methodology described in Section 1.4.2.2.4.

The individual risk is defined as the maximum risk inside the 1 km radius. Since all the personnel are exposed to this risk, this corresponds to the peak and average site personnel risks due to severe accidents. The results for the peak and average site personnel risks are displayed in Table 49.

Table 49: Peak and Average Site Personnel Risks for the Cask Drop with SFP Liner Break Accident

Accident	Frequency (Per Year)	Average Site Personnel Conditional Risk*	Average Site Personnel Risk (Per Year)**	Peak Site Personnel Conditional Risk*	Peak Site Personnel Risk (Per Year)**
Cask Drop with SFP Liner Break	2.24E-07	1.21E-01	2.71E-07	1.21E-01	2.71E-07

* The average and peak site personnel conditional risks are determined as the respective average and peak station risk divided by the frequency.
** As per the discussion in Section 1.4.2.2.4, scaling of the peak and average site personnel risks by a factor of 10 are included.

5.2.2.2 Peak and Average Public Risks

The peak and average public risks for the cask drop accident with SFP Liner Break were calculated using the PC COSYMA results given in Appendix F, Table F33 (based on the release inputs described in Sections 4.2.1 to 4.2.3) and the public risk methodology presented in Section 1.4.2.2. The results for the peak and average public risks are presented in Table 50.

Table 50: Peak and Average Public Risks for the Cask Drop with SFP Liner Break Accident

Accident	Frequency	Average Public Conditional Risk	Average Public Risk	Peak Public Conditional Risk	Peak Public Risk
Cask Drop with SFP Liner Break (2008 National Population)	2.24E-07	2.54E-03	5.70E-10	1.11E-01	2.49E-08

5.3 Cask Seal Failure Accident

5.3.1 Peak and Average Site Personnel Risks

Mortality risks to site personnel require the computation of doses received from cloudshine and inhalation. The first step is to calculate the atmospheric concentration of each isotope in the radioactive release. The table below presents the atmospheric concentrations for the cask seal failure accidents using the cask initial inventory for a 3600 days decay period presented in Appendix B, Table B2.1, and the total release fractions from Table 29 in Section 4.1.2. The radionuclides with atmospheric concentrations below 0.1 Bq/m^3 are not presented and included in the atmospheric concentration tables for cask accidents. This provides a reasonable estimate of the dose since some radioactive isotopes have a concentration greater than 1.00E+03 Bq/m^3.

Table 51: Atmospheric Concentration for the Cask Seal Failure Accident

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (0.02% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[9] (Bq/m^3)
Am-241	1.63E+15	1.03E-10	1.68E+05	8.01E+01
Am-242	1.37E+13	1.03E-10	1.41E+03	6.74E-01
Am-242m	1.37E+13	1.03E-10	1.41E+03	6.74E-01
Am-243	2.77E+13	1.03E-10	2.85E+03	1.36E+00
Ce-144	1.04E+14	1.03E-10	1.07E+04	5.10E+00
Cm-242	1.13E+13	1.03E-10	1.17E+03	5.56E-01
Cm-243	2.53E+13	1.03E-10	2.61E+03	1.24E+00
Cm-244	2.88E+15	1.03E-10	2.96E+05	1.41E+02
Co-60	1.61E+14	1.03E-10	1.66E+04	7.90E+00

[9] Atmospheric Concentration = Released to Atmosphere / 2100 m^3 [5].

Nuclide	Cask Initial Inventory (Bq)	Total Release Fraction (0.02% cladding failure)	Released to Atmosphere (Bq)	Atmospheric Concentration[9] (Bq/m^3)
Cs-134	5.30E+15	3.42E-11	1.81E+05	8.64E+01
Cs-137	6.88E+16	3.42E-11	2.35E+06	1.12E+03
Eu-152	4.05E+12	1.03E-10	4.17E+02	1.99E-01
Eu-154	4.78E+15	1.03E-10	4.92E+05	2.34E+02
Eu-155	1.86E+15	1.03E-10	1.91E+05	9.11E+01
Fe-55	1.87E+13	1.03E-10	1.93E+03	9.18E-01
H-3	1.92E+14	5.13E-05	9.84E+09	4.69E+06
I-129	2.56E+10	3.42E-07	8.75E+03	4.16E+00
Kr-85	3.63E+15	5.13E-05	1.86E+11	8.88E+07
Nb-93m	3.42E+12	1.03E-10	3.52E+02	1.68E-01
Ni-63	3.02E+13	1.03E-10	3.11E+03	1.48E+00
Np-239	2.77E+13	1.03E-10	2.85E+03	1.36E+00
Pm-147	7.48E+15	1.03E-10	7.71E+05	3.67E+02
Pu-238	3.54E+15	1.03E-10	3.65E+05	1.74E+02
Pu-239	2.30E+14	1.03E-10	2.37E+04	1.13E+01
Pu-240	2.63E+14	1.03E-10	2.71E+04	1.29E+01
Pu-241	7.40E+16	1.03E-10	7.62E+06	3.63E+03
Ru-106	4.46E+14	6.84E-10	3.05E+05	1.45E+02
Sb-125	5.22E+14	1.03E-10	5.38E+04	2.56E+01
Sr-90	4.72E+16	6.84E-10	3.23E+07	1.54E+04
Tc-99	1.03E+13	1.03E-10	1.06E+03	5.05E-01
Te-125m	1.28E+14	1.03E-10	1.31E+04	6.26E+00
Y-90	4.72E+16	1.03E-10	4.87E+06	2.32E+03

From the atmospheric concentration, the gamma effective dose due to cloudshine and beta skin dose presented in Table 52 below were calculated for an exposure time of 10 minutes as follows:

$$\text{Gamma effective dose} = 2.5\times10^{-8}\times\Sigma(f_i\times f_E)\times b_c\times R\times T \qquad (26)$$

$$\text{Beta Skin Dose} = \text{Beta Conversion Factor}\times b_c\times T \qquad (27)$$

Where: b_c = Atmospheric Concentration (Bq.m^{-3})
R = Radius of the hemispherical cloud (m)
T = Duration of the exposure (hrs)

Table 52: Doses for Immersion for the Cask Seal Failure Accident

Nuclide	$\Sigma(f_i\times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m^3/Bq.hr)	Beta Skin Dose (Sv)
Am-241	7.17E-06	2.39E-11	9.86E-12	1.32E-10
Am-242	5.31E-06	1.49E-13	2.95E-11	3.31E-12
Am-242m	2.56E-06	7.19E-14	4.90E-13	5.50E-14
Am-243	4.06E-06	2.30E-13	9.86E-12	2.23E-12
Ce-144	1.67E-06	3.55E-13	1.05E-11	8.92E-12
Cm-242	1.01E-06	2.34E-14	1.54E-13	1.43E-14

Nuclide	$\Sigma(f_i \times f_E)$	Gamma Effective Dose (Sv)	Beta Conversion Factor (Sv.m³/Bq.hr)	Beta Skin Dose (Sv)
Cm-243	8.87E-06	4.59E-13	3.52E-11	7.29E-12
Cm-244	9.36E-07	5.50E-12	1.41E-13	3.32E-12
Co-60	4.84E-05	1.59E-11	5.22E-10	6.87E-10
Cs-134	3.38E-05	1.22E-10	3.40E-10	4.90E-09
Cs-137	1.42E-05	6.63E-10	3.11E-11	5.81E-09
Eu-152	2.98E-05	2.47E-13	2.48E-10	8.21E-12
Eu-154	2.63E-05	2.57E-10	2.98E-10	1.16E-08
Eu-155	4.47E-06	1.70E-11	1.22E-11	1.85E-10
Fe-55	2.67E-06	1.02E-13	0.00E+00	0.00E+00
H-3	N/A	N/A	0.00E+00	0.00E+00
I-129	7.86E-06	1.36E-12	3.96E-12	2.75E-12
Kr-85	5.03E-08	1.86E-07	4.75E-11	7.03E-04
Nb-93m	1.22E-06	8.53E-15	1.54E-13	4.30E-15
Ni-63	N/A	N/A	0.00E+00	0.00E+00
Np-239	1.01E-05	5.72E-13	5.76E-11	1.30E-11
Pm-147	8.65E-10	1.32E-14	2.92E-12	1.79E-10
Pu-238	1.04E-06	7.52E-12	1.47E-13	4.25E-12
Pu-239	9.96E-06	4.68E-12	6.70E-14	1.26E-13
Pu-240	9.96E-07	5.35E-13	1.41E-13	3.03E-13
Pu-241	6.29E-10	9.51E-14	4.21E-16	2.55E-13
Ru-106	N/A	N/A	0.00E+00	0.00E+00
Sb-125	1.53E-05	1.63E-11	9.54E-11	4.07E-10
Sr-90	N/A	N/A	3.31E-11	8.49E-08
Tc-99	N/A	N/A	9.86E-12	8.30E-13
Te-125m	1.25E-05	3.26E-12	6.98E-12	7.28E-12
Y-90	1.02E-09	9.85E-14	2.28E-10	8.80E-08
Totals		**1.87E-07**		**7.03E-04**

The committed effective dose and committed equivalent doses to specific organs from inhalation and a summary of the total effective and normalised organ doses for cask seal failure accidents are presented in Table 53. The committed effective dose and committed equivalent organ doses from inhalation were calculated using the database of ICRP Publication 68 dose conversion factors from Radiological Toolbox.

Table 53: Doses for Inhalation and a Summary of Total Effective and Normalised Organ Doses for the Cask Seal Failure Accident

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
H-3	4.80E-05	4.80E-05	4.80E-05	4.80E-05
I-129	1.00E-07	1.35E-10	3.64E-10	1.25E-10
Cs-134	2.07E-07	1.94E-07	1.84E-07	1.94E-07
Cs-137	1.88E-06	1.76E-06	1.71E-06	1.76E-06
Ru-106	1.27E-06	5.45E-07	9.45E-06	5.82E-07
Sr-90	2.96E-04	7.69E-04	2.42E-03	3.08E-06
Am-241	5.41E-04	7.61E-04	4.81E-04	3.61E-05

Nuclide	Committed Effective Dose (50 Years) (Sv)	Committed Equivalent Dose to Bone Marrow (30 Days) (Sv)	Committed Equivalent Dose to Lung (30 Days) (Sv)	Committed Equivalent Dose to GI Tract (30 Days) (Sv)
Am-242	2.02E-09	7.58E-10	1.38E-08	2.69E-11
Am-242m	4.04E-06	6.06E-06	9.26E-07	3.03E-07
Am-243	9.17E-06	1.26E-05	7.47E-06	6.45E-07
Ce-144	3.70E-08	2.42E-08	2.80E-07	2.29E-09
Cm-242	5.14E-07	1.81E-07	3.47E-06	3.33E-09
Cm-243	6.21E-06	9.01E-06	8.39E-06	3.42E-07
Cm-244	6.00E-04	8.82E-04	9.17E-04	2.93E-05
Co-60	3.36E-08	1.24E-08	1.90E-07	1.28E-08
Eu-152	1.34E-09	2.28E-09	1.99E-09	5.46E-10
Eu-154	2.05E-06	3.51E-06	3.81E-06	5.86E-07
Eu-155	1.07E-07	1.55E-07	2.96E-07	9.80E-09
Fe-55	2.11E-10	7.57E-10	5.96E-11	5.96E-11
Nb-93m	3.61E-11	3.90E-12	2.81E-10	1.59E-12
Ni-63	7.40E-10	6.29E-10	1.04E-09	6.29E-10
Np-239	3.74E-10	1.63E-11	1.73E-09	4.76E-11
Pm-147	3.21E-07	3.76E-07	2.29E-06	3.03E-09
Pu-238	1.30E-03	1.95E-03	2.21E-03	6.95E-05
Pu-239	9.01E-05	1.35E-04	1.32E-04	4.79E-06
Pu-240	1.03E-04	1.55E-04	1.51E-04	5.48E-06
Pu-241	5.26E-04	7.26E-04	1.91E-04	3.27E-05
Sb-125	2.11E-08	2.69E-08	1.41E-07	5.18E-09
Tc-99	4.04E-10	4.29E-12	3.03E-09	2.27E-10
Te-125m	4.54E-09	7.20E-09	3.29E-08	2.50E-10
Y-90	9.85E-07	6.37E-08	2.95E-06	2.55E-07
Total[a]	3.53E-03	5.46E-03	6.60E-03	2.34E-04
Total[b]	3.53E-03	N/A	N/A	N/A
Total[c]	**3.54E-03**	**N/A**	**N/A**	**N/A**
Total[d]	**N/A**	**3.52E-39**	**9.39E-62**	**5.85E-49**

[a] Assumes no iodine tablets are administered to victims.

[b] Assumes iodine tablets are administered to victims within 30 minutes of the accident.

[c] Is the total effective dose over 50 years and include the committed effective, gamma effective and beta skin doses.
[d] Is the 30 day normalised dose to the relevant organs from internal (i.e., inhalation) and external (i.e., gamma immersion) exposure pathways.

Total[c] = 50 year committed effective dose (Total[b]) + gamma effective dose + beta skin dose × tissue weighting factor.

Total[d] = 30 day normalised organ dose from inhalation (Total[a]) + normalised organ dose from gamma exposure.

Since the dose rates are relatively low and the short-term (30 day) committed equivalent doses to the specified organs are all less than 1 Sv (see Total[d] in Table 53), the deterministic risk contributes insignificantly to the overall risk. Only once the short-term (30 day) committed equivalent dose to the specified organs is above 4 Sv does the deterministic risk become significant. Therefore, since the stochastic risk dominates, only this risk will be calculated.

Table 54 below presents the peak and average site personnel conditional risks used to determine the overall site personnel risk. The stochastic risk conversion factor of 5% per Sv is applied to the stochastic dose (see Section 1.4.2.1.3) resulting in an individual risk of mortality of 1.77E-04 (3.54E-03 × 0.05). For the cask seal failure accident, it is assumed that the number of site personnel that can potentially be exposed consists of only 2 personnel in the TISF. The total number of site personnel is assumed to be 1000.

Table 54: Peak and Average Site Personnel Conditional Risks for the Cask Seal Failure Accident

Frequency (/yr)	Consequence (Sv)	Consequence (Ind. Risk of Mortality)	Number of Site Personnel Exposed	Peak Station Risk (/yr)	Average Station Risk (/yr)	Average Site Personnel Conditional Risk*	Peak Site Personnel Conditional Risk*
7.76E-05	3.54E-03	1.77E-04	2	1.37E-08	2.75E-11	3.54E-07	1.77E-04

* The average and peak site personnel conditional risks are determined as the respective average and peak station risk divided by the frequency.

5.3.2 Peak and Average Public Risks

The average and peak public risks for a cask seal leak accident were calculated using the PC COSYMA results presented in Appendix F, Table F33 (based on the release inputs described in Sections 4.1.1 to 4.1.3) and the methodology described in Chapter 1.4.2.2 and are displayed in Table 55.

Table 55: Peak and Average Public Risks for the Cask Seal Failure Accident

Accident	Frequency (Per Year)	Average Public Conditional Risk	Average Public Risk (Per Year)	Peak Public Conditional Risk	Peak Public Risk (Per Year)
Cask Seal Failure (2008 National Population)	2.24E-02	1.84E-13	4.11E-15	1.67E-10	3.73E-12

5.4 Heavy Aircraft Crash

5.4.1 Peak and Average Site Personnel Risks

The peak and average site personnel risks for a heavy aircraft crash induced fire impacting the TISF were calculated using the PC COSYMA results presented in Appendix F, Table F37 (based on the release inputs described in Sections 4.4.1 to 4.4.3) and the methodology described in Section 1.4.2.2.4.

The individual risk is defined as the maximum risk inside the 1 km radius. Since all the personnel are exposed to this risk, this corresponds to the peak and average site personnel risks due to severe accidents. The results for the peak and average site personnel risks are displayed in Table 56.

Table 56: Peak and Average Site Personnel Risks for Heavy Aircraft Crash Induced Fire Impacting the TISF

Accident	Frequency (Per Year)	Average Site Personnel Conditional Risk*	Average Site Personnel Risk (Per Year)**	Peak Site Personnel Conditional Risk*	Peak Site Personnel Risk (Per Year)**
Heavy Aircraft Crash - Fire	8.91E-08	2.02E-02	1.80E-08	2.02E-02	1.80E-08

* The average and peak site personnel conditional risks are determined as the respective average and peak station risk divided by the frequency.
** As per the discussion in Section 1.4.2.2.4, scaling of the peak and average site personnel risks by a factor of 10 are included.

5.4.2 Peak and Average Public Risks

The peak and average public risks for for a heavy aircraft crash induced fire impacting the TISF were calculated using the PC COSYMA results given in Appendix F, Table F33 (based on the release inputs described in Sections 4.4.1 to 4.4.3) and the public risk methodology presented in Section 1.4.2.2. The results for the peak and average public risks are presented in Table 57.

Table 57: Peak and Average Public Risks for Heavy Aircraft Crash Induced Fire Impacting the TISF

Accident	Frequency (Per Year)	Average Public Conditional Risk	Average Public Risk (Per Year)	Peak Public Conditional Risk	Peak Public Risk (Per Year)
Heavy Aircraft Crash – Fire (2008 National Population)	8.91E-08	1.25E-05	1.11E-12	7.63E-03	6.80E-10

6 CONCLUSION

6.1 Overall Results

The overall results for the peak and average site personnel and public risks for cask related accidents during all cask phases analysed in this study are summarised in Table 58 and respectively.

Table 58: Peak and Average Site Personnel Risks for All Cask Accidents

Cask Accident	Frequency	Average Site Pers. Conditional Risk	Average Site Personnel Risk	% Risks	Peak Site Pers. Conditional Risk	Peak Site Personnel Risk	% Risks
Cask Loading Error	1.02E-06	2.67E-03	2.73E-09	0.93%	4.46E-02	4.54E-08	13.46%
Cask Drop	2.80E-06	7.22E-05	2.02E-10	0.07%	1.20E-03	3.37E-09	1.00%
Cask Drop with SFP Liner Break*	2.24E-07	1.21E-01	2.71E-07	92.84%	1.21E-01	2.71E-07	80.23%
Cask Seal Failure	7.76E-05	3.54E-07	2.75E-11	0.01%	1.77E-04	1.37E-08	0.00%
Aircraft Crash - Fire*	8.91E-08	2.02E-02	1.80E-08	6.15%	2.02E-02	1.80E-08	5.32%
TOTAL	***8.17E-05***	***1.44E-01***	***2.92E-07***	***100.00%***	***1.87E-01***	***3.38E-07***	***100.00%***
* Scaling of the peak and average site personnel risks by a factor of 10 are included.							
NNR Criteria			**1.00E-05**			**5.00E-05**	
% of NNR Criteria			**2.92%**			**0.68%**	

The overall average site personnel risk is determined as the sum of the average risks for all cask accident scenarios.

The overall peak site personnel risk is determined as follows:
The highest risk value of either:
(i) the cask seal failure accident (occurs at TISF)
(ii) the sum of cask drop accident / 4 and cask loading error accident / 4 (occurs in SF Building)
+ Cask drop inside SF Building with SFP liner break (expose all personnel on site)
+ Cask failure due to aircraft crash-fire (expose all personnel on site)

Table 59: Peak and Average Public Risks for All Cask Accidents

Cask Accident	Frequency	Average Public Conditional Risk	Average Public Risk	% Risks	Peak Public Conditional Risk	Peak Public Risk	% Risks
Cask Loading Error	1.02E-06	3.97E-10	4.05E-16	0.00%	1.78E-07	1.82E-13	0.00%
Cask Drop	2.80E-06	6.54E-12	1.83E-17	0.00%	2.91E-09	8.14E-15	0.00%
Cask Drop with SFP Liner Break	2.24E-07	2.54E-03	5.70E-10	99.80%	1.11E-01	2.49E-08	97.33%
Cask Seal Failure	2.24E-02	1.84E-13	4.11E-15	0.00%	1.67E-10	3.73E-12	0.01%
Aircraft Crash - Fire	8.91E-08	1.25E-05	1.11E-12	0.19%	7.63E-03	6.80E-10	2.66%
TOTAL (2008)	***2.24E-02***	***2.56E-03***	***5.71E-10***	***100.00%***	***1.19E-01***	***2.56E-08***	***100.00%***
TOTAL (2025)*			***1.31E-09***				
* 2008 average public risk scaled by 2.3 to be representative of the year 2025 (see Section 1.4.2.2.3).							
NNR Criteria			**1.00E-08**			**5.00E-06**	
% of NNR Criteria (2008)			**5.71%**			**0.51%**	
% of NNR Criteria (2025)			**13.13%**				

6.2 Comparison to NNR Criteria

The NNR sets out licensing risk criteria in the report RD-0024 [1] which must be satisfied by any licensee of a nuclear installation. The risk criteria have been listed in Section 1.1 for both the public and site personnel. These risk limits were used to verify that the risk due to the dry storage cask system is acceptable. The total annual risk results for the pre-SGR case are summarised below for cask and other accidents (excluding casks) taken from Reference [71]. Since the average public risk figure taken from the RAR [71] is representative of the year 2011, it was multiplied by a factor of 1.0633 to be representative of the year 2008 as per the NNR accepted interim arrangement for addressing the use of outdated population data in PSA Level 3 studies and an additional scaling by a factor of 2.3 determined for the year 2025 was applied to the total average public risk result as described in memo PSA21-0001 [72] (also see Section 1.4.2.2.3). The risks results are further categorised into cask accidents from normal operations and cask movements.

Table 60: Total Annual Risk to the Station from All Accidents – Pre-SGR

Criteria	Annual Risk from Casks (Internal & Aircraft Crash-Fire)*	% of NNR Criteria	Annual Risk Excluding Casks**	% of NNR Criteria	Total Annual Risk	Total % of NNR Criteria
Peak Public Risk (fatalities/year)	2.56E-08	0.51%	5.06E-08	1.01%	**7.62E-08**	**1.52%**
Average Public Risk (fatalities/person/year) - Using 2008 National Population	5.71E-10	5.71%	1.14E-10	1.14%	**6.85E-10**	**6.85%**

Criteria	Annual Risk from Casks (Internal & Aircraft Crash-Fire)*	% of NNR Criteria	Annual Risk Excluding Casks**	% of NNR Criteria	Total Annual Risk	Total % of NNR Criteria
Average Public Risk (fatalities/person/year) - Using 2025 National Population	1.31E-09	13.13%	2.62E-10	2.62%	**1.58E-09**	**15.76%**
Peak Site Personnel Risk (fatalities/year)	3.38E-07	0.68%	2.51E-06	5.02%	**2.85E-06**	**5.70%**
Average Site Personnel Risk (fatalities/person/year)	2.92E-07	2.92%	8.10E-07	8.10%	**1.10E-06**	**11.02%**

* Scaling of the peak and average site personnel risks by a factor of 10 are included.
** For the Annual Risk Excluding Casks, the peak and average site personnel risks taken from the RAR [71] do not include the scaling factor of 10.

<u>The comparison to NNR criteria for the sum of all accidents including casks is within the NNR limits for both peak and average site personnel and public risks with sufficient margin available.</u>

The cask drop with SFP Liner Break accident is the dominant contributor to the overall annual average and peak public risks for cask accidents only with a contribution of 99.80% (for average public risk) and is sensitive to the cask drop frequency which is dependent on the number of cask movements per year. A sensitivity analysis is presented in Section 6.3 to show the impact of varying the number of cask movements per year on the cask risk results. The SFP radionuclide inventory used for the calculation of the consequences is conservative as it assumes that the entire SFP contains assemblies for the 15 day case after criticality. This represents a bounding case as the spent fuel pool contains spent fuel assemblies that have been unloaded from the core at different time periods (mainly older) and will therefore have a lower radionuclide inventory and decay heat. Further, cask loading operations can only take place 90 days after core unload.

The cask drop with SFP Liner Break accident is the dominant contributor to the average and peak site personnel risk with a contribution of 92.84% and 80.23% respectively.

Since all cask accidents cannot occur simultaneously due to the different phases of the dry cask storage system it is worthwhile to separate the risks into cask loading phase and cask storage phase and then compare the risk results to the NNR Criteria.

The accidents that can occur during the cask loading phase are:

- Cask loading error,
- Cask drop (no SFP Liner Break), and
- Cask drop with SFP Liner Break.

The accidents that can occur during the cask storage phase are:

- Seal Failure, and
- Heavy aircraft crash induced fire impacting TISF.

Table 61 and Table 62 present the peak and average site personnel and public risks due to cask accidents during the loading and storage phases respectively.

Table 61: Annual Risk to the Station during the Cask Loading Phase

Criteria	Annual Risk (Station)	% of NNR Criteria
Peak Public Risk (fatalities/year)	2.49E-08	0.50%
Average Public Risk (fatalities/person/year) - Using 2008 National Population	5.70E-10	5.70%
Average Public Risk (fatalities/person/year) - Using 2025 National Population	1.31E-09	13.11%
Peak Site Personnel Risk (fatalities/year)*	3.20E-07	0.64%
Average Site Personnel Risk (fatalities/person/year)*	2.74E-07	2.74%

* Scaling of the peak and average site personnel risks by a factor of 10 are included.

Table 62: Annual Risk to the Station during the Cask Storage Phase

Criteria	Annual Risk (Station)	% of NNR Criteria
Peak Public Risk (fatalities/year)	6.84E-10	0.01%
Average Public Risk (fatalities/person/year) - Using 2008 National Population	1.12E-12	0.01%
Average Public Risk (fatalities/person/year) - Using 2025 National Population	2.57E-12	0.03%
Peak Site Personnel Risk (fatalities/year)*	3.17E-08	0.06%
Average Site Personnel Risk (fatalities/person/year)*	1.80E-08	0.18%

* Scaling of the peak and average site personnel risks by a factor of 10 are included.

The annual risk is dominated by accidents occurring during the cask loading phase which contributes to approximately 13% of the NNR criteria for the average public risk (for the year 2025). Accidents occurring during the storage phase have no significant impact on the annual station risks.

For the SGR project a study was conducted in PSA18-0044, Comparison of the pre- and post-SGR (without TPU) SFP Source Terms [78], which demonstrated that the post-SGR without TPU source term is not significantly different from the pre-SGR SFP source term. It is therefore acceptable to continue using the pre-SGR SFP source term (and the radiological consequence of a SFP severe accident) for the post-SGR without TPU case.

The total annual risk results for the station post-SGR are summarised in Table 63. The annual risk for all accidents excluding cask accidents are taken from the PSA baseline risk for the post-SGR case [79].

Table 63: Total Annual Risk to the Station from All Accidents – Post-SGR

Criteria	Annual Risk from Casks (Internal & Aircraft Crash-Fire)	% of NNR Criteria	Annual Risk Excluding Casks	% of NNR Criteria	Total Annual Risk	Total % of NNR Criteria
Peak Public Risk (fatalities/year)	2.56E-08	0.51%	6.51E-08	1.30%	**9.07E-08**	**1.81%**
Average Public Risk (fatalities/person/year) - Using 2008 National Population	5.71E-10	5.71%	2.76E-10	2.76%	**8.47E-10**	**8.47%**
Average Public Risk (fatalities/person/year) - Using 2025 National Population	1.31E-09	13.13%	6.35E-10	6.35%	**1.95E-09**	**19.48%**
Peak Site Personnel Risk (fatalities/year)*	3.38E-07	0.68%	6.62E-06	13.24%	**6.96E-06**	**13.91%**
Average Site Personnel Risk (fatalities/person/year)*	2.92E-07	2.92%	3.17E-06	31.71%	**3.46E-06**	**34.63%**

* Scaling of the peak and average site personnel risks by a factor of 10 are included.

The comparison to NNR criteria for the sum of all accidents including casks for the post-SGR case is within the NNR limits for both peak and average site personnel and public risks with sufficient margin available.

6.3 Sensitivity Analysis

The peak and average public risk is dominated by the cask accident involving cask drop with SFP Liner Break. The parameters that have a significant impact on this cask accident are the number of cask movements per year and the frequency of the cask drop with SFP liner break. A sensitivity analysis was conducted to determine the impact on the peak and average public risks by varying the number of cask movements per year for the cask drop with SFP Liner Break accident PAIA section 44 (2)a.Redacted information could jeopardise effectiveness of testing procedure if disclosed

For a cask drop accident with no SFP liner break, the loaded cask has to be hoisted from the 20 m level to the 0 m level onto the transport vehicle. The cask is designed to withstand a 9 m drop and the SAR states that it appears to be certain that the cask will retain its leak tightness for a drop of 20 m. The cask drop accident analysis done in Section 4.1.2 followed EPRI Guidelines [3] and the analysis was conducted for a cask drop from a height of 9 m. A sensitivity analysis was conducted for a cask drop from a height of 20 m to determine the impact on peak and average site personnel risks.

Sensitivity analysis was not required for cask storage accidents as no cask movements take place during this phase and varying these parameters have no significant impact on the peak and average public risks.

6.3.1 Sensitivity Analysis Varying the Number of Cask Movements for Cask Drop with SFP Liner Break Accident Only

The main analysis has assumed that 7 cask movements occur per year. The previous cask assessment report [47] considered both 4 and 12 cask movements per year. Both these values will be used to evaluate the impact on the peak and average public risks.

6.3.1.1 Four (4) Cask Movements Per Year

The table below shows the impact on the peak and average public risks for all cask accidents when the number of cask movements is 4 per year for the cask drop with SFP Liner Break accident only.

Table 64: Peak and Average Public Risks for 4 Cask Movements Per Year

Release Category	Frequency	Average Public Conditional Risk	Average Public Risk	% Risks	Peak Public Conditional Risk	Peak Public Risk	% Risks
Cask Loading Error	1.02E-06	3.97E-10	4.05E-16	0.00%	1.78E-07	1.82E-13	0.00%
Cask Drop	2.80E-06	6.54E-12	1.83E-17	0.00%	2.91E-09	8.14E-15	0.00%
Cask Drop with SFP Liner Break	**1.28E-07**	**2.54E-03**	**3.26E-10**	**99.66%**	**1.11E-01**	**1.42E-08**	**95.42%**
Cask Seal Failure	2.24E-02	1.84E-13	4.11E-15	0.00%	1.67E-10	3.73E-12	0.03%
Aircraft Crash - Fire	8.91E-08	1.25E-05	1.11E-12	0.34%	7.63E-03	6.80E-10	4.56%
TOTAL (2008)	***2.24E-02***	***2.56E-03***	***3.27E-10***	***100.00%***	***1.19E-01***	***1.49E-08***	***100.00%***
TOTAL (2025)*			***7.52E-10***				
* 2008 average public risk scaled by 2.3 to be representative of the year 2025 (see Section 1.4.2.2.3).							
NNR Criteria			**1.00E-08**			**5.00E-06**	
% of NNR Criteria (2008)			**3.27%**			**0.30%**	
% of NNR Criteria (2025)			**7.52%**				

The above analysis shows that changing the number of cask movements to 4 per year results in a respective 42% and 43% drop in the total peak and average public risks for all accidents analysed. The NNR risk limits are well met. It is observed that even though the number of cask movements has been reduced, thereby reducing the frequency of the accident; this accident still contributes over 99% to the overall average public risks. This accident dominates the risk since the source term considers a conservative SFP radionuclide inventory for the consequence calculations.

The annual peak and average public risks to the station for the cask loading phase is shown below:

Table 65: Annual Public Risks to the Station for the Cask Loading Phase - 4 Cask Movements Per Year

Criteria	Annual Risk (Station)	% of NNR Criteria
Peak Public Risk (fatalities/year)	1.42E-08	0.28%
Average Public Risk (fatalities/person/year) - Using 2008 National Population	3.26E-10	3.26%
Average Public Risk (fatalities/person/year) - Using 2025 National Population	7.49E-10	7.49%

6.3.1.2 Twelve (12) Cask Movements Per Year

The table below shows the impact on the peak and average public risks for all casks accidents when the number of cask movements is 12 per year for the cask drop with SFP Liner Break accident only.

Table 66: Peak and Average Public Risks for 12 Cask Movements Per Year

Release Category	Frequency	Average Public Conditional Risk	Average Public Risk	% Risks	Peak Public Conditional Risk	Peak Public Risk	% Risks
Cask Loading Error	1.02E-06	3.97E-10	4.05E-16	0.00%	1.78E-07	1.82E-13	0.00%
Cask Drop	2.80E-06	6.54E-12	1.83E-17	0.00%	2.91E-09	8.14E-15	0.00%
Cask Drop with SFP Liner Break	**3.84E-07**	**2.54E-03**	**9.77E-10**	**99.89%**	**1.11E-01**	**4.27E-08**	**98.42%**
Cask Seal Failure	2.24E-02	1.84E-13	4.11E-15	0.00%	1.67E-10	3.73E-12	0.01%
Aircraft Crash - Fire	8.91E-08	1.25E-05	1.11E-12	0.11%	7.63E-03	6.80E-10	1.57%
TOTAL (2008)	***2.24E-02***	***2.56E-03***	***9.78E-10***	***100.00%***	***1.19E-01***	***4.34E-08***	***100.00%***
TOTAL (2025)*			***2.25E-09***				
NNR Criteria			**1.00E-08**			**5.00E-06**	
% of NNR Criteria (2008)			**9.78%**			**0.87%**	
% of NNR Criteria (2025)			**22.50%**				

* 2008 average public risk scaled by 2.3 to be representative of the year 2025 (see Section 1.4.2.2.3).

The above analysis shows that changing the number of cask movements to 12 per year results in a 70% and 71% increase in total peak and average public risks respectively. However, the NNR risk limits are still met for all cask accidents analysed.

The annual peak and average public risk to the station for the cask loading phase is shown below:

Table 67: Annual Public Risk to the Station for Cask Loading Phase - 12 Cask Movements Per Year

Criteria	Annual Risk (Station)	% of NNR Criteria
Peak Public Risk (fatalities/year)	4.27E-08	0.85%
Average Public Risk (fatalities/person/year) - Using 2008 National Population	9.77E-10	9.77%
Average Public Risk (fatalities/person/year) - Using 2025 National Population	2.25E-09	22.47%

PAIA section 44 (2)a. Redacted information could jeopardise effectiveness of testing procedure if disclosed

PAIA section 44 (2)a.Redacted information could jeopardise effectiveness of testing procedure if disclosed

6.3.3 Sensitivity Analysis Varying the Cask Drop Height

The sensitivity analysis for varying the cask drop height from 9 m to 20 m required that the percentage of cladding failure be adjusting from 0.02% to 100% [4] respectively. Table 69 shows the final release fraction used for the sensitivity analyses.

Table 69: Total Activity Released to Atmosphere for a 20 m Cask Drop inside the SF Building (No SFP Liner Break)

Radionuclide Group No.	Nuclide	Cask Initial Inventory for 10 Year Old Fuel (Bq)	Total Release Fraction	Total Activity Released to Atmosphere (Bq)
1	H-3	2.19E+14	2.57E-01	5.62E+13
	Kr-85	3.63E+15		9.32E+14
2	I-129	2.56E+10	4.70E-02	1.20E+09
3	Cs-134	5.30E+15	6.84E-05	3.63E+11
	Cs-135	4.22E+11		2.88E+07
	Cs-137	6.88E+16		4.71E+12
4	Ag-108m	8.49E+09	1.41E-05	1.20E+05
	Ag-110	2.15E+09		3.04E+04
	Ag-110m	1.59E+11		2.24E+06
	Am-241	1.63E+15		2.30E+10
	Am-242	1.37E+13		1.94E+08
	Am-242m	1.37E+13		1.94E+08
	Am-243	2.77E+13		3.91E+08
	Be-10	4.45E+06		6.28E+01
	Ce-144	1.04E+14		1.47E+09
	Cm-242	1.13E+13		1.60E+08
	Cm-243	2.53E+13		3.57E+08
	Cm-244	2.88E+15		4.06E+10
	Cm-245	4.82E+11		6.79E+06
	Cm-246	1.31E+11		1.85E+06
	Cm-247	8.71E+05		1.23E+01

Radionuclide Group No.	Nuclide	Cask Initial Inventory for 10 Year Old Fuel (Bq)	Total Release Fraction	Total Activity Released to Atmosphere (Bq)
	Cm-248	4.98E+06		7.03E+01
	Co-58	2.68E-01		3.77E-06
	Co-60	1.61E+14		2.27E+09
	Eu-152	4.05E+12		5.71E+07
	Eu-154	4.78E+15		6.73E+10
	Eu-155	1.86E+15		2.62E+10
	Fe-55	1.87E+13		2.64E+08
	Hf-175	2.33E-03		3.29E-08
	Hf-182	4.38E+05		6.18E+00
	Mn-54	1.85E+10		2.60E+05
	Mo-93	3.69E+09		5.21E+04
	Na-22	2.78E-05		3.92E-10
	Nb-92	1.26E+05		1.77E+00
	Nb-93m	3.42E+12		4.82E+07
	Nb-94	1.04E+11		1.47E+06
	Nb-95	2.02E+01		2.85E-04
	Nb-95m	1.08E-01		1.53E-06
	Ni-59	2.26E+11		3.19E+06
	Ni-63	3.02E+13		4.26E+08
	Np-237	3.37E+11		4.76E+06
	Np-238	6.18E+10		8.71E+05
	Np-239	2.77E+13		3.91E+08
	P-32	1.46E+03		2.05E-02
	Pm-147	7.48E+15		1.06E+11
	Po-210	3.12E+04		4.39E-01
	Pu-236	1.75E+11		2.47E+06
	Pu-238	3.54E+15		4.99E+10
	Pu-239	2.30E+14		3.24E+09
	Pu-240	2.63E+14		3.71E+09
	Pu-241	7.40E+16		1.04E+12
	Pu-242	1.72E+12		2.42E+07
	Ra-226	2.08E+05		2.94E+00
	Re-188	1.47E-03		2.07E-08
	Sb-124	5.89E-04		8.31E-09
	Sb-125	5.22E+14		7.36E+09
	Sb-126	6.14E+10		8.66E+05
	Sc-46	7.40E-02		1.04E-06
	Si-32	1.46E+03		2.05E-02
	Ta-182	5.01E+05		7.06E+00
	Tc-99	1.03E+13		1.45E+08
	Te-125m	1.28E+14		1.80E+09
	Te-127	8.67E+05		1.22E+01

Radionuclide Group No.	Nuclide	Cask Initial Inventory for 10 Year Old Fuel (Bq)	Total Release Fraction	Total Activity Released to Atmosphere (Bq)
	Te-127m	8.84E+05		1.25E+01
	U-234	7.65E+11		1.08E+07
	U-235	1.10E+10		1.56E+05
	U-238	1.69E+11		2.39E+06
	W-181	4.40E+03		6.21E-02
	W-185	3.77E-01		5.31E-06
	Y-90	4.72E+16		6.66E+11
	Y-91	1.55E-01		2.19E-06
	Zn-65	8.57E+06		1.21E+02
	Zr-93	1.05E+12		1.47E+07
	Zr-95	9.19E+00		1.30E-04
5	Ru-106	4.46E+14	9.40E-05	4.20E+10
	Sr-89	1.41E-04		1.32E-08
	Sr-90	4.72E+16		4.44E+12

Table 70 shows the impact on the peak and average public risks for all cask accidents when the cask drop height is assumed to be 20 m.

Table 70: Peak and Average Public Risks for a 20 m Cask Drop Accident

Cask Accident	Frequency	Average Public Conditional Risk	Average Public Risk	% Risks	Peak Public Conditional Risk	Peak Public Risk	% Risks
Cask Loading Error	1.02E-06	3.97E-10	4.05E-16	0.00%	1.78E-07	1.82E-13	0.00%
Cask Drop (20m)	**2.80E-06**	**3.27E-08**	**9.15E-14**	**0.02%**	**1.45E-05**	**4.07E-11**	**0.16%**
Cask Drop with SFP Liner Break	2.24E-07	2.54E-03	5.70E-10	99.79%	1.11E-01	2.49E-08	97.17%
Cask Seal Failure	2.24E-02	1.84E-13	4.11E-15	0.00%	1.67E-10	3.73E-12	0.01%
Aircraft Crash - Fire	8.91E-08	1.25E-05	1.11E-12	0.19%	7.63E-03	6.80E-10	2.65%
TOTAL (2008)	***2.24E-02***	***2.56E-03***	***5.71E-10***	***100.00%***	***1.19E-01***	***2.56E-08***	***100.00%***
TOTAL (2025)*			***1.31E-09***				
* 2008 average public risk scaled by 2.3 to be representative of the year 2025 (see Section 1.4.2.2.3).							
NNR Criteria			**1.00E-08**			**5.00E-06**	
% of NNR Criteria (2008)			**5.71%**			**0.51%**	
% of NNR Criteria (2025)			**13.14%**				

Although the consequence of the cask drop accident has increased due to the increase in the percentage of rod cladding failure, the cask drop accident contribution remains below 1.00% to the overall peak and average public risks for cask accidents. The Cask Drop with

SFP Liner Break accident still remains the dominant contributor to the overall peak and average public risks.

Therefore, varying the cask drop height from 9 m to 20 m has no significant impact and the overall peak and average public risks are well within the NNR risk limits for all cask accidents.

Table 71 shows the impact on the peak and average site personnel risks for all cask accidents when the cask drop height is assumed to be 20 m.

Table 71: Peak and Average Site Personnel Risks for a 20 m Cask Drop Accident

Cask Accident	Frequency	Average Site Pers. Conditional Risk	Average Site Personnel Risk	% Risks	Peak Site Pers. Conditional Risk	Peak Site Personnel Risk	% Risks
Cask Loading Error	1.02E-06	2.67E-03	2.73E-09	0.82%	4.46E-02	4.54E-08	4.39%
Cask Drop (20m)	**2.80E-06**	**1.50E-02**	**4.20E-08**	**12.59%**	**2.50E-01**	**7.00E-07**	**67.67%**
Cask Drop with SFP Liner Break*	2.24E-07	1.21E-01	2.71E-07	81.21%	1.21E-01	2.71E-07	26.20%
Cask Seal Failure	7.76E-05	3.54E-07	2.75E-11	0.01%	1.77E-04	1.37E-08	0.00%
Aircraft Crash - Fire*	8.91E-08	2.02E-02	1.80E-08	5.38%	2.02E-02	1.80E-08	1.74%
TOTAL	***8.17E-05***	***1.59E-01***	***3.34E-07***	***100.00%***	***4.36E-01***	***1.03E-06***	***100.00%***
* Scaling of the peak and average site personnel risks by a factor of 10 are included.							
NNR Criteria			**1.00E-05**			**5.00E-05**	
% of NNR Criteria			**3.34%**			**2.07%**	

The 20 m cask drop accident dominates the peak site personnel risks (approximately 68% contribution) due to the increase in the conditional mortality risks from assuming 100% fuel cladding failure during a cask drop accident inside the spent fuel building. The cask drop with SPF liner break accident dominates the average site personnel risk (81% contribution).

Therefore, varying the cask drop height from 9 m to 20 m has no significant impact, and the overall peak and average site personnel risks remain within the NNR risk limits for all cask accidents.

6.3.4 Recommendations

The cask risk assessment for the dry cask storage system has shown that the peak and average public and site personnel risks from all cask accidents are acceptable for the key assumptions used in this study and meet the NNR risk limits set out in RD-0024 [1].

The dominant contributor to the average and peak public and site personnel risks is the Cask Drop with SFP Liner Break accident. Thus, cask rigging operations are critical to nuclear safety and need to be appropriately controlled.

A sensitivity case for increasing the number of cask movements to 12 per year for the cask drop with SPF liner break accident only demonstrated that increasing the number of cask movements per year has an impact on the risk and must be minimised. The NNR risk limits are still met for all cask accidents analysed.

PAIA section 44 (2)a.Redacted information could jepoardise effectiveness of testing procedure if disclosed

The sensitivity results for varying the cask drop height shows a shift in the dominant contributor to the peak site personnel risk from the cask drop with SFP Liner Break accident to the 20 m cask drop accident due to the increase in site personnel conditional mortality risks (100% fuel cladding failure assumed). All NNR risk limits are still met for all cask accidents analysed.

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8 JUSTIFICATION

Revision 0: This is a new study for the probabilistic risk assessment of additional metal casks for the Koeberg Nuclear Power Station.

Revision 1: A sensitivity analysis for varying the cask drop (no SFP Liner Break) height to 20 m was added as Section 6.3.2 of the report.

Appendix H was added for the assessment of additional Concrete Casks.

Revision 2: This study estimates 5115 spent FAs will be generated until 2045 (with TPU).
The HOLTEC HI-STAR 100 is the chosen design for the 7 new metal casks to be procured with a capacity of 32 spent FAs.
The number of cask movements was revised to 6 cask movements per year.
The TISF design was revised to be a concrete pad with security fencing.
Appendix H: Concrete Cask PSA was revised for a concrete cask capacity of 37 spent FAs.
Initiating Event Frequencies were revised.

Revision 2a: The number of cask movements was revised to 7 cask movements per year.
The methodology for calculation the inhalation doses for the site personnel risk was revised to use the database of ICRP Publication 68 Dose Conversion Factors extracted from Radiological Toolbox, Version 3.0.
The pool decontamination factors values for Iodine used in Appendix G for FHA during cask loading inside the Spent Fuel Building were corrected.
The occupancy factor was only applied to the site personnel when calculating the cask seal failure frequency.
A sensitivity analysis for varying the overall cask drop frequency based on NUREG-1738 was added.
The frequency for the 20 m cask drop accident was revised. An error was corrected in the site personnel conditional risk mortality calculation.
Comments received from NNR letter k25189N were addressed.
General editorial improvements were addressed.

Revision 3: Initiating Event Frequencies for cask loading error accident, cask drop accident and seal failure accidents were improved and revised.
The calculation of the peak risk for site personnel involved in cask handling activities was revised to consider the fact that fuel handlers/shift supervisors are only involved in ¼ of the fuel/cask handling activities.
Screening of SGZ plant included in Appendix A.
As per the NNR accepted interim arrangement for addressing the use of outdated population data in PSA Level 3 studies described in memo PSA21-0001 [72], the average public risk is revised to be based on the 2008 total national population (instead of 2011) and is further also determined for the year 2025 by applying an additional scaling by a factor of 2.3.
General editorial improvements were addressed.

Revision 4: Improved Section 1.4.2.2.4 to clarify that the scaling factor of 10 to the peak and average risks to site personnel from accidents related to releases from cask drop with SFP liner break and aircraft crash induced accidents, as proposed in PSA-R-T18-03 [73] and accepted by the NNR in letter k27997N

[74] were applied in the present report. Furthermore, the peak and average site personnel risk results for cask drop with SFP liner break and aircraft crash induced fire accidents presented in Sections 5.2.2 and 5.4.1 respectively were adjusted accordingly.

9 APPENDIX A

Appendix A contains the following information:

- Table A1: Internal Events Requiring Consideration
- Table A2: External Events Requiring Consideration

Table A1: Internal Events Requiring Consideration

No.	Event	Description	Exclusion Criteria	Remarks
1	Loading error - wrong assemblies placed into cask	Cask loading error. Wrong assemblies placed into cask.	Not excluded	Needs further consideration.
2	Loading error - high burnup or short storage	The loading of fuel with inappropriate burnup or fuel that has been left to cool for too short a time	4	The inadvertent loading of fuel assemblies who has the incorrect burnup or incorrect age is considered in "Loading error - wrong assemblies placed into cask"
3	Loading error - wrong poison	Loading error - wrong poison	1, 4	The current design of the casks operated at Koeberg do not employ the use of poisons to control reactivity of the casks. [Ref. 5]
4	Overall Cask Drop	All the various modes by which a cask could drop.	Not excluded	This must be considered. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
5	Drop into spent fuel pool	Cask drop into spent fuel pool	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
6	Drop while moving to preparation area	Cask drop while moving to preparation area	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
7	Tip-over before sealing	Cask tip-over before sealing	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
8	Drop while moving to equipment hatch	Cash drop while moving to equipment hatch	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.

9	Drop while moving through containment to transport area	Cask drop while moving through containment to transport area	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
10	Drop while moving from preparation area to containment boundary	Cask drop while moving from preparation area to containment boundary	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
11	Drop from poor rigging	Cask drop from poor rigging	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
12	Drop from performing minor maintenance while load in motion	Cask drop from performing minor maintenance while load in motion	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
13	Drop from operating crane without proper authorization or signals	Cask drop from operating crane without proper authorization or signals	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
14	Drop from failure of defective boom, cable or sheaves	Cask drop from failure of defective boom, cable or sheaves	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
15	Drop from crane failure due to over loading	Cask drop from crane failure due to over loading	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.

16	Drop from handling load near stationary equipment	Cask drop from handling load near stationary equipment	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
17	Drop from other causes (control systems failure, skipped maintenance inspections)	Cask drop from other causes (control systems failure, skipped maintenance inspections)	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
18	Drop on to concrete at storage building	Cask drop on to concrete at storage building	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
19	Drop onto asphalt, gravel, soil	Cask drop onto asphalt, gravel, soil	4	The event is included in overall cask drop. The Framatome Cask Handling Crane Risk Analysis [Ref. 1] is used in this analysis as it examines the various credible modes of cask drops and their associated frequencies.
20	Tip-over while moving	Cask tip-over while moving	1	Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] and the casks are transported horizontally in a vehicle where the height from the cask to the ground is much less than 9 m, tip over of the cask is considered to be much less serve than a 9 m vertical drop.
21	Tip-over while moving due to impact on transporter	Cask tip-over while moving due to impact on transporter	1, 4	Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] and the casks are transported horizontally in a vehicle where the height from the cask to the ground is much less than 9 m, tip over of the cask is considered to be much less serve than a 9 m vertical drop. This is also considered in "Tip-over while moving".

22	Tip-over when placing additional cask	Cask tip-over when placing additional cask	1, 4	Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] and the casks are transported horizontally in a vehicle where the height from the cask to the ground is much less than 9 m, tip over of the cask is considered to be much less serve than a 9 m vertical drop. This is also considered in "Tip-over while moving".
23	Transfer events	Accident occurs as a result of moving the casks	4	This is considered in all cask drop and tip over accidents.
24	Storage building structural failure	The cask storage building collapses on the casks and damages the casks.	1	The new casks will be similar to the current transport cask operated by Koeberg. They are designed to deal with 9 m drop (i.e. cask impacting the floor at 47.81 km/h) [Ref. 2]. Thus it is not considered credible that a structural collapse of the storage building could damage the casks.
25	Refuelling building structural failure	The refuelling building collapses on the casks and damages the casks.	1	The new casks will be similar to the current transport cask operated by Koeberg. They are designed to deal with 9 m drop (i.e. cask impacting the floor at 47.81 km/h) [Ref. 2]. Thus it is not considered credible that a structural collapse of the refuelling building could damage the casks.
26	Long term corrosion of storage building	Long term corrosion of storage building	1, 4, 5	The casks do not depend on the storage building to perform their function as a radiological barrier. Collapse of storage building is also considered in “Storage building structural failure”. This is also a relatively slow moving accident with plenty of time to respond.
27	Long term corrosion of cask	Long term corrosion of cask	1, 4, 5	The design of the cask ensures corrosion resistance in the proposed environment. In addition, corrosion inspections are performed under appropriate service notifications [Ref. 4]. This is also a relatively slow moving accident with plenty of time to respond. This event is also scoped by seal leaks.
28	Fire from transport vehicle fuel	Fire from transport vehicle fuel	1	It is not considered credible that a diesel truck can burn violently enough to damage a cask. The casks are transport casks and

				are designed to deal with fire resulting from vehicles [Ref. 6].
29	Fire causes pressurization and differential heating	Fire causes pressurization and differential heating	3	No flammable materials are stored in or adjacent to the TISF. Smoke detectors with remote and local alarms are installed. [Ref. 7]
30	Fire and tip-over from onsite transportation accident causes	Fire and tip-over from onsite transportation accident causes	4	This is considered in “Fire from transport vehicle fuel” and in all “trip-over” accidents.
31	Seal Leaks	Seal Leaks failures	Not excluded	This event must be considered.
32	Loss of shielding integrity	Loss of shielding integrity	4	The main process of loss of shielding integrity is considered in all cask drop, cask tip over, cask corrosion, fire and cask seal leak events.
33	Equipment failure in fuel pool	Equipment failure in fuel pool	1	The casks operate independently of any equipment used by the spent fuel pool.

Table A2: External Events requiring Consideration

No.	External Event	Description	Exclusion Criteria	Remarks
1	Tip-over due to high wind	Tip-over due to high wind	1	Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] a tip over of the cask from a height much less than 9 m is considered to be much less serve.
2	Tip-over due to high water	Tip-over due to high water	1	Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] a tip over of the cask from a height much less than 9 m is considered to be much less serve.
3	Tip-over due to tsunami	Tip-over due to tsunami	4, 1	(a) This is considered in Tip-over due to high water (b) In the Fukushima tsunami event, the cask storage building was damaged by flood water and the some of the casks got wet, however none of them moved from their horizontal position or were damaged.
4	Tip-over due to soil settling/erosion	Tip-over due to soil settling/ erosion	4, 1, 5, 6	(a) This event is included in the considerations of other "tip over" accidents. (b) Since the casks are designed to withstand a 9 m vertical drop [Ref. 3] a tip over of the cask from a height less than 9 m is considered to be much less severe. (c) Erosion is a process which occurs over an extended time period, allowing sufficient time to detect and remedy the issue. (d) Regular surveys have indicated that no long-term erosion or accretion of the beach or seabed in the vicinity of the cooling water intake basin has occurred, except for the need to carry out minor erosion damage repair on the south side of the basin. The programme of ongoing surveys will continue. Coastal erosion can also be caused by scouring action during a flooding event. In this case the erosion would be rapid and not allow enough time to detect or remedy the damage. However, the plant is protected from scouring by the intake basin walls, providing a relatively sheltered harbour for the SEC and CRF inlets. Scouring outside the intake basin would not affect the safety systems of the plant and TISF is to be located north of the Low level Waste Building will not be affected by soil erosion. [Ref. 8]
5	Seismic events	Seismic events	1	(a) Post Fukushima, nuclear utilities worldwide are considering the option to move spent fuel out of SFPs into dry storage. In the 2011 accident, the Fukushima Daiichi plant experienced peak seismic accelerations of 0.561g (~26% higher than the design basis acceleration of 0.447g) in Unit 2. This was a result of a massive earthquake measuring 9.0 on the Richter scale that occurred 180km from the location of the plant. The severe challenges experienced at the plant were not applicable to the casks as cooling of the casks is via natural convection; shielding and containment of the fuel is provided by the casks and the storage building; lastly no water is required to cool the fuel. The negative impact from LOSP was the loss of monitoring of the casks. In Fukushima, the cask storage building was damaged by the tsunami and some of the casks got wet. However, none of the 9 metal casks were moved from their horizontal positions or were damaged by the accident. [Ref.4] (b) It is estimated that at Koeberg, for an extreme earthquake of 0,55g; the casks would move a maximum of 1m horizontally and 100mm vertically. The casks would therefore be able to withstand conditions similar to those experienced in Fukushima. [Ref. 4]. (b) The proposed design of the concrete slab for the TISF is based on the Paul C. Rizzo (PCR) 0.5g response spectra for beyond design basis and a PGA = 0.5g was used as an input for the seismic loading calculations [14].

6	Ground vehicle impact on storage vault	Ground vehicle impact on storage vault	1	The casks are designed to withstand a 9 m drop which corresponds to an impact velocity of 47.81 km/hr [Ref. 2]. The ground vehicle speed limit is 35 km/h on site and therefore a collision into the TISF or the cask will not affect the integrity of the cask.
7	Wind/flood driven objects	Wind/flood driven objects	1	The Castor X/28F is a heavy transport cask that is designed to deal with a 9 m vertical drop onto concrete which corresponds to a 47.81 km/h impact into a concrete barrier during transport [Ref. 2]. This is a large momentum and it is therefore not considered possible that wind or water can drive an object into the TISF with equal or greater momentum.
8	Meteorite Strikes	Meteorite Strikes	6	An American National Standard [Ref. 10] states that this event can be screened out as all sites have approximately the same very low frequency.
9	Intense precipitation	Rain, hail, sleet, snow, dew, etc. basically any form of water that falls or condenses onto the ground	1, 4	(a) The Castor X/28F is a heavy transport cask that is designed to deal with a 9 m vertical drop onto concrete which corresponds to a 47.81 km/h impact into a concrete barrier during transport [Ref. 2]. This is a large momentum and it is therefore not considered credible that any form of precipitation could compromise it's integrity. (b) This event is bounded by tip over due to high water. (c) The cask design does not have vent holes or heat exchanger fins that could get blocked by hail, snow, etc. (d) LOPP 066 ensures that the operability of the ventilation system of the storage building throughout the storage period is checked. (e) Upon failure of the ventilation system, the operator is prompted to opens the roof louvers and door of the cask storage building. (f) It is not considered credible that fuel melt will occur with complete loss of natural ventilation (forced ventilation is not part of the cask design).
10	Hail	Hail	4	This event is included in intense precipitation.
11	Light aircraft	Light aircraft	1	It was determined that none of the sensitive buildings would be impacted by a light aircraft or helicopter crash, but all other aircraft categories are liable to penetrate any building at the time of the impact. [Ref. 2]
12	Heavy aircraft	Heavy aircraft	Not excluded	This event requires further investigation.
13	Flying vehicles impact cask	Flying vehicles impact cask	4	This event is bounded by all aircraft crash events.
14	Strikes from heavy objects	Strikes from heavy objects	4, 3	(a) This event is bounded by vehicle impacts, meteorite strikes, aircraft crashes, hail, wind and water driven objects (b) The rotational axes of the Koeberg turbines are such that any fragments generated during a turbine disintegration accident will be thrown in the east and west directions. Since the first and second choice for the TISF is north and south, respectively, of the turbine hall, any turbine generated missiles (turbine disc fragments or blades) are not expected to reach the TISF.
15	Fire or explosion from storage tanks	Fire or explosion from storage tanks	3	Although there is a likelihood of a hydrogen explosion at the SHY plant, the shock waves from the explosion are not expected to affect the TISF or the integrity of the casks due to its location. Even the diesels which are closer to the SHY plant are expected to survive a hydrogen explosion.

				The hydrogen gas production and storage plant (SGZ plant) is located on the alternate haul path however they have a direct line of sight to the Unit 2 fuel building entrance and could pose a hazard during transfer of casks if this path is used [15]. The hydrogen storage vessels in the SGZ plant merely rest on narrow plinths with no secure connection (there is a light connection for electrical earthing purposes). Thus, if a significant earthquake occurs, these vessels may move off their plinths. If this occurs, there may be damage to pipes and concomitant hydrogen leaks. This may result in a hydrogen fire and possibly in a hydrogen explosion. Assuming, that a 0.1 g earthquake can move the hydrogen storage vessels off their plinths, we can obtain from the Dames & Moore hazard curve an annual frequency of exceedance of such earthquakes. This can be scaled assuming that the casks will be in danger for 3 minutes (discussion between E. Lamprecht and M. Makhothe) to obtain a probability of a cask movement due to the force experienced from the explosion hazard. Therefore, the probability of a co-incident cask movement and >0.1g earthquake together with the cask being in range of an explosion hazard is approximately 1.73E-8 ((0.05/8760) × 3.03E-03) for each cask handled at Unit 2. Considering that the consequences and frequency of a cask movement due to explosion hazard is much less severe than a cask drop accident this event is scoped under the cask drop accident and is screened out.
16	Fire or explosions from transformers	Fire or explosions from transformers	3	On-site sources of potential pressure waves that were investigated include diesel and petrol storage and filling, gas storage and filling, hydrogen production plant, chlorination plant, and generator and Unit HV transformers. It was found that none of these, with the possible exception of the hydrogen production plant, could explode with a resulting blast wave that would affect facilities on the Koeberg site. [Ref. 10]
17	Fire or explosions from nearby barge or ship	Fire or explosions from nearby barge or ship	3	The intake basin is shallow and a large ship or oil tanker cannot get close enough for a shock wave from an explosion to affect the integrity of the casks.
18	Fire or explosions from nearby trucks or railcars	Fire or explosions from nearby trucks or railcars	3	(a) On-site sources of potential pressure waves that were investigated include diesel and petrol storage and filling, gas storage and filling, hydrogen production plant, chlorination plant, and generator and Unit HV transformers. It was found that none of these, with the possible exception of the hydrogen production plant, could explode with a resulting blast wave that would affect facilities on the Koeberg site. [Ref. 10] (b) Off-site accidents include pressure waves from road accidents involving the transportation of explosives or hazardous chemicals. Petroleum tankers frequently use the R27 as well. A blast wave resulting from a tanker accident and a subsequent probable explosion will have no effect on the sensitive plant buildings. Thermal effects from such an accident will have significant localised impact in the immediate vicinity of the accident, but none at all within ACP1. [Ref. 10] (c) No railroad or railcars exists in the vicinity of the TISF.
19	Fire or explosions from military missile	Fire or explosions from military missile	2	The event of an externally generated missile impacting a sensitive building is bounded by an aircraft crash into a sensitive building.

20	Fire or explosions from other facilities	Fire or explosions from other facilities	3	Industrial areas surrounding KNPS include: Atlantis Industrial Areas (10 km NNE), Montague Gardens (22 km SSE), Metro/Paardeneiland (25 km S), Maitland/N'dabeni (28 km SSE), Epping (30 km SSE), Vredenburg/ Saldanha (85 – 95 km NNW), Marconi Beam (22 km SSE of KNPS),Killarney Gardens (29 km SSE) and Doornbach Industrial Area (18 km SSE) [Ref. 10]. The scenario of an explosion at one of these facilities is scoped by an explosion at Atlantis, which is the closest and one of the largest industrial areas (second only to Epping Industrial Area). The magnitude of a source 10 km from the existing Koeberg 900 MW PWR units 1 and 2 (Atlantis) yielding an overpressure of 70 mbar is just over 94 kt TNT equivalent. The value of 94 kt was calculated using the methodology outlined in External Event Risks [Ref. 11]. For perspective, the atomic bomb dropped on Hiroshima was in the order of 20 kt TNT equivalent. Thus, due to the distances of these locations this event is excluded.
21	Explosions	Explosions	4	This event is bounded by all explosion accidents
22	Volcanic activity	Volcanic activity	3	South Africa is volcanically inert, as it does not lie on a tectonic plate boundary where volcanoes are generally found. The nearest active volcano is on Marion Island, off the East Coast of South Africa, where it forms part of the Middle East and Indian Ocean chain of volcanoes. The volcanic islands in the Atlantic Ocean which form near the Mid-Atlantic Ridge define the plate boundary off the West Coast of Africa. [Ref. 9]
23	Vent blockage - loss of cooling	The blocking of vents on the cask and the blocking of the ventilation system of the cask storage building.	1, 5	(a) The cask design does not have vent holes or heat exchanger fins. (b) The storage building ventilation system consists of a louvre system with 4 levels of filtration. It is well designed to protect against intrusion from foreign material. (c) LOPP 066 states that the ventilation system for the cask storage building will be inspected on a monthly basis to ensure the operability of the system. (d) Upon failure of the ventilation system, the operator is prompted to opens the roof louvers and door of the cask storage building. (e) It is not considered credible that fuel melt will occur with complete loss of natural ventilation (forced ventilation is not part of the cask design).
24	Wind carrying dirt and debris	The blocking of vents on the cask and the blocking of the ventilation system of the cask storage building by dirt or debris	1	(a) The cask design does not have vent holes or heat exchanger fins (b) LOPP 066 ensures that the operability of the ventilation system of the storage building throughout the storage period is checked. (c) Upon failure of the ventilation system, the operator is prompted to opens the roof louvers and door of the cask storage building. (d) It is not considered credible that fuel melt will occur with complete loss of natural ventilation (force ventilation is not part of the cask design).
25	Accumulation of snow, dirt or ice on vents	Accumulation of snow, dirt or ice on vents	4	This event is included in intense precipitation and vent blocking.

26	Dirt from landslide / heavy rain	Dirt from landslide / heavy rain	3, 4	(a) The terrain surrounding the Koeberg site is such that a landslide poses no risk. The land around the site is generally flat, broken only by a series of dunes, the highest of which is 10 m [Ref. 12]. (b) Heavy rain is considered in intense precipitation. (c) Dirt blocking the ventilation on the cask and the cask storage building is considered in vent blockage.
27	Dirt from volcano ash deposits	Dirt from volcano ash deposits	4	The event is included in volcanic activity.
28	Biological intrusion into vents	Biological intrusion into vents	4	This event is included in vent blockage.
29	Flood water over vent below storage building	Flood water over vent below storage building	4	This event is included in vent blockage.
30	Flood water cover storage vault	Flood water cover storage vault	1	In the Fukushima tsunami event, the cask storage building was damaged by flood water and some of the casks got wet, however none of them moved from their horizontal position or were damaged by the event. The casks can be recovered from the ocean if submerged.
31	Flood water partially covering the storage vault	Flood water partially covering the storage vault	4	This event is included in flood water covers storage vaults.
32	High ambient temperature causes pressurization	High ambient temperature causes pressurizatio n	1,5	The IAEA transportation standard (TS-R-1) requires that the maximum surface temperature of the casks be 85°C while the maximum ambient temperature be 38°C. The temperature limits were established to ensure that even maximum heat load will be dissipated without affecting the contents, shielding and the confinement of the casks. The ambient temperature in the TISF is controlled via a ventilation system. The ambient and surface temperature of the casks are monitored and recorded daily and thus far are well below the 85°C and 38°C thresholds, respectively.
33	Lightning	Lightning	1	Lightning cannot damage the fuel in the cask due to the Faraday Cage effect in which electricity does not enter a conductor but rather travels along the surface. This is due to the fact that electric flux does not exist inside a closed structure.
34	Fire (external) causes pressurization and differential heating	Fire (external) causes pressurizatio n and differential heating	3	No flammable materials are stored in or adjacent to the TISF. Smoke detectors with remote and local alarms are installed.
35	Fire from a gas main	Fire from a gas main	3	There is no gas extraction in the vicinity of the TISF.

36	Forest fire	Fire from a gas main	3	The land within the 5 km radius from the Koeberg site is predominantly covered by bare sand, shrubland and thicket [Ref: Koeberg Site Safety Report, Part II, Chapter 4 Section 3]. The nature reserve area is characterised by mainly the Atlantis Sand Fynbos and the Cape Flats Dune Strandveld. Both the fynbos and strandveld are fire prone and are subject to fire management. Therefore firebreaks are well defined and there are water points for fire fighting appliances [Ref. 13] Also, the area surrounding the casks is clear of vegetation and a veld fire could not spread close enough to this area to affect the casks.

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12	Koeberg Site Safety Report, Part II, Chapter 2 Section 2.2
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14	NSE, Transient Interim Cask Storage Facility, JN683-NSE-ESKB-R-6570, Rev B, May 2016
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Cask Loading Human Reliability Assessment Workshop
Attendance List
Held on Mon, 07-Apr-2014

Name	Subject Matter	Contact	Signature
Lindley Perryman	Corporate Consultant	(021) 550-4657	
Herman Bosman	Fuel Handling	(021) 550-5448	
Judith Ncapayi	Fuel Handling	(021) 550-5645	
Danette Moller	Human Reliability	(021) 550-5512	
Thavy Krishna	Cask Risk Assessment	(011) 800-2589	
Avinash Rajkumar	Cask Risk Assessment	(021) 550-5429	

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14 APPENDIX F

Appendix F contains the following information:

- PC COSYMA Risk Results

  The headings in the tables refer to the following accidents:

  MC_LOAD1: Cask Loading Error
  MC_SFB1: Cask Drop
  MC_SFPL1: Cask Drop with SFP Liner Break
  MC_SEAL1: Cask Seal Failure
  MC_FIRE1: Heavy Aircraft Crash Induced Fire impacting TISF

Table F1: Mean Short Term Individual Dose (Sievert) for MC_LOAD1 – 30 Days

Distance (km)	Effective	Thyroid	Eye Lens	Ovaries	Skin	Lung	B Marrow	GI-Tract
0.5	9.70E-06	4.17E-06	2.02E-06	1.70E-06	4.36E-05	6.22E-05	2.02E-06	6.94E-06
1.75	1.40E-06	6.10E-07	3.54E-07	2.87E-07	5.76E-06	8.64E-06	3.39E-07	1.01E-06
3.75	3.91E-07	1.75E-07	1.13E-07	8.96E-08	1.50E-06	2.34E-06	1.06E-07	2.85E-07
6.25	1.96E-07	8.70E-08	6.12E-08	4.75E-08	7.07E-07	1.15E-06	5.60E-08	1.44E-07
8.75	1.29E-07	5.53E-08	4.01E-08	3.09E-08	4.55E-07	7.57E-07	3.66E-08	9.44E-08
11.25	5.71E-08	2.83E-08	2.13E-08	1.64E-08	1.92E-07	3.14E-07	1.90E-08	4.24E-08
13.75	4.69E-08	2.21E-08	1.62E-08	1.25E-08	1.62E-07	2.65E-07	1.47E-08	3.46E-08
16.25	3.80E-08	1.77E-08	1.31E-08	1.01E-08	1.30E-07	2.15E-07	1.18E-08	2.81E-08
18.75	3.06E-08	1.40E-08	1.05E-08	8.08E-09	1.04E-07	1.74E-07	9.48E-09	2.26E-08
21.25	2.65E-08	1.13E-08	8.12E-09	6.34E-09	9.34E-08	1.56E-07	7.47E-09	1.94E-08
23.75	2.26E-08	9.53E-09	6.84E-09	5.33E-09	8.04E-08	1.34E-07	6.29E-09	1.66E-08
26.25	2.07E-08	8.83E-09	6.46E-09	5.05E-09	7.21E-08	1.21E-07	5.93E-09	1.52E-08
28.75	1.90E-08	8.59E-09	6.44E-09	5.07E-09	6.44E-08	1.08E-07	5.89E-09	1.41E-08
31.25	1.75E-08	8.60E-09	6.69E-09	5.32E-09	5.58E-08	9.48E-08	6.07E-09	1.31E-08
33.75	1.48E-08	6.97E-09	5.33E-09	4.21E-09	4.86E-08	8.23E-08	4.85E-09	1.10E-08
36.25	1.29E-08	5.44E-09	3.98E-09	3.10E-09	4.50E-08	7.57E-08	3.65E-09	9.44E-09
38.75	1.42E-08	5.66E-09	4.11E-09	3.18E-09	5.04E-08	8.53E-08	3.79E-09	1.04E-08
41.25	1.72E-08	6.49E-09	4.85E-09	3.74E-09	5.97E-08	1.04E-07	4.47E-09	1.25E-08
43.75	1.88E-08	6.93E-09	5.29E-09	4.07E-09	6.46E-08	1.14E-07	4.88E-09	1.37E-08
46.25	1.58E-08	5.93E-09	4.50E-09	3.47E-09	5.44E-08	9.56E-08	4.15E-09	1.15E-08
48.75	1.23E-08	4.72E-09	3.55E-09	2.75E-09	4.26E-08	7.41E-08	3.27E-09	9.00E-09
51.25	8.91E-09	3.45E-09	2.59E-09	2.00E-09	3.07E-08	5.34E-08	2.38E-09	6.50E-09
53.75	7.43E-09	2.87E-09	2.15E-09	1.66E-09	2.57E-08	4.46E-08	1.98E-09	5.42E-09
56.25	7.03E-09	2.74E-09	2.07E-09	1.60E-09	2.41E-08	4.20E-08	1.90E-09	5.14E-09
58.75	7.04E-09	2.79E-09	2.15E-09	1.67E-09	2.37E-08	4.16E-08	1.97E-09	5.16E-09

Table F2: Mean Short Term Individual Dose (Sievert) for MC_SFB1 – 30 Days

Distance (km)	Effective	Thyroid	Eye Lens	Ovaries	Skin	Lung	B Marrow	GI-Tract
0.5	7.66E-08	7.29E-09	5.79E-09	6.17E-09	7.41E-07	5.77E-07	1.11E-08	1.14E-08
1.75	1.07E-08	1.14E-09	9.25E-10	9.56E-10	1.02E-07	7.97E-08	1.65E-09	1.67E-09
3.75	2.89E-09	3.30E-10	2.72E-10	2.76E-10	2.74E-08	2.14E-08	4.62E-10	4.69E-10
6.25	1.42E-09	1.65E-10	1.37E-10	1.38E-10	1.34E-08	1.05E-08	2.30E-10	2.34E-10
8.75	9.31E-10	1.05E-10	8.62E-11	8.77E-11	8.86E-09	6.91E-09	1.48E-10	1.51E-10
11.25	3.93E-10	5.59E-11	4.77E-11	4.63E-11	3.63E-09	2.85E-09	7.16E-11	7.21E-11
13.75	3.30E-10	4.29E-11	3.62E-11	3.57E-11	3.09E-09	2.41E-09	5.69E-11	5.78E-11
16.25	2.68E-10	3.45E-11	2.90E-11	2.87E-11	2.51E-09	1.96E-09	4.59E-11	4.67E-11
18.75	2.15E-10	2.73E-11	2.30E-11	2.28E-11	2.02E-09	1.58E-09	3.66E-11	3.74E-11
21.25	1.93E-10	2.26E-11	1.88E-11	1.89E-11	1.83E-09	1.43E-09	3.13E-11	3.22E-11
23.75	1.65E-10	1.89E-11	1.56E-11	1.58E-11	1.57E-09	1.23E-09	2.64E-11	2.73E-11
26.25	1.50E-10	1.81E-11	1.51E-11	1.52E-11	1.42E-09	1.11E-09	2.48E-11	2.55E-11
28.75	1.36E-10	1.90E-11	1.61E-11	1.58E-11	1.26E-09	9.88E-10	2.45E-11	2.49E-11
31.25	1.22E-10	2.10E-11	1.83E-11	1.73E-11	1.09E-09	8.59E-10	2.51E-11	2.51E-11
33.75	1.05E-10	1.61E-11	1.39E-11	1.33E-11	9.55E-10	7.49E-10	2.00E-11	2.02E-11
36.25	9.38E-11	1.10E-11	9.10E-12	9.18E-12	8.89E-10	6.93E-10	1.52E-11	1.58E-11
38.75	1.05E-10	1.09E-11	8.83E-12	9.15E-12	1.01E-09	7.83E-10	1.59E-11	1.67E-11
41.25	1.27E-10	1.26E-11	1.01E-11	1.06E-11	1.23E-09	9.53E-10	1.88E-11	1.98E-11
43.75	1.40E-10	1.37E-11	1.09E-11	1.15E-11	1.35E-09	1.05E-09	2.05E-11	2.18E-11
46.25	1.17E-10	1.18E-11	9.46E-12	9.90E-12	1.13E-09	8.79E-10	1.75E-11	1.85E-11
48.75	9.11E-11	9.39E-12	7.61E-12	7.90E-12	8.75E-10	6.81E-10	1.38E-11	1.45E-11
51.25	6.56E-11	6.86E-12	5.57E-12	5.77E-12	6.30E-10	4.90E-10	1.00E-11	1.06E-11
53.75	5.48E-11	5.66E-12	4.59E-12	4.76E-12	5.26E-10	4.09E-10	8.30E-12	8.77E-12
56.25	5.17E-11	5.50E-12	4.48E-12	4.62E-12	4.95E-10	3.86E-10	7.95E-12	8.40E-12
58.75	5.14E-11	5.85E-12	4.82E-12	4.90E-12	4.90E-10	3.81E-10	8.21E-12	8.64E-12

Table F3: Mean Short Term Individual Dose (Sievert) for MC_SFPL1 – 30 Days

Distance (km)	Effective	Thyroid	Eye Lens	Ovaries	Skin	Lung	B Marrow	GI-Tract
0.5	3.20E+01	6.52E+01	2.89E+01	2.86E+01	1.13E+03	3.11E+01	2.96E+01	2.84E+01
1.75	4.94E+00	9.47E+00	4.54E+00	4.44E+00	1.63E+02	4.84E+00	4.60E+00	4.41E+00
3.75	1.47E+00	2.68E+00	1.37E+00	1.33E+00	4.56E+01	1.45E+00	1.38E+00	1.32E+00
6.25	6.88E-01	1.18E+00	6.53E-01	6.24E-01	1.93E+01	6.83E-01	6.50E-01	6.18E-01
8.75	4.44E-01	7.17E-01	4.31E-01	4.04E-01	1.07E+01	4.44E-01	4.22E-01	3.98E-01
11.25	3.47E-01	5.40E-01	3.40E-01	3.17E-01	7.76E+00	3.48E-01	3.31E-01	3.12E-01
13.75	2.83E-01	4.46E-01	2.72E-01	2.58E-01	7.46E+00	2.83E-01	2.69E-01	2.55E-01
16.25	1.87E-01	2.95E-01	1.79E-01	1.71E-01	4.95E+00	1.87E-01	1.78E-01	1.69E-01
18.75	1.49E-01	2.40E-01	1.41E-01	1.36E-01	4.33E+00	1.48E-01	1.41E-01	1.35E-01
21.25	1.42E-01	2.22E-01	1.36E-01	1.30E-01	3.86E+00	1.42E-01	1.35E-01	1.28E-01
23.75	1.24E-01	1.94E-01	1.18E-01	1.14E-01	3.50E+00	1.24E-01	1.18E-01	1.13E-01
26.25	1.03E-01	1.61E-01	9.73E-02	9.43E-02	3.06E+00	1.03E-01	9.79E-02	9.36E-02
28.75	9.92E-02	1.52E-01	9.43E-02	9.08E-02	2.83E+00	9.93E-02	9.44E-02	9.01E-02
31.25	9.45E-02	1.42E-01	8.95E-02	8.67E-02	2.76E+00	9.47E-02	9.01E-02	8.61E-02
33.75	7.74E-02	1.16E-01	7.22E-02	7.10E-02	2.48E+00	7.74E-02	7.37E-02	7.08E-02
36.25	9.28E-02	1.35E-01	8.56E-02	8.53E-02	3.15E+00	9.28E-02	8.83E-02	8.52E-02
38.75	9.86E-02	1.41E-01	9.14E-02	9.08E-02	3.28E+00	9.88E-02	9.40E-02	9.06E-02
41.25	6.36E-02	9.30E-02	5.94E-02	5.85E-02	2.03E+00	6.38E-02	6.07E-02	5.83E-02
43.75	6.72E-02	9.45E-02	6.23E-02	6.20E-02	2.25E+00	6.74E-02	6.42E-02	6.19E-02
46.25	7.39E-02	1.00E-01	6.85E-02	6.83E-02	2.48E+00	7.43E-02	7.07E-02	6.83E-02
48.75	6.02E-02	8.30E-02	5.61E-02	5.56E-02	1.98E+00	6.05E-02	5.76E-02	5.55E-02
51.25	4.33E-02	6.25E-02	4.06E-02	3.98E-02	1.34E+00	4.34E-02	4.13E-02	3.97E-02
53.75	3.50E-02	5.21E-02	3.31E-02	3.22E-02	1.05E+00	3.51E-02	3.34E-02	3.20E-02
56.25	3.08E-02	4.56E-02	2.92E-02	2.83E-02	9.07E-01	3.09E-02	2.94E-02	2.81E-02
58.75	2.69E-02	3.93E-02	2.56E-02	2.47E-02	7.72E-01	2.70E-02	2.57E-02	2.46E-02

Table F4: Mean Short Term Individual Dose (Sievert) for MC_SEAL1 – 30 Days

Distance (km)	Effective	Thyroid	Eye Lens	Ovaries	Skin	Lung	B Marrow	GI-Tract
0.5	2.36E-09	5.87E-11	4.58E-11	4.50E-11	1.67E-08	1.89E-08	2.06E-10	2.16E-10
1.75	3.04E-10	1.08E-11	9.23E-12	7.98E-12	2.13E-09	2.40E-09	2.89E-11	3.00E-11
3.75	8.29E-11	3.73E-12	3.33E-12	2.71E-12	5.76E-10	6.52E-10	8.46E-12	8.76E-12
6.25	3.45E-11	1.85E-12	1.69E-12	1.33E-12	2.38E-10	2.69E-10	3.75E-12	3.85E-12
8.75	2.01E-11	1.21E-12	1.12E-12	8.62E-13	1.37E-10	1.56E-10	2.28E-12	2.34E-12
11.25	1.58E-11	1.02E-12	9.50E-13	7.28E-13	1.08E-10	1.22E-10	1.84E-12	1.89E-12
13.75	1.09E-11	7.77E-13	7.31E-13	5.52E-13	7.38E-11	8.36E-11	1.33E-12	1.36E-12
16.25	8.88E-12	6.34E-13	5.96E-13	4.49E-13	6.02E-11	6.83E-11	1.08E-12	1.11E-12
18.75	7.34E-12	5.04E-13	4.73E-13	3.58E-13	4.99E-11	5.66E-11	8.79E-13	9.06E-13
21.25	6.59E-12	3.55E-13	3.23E-13	2.57E-13	4.55E-11	5.14E-11	7.17E-13	7.50E-13
23.75	5.93E-12	3.18E-13	2.90E-13	2.30E-13	4.10E-11	4.63E-11	6.44E-13	6.76E-13
26.25	5.40E-12	2.87E-13	2.62E-13	2.08E-13	3.73E-11	4.21E-11	5.84E-13	6.14E-13
28.75	4.34E-12	2.33E-13	2.13E-13	1.69E-13	3.00E-11	3.39E-11	4.72E-13	4.97E-13
31.25	3.91E-12	2.10E-13	1.92E-13	1.52E-13	2.70E-11	3.05E-11	4.26E-13	4.50E-13
33.75	3.74E-12	2.00E-13	1.83E-13	1.45E-13	2.59E-11	2.92E-11	4.06E-13	4.31E-13
36.25	3.55E-12	1.87E-13	1.71E-13	1.35E-13	2.45E-11	2.77E-11	3.83E-13	4.07E-13
38.75	3.20E-12	1.69E-13	1.54E-13	1.22E-13	2.21E-11	2.50E-11	3.45E-13	3.67E-13
41.25	2.76E-12	1.46E-13	1.33E-13	1.05E-13	1.90E-11	2.15E-11	2.98E-13	3.16E-13
43.75	2.50E-12	1.32E-13	1.20E-13	9.51E-14	1.73E-11	1.96E-11	2.70E-13	2.87E-13
46.25	2.34E-12	1.23E-13	1.12E-13	8.85E-14	1.62E-11	1.83E-11	2.52E-13	2.69E-13
48.75	2.32E-12	1.21E-13	1.11E-13	8.74E-14	1.61E-11	1.81E-11	2.50E-13	2.67E-13
51.25	2.16E-12	1.14E-13	1.04E-13	8.18E-14	1.50E-11	1.69E-11	2.33E-13	2.50E-13
53.75	1.92E-12	1.03E-13	9.45E-14	7.43E-14	1.33E-11	1.50E-11	2.09E-13	2.24E-13
56.25	1.80E-12	9.96E-14	9.14E-14	7.19E-14	1.24E-11	1.40E-11	1.98E-13	2.12E-13
58.75	1.70E-12	9.56E-14	8.78E-14	6.92E-14	1.17E-11	1.32E-11	1.88E-13	2.02E-13

Table F5: Mean Short Term Individual Dose (Sievert) for MC_FIRE1 – 30 Days

Distance (km)	Effective	Thyroid	Eye Lens	Ovaries	Skin	Lung	B Marrow	GI-Tract
0.5	3.83E-02	3.75E-03	3.08E-03	3.14E-03	1.71E-01	2.91E-01	4.23E-03	4.20E-03
1.75	8.70E-03	8.68E-04	7.16E-04	7.27E-04	3.89E-02	6.59E-02	9.74E-04	9.66E-04
3.75	2.61E-03	2.80E-04	2.34E-04	2.34E-04	1.16E-02	1.96E-02	3.08E-04	3.04E-04
6.25	1.14E-03	1.37E-04	1.17E-04	1.14E-04	5.00E-03	8.51E-03	1.47E-04	1.44E-04
8.75	8.02E-04	9.55E-05	8.12E-05	7.94E-05	3.51E-03	5.97E-03	1.03E-04	1.01E-04
11.25	5.69E-04	6.44E-05	5.44E-05	5.36E-05	2.51E-03	4.26E-03	7.00E-05	6.88E-05
13.75	3.88E-04	4.64E-05	3.95E-05	3.85E-05	1.70E-03	2.89E-03	4.98E-05	4.88E-05
16.25	3.25E-04	4.00E-05	3.41E-05	3.32E-05	1.42E-03	2.41E-03	4.26E-05	4.17E-05
18.75	2.76E-04	3.55E-05	3.05E-05	2.94E-05	1.20E-03	2.04E-03	3.75E-05	3.66E-05
21.25	2.81E-04	3.48E-05	2.97E-05	2.89E-05	1.23E-03	2.08E-03	3.71E-05	3.62E-05
23.75	2.35E-04	3.03E-05	2.60E-05	2.51E-05	1.02E-03	1.74E-03	3.20E-05	3.12E-05
26.25	2.01E-04	2.61E-05	2.24E-05	2.16E-05	8.72E-04	1.48E-03	2.75E-05	2.68E-05
28.75	1.77E-04	2.12E-05	1.81E-05	1.77E-05	7.73E-04	1.31E-03	2.28E-05	2.23E-05
31.25	1.57E-04	1.84E-05	1.56E-05	1.53E-05	6.87E-04	1.17E-03	1.98E-05	1.94E-05
33.75	1.53E-04	1.72E-05	1.45E-05	1.44E-05	6.75E-04	1.15E-03	1.88E-05	1.85E-05
36.25	1.64E-04	1.77E-05	1.49E-05	1.48E-05	7.28E-04	1.24E-03	1.95E-05	1.93E-05
38.75	1.72E-04	1.82E-05	1.52E-05	1.52E-05	7.64E-04	1.30E-03	2.02E-05	1.99E-05
41.25	1.52E-04	1.73E-05	1.46E-05	1.44E-05	6.70E-04	1.14E-03	1.88E-05	1.84E-05
43.75	1.15E-04	1.71E-05	1.50E-05	1.42E-05	4.90E-04	8.36E-04	1.76E-05	1.70E-05
46.25	1.01E-04	1.65E-05	1.45E-05	1.36E-05	4.24E-04	7.26E-04	1.66E-05	1.60E-05
48.75	9.67E-05	1.52E-05	1.33E-05	1.25E-05	4.08E-04	6.98E-04	1.54E-05	1.48E-05
51.25	1.01E-04	1.48E-05	1.29E-05	1.22E-05	4.31E-04	7.36E-04	1.52E-05	1.47E-05
53.75	9.50E-05	1.27E-05	1.10E-05	1.05E-05	4.11E-04	6.99E-04	1.33E-05	1.30E-05
56.25	7.96E-05	9.96E-06	8.52E-06	8.28E-06	3.47E-04	5.90E-04	1.06E-05	1.03E-05
58.75	7.19E-05	8.73E-06	7.45E-06	7.26E-06	3.14E-04	5.35E-04	9.35E-06	9.15E-06

Table F6: Mean Long Term Individual Dose (Sievert) for MC_LOAD1 – 50 Years

Distance (km)	Effective	Skin	B Marrow	B Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Gonads	Remainder
0.5	5.19E-05	6.37E-06	3.33E-05	2.65E-04	1.57E-05	2.50E-04	1.45E-05	2.00E-05	6.45E-05	1.34E-05	1.99E-05	1.79E-05	1.60E-05
1.75	7.49E-06	8.52E-07	4.92E-06	3.69E-05	2.50E-06	3.49E-05	2.32E-06	3.06E-06	9.21E-06	2.14E-06	3.09E-06	2.79E-06	2.56E-06
3.75	2.08E-06	2.24E-07	1.38E-06	9.98E-06	7.36E-07	9.43E-06	6.80E-07	8.78E-07	2.53E-06	6.28E-07	8.95E-07	8.08E-07	7.51E-07
6.25	1.03E-06	1.07E-07	6.87E-07	4.90E-06	3.72E-07	4.63E-06	3.43E-07	4.40E-07	1.25E-06	3.17E-07	4.46E-07	4.06E-07	3.79E-07
8.75	6.67E-07	6.92E-08	4.44E-07	3.22E-06	2.36E-07	3.04E-06	2.17E-07	2.81E-07	8.15E-07	2.01E-07	2.81E-07	2.58E-07	2.40E-07
11.25	3.05E-07	2.89E-08	2.13E-07	1.35E-06	1.29E-07	1.28E-06	1.19E-07	1.44E-07	3.64E-07	1.09E-07	1.53E-07	1.36E-07	1.31E-07
13.75	2.48E-07	2.45E-08	1.70E-07	1.14E-06	9.80E-08	1.08E-06	9.03E-08	1.12E-07	2.98E-07	8.33E-08	1.17E-07	1.05E-07	9.98E-08
16.25	2.01E-07	1.97E-08	1.37E-07	9.23E-07	7.88E-08	8.72E-07	7.25E-08	9.01E-08	2.41E-07	6.69E-08	9.36E-08	8.44E-08	8.02E-08
18.75	1.61E-07	1.58E-08	1.10E-07	7.43E-07	6.24E-08	7.02E-07	5.75E-08	7.17E-08	1.94E-07	5.30E-08	7.40E-08	6.70E-08	6.35E-08
21.25	1.40E-07	1.42E-08	9.37E-08	6.66E-07	5.09E-08	6.29E-07	4.70E-08	6.00E-08	1.70E-07	4.34E-08	6.06E-08	5.55E-08	5.19E-08
23.75	1.19E-07	1.22E-08	7.92E-08	5.71E-07	4.24E-08	5.39E-07	3.91E-08	5.03E-08	1.45E-07	3.61E-08	5.05E-08	4.63E-08	4.32E-08
26.25	1.10E-07	1.10E-08	7.41E-08	5.18E-07	4.09E-08	4.89E-07	3.78E-08	4.78E-08	1.33E-07	3.48E-08	4.86E-08	4.44E-08	4.17E-08
28.75	1.05E-07	9.81E-09	7.26E-08	4.69E-07	4.32E-08	4.43E-07	3.99E-08	4.86E-08	1.25E-07	3.68E-08	5.11E-08	4.60E-08	4.40E-08
31.25	1.01E-07	8.50E-09	7.36E-08	4.17E-07	4.83E-08	3.95E-07	4.46E-08	5.18E-08	1.18E-07	4.11E-08	5.68E-08	5.02E-08	4.93E-08
33.75	8.33E-08	7.42E-09	5.91E-08	3.59E-07	3.69E-08	3.39E-07	3.41E-08	4.06E-08	9.84E-08	3.15E-08	4.35E-08	3.89E-08	3.77E-08
36.25	6.79E-08	6.88E-09	4.55E-08	3.24E-07	2.47E-08	3.06E-07	2.28E-08	2.92E-08	8.26E-08	2.11E-08	2.94E-08	2.69E-08	2.52E-08
38.75	7.32E-08	7.72E-09	4.79E-08	3.62E-07	2.43E-08	3.42E-07	2.24E-08	2.97E-08	9.01E-08	2.07E-08	2.89E-08	2.70E-08	2.48E-08
41.25	8.75E-08	9.23E-09	5.67E-08	4.40E-07	2.80E-08	4.15E-07	2.58E-08	3.47E-08	1.08E-07	2.38E-08	3.31E-08	3.13E-08	2.85E-08
43.75	9.58E-08	1.00E-08	6.20E-08	4.83E-07	3.03E-08	4.56E-07	2.79E-08	3.78E-08	1.19E-07	2.58E-08	3.57E-08	3.40E-08	3.09E-08
46.25	8.10E-08	8.45E-09	5.26E-08	4.06E-07	2.61E-08	3.83E-07	2.41E-08	3.23E-08	1.00E-07	2.22E-08	3.08E-08	2.92E-08	2.66E-08
48.75	6.34E-08	6.59E-09	4.15E-08	3.15E-07	2.10E-08	2.97E-07	1.93E-08	2.57E-08	7.81E-08	1.78E-08	2.47E-08	2.33E-08	2.13E-08
51.25	4.59E-08	4.75E-09	3.01E-08	2.27E-07	1.53E-08	2.14E-07	1.41E-08	1.87E-08	5.65E-08	1.30E-08	1.81E-08	1.70E-08	1.56E-08
53.75	3.82E-08	3.97E-09	2.50E-08	1.89E-07	1.26E-08	1.79E-07	1.17E-08	1.55E-08	4.70E-08	1.08E-08	1.49E-08	1.40E-08	1.29E-08
56.25	3.63E-08	3.73E-09	2.39E-08	1.79E-07	1.23E-08	1.69E-07	1.13E-08	1.49E-08	4.46E-08	1.05E-08	1.45E-08	1.36E-08	1.25E-08
58.75	3.69E-08	3.67E-09	2.46E-08	1.78E-07	1.32E-08	1.68E-07	1.21E-08	1.56E-08	4.50E-08	1.12E-08	1.55E-08	1.44E-08	1.34E-08

Table F7: Mean Long Term Individual Dose (Sievert) for MC_SFB1 – 50 Years

Distance (km)	Effective	Skin	B Marrow	B Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Gonads	Remainder
0.5	1.06E-06	1.51E-07	1.54E-06	2.10E-05	2.81E-07	2.09E-06	2.64E-07	2.62E-07	3.10E-06	2.45E-07	3.23E-07	5.73E-07	2.97E-07
1.75	1.51E-07	2.09E-08	2.18E-07	2.90E-06	4.41E-08	2.94E-07	4.13E-08	4.10E-08	4.33E-07	3.84E-08	5.07E-08	8.42E-08	4.65E-08
3.75	4.16E-08	5.60E-09	5.94E-08	7.80E-07	1.28E-08	7.99E-08	1.20E-08	1.18E-08	1.17E-07	1.11E-08	1.47E-08	2.35E-08	1.35E-08
6.25	2.05E-08	2.74E-09	2.92E-08	3.82E-07	6.39E-09	3.93E-08	5.98E-09	5.91E-09	5.75E-08	5.55E-09	7.35E-09	1.16E-08	6.72E-09
8.75	1.33E-08	1.81E-09	1.91E-08	2.52E-07	4.03E-09	2.57E-08	3.77E-09	3.74E-09	3.77E-08	3.50E-09	4.63E-09	7.50E-09	4.24E-09
11.25	6.01E-09	7.41E-10	8.35E-09	1.04E-07	2.19E-09	1.11E-08	2.05E-09	2.02E-09	1.60E-08	1.90E-09	2.53E-09	3.59E-09	2.30E-09
13.75	4.91E-09	6.29E-10	6.91E-09	8.79E-08	1.67E-09	9.23E-09	1.56E-09	1.54E-09	1.34E-08	1.45E-09	1.93E-09	2.87E-09	1.75E-09
16.25	3.97E-09	5.11E-10	5.59E-09	7.14E-08	1.34E-09	7.48E-09	1.26E-09	1.24E-09	1.09E-08	1.17E-09	1.55E-09	2.32E-09	1.41E-09
18.75	3.18E-09	4.12E-10	4.49E-09	5.75E-08	1.06E-09	6.01E-09	9.94E-10	9.81E-10	8.74E-09	9.22E-10	1.22E-09	1.85E-09	1.12E-09
21.25	2.79E-09	3.73E-10	3.98E-09	5.19E-08	8.78E-10	5.34E-09	8.22E-10	8.13E-10	7.82E-09	7.63E-10	1.01E-09	1.59E-09	9.23E-10
23.75	2.38E-09	3.20E-10	3.39E-09	4.46E-08	7.29E-10	4.57E-09	6.83E-10	6.76E-10	6.70E-09	6.34E-10	8.38E-10	1.34E-09	7.67E-10
26.25	2.19E-09	2.89E-10	3.11E-09	4.03E-08	7.06E-10	4.17E-09	6.61E-10	6.53E-10	6.09E-09	6.13E-10	8.12E-10	1.26E-09	7.42E-10
28.75	2.07E-09	2.58E-10	2.89E-09	3.60E-08	7.49E-10	3.84E-09	7.00E-10	6.89E-10	5.54E-09	6.49E-10	8.63E-10	1.24E-09	7.84E-10
31.25	1.99E-09	2.23E-10	2.69E-09	3.14E-08	8.43E-10	3.53E-09	7.86E-10	7.71E-10	4.97E-09	7.28E-10	9.72E-10	1.26E-09	8.79E-10
33.75	1.64E-09	1.95E-10	2.26E-09	2.73E-08	6.42E-10	2.99E-09	5.99E-10	5.89E-10	4.26E-09	5.55E-10	7.40E-10	1.01E-09	6.71E-10
36.25	1.36E-09	1.81E-10	1.93E-09	2.52E-08	4.26E-10	2.60E-09	3.98E-10	3.94E-10	3.80E-09	3.70E-10	4.90E-10	7.72E-10	4.48E-10
38.75	1.47E-09	2.05E-10	2.12E-09	2.85E-08	4.16E-10	2.87E-09	3.90E-10	3.88E-10	4.24E-09	3.63E-10	4.78E-10	8.11E-10	4.39E-10
41.25	1.76E-09	2.50E-10	2.55E-09	3.46E-08	4.78E-10	3.46E-09	4.48E-10	4.46E-10	5.13E-09	4.17E-10	5.49E-10	9.60E-10	5.05E-10
43.75	1.93E-09	2.75E-10	2.80E-09	3.81E-08	5.18E-10	3.80E-09	4.85E-10	4.84E-10	5.64E-09	4.52E-10	5.94E-10	1.05E-09	5.47E-10
46.25	1.63E-09	2.30E-10	2.36E-09	3.19E-08	4.47E-10	3.20E-09	4.19E-10	4.17E-10	4.74E-09	3.90E-10	5.13E-10	8.91E-10	4.72E-10
48.75	1.28E-09	1.78E-10	1.84E-09	2.48E-08	3.59E-10	2.49E-09	3.36E-10	3.34E-10	3.68E-09	3.13E-10	4.12E-10	7.02E-10	3.79E-10
51.25	9.22E-10	1.28E-10	1.33E-09	1.78E-08	2.62E-10	1.80E-09	2.46E-10	2.44E-10	2.65E-09	2.29E-10	3.01E-10	5.09E-10	2.77E-10
53.75	7.67E-10	1.07E-10	1.11E-09	1.49E-08	2.16E-10	1.50E-09	2.03E-10	2.02E-10	2.21E-09	1.89E-10	2.48E-10	4.23E-10	2.28E-10
56.25	7.29E-10	1.01E-10	1.05E-09	1.40E-08	2.11E-10	1.42E-09	1.98E-10	1.96E-10	2.09E-09	1.84E-10	2.42E-10	4.05E-10	2.22E-10
58.75	7.38E-10	9.97E-11	1.05E-09	1.39E-08	2.26E-10	1.42E-09	2.12E-10	2.10E-10	2.08E-09	1.97E-10	2.60E-10	4.17E-10	2.38E-10

Table F8: Mean Long Term Individual Dose (Sievert) for MC_SFPL1 – 50 Years

Distance (km)	Effective	Skin	B Marrow	B Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Gonads	Remainder
0.5	9.64E+02	2.05E+02	9.51E+02	1.01E+03	9.59E+02	1.00E+03	8.95E+02	8.68E+02	8.96E+02	8.28E+02	1.15E+03	9.23E+02	9.90E+02
1.75	1.52E+02	2.97E+01	1.50E+02	1.59E+02	1.52E+02	1.58E+02	1.41E+02	1.37E+02	1.42E+02	1.31E+02	1.80E+02	1.46E+02	1.57E+02
3.75	4.62E+01	8.39E+00	4.56E+01	4.82E+01	4.60E+01	4.81E+01	4.29E+01	4.16E+01	4.30E+01	3.97E+01	5.46E+01	4.43E+01	4.75E+01
6.25	2.22E+01	3.57E+00	2.19E+01	2.31E+01	2.21E+01	2.31E+01	2.06E+01	1.99E+01	2.06E+01	1.90E+01	2.61E+01	2.12E+01	2.28E+01
8.75	1.47E+01	1.99E+00	1.45E+01	1.53E+01	1.47E+01	1.53E+01	1.37E+01	1.32E+01	1.37E+01	1.26E+01	1.73E+01	1.41E+01	1.51E+01
11.25	1.17E+01	1.45E+00	1.15E+01	1.22E+01	1.17E+01	1.22E+01	1.09E+01	1.05E+01	1.09E+01	1.00E+01	1.37E+01	1.12E+01	1.20E+01
13.75	9.31E+00	1.40E+00	9.18E+00	9.71E+00	9.27E+00	9.69E+00	8.64E+00	8.37E+00	8.65E+00	7.98E+00	1.09E+01	8.91E+00	9.57E+00
16.25	6.13E+00	9.28E-01	6.05E+00	6.40E+00	6.11E+00	6.39E+00	5.70E+00	5.52E+00	5.70E+00	5.26E+00	7.19E+00	5.88E+00	6.31E+00
18.75	4.79E+00	8.13E-01	4.72E+00	5.00E+00	4.77E+00	4.98E+00	4.45E+00	4.31E+00	4.45E+00	4.11E+00	5.61E+00	4.59E+00	4.92E+00
21.25	4.68E+00	7.27E-01	4.61E+00	4.88E+00	4.66E+00	4.87E+00	4.34E+00	4.21E+00	4.35E+00	4.01E+00	5.48E+00	4.48E+00	4.81E+00
23.75	4.08E+00	6.60E-01	4.03E+00	4.26E+00	4.06E+00	4.25E+00	3.79E+00	3.67E+00	3.79E+00	3.50E+00	4.78E+00	3.91E+00	4.19E+00
26.25	3.35E+00	5.78E-01	3.31E+00	3.50E+00	3.34E+00	3.49E+00	3.12E+00	3.02E+00	3.12E+00	2.88E+00	3.93E+00	3.21E+00	3.45E+00
28.75	3.26E+00	5.35E-01	3.22E+00	3.40E+00	3.25E+00	3.40E+00	3.03E+00	2.94E+00	3.03E+00	2.80E+00	3.81E+00	3.12E+00	3.35E+00
31.25	3.10E+00	5.26E-01	3.06E+00	3.24E+00	3.09E+00	3.23E+00	2.88E+00	2.80E+00	2.89E+00	2.67E+00	3.63E+00	2.97E+00	3.19E+00
33.75	2.50E+00	4.74E-01	2.47E+00	2.61E+00	2.49E+00	2.61E+00	2.33E+00	2.26E+00	2.33E+00	2.15E+00	2.93E+00	2.40E+00	2.58E+00
36.25	2.98E+00	6.05E-01	2.94E+00	3.12E+00	2.97E+00	3.11E+00	2.77E+00	2.69E+00	2.78E+00	2.56E+00	3.48E+00	2.86E+00	3.07E+00
38.75	3.19E+00	6.32E-01	3.15E+00	3.33E+00	3.18E+00	3.32E+00	2.97E+00	2.88E+00	2.97E+00	2.74E+00	3.72E+00	3.06E+00	3.28E+00
41.25	2.07E+00	3.90E-01	2.04E+00	2.16E+00	2.06E+00	2.15E+00	1.92E+00	1.86E+00	1.92E+00	1.78E+00	2.41E+00	1.98E+00	2.13E+00
43.75	2.18E+00	4.34E-01	2.15E+00	2.28E+00	2.17E+00	2.27E+00	2.03E+00	1.97E+00	2.03E+00	1.87E+00	2.54E+00	2.09E+00	2.24E+00
46.25	2.41E+00	4.82E-01	2.38E+00	2.52E+00	2.40E+00	2.51E+00	2.24E+00	2.17E+00	2.24E+00	2.07E+00	2.80E+00	2.31E+00	2.48E+00
48.75	1.97E+00	3.83E-01	1.94E+00	2.05E+00	1.96E+00	2.05E+00	1.83E+00	1.77E+00	1.83E+00	1.69E+00	2.29E+00	1.89E+00	2.02E+00
51.25	1.42E+00	2.58E-01	1.40E+00	1.48E+00	1.41E+00	1.48E+00	1.32E+00	1.28E+00	1.32E+00	1.22E+00	1.65E+00	1.36E+00	1.46E+00
53.75	1.15E+00	1.99E-01	1.13E+00	1.20E+00	1.15E+00	1.20E+00	1.07E+00	1.04E+00	1.07E+00	9.87E-01	1.34E+00	1.10E+00	1.18E+00
56.25	1.01E+00	1.73E-01	1.00E+00	1.06E+00	1.01E+00	1.06E+00	9.42E-01	9.13E-01	9.43E-01	8.70E-01	1.18E+00	9.71E-01	1.04E+00
58.75	8.91E-01	1.47E-01	8.80E-01	9.30E-01	8.88E-01	9.28E-01	8.28E-01	8.03E-01	8.29E-01	7.65E-01	1.04E+00	8.54E-01	9.17E-01

Table F9: Mean Long Term Individual Dose (Sievert) for MC_SEAL1 – 50 Years

Distance (km)	Effective	Skin	B Marrow	B Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Gonads	Remainder
0.5	2.72E-08	3.45E-09	4.32E-08	6.85E-07	1.57E-09	6.09E-08	1.51E-09	1.68E-09	9.53E-08	1.45E-09	1.71E-09	1.15E-08	1.85E-09
1.75	3.47E-09	4.39E-10	5.50E-09	8.71E-08	2.12E-10	7.77E-09	2.03E-10	2.25E-10	1.21E-08	1.95E-10	2.31E-10	1.48E-09	2.48E-10
3.75	9.45E-10	1.19E-10	1.49E-09	2.36E-08	6.15E-11	2.11E-09	5.87E-11	6.43E-11	3.29E-09	5.62E-11	6.71E-11	4.03E-10	7.13E-11
6.25	3.92E-10	4.91E-11	6.19E-10	9.75E-09	2.74E-11	8.72E-10	2.61E-11	2.83E-11	1.36E-09	2.49E-11	3.00E-11	1.68E-10	3.15E-11
8.75	2.26E-10	2.83E-11	3.57E-10	5.63E-09	1.56E-11	5.03E-10	1.48E-11	1.62E-11	7.85E-10	1.42E-11	1.71E-11	9.70E-11	1.79E-11
11.25	1.78E-10	2.22E-11	2.81E-10	4.41E-09	1.34E-11	3.96E-10	1.27E-11	1.37E-11	6.16E-10	1.21E-11	1.47E-11	7.71E-11	1.52E-11
13.75	1.22E-10	1.52E-11	1.93E-10	3.02E-09	9.45E-12	2.71E-10	8.95E-12	9.62E-12	4.22E-10	8.52E-12	1.04E-11	5.31E-11	1.07E-11
16.25	9.98E-11	1.24E-11	1.57E-10	2.47E-09	7.58E-12	2.21E-10	7.18E-12	7.74E-12	3.45E-10	6.84E-12	8.33E-12	4.32E-11	8.62E-12
18.75	8.25E-11	1.03E-11	1.30E-10	2.04E-09	6.08E-12	1.83E-10	5.77E-12	6.24E-12	2.85E-10	5.50E-12	6.67E-12	3.56E-11	6.94E-12
21.25	7.54E-11	9.37E-12	1.19E-10	1.86E-09	5.77E-12	1.67E-10	5.48E-12	5.91E-12	2.60E-10	5.22E-12	6.35E-12	3.27E-11	6.56E-12
23.75	6.78E-11	8.44E-12	1.07E-10	1.68E-09	5.07E-12	1.50E-10	4.81E-12	5.20E-12	2.34E-10	4.59E-12	5.57E-12	2.93E-11	5.78E-12
26.25	6.14E-11	7.67E-12	9.69E-11	1.52E-09	4.42E-12	1.37E-10	4.21E-12	4.57E-12	2.13E-10	4.02E-12	4.85E-12	2.65E-11	5.07E-12
28.75	4.95E-11	6.17E-12	7.81E-11	1.23E-09	3.70E-12	1.10E-10	3.51E-12	3.80E-12	1.71E-10	3.35E-12	4.07E-12	2.14E-11	4.22E-12
31.25	4.47E-11	5.56E-12	7.04E-11	1.11E-09	3.33E-12	9.91E-11	3.16E-12	3.42E-12	1.54E-10	3.01E-12	3.66E-12	1.93E-11	3.80E-12
33.75	4.26E-11	5.33E-12	6.72E-11	1.06E-09	3.08E-12	9.47E-11	2.93E-12	3.19E-12	1.48E-10	2.80E-12	3.38E-12	1.84E-11	3.53E-12
36.25	4.03E-11	5.05E-12	6.36E-11	1.00E-09	2.78E-12	8.97E-11	2.65E-12	2.89E-12	1.40E-10	2.53E-12	3.04E-12	1.73E-11	3.20E-12
38.75	3.63E-11	4.55E-12	5.73E-11	9.03E-10	2.51E-12	8.08E-11	2.39E-12	2.61E-12	1.26E-10	2.28E-12	2.74E-12	1.56E-11	2.88E-12
41.25	3.13E-11	3.92E-12	4.94E-11	7.78E-10	2.15E-12	6.96E-11	2.05E-12	2.24E-12	1.09E-10	1.96E-12	2.35E-12	1.34E-11	2.48E-12
43.75	2.84E-11	3.56E-12	4.48E-11	7.07E-10	1.92E-12	6.32E-11	1.83E-12	2.00E-12	9.86E-11	1.75E-12	2.10E-12	1.22E-11	2.21E-12
46.25	2.65E-11	3.34E-12	4.19E-11	6.61E-10	1.76E-12	5.91E-11	1.68E-12	1.84E-12	9.22E-11	1.60E-12	1.92E-12	1.13E-11	2.03E-12
48.75	2.62E-11	3.30E-12	4.15E-11	6.55E-10	1.70E-12	5.85E-11	1.62E-12	1.79E-12	9.13E-11	1.55E-12	1.85E-12	1.12E-11	1.97E-12
51.25	2.44E-11	3.08E-12	3.86E-11	6.10E-10	1.58E-12	5.45E-11	1.51E-12	1.66E-12	8.51E-11	1.45E-12	1.72E-12	1.04E-11	1.83E-12
53.75	2.17E-11	2.73E-12	3.43E-11	5.41E-10	1.49E-12	4.84E-11	1.42E-12	1.55E-12	7.55E-11	1.35E-12	1.62E-12	9.32E-12	1.71E-12
56.25	2.05E-11	2.56E-12	3.23E-11	5.07E-10	1.49E-12	4.55E-11	1.42E-12	1.55E-12	7.08E-11	1.36E-12	1.64E-12	8.83E-12	1.71E-12
58.75	1.94E-11	2.41E-12	3.05E-11	4.77E-10	1.50E-12	4.29E-11	1.42E-12	1.54E-12	6.67E-11	1.35E-12	1.65E-12	8.40E-12	1.70E-12

Table F10: Mean Long Term Individual Dose (Sievert) for MC_FIRE1 – 50 Years

Distance (km)	Effective	Skin	B Marrow	B Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Gonads	Remainder
0.5	5.30E-01	3.42E-02	7.14E-01	1.04E+01	1.49E-01	1.06E+00	1.39E-01	1.37E-01	1.57E+00	1.30E-01	1.71E-01	2.96E-01	1.57E-01
1.75	1.21E-01	7.75E-03	1.63E-01	2.36E+00	3.43E-02	2.41E-01	3.22E-02	3.15E-02	3.56E-01	2.99E-02	3.95E-02	6.76E-02	3.62E-02
3.75	3.69E-02	2.31E-03	4.93E-02	7.05E-01	1.11E-02	7.26E-02	1.04E-02	1.02E-02	1.07E-01	9.66E-03	1.28E-02	2.10E-02	1.17E-02
6.25	1.66E-02	9.99E-04	2.20E-02	3.06E-01	5.47E-03	3.21E-02	5.12E-03	5.00E-03	4.69E-02	4.75E-03	6.29E-03	9.72E-03	5.74E-03
8.75	1.16E-02	7.01E-04	1.54E-02	2.15E-01	3.79E-03	2.25E-02	3.54E-03	3.46E-03	3.29E-02	3.29E-03	4.36E-03	6.77E-03	3.98E-03
11.25	8.12E-03	5.00E-04	1.08E-02	1.53E-01	2.54E-03	1.59E-02	2.38E-03	2.32E-03	2.33E-02	2.21E-03	2.92E-03	4.67E-03	2.67E-03
13.75	5.62E-03	3.39E-04	7.44E-03	1.04E-01	1.83E-03	1.09E-02	1.72E-03	1.68E-03	1.59E-02	1.59E-03	2.11E-03	3.28E-03	1.93E-03
16.25	4.75E-03	2.83E-04	6.27E-03	8.67E-02	1.59E-03	9.14E-03	1.48E-03	1.45E-03	1.33E-02	1.38E-03	1.83E-03	2.79E-03	1.66E-03
18.75	4.09E-03	2.39E-04	5.37E-03	7.34E-02	1.41E-03	7.81E-03	1.32E-03	1.29E-03	1.13E-02	1.23E-03	1.63E-03	2.43E-03	1.48E-03
21.25	4.12E-03	2.45E-04	5.44E-03	7.49E-02	1.39E-03	7.92E-03	1.30E-03	1.27E-03	1.15E-02	1.21E-03	1.60E-03	2.43E-03	1.46E-03
23.75	3.49E-03	2.04E-04	4.58E-03	6.25E-02	1.22E-03	6.66E-03	1.14E-03	1.11E-03	9.66E-03	1.06E-03	1.40E-03	2.08E-03	1.28E-03
26.25	2.99E-03	1.74E-04	3.92E-03	5.34E-02	1.05E-03	5.70E-03	9.79E-04	9.55E-04	8.26E-03	9.08E-04	1.21E-03	1.78E-03	1.10E-03
28.75	2.57E-03	1.54E-04	3.40E-03	4.72E-02	8.47E-04	4.97E-03	7.93E-04	7.75E-04	7.25E-03	7.36E-04	9.75E-04	1.50E-03	8.90E-04
31.25	2.26E-03	1.37E-04	3.00E-03	4.20E-02	7.33E-04	4.39E-03	6.86E-04	6.71E-04	6.42E-03	6.37E-04	8.44E-04	1.32E-03	7.70E-04
33.75	2.19E-03	1.35E-04	2.91E-03	4.12E-02	6.84E-04	4.28E-03	6.40E-04	6.26E-04	6.28E-03	5.95E-04	7.87E-04	1.26E-03	7.20E-04
36.25	2.32E-03	1.45E-04	3.11E-03	4.44E-02	7.02E-04	4.57E-03	6.58E-04	6.44E-04	6.74E-03	6.11E-04	8.07E-04	1.32E-03	7.40E-04
38.75	2.42E-03	1.52E-04	3.24E-03	4.65E-02	7.20E-04	4.78E-03	6.75E-04	6.61E-04	7.05E-03	6.27E-04	8.28E-04	1.37E-03	7.59E-04
41.25	2.18E-03	1.34E-04	2.90E-03	4.09E-02	6.86E-04	4.25E-03	6.42E-04	6.28E-04	6.23E-03	5.97E-04	7.89E-04	1.26E-03	7.22E-04
43.75	1.79E-03	9.77E-05	2.31E-03	3.01E-02	6.95E-04	3.31E-03	6.49E-04	6.32E-04	4.74E-03	6.01E-04	8.01E-04	1.10E-03	7.26E-04
46.25	1.62E-03	8.46E-05	2.07E-03	2.62E-02	6.72E-04	2.94E-03	6.27E-04	6.10E-04	4.17E-03	5.81E-04	7.75E-04	1.02E-03	7.01E-04
48.75	1.53E-03	8.15E-05	1.96E-03	2.51E-02	6.18E-04	2.80E-03	5.77E-04	5.61E-04	3.99E-03	5.34E-04	7.12E-04	9.57E-04	6.45E-04
51.25	1.56E-03	8.61E-05	2.02E-03	2.65E-02	5.98E-04	2.90E-03	5.59E-04	5.45E-04	4.16E-03	5.18E-04	6.90E-04	9.60E-04	6.26E-04
53.75	1.43E-03	8.19E-05	1.87E-03	2.52E-02	5.12E-04	2.70E-03	4.79E-04	4.67E-04	3.91E-03	4.44E-04	5.90E-04	8.58E-04	5.37E-04
56.25	1.17E-03	6.92E-05	1.54E-03	2.12E-02	3.99E-04	2.25E-03	3.73E-04	3.64E-04	3.27E-03	3.46E-04	4.59E-04	6.93E-04	4.19E-04
58.75	1.05E-03	6.28E-05	1.39E-03	1.92E-02	3.49E-04	2.02E-03	3.27E-04	3.19E-04	2.95E-03	3.03E-04	4.02E-04	6.16E-04	3.67E-04

Table F11: Mean Number of Early Fatalities for MC_LOAD1

Distance (km)	Total	Pulmonary Syndrome	Hematop. Syndrome	GI syndrome	Pre-neonatal	Skin Burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F12: Mean Number of Early Fatalities for MC_SFB1

Distance (km)	Total	Pulmonary Syndrome	Hematop. Syndrome	GI syndrome	Pre-neonatal	Skin Burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F13: Mean Number of Early Fatalities for MC_SFPL1

Distance (km)	Total	Pulmonary Syndrome	Hematop. Syndrome	GI syndrome	Pre-neonatal	Skin Burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	1.41E+02	5.28E+01	1.38E+02	4.79E+01	2.02E+00	9.84E+00
3.75	5.73E+01	1.27E+01	5.66E+01	1.20E+01	7.47E-01	3.44E+00
6.25	2.37E+01	2.34E+00	1.94E+01	1.80E+00	1.25E+00	5.26E+00
8.75	9.35E+00	2.33E+00	7.73E+00	1.92E+00	4.57E-01	1.92E+00
11.25	2.02E+02	3.06E+00	1.95E+02	2.66E+00	3.67E+00	1.67E+01
13.75	2.04E+03	3.54E+02	1.98E+03	1.10E+02	3.50E+01	1.60E+02
16.25	3.93E+02	2.83E-01	3.13E+02	1.21E-01	2.02E+01	9.50E+01
18.75	1.29E+02	4.47E+00	6.63E+01	1.93E+00	1.38E+01	6.57E+01
21.25	5.10E+01	1.57E-01	2.48E+01	1.04E-01	5.86E+00	2.73E+01
23.75	1.68E+02	4.50E-02	1.03E+02	3.91E-02	1.54E+01	6.93E+01
26.25	3.62E+02	8.93E-04	2.35E+02	1.88E-04	3.25E+01	1.37E+02
28.75	3.51E+02	7.94E+01	1.61E+02	7.94E+01	4.57E+01	1.96E+02
31.25	4.20E+02	1.75E+02	2.03E+02	1.11E+02	6.96E+01	2.25E+02
33.75	5.22E+02	3.83E+01	1.76E+02	5.54E+00	8.29E+01	3.46E+02
36.25	3.54E+02	0.00E+00	1.38E+02	0.00E+00	5.48E+01	2.16E+02
38.75	1.82E+02	0.00E+00	4.87E+01	0.00E+00	3.08E+01	1.34E+02
41.25	9.09E+01	0.00E+00	2.48E+01	0.00E+00	2.27E+01	6.65E+01
43.75	7.84E+01	0.00E+00	1.20E+01	0.00E+00	2.43E+01	6.64E+01
46.25	1.34E+02	0.00E+00	4.31E+01	0.00E+00	2.49E+01	9.06E+01
48.75	3.39E+01	0.00E+00	4.13E-01	0.00E+00	1.27E+01	3.35E+01
51.25	1.44E+01	0.00E+00	5.16E+00	0.00E+00	5.80E+00	9.25E+00
53.75	4.39E+01	0.00E+00	2.90E+01	0.00E+00	7.40E+00	1.61E+01
56.25	4.74E+01	0.00E+00	3.67E+01	0.00E+00	4.02E+00	1.24E+01
58.75	1.64E+01	0.00E+00	5.10E+00	0.00E+00	4.82E+00	1.14E+01

Table F14: Mean Number of Early Fatalities for MC_SEAL1

Distance (km)	Total	Pulmonary Syndrome	Hematop. Syndrome	GI syndrome	Pre-neonatal	Skin Burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F15: Mean Number of Early Fatalities for MC_FIRE1

Distance (km)	Total	Pulmonary Syndrome	Hematop. Syndrome	GI syndrome	Pre-neonatal	Skin Burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.12E-07	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F16: Mean Number of Latent Cancer Fatalities for MC_LOAD1

Distance (km)	Total	Bone Marrow	Bone Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Remainder	Skin	Hereditary Effects
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	3.70E-04	2.22E-05	1.44E-05	5.22E-06	2.32E-04	2.65E-05	2.51E-05	1.15E-05	5.79E-06	2.54E-06	2.48E-05	1.32E-07	2.79E-05
3.75	1.72E-04	1.07E-05	6.44E-06	2.67E-06	1.04E-04	1.36E-05	1.25E-05	5.31E-06	2.96E-06	1.29E-06	1.27E-05	5.76E-08	1.41E-05
6.25	2.30E-04	1.77E-05	6.39E-06	5.79E-06	1.03E-04	2.95E-05	2.40E-05	6.96E-06	6.42E-06	2.71E-06	2.75E-05	4.73E-08	2.88E-05
8.75	2.44E-05	1.60E-06	8.61E-07	4.35E-07	1.39E-05	2.21E-06	1.95E-06	7.52E-07	4.81E-07	2.06E-07	2.06E-06	7.31E-09	2.24E-06
11.25	5.53E-05	3.19E-06	2.24E-06	7.04E-07	3.59E-05	3.56E-06	3.49E-06	1.72E-06	7.76E-07	3.38E-07	3.33E-06	1.97E-08	3.80E-06
13.75	6.59E-04	3.91E-05	2.59E-05	9.11E-06	4.16E-04	4.62E-05	4.40E-05	2.05E-05	1.01E-05	4.36E-06	4.31E-05	2.27E-07	4.87E-05
16.25	1.05E-03	6.75E-05	3.77E-05	1.79E-05	6.07E-04	9.09E-05	8.13E-05	3.23E-05	1.98E-05	8.47E-06	8.50E-05	3.15E-07	9.29E-05
18.75	5.88E-04	3.92E-05	2.03E-05	1.09E-05	3.26E-04	5.55E-05	4.85E-05	1.81E-05	1.21E-05	5.15E-06	5.19E-05	1.66E-07	5.61E-05
21.25	2.88E-04	1.87E-05	1.03E-05	4.99E-06	1.66E-04	2.54E-05	2.26E-05	8.88E-06	5.54E-06	2.36E-06	2.37E-05	8.58E-08	2.59E-05
23.75	7.16E-04	4.74E-05	2.49E-05	1.31E-05	4.01E-04	6.64E-05	5.83E-05	2.20E-05	1.45E-05	6.17E-06	6.21E-05	2.06E-07	6.73E-05
26.25	1.62E-03	1.06E-04	5.73E-05	2.87E-05	9.22E-04	1.46E-04	1.29E-04	4.99E-05	3.18E-05	1.35E-05	1.36E-04	4.66E-07	1.48E-04
28.75	1.96E-03	1.37E-04	6.31E-05	4.05E-05	1.02E-03	2.06E-04	1.75E-04	5.98E-05	4.49E-05	1.90E-05	1.93E-04	4.91E-07	2.06E-04
31.25	2.17E-03	1.65E-04	6.15E-05	5.31E-05	9.95E-04	2.70E-04	2.21E-04	6.56E-05	5.90E-05	2.48E-05	2.53E-04	4.50E-07	2.65E-04
33.75	1.89E-03	1.29E-04	6.31E-05	3.69E-05	1.02E-03	1.88E-04	1.62E-04	5.78E-05	4.09E-05	1.73E-05	1.75E-04	4.99E-07	1.88E-04
36.25	1.51E-03	8.50E-05	6.25E-05	1.78E-05	1.00E-03	9.02E-05	9.08E-05	4.72E-05	1.97E-05	8.46E-06	8.42E-05	5.34E-07	9.78E-05
38.75	1.49E-03	8.67E-05	5.95E-05	1.95E-05	9.55E-04	9.89E-05	9.59E-05	4.63E-05	2.16E-05	9.26E-06	9.24E-05	5.04E-07	1.05E-04
41.25	1.19E-03	7.37E-05	4.47E-05	1.85E-05	7.18E-04	9.37E-05	8.61E-05	3.68E-05	2.04E-05	8.71E-06	8.75E-05	3.70E-07	9.70E-05
43.75	1.21E-03	7.61E-05	4.51E-05	1.94E-05	7.25E-04	9.83E-05	8.96E-05	3.75E-05	2.14E-05	9.12E-06	9.18E-05	3.70E-07	1.01E-04
46.25	1.13E-03	7.12E-05	4.14E-05	1.84E-05	6.66E-04	9.33E-05	8.45E-05	3.48E-05	2.04E-05	8.61E-06	8.72E-05	3.32E-07	9.59E-05
48.75	3.63E-04	2.18E-05	1.41E-05	5.16E-06	2.27E-04	2.62E-05	2.47E-05	1.13E-05	5.71E-06	2.42E-06	2.45E-05	1.15E-07	2.75E-05
51.25	3.30E-04	1.85E-05	1.37E-05	3.84E-06	2.20E-04	1.95E-05	1.97E-05	1.03E-05	4.24E-06	1.81E-06	1.82E-05	1.15E-07	2.11E-05
53.75	2.68E-04	1.55E-05	1.09E-05	3.41E-06	1.74E-04	1.73E-05	1.70E-05	8.37E-06	3.77E-06	1.61E-06	1.62E-05	9.02E-08	1.85E-05
56.25	3.99E-05	2.37E-06	1.58E-06	5.49E-07	2.53E-05	2.79E-06	2.66E-06	1.24E-06	6.08E-07	2.58E-07	2.60E-06	1.29E-08	2.94E-06
58.75	4.44E-05	3.24E-06	1.35E-06	1.01E-06	2.17E-05	5.12E-06	4.26E-06	1.35E-06	1.12E-06	4.69E-07	4.78E-06	9.96E-09	5.05E-06

Table F17: Mean Number of Latent Cancer Fatalities for MC_SFB1

Distance (km)	Total	Bone Marrow	Bone Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Remainder	Skin	Hereditary Effects
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	6.04E-06	8.89E-07	1.11E-06	9.15E-08	2.01E-06	4.70E-07	3.58E-07	5.12E-07	1.03E-07	4.22E-08	4.46E-07	3.17E-09	7.58E-07
3.75	2.81E-06	4.07E-07	4.90E-07	4.66E-08	9.12E-07	2.40E-07	1.82E-07	2.29E-07	5.24E-08	2.15E-08	2.27E-07	1.39E-09	3.64E-07
6.25	3.90E-06	5.00E-07	4.33E-07	1.02E-07	1.05E-06	5.23E-07	3.93E-07	2.39E-07	1.14E-07	4.73E-08	4.92E-07	1.18E-09	6.09E-07
8.75	4.01E-07	5.65E-08	6.42E-08	7.53E-09	1.25E-07	3.86E-08	2.92E-08	3.09E-08	8.44E-09	3.48E-09	3.65E-08	1.82E-10	5.43E-08
11.25	8.88E-07	1.33E-07	1.74E-07	1.19E-08	3.05E-07	6.11E-08	4.67E-08	7.87E-08	1.34E-08	5.46E-09	5.80E-08	4.99E-10	1.07E-07
13.75	1.07E-05	1.58E-06	2.00E-06	1.56E-07	3.58E-06	8.01E-07	6.10E-07	9.16E-07	1.76E-07	7.18E-08	7.60E-07	5.72E-09	1.32E-06
16.25	1.72E-05	2.45E-06	2.83E-06	3.10E-07	5.44E-06	1.59E-06	1.21E-06	1.35E-06	3.49E-07	1.43E-07	1.51E-06	8.03E-09	2.30E-06
18.75	9.69E-06	1.35E-06	1.50E-06	1.90E-07	2.98E-06	9.75E-07	7.36E-07	7.30E-07	2.13E-07	8.78E-08	9.20E-07	4.23E-09	1.34E-06
21.25	4.74E-06	6.72E-07	7.72E-07	8.73E-08	1.49E-06	4.48E-07	3.39E-07	3.70E-07	9.80E-08	4.03E-08	4.23E-07	2.19E-09	6.38E-07
23.75	1.18E-05	1.66E-06	1.85E-06	2.29E-07	3.66E-06	1.17E-06	8.86E-07	8.96E-07	2.56E-07	1.06E-07	1.11E-06	5.22E-09	1.62E-06
26.25	2.67E-05	3.77E-06	4.28E-06	5.02E-07	8.34E-06	2.58E-06	1.95E-06	2.06E-06	5.63E-07	2.32E-07	2.43E-06	1.21E-08	3.62E-06
28.75	3.26E-05	4.43E-06	4.56E-06	7.13E-07	9.62E-06	3.65E-06	2.75E-06	2.30E-06	7.97E-07	3.29E-07	3.44E-06	1.28E-08	4.70E-06
31.25	3.66E-05	4.74E-06	4.22E-06	9.39E-07	1.00E-05	4.81E-06	3.61E-06	2.29E-06	1.05E-06	4.34E-07	4.52E-06	1.15E-08	5.66E-06
33.75	3.13E-05	4.32E-06	4.63E-06	6.47E-07	9.45E-06	3.32E-06	2.50E-06	2.29E-06	7.25E-07	2.99E-07	3.13E-06	1.30E-08	4.41E-06
36.25	2.43E-05	3.69E-06	4.90E-06	3.05E-07	8.47E-06	1.57E-06	1.21E-06	2.20E-06	3.45E-07	1.40E-07	1.50E-06	1.41E-08	2.88E-06
38.75	2.41E-05	3.59E-06	4.61E-06	3.37E-07	8.17E-06	1.73E-06	1.32E-06	2.10E-06	3.80E-07	1.55E-07	1.64E-06	1.32E-08	2.94E-06
41.25	1.94E-05	2.82E-06	3.40E-06	3.21E-07	6.32E-06	1.65E-06	1.25E-06	1.59E-06	3.61E-07	1.48E-07	1.56E-06	9.69E-09	2.51E-06
43.75	1.99E-05	2.86E-06	3.42E-06	3.37E-07	6.41E-06	1.73E-06	1.31E-06	1.61E-06	3.79E-07	1.55E-07	1.64E-06	9.73E-09	2.59E-06
46.25	1.85E-05	2.65E-06	3.13E-06	3.20E-07	5.92E-06	1.64E-06	1.25E-06	1.48E-06	3.60E-07	1.48E-07	1.55E-06	8.90E-09	2.43E-06
48.75	5.90E-06	8.70E-07	1.09E-06	8.91E-08	1.97E-06	4.58E-07	3.49E-07	5.01E-07	1.00E-07	4.11E-08	4.34E-07	3.11E-09	7.40E-07
51.25	5.31E-06	8.07E-07	1.07E-06	6.58E-08	1.85E-06	3.39E-07	2.60E-07	4.81E-07	7.45E-08	3.02E-08	3.22E-07	3.09E-09	6.26E-07
53.75	4.34E-06	6.51E-07	8.45E-07	5.87E-08	1.49E-06	3.02E-07	2.31E-07	3.83E-07	6.64E-08	2.70E-08	2.87E-07	2.43E-09	5.25E-07
56.25	6.48E-07	9.60E-08	1.22E-07	9.47E-09	2.18E-07	4.87E-08	3.71E-08	5.57E-08	1.07E-08	4.36E-09	4.62E-08	3.49E-10	8.04E-08
58.75	7.45E-07	9.87E-08	9.48E-08	1.77E-08	2.12E-07	9.07E-08	6.82E-08	4.95E-08	1.98E-08	8.19E-09	8.54E-08	2.63E-10	1.11E-07

Table F18: Mean Number of Latent Cancer Fatalities for MC_SFPL1

Distance (km)	Total	Bone Marrow	Bone Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Remainder	Skin	Hereditary Effects
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	9.03E+01	4.99E+01	6.25E+00	2.20E+01	6.36E+01	6.68E+01	6.04E+01	1.67E+01	2.68E+01	1.14E+01	6.54E+01	4.55E-01	3.60E+03
3.75	3.80E+01	1.51E+01	1.87E+00	6.75E+00	2.01E+01	2.15E+01	1.88E+01	4.99E+00	7.99E+00	3.39E+00	2.08E+01	1.28E-01	1.55E+03
6.25	2.04E+02	6.84E+01	7.62E+00	2.84E+01	1.11E+02	1.19E+02	9.95E+01	2.04E+01	3.26E+01	1.38E+01	1.15E+02	6.18E-01	3.54E+02
8.75	7.95E+01	2.68E+01	3.06E+00	1.13E+01	3.96E+01	4.33E+01	3.63E+01	8.17E+00	1.31E+01	5.52E+00	4.16E+01	2.39E-01	2.01E+02
11.25	2.64E+02	1.22E+02	1.33E+01	4.98E+01	1.67E+02	1.79E+02	1.56E+02	3.54E+01	5.67E+01	2.40E+01	1.74E+02	1.08E+00	1.67E+03
13.75	2.66E+03	1.13E+03	1.31E+02	4.72E+02	1.60E+03	1.69E+03	1.51E+03	3.50E+02	5.61E+02	2.37E+02	1.65E+03	1.02E+01	2.87E+04
16.25	2.83E+03	1.31E+03	1.47E+02	5.46E+02	1.79E+03	1.89E+03	1.69E+03	3.93E+02	6.30E+02	2.65E+02	1.85E+03	1.12E+01	4.86E+03
18.75	1.89E+03	1.08E+03	1.36E+02	4.91E+02	1.33E+03	1.38E+03	1.28E+03	3.64E+02	5.83E+02	2.46E+02	1.35E+03	1.00E+01	3.05E+03
21.25	8.23E+02	4.90E+02	5.36E+01	2.03E+02	5.78E+02	5.94E+02	5.57E+02	1.43E+02	2.30E+02	9.66E+01	5.86E+02	4.41E+00	1.20E+03
23.75	2.60E+03	1.27E+03	1.57E+02	5.78E+02	1.59E+03	1.66E+03	1.53E+03	4.21E+02	6.73E+02	2.83E+02	1.63E+03	1.13E+01	3.47E+03
26.25	6.14E+03	2.13E+03	2.45E+02	9.08E+02	3.19E+03	3.52E+03	2.90E+03	6.55E+02	1.05E+03	4.42E+02	3.37E+03	1.88E+01	6.14E+03
28.75	8.26E+03	3.37E+03	3.64E+02	1.38E+03	4.74E+03	5.11E+03	4.38E+03	9.73E+02	1.56E+03	6.55E+02	4.94E+03	2.91E+01	1.12E+04
31.25	1.49E+04	5.19E+03	5.74E+02	2.18E+03	7.67E+03	8.29E+03	6.98E+03	1.53E+03	2.45E+03	1.03E+03	8.01E+03	4.29E+01	1.63E+04
33.75	1.52E+04	5.40E+03	5.78E+02	2.20E+03	8.71E+03	9.24E+03	8.06E+03	1.54E+03	2.47E+03	1.04E+03	8.99E+03	4.71E+01	1.32E+04
36.25	1.32E+04	4.26E+03	4.59E+02	1.73E+03	6.45E+03	6.99E+03	5.96E+03	1.23E+03	1.96E+03	8.22E+02	6.74E+03	3.66E+01	9.39E+03
38.75	8.13E+03	2.07E+03	2.28E+02	8.54E+02	3.56E+03	3.99E+03	3.11E+03	6.09E+02	9.75E+02	4.08E+02	3.80E+03	1.69E+01	4.52E+03
41.25	7.92E+03	2.02E+03	2.19E+02	8.24E+02	3.22E+03	3.52E+03	2.96E+03	5.86E+02	9.38E+02	3.92E+02	3.38E+03	1.60E+01	4.22E+03
43.75	1.15E+04	2.38E+03	2.53E+02	9.62E+02	4.12E+03	4.62E+03	3.63E+03	6.75E+02	1.08E+03	4.53E+02	4.40E+03	1.96E+01	4.78E+03
46.25	7.96E+03	1.74E+03	1.84E+02	7.00E+02	3.06E+03	3.48E+03	2.66E+03	4.91E+02	7.86E+02	3.29E+02	3.29E+03	1.45E+01	3.68E+03
48.75	4.17E+03	8.79E+02	9.32E+01	3.55E+02	1.57E+03	1.81E+03	1.36E+03	2.49E+02	3.99E+02	1.67E+02	1.70E+03	7.81E+00	1.73E+03
51.25	3.78E+03	7.18E+02	7.79E+01	2.95E+02	1.20E+03	1.37E+03	1.06E+03	2.08E+02	3.33E+02	1.40E+02	1.29E+03	5.34E+00	1.46E+03
53.75	2.99E+03	7.02E+02	7.69E+01	2.89E+02	1.15E+03	1.28E+03	1.02E+03	2.06E+02	3.29E+02	1.38E+02	1.22E+03	4.79E+00	1.59E+03
56.25	9.81E+02	2.59E+02	2.81E+01	1.06E+02	4.43E+02	5.00E+02	3.92E+02	7.50E+01	1.20E+02	5.03E+01	4.73E+02	1.80E+00	7.22E+02
58.75	1.49E+03	3.86E+02	4.21E+01	1.61E+02	6.19E+02	6.94E+02	5.53E+02	1.12E+02	1.80E+02	7.54E+01	6.58E+02	2.86E+00	8.11E+02

Table F19: Mean Number of Latent Cancer Fatalities for MC_SEAL1

Distance (km)	Total	Bone Marrow	Bone Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Remainder	Skin	Hereditary Effects
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	3.46E-07	5.80E-08	9.10E-08	1.12E-09	1.39E-07	5.84E-09	4.86E-09	3.82E-08	1.32E-09	4.93E-10	5.92E-09	1.83E-10	3.19E-08
3.75	1.12E-07	1.85E-08	2.84E-08	5.40E-10	4.40E-08	2.80E-09	2.24E-09	1.20E-08	6.22E-10	2.42E-10	2.76E-09	5.68E-11	1.08E-08
6.25	3.60E-08	5.82E-09	8.63E-09	2.44E-10	1.37E-08	1.26E-09	9.85E-10	3.70E-09	2.78E-10	1.11E-10	1.22E-09	1.72E-11	3.67E-09
8.75	1.19E-08	1.96E-09	2.98E-09	6.19E-11	4.64E-09	3.20E-10	2.55E-10	1.26E-09	7.11E-11	2.78E-11	3.14E-10	5.96E-12	1.16E-09
11.25	4.57E-08	7.53E-09	1.15E-08	2.31E-10	1.79E-08	1.20E-09	9.56E-10	4.87E-09	2.66E-10	1.04E-10	1.18E-09	2.30E-11	4.45E-09
13.75	4.20E-07	6.87E-08	1.04E-07	2.33E-09	1.63E-07	1.20E-08	9.55E-09	4.42E-08	2.67E-09	1.05E-09	1.18E-08	2.08E-10	4.14E-08
16.25	6.53E-07	1.08E-07	1.64E-07	3.36E-09	2.55E-07	1.73E-08	1.38E-08	6.94E-08	3.85E-09	1.51E-09	1.71E-08	3.28E-10	6.37E-08
18.75	7.31E-07	1.23E-07	1.92E-07	2.39E-09	2.94E-07	1.25E-08	1.04E-08	8.06E-08	2.81E-09	1.05E-09	1.26E-08	3.87E-10	6.76E-08
21.25	2.25E-07	3.79E-08	5.98E-08	6.39E-10	9.09E-08	3.35E-09	2.84E-09	2.50E-08	7.58E-10	2.79E-10	3.43E-09	1.21E-10	2.05E-08
23.75	3.59E-07	6.02E-08	9.42E-08	1.22E-09	1.44E-07	6.37E-09	5.28E-09	3.95E-08	1.43E-09	5.38E-10	6.43E-09	1.90E-10	3.33E-08
26.25	6.42E-07	1.08E-07	1.69E-07	2.15E-09	2.57E-07	1.12E-08	9.33E-09	7.07E-08	2.53E-09	9.49E-10	1.14E-08	3.39E-10	5.95E-08
28.75	6.32E-07	1.06E-07	1.67E-07	1.98E-09	2.54E-07	1.03E-08	8.66E-09	6.99E-08	2.33E-09	8.68E-10	1.05E-08	3.36E-10	5.82E-08
31.25	1.01E-06	1.69E-07	2.63E-07	3.70E-09	4.04E-07	1.93E-08	1.59E-08	1.11E-07	4.32E-09	1.64E-09	1.93E-08	5.30E-10	9.45E-08
33.75	9.86E-07	1.63E-07	2.51E-07	4.44E-09	3.89E-07	2.30E-08	1.86E-08	1.06E-07	5.13E-09	1.99E-09	2.28E-08	5.05E-10	9.45E-08
36.25	5.98E-07	9.98E-08	1.55E-07	2.27E-09	2.38E-07	1.18E-08	9.68E-09	6.53E-08	2.64E-09	1.01E-09	1.18E-08	3.12E-10	5.61E-08
38.75	3.88E-07	6.51E-08	1.02E-07	1.28E-09	1.56E-07	6.68E-09	5.56E-09	4.28E-08	1.50E-09	5.64E-10	6.76E-09	2.05E-10	3.59E-08
41.25	4.53E-07	7.62E-08	1.20E-07	1.36E-09	1.83E-07	7.13E-09	6.00E-09	5.02E-08	1.61E-09	5.97E-10	7.27E-09	2.42E-10	4.15E-08
43.75	5.43E-07	9.15E-08	1.45E-07	1.50E-09	2.19E-07	7.86E-09	6.69E-09	6.04E-08	1.78E-09	6.54E-10	8.08E-09	2.91E-10	4.94E-08
46.25	4.13E-07	6.95E-08	1.09E-07	1.25E-09	1.67E-07	6.54E-09	5.50E-09	4.58E-08	1.48E-09	5.48E-10	6.67E-09	2.20E-10	3.79E-08
48.75	1.09E-07	1.84E-08	2.90E-08	3.19E-10	4.41E-08	1.67E-09	1.42E-09	1.21E-08	3.78E-10	1.40E-10	1.71E-09	5.85E-11	9.99E-09
51.25	1.13E-07	1.90E-08	3.01E-08	3.07E-10	4.56E-08	1.61E-09	1.38E-09	1.26E-08	3.65E-10	1.34E-10	1.66E-09	6.07E-11	1.02E-08
53.75	8.34E-08	1.40E-08	2.21E-08	2.46E-10	3.36E-08	1.29E-09	1.09E-09	9.26E-09	2.91E-10	1.08E-10	1.32E-09	4.46E-11	7.63E-09
56.25	1.66E-08	2.77E-09	4.32E-09	6.03E-11	6.62E-09	3.14E-10	2.59E-10	1.81E-09	7.04E-11	2.67E-11	3.15E-10	8.70E-12	1.55E-09
58.75	1.21E-08	1.99E-09	3.06E-09	5.58E-11	4.74E-09	2.89E-10	2.34E-10	1.29E-09	6.44E-11	2.49E-11	2.86E-10	6.15E-12	1.16E-09

Table F20: Mean Number of Latent Cancer Fatalities for MC_FIRE1

Distance (km)	Total	Bone Marrow	Bone Surface	Breast	Lung	Stomach	Colon	Liver	Pancreas	Thyroid	Remainder	Skin	Hereditary Effects
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	1.58E+01	2.41E+00	3.40E+00	2.26E-01	6.01E+00	1.17E+00	8.80E-01	1.56E+00	2.56E-01	1.04E-01	1.11E+00	4.45E-03	2.08E+00
3.75	3.46E+00	5.04E-01	7.17E-01	4.66E-02	1.26E+00	2.40E-01	1.81E-01	3.27E-01	5.27E-02	2.14E-02	2.28E-01	9.39E-04	4.33E-01
6.25	6.15E-01	8.53E-02	1.14E-01	9.72E-03	2.09E-01	4.99E-02	3.76E-02	5.32E-02	1.09E-02	4.48E-03	4.73E-02	1.48E-04	7.97E-02
8.75	1.37E+00	2.00E-01	2.94E-01	1.62E-02	5.05E-01	8.36E-02	6.34E-02	1.32E-01	1.84E-02	7.44E-03	7.97E-02	3.86E-04	1.64E-01
11.25	1.54E+00	2.14E-01	2.90E-01	2.30E-02	5.27E-01	1.18E-01	8.90E-02	1.35E-01	2.59E-02	1.06E-02	1.12E-01	3.79E-04	1.95E-01
13.75	1.15E+01	1.61E+00	2.24E+00	1.62E-01	4.01E+00	8.33E-01	6.29E-01	1.03E+00	1.83E-01	7.46E-02	7.91E-01	2.93E-03	1.43E+00
16.25	3.11E+01	4.46E+00	6.45E+00	3.85E-01	1.12E+01	1.99E+00	1.50E+00	2.92E+00	4.37E-01	1.77E-01	1.89E+00	8.46E-03	3.74E+00
18.75	1.41E+01	2.01E+00	2.90E+00	1.76E-01	5.05E+00	9.09E-01	6.88E-01	1.32E+00	2.00E-01	8.11E-02	8.65E-01	3.80E-03	1.70E+00
21.25	1.36E+01	1.96E+00	2.73E+00	1.94E-01	4.87E+00	9.97E-01	7.53E-01	1.26E+00	2.19E-01	8.92E-02	9.46E-01	3.57E-03	1.73E+00
23.75	3.84E+01	5.40E+00	7.27E+00	5.97E-01	1.33E+01	3.07E+00	2.31E+00	3.39E+00	6.73E-01	2.75E-01	2.91E+00	9.46E-03	4.98E+00
26.25	4.13E+01	5.60E+00	7.12E+00	7.18E-01	1.36E+01	3.69E+00	2.77E+00	3.40E+00	8.07E-01	3.31E-01	3.48E+00	9.22E-03	5.51E+00
28.75	3.78E+01	5.08E+00	6.31E+00	6.85E-01	1.22E+01	3.52E+00	2.64E+00	3.04E+00	7.70E-01	3.16E-01	3.32E+00	8.15E-03	5.11E+00
31.25	5.19E+01	6.96E+00	8.56E+00	9.60E-01	1.67E+01	4.93E+00	3.70E+00	4.14E+00	1.08E+00	4.43E-01	4.65E+00	1.11E-02	7.08E+00
33.75	4.66E+01	6.31E+00	7.98E+00	8.15E-01	1.52E+01	4.18E+00	3.14E+00	3.82E+00	9.15E-01	3.76E-01	3.95E+00	1.03E-02	6.22E+00
36.25	4.21E+01	5.84E+00	7.92E+00	6.30E-01	1.44E+01	3.24E+00	2.44E+00	3.68E+00	7.11E-01	2.90E-01	3.07E+00	1.03E-02	5.33E+00
38.75	3.04E+01	4.02E+00	4.76E+00	5.96E-01	9.54E+00	3.06E+00	2.29E+00	2.34E+00	6.68E-01	2.75E-01	2.88E+00	6.12E-03	4.23E+00
41.25	3.09E+01	3.83E+00	3.63E+00	7.86E-01	8.61E+00	4.03E+00	3.01E+00	1.98E+00	8.78E-01	3.64E-01	3.79E+00	4.54E-03	4.79E+00
43.75	6.62E+01	7.62E+00	4.64E+00	2.18E+00	1.58E+01	1.11E+01	8.30E+00	3.22E+00	2.42E+00	1.01E+00	1.04E+01	5.35E-03	1.16E+01
46.25	5.46E+01	6.46E+00	4.68E+00	1.67E+00	1.38E+01	8.53E+00	6.37E+00	2.94E+00	1.86E+00	7.73E-01	8.01E+00	5.59E-03	9.26E+00
48.75	4.47E+01	4.98E+00	2.20E+00	1.62E+00	9.85E+00	8.29E+00	6.18E+00	1.87E+00	1.81E+00	7.52E-01	7.77E+00	2.30E-03	8.30E+00
51.25	1.41E+01	1.87E+00	2.19E+00	2.82E-01	4.42E+00	1.45E+00	1.09E+00	1.08E+00	3.16E-01	1.30E-01	1.36E+00	2.81E-03	1.98E+00
53.75	1.03E+01	1.41E+00	1.88E+00	1.61E-01	3.46E+00	8.29E-01	6.25E-01	8.79E-01	1.82E-01	7.44E-02	7.85E-01	2.44E-03	1.32E+00
56.25	2.53E+00	3.56E-01	5.03E-01	3.34E-02	8.88E-01	1.72E-01	1.30E-01	2.30E-01	3.78E-02	1.54E-02	1.63E-01	6.59E-04	3.08E-01
58.75	2.35E+00	3.29E-01	4.61E-01	3.19E-02	8.19E-01	1.64E-01	1.24E-01	2.12E-01	3.61E-02	1.47E-02	1.56E-01	6.03E-04	2.88E-01

Table F21: Mean Individual Short Term Risk of Mortality for MC_LOAD1

Distance (km)	Sum over organs	pulmonary syn.	hematop. syn.	GI syndrome	pre-/neo natal	skin burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F22: Mean Individual Short Term Risk of Mortality for MC_SFB1

Distance (km)	Sum over organs	pulmonary syn.	hematop. syn.	GI syndrome	pre-/neo natal	skin burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F23: Mean Individual Short Term Risk of Mortality for MC_SFPL1

Distance (km)	Sum over organs	pulmonary syn.	hematop. syn.	GI syndrome	pre-/neo natal	skin burns
0.5	8.68E-02	6.13E-02	8.59E-02	5.95E-02	1.08E-01	5.15E-03
1.75	4.87E-02	2.18E-02	4.76E-02	1.98E-02	7.39E-02	3.53E-03
3.75	3.05E-02	5.83E-03	2.95E-02	4.11E-03	5.29E-02	2.48E-03
6.25	1.83E-02	1.23E-03	1.72E-02	1.03E-03	4.31E-02	2.00E-03
8.75	1.01E-02	1.08E-03	9.08E-03	8.99E-04	3.29E-02	1.48E-03
11.25	7.60E-03	8.93E-04	6.64E-03	7.25E-04	2.89E-02	1.26E-03
13.75	5.82E-03	7.27E-04	5.05E-03	4.91E-04	2.41E-02	9.77E-04
16.25	3.83E-03	2.12E-04	3.12E-03	1.73E-04	2.10E-02	8.31E-04
18.75	3.64E-03	6.99E-05	2.93E-03	3.23E-05	2.04E-02	8.32E-04
21.25	2.87E-03	7.82E-05	2.12E-03	6.19E-05	2.07E-02	8.39E-04
23.75	2.64E-03	5.60E-05	2.09E-03	3.83E-05	1.69E-02	6.33E-04
26.25	2.13E-03	7.93E-06	1.62E-03	6.70E-06	1.54E-02	5.74E-04
28.75	1.91E-03	6.55E-05	1.37E-03	5.65E-05	1.56E-02	5.94E-04
31.25	1.33E-03	8.11E-05	8.12E-04	5.46E-05	1.46E-02	5.41E-04
33.75	8.71E-04	1.44E-05	3.74E-04	2.10E-06	1.43E-02	5.08E-04
36.25	8.68E-04	0.00E+00	2.19E-04	0.00E+00	1.73E-02	6.57E-04
38.75	2.52E-03	0.00E+00	1.92E-03	0.00E+00	1.68E-02	6.92E-04
41.25	1.00E-03	0.00E+00	5.70E-04	0.00E+00	1.22E-02	4.54E-04
43.75	7.05E-04	0.00E+00	1.11E-04	0.00E+00	1.44E-02	5.95E-04
46.25	1.05E-03	0.00E+00	5.77E-04	0.00E+00	1.28E-02	4.99E-04
48.75	1.27E-03	0.00E+00	8.99E-04	0.00E+00	1.06E-02	4.12E-04
51.25	5.13E-04	0.00E+00	2.00E-04	0.00E+00	8.57E-03	3.18E-04
53.75	4.64E-04	0.00E+00	2.54E-04	0.00E+00	6.52E-03	2.18E-04
56.25	2.99E-04	0.00E+00	1.50E-04	0.00E+00	5.63E-03	1.53E-04
58.75	2.84E-04	0.00E+00	1.83E-04	0.00E+00	4.53E-03	1.02E-04

Table F24: Mean Individual Short Term Risk of Mortality for MC_SEAL1

Distance (km)	Sum over organs	pulmonary syn.	hematop. syn.	GI syndrome	pre-/neo natal	skin burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table F25: Mean Individual Short Term Risk of Mortality for MC_FIRE1

Distance (km)	Sum over organs	pulmonary syn.	hematop. syn.	GI syndrome	pre-/neo natal	skin burns
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.74E-05	0.00E+00
1.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.47E-06	0.00E+00
3.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.94E-08	0.00E+00
6.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
13.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
16.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
18.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
21.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
23.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
26.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
31.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
33.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
36.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
38.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
41.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
43.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
46.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
48.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
51.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
53.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
56.25	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
58.75	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Table 26: Mean Long Term Individual Risk of Mortality for MC_LOAD1

Distance (km)	TOTAL	b.marrow	b.surface	breast	lung	stomach	colon	liver	pancreas	thyroid	Hered.Eff	remainder	skin
0.5	3.09E-06	1.66E-07	1.33E-07	6.26E-08	2.13E-06	1.60E-07	1.70E-07	9.67E-08	3.49E-08	1.59E-08	1.79E-07	1.49E-07	1.27E-09
1.75	4.42E-07	2.46E-08	1.85E-08	1.00E-08	2.96E-07	2.55E-08	2.60E-08	1.38E-08	5.56E-09	2.47E-09	2.79E-08	2.38E-08	1.70E-10
3.75	1.22E-07	6.91E-09	4.99E-09	2.95E-09	8.01E-08	7.48E-09	7.46E-09	3.80E-09	1.63E-09	7.16E-10	8.08E-09	6.99E-09	4.48E-11
6.25	6.01E-08	3.44E-09	2.45E-09	1.49E-09	3.93E-08	3.78E-09	3.74E-09	1.87E-09	8.24E-10	3.57E-10	4.06E-09	3.53E-09	2.14E-11
8.75	3.91E-08	2.22E-09	1.61E-09	9.44E-10	2.58E-08	2.39E-09	2.39E-09	1.22E-09	5.22E-10	2.25E-10	2.58E-09	2.24E-09	1.39E-11
11.25	1.76E-08	1.07E-09	6.77E-10	5.15E-10	1.09E-08	1.30E-09	1.22E-09	5.45E-10	2.84E-10	1.22E-10	1.36E-09	1.22E-09	5.79E-12
13.75	1.44E-08	8.49E-10	5.69E-10	3.92E-10	9.14E-09	9.93E-10	9.51E-10	4.47E-10	2.17E-10	9.34E-11	1.05E-09	9.28E-10	4.90E-12
16.25	1.16E-08	6.86E-10	4.62E-10	3.15E-10	7.41E-09	7.98E-10	7.66E-10	3.62E-10	1.74E-10	7.49E-11	8.44E-10	7.46E-10	3.94E-12
18.75	9.33E-09	5.47E-10	3.72E-10	2.50E-10	5.97E-09	6.32E-10	6.09E-10	2.90E-10	1.38E-10	5.92E-11	6.70E-10	5.91E-10	3.16E-12
21.25	8.18E-09	4.69E-10	3.33E-10	2.04E-10	5.34E-09	5.17E-10	5.10E-10	2.55E-10	1.13E-10	4.85E-11	5.55E-10	4.83E-10	2.85E-12
23.75	6.96E-09	3.96E-10	2.86E-10	1.69E-10	4.58E-09	4.30E-10	4.28E-10	2.17E-10	9.37E-11	4.04E-11	4.63E-10	4.01E-10	2.45E-12
26.25	6.41E-09	3.71E-10	2.59E-10	1.64E-10	4.16E-09	4.15E-10	4.07E-10	2.00E-10	9.06E-11	3.89E-11	4.44E-10	3.88E-10	2.20E-12
28.75	6.04E-09	3.63E-10	2.34E-10	1.73E-10	3.77E-09	4.38E-10	4.13E-10	1.87E-10	9.56E-11	4.09E-11	4.60E-10	4.10E-10	1.96E-12
31.25	5.75E-09	3.68E-10	2.08E-10	1.93E-10	3.35E-09	4.91E-10	4.40E-10	1.77E-10	1.07E-10	4.54E-11	5.02E-10	4.58E-10	1.70E-12
33.75	4.77E-09	2.96E-10	1.79E-10	1.48E-10	2.88E-09	3.75E-10	3.45E-10	1.48E-10	8.18E-11	3.48E-11	3.89E-10	3.50E-10	1.48E-12
36.25	3.97E-09	2.28E-10	1.62E-10	9.89E-11	2.60E-09	2.51E-10	2.48E-10	1.24E-10	5.47E-11	2.35E-11	2.69E-10	2.34E-10	1.38E-12
38.75	4.32E-09	2.40E-10	1.81E-10	9.72E-11	2.91E-09	2.46E-10	2.52E-10	1.35E-10	5.38E-11	2.31E-11	2.70E-10	2.30E-10	1.54E-12
41.25	5.18E-09	2.84E-10	2.20E-10	1.12E-10	3.52E-09	2.83E-10	2.95E-10	1.62E-10	6.19E-11	2.65E-11	3.13E-10	2.65E-10	1.85E-12
43.75	5.68E-09	3.10E-10	2.42E-10	1.21E-10	3.87E-09	3.07E-10	3.21E-10	1.78E-10	6.70E-11	2.86E-11	3.40E-10	2.87E-10	2.01E-12
46.25	4.79E-09	2.63E-10	2.03E-10	1.05E-10	3.25E-09	2.65E-10	2.75E-10	1.50E-10	5.78E-11	2.46E-11	2.92E-10	2.48E-10	1.69E-12
48.75	3.75E-09	2.07E-10	1.57E-10	8.38E-11	2.53E-09	2.12E-10	2.18E-10	1.17E-10	4.63E-11	1.98E-11	2.33E-10	1.98E-10	1.32E-12
51.25	2.71E-09	1.50E-10	1.13E-10	6.13E-11	1.82E-09	1.55E-10	1.59E-10	8.47E-11	3.39E-11	1.45E-11	1.70E-10	1.45E-10	9.50E-13
53.75	2.25E-09	1.25E-10	9.47E-11	5.06E-11	1.52E-09	1.28E-10	1.31E-10	7.05E-11	2.80E-11	1.20E-11	1.40E-10	1.20E-10	7.94E-13
56.25	2.14E-09	1.20E-10	8.93E-11	4.92E-11	1.43E-09	1.25E-10	1.27E-10	6.70E-11	2.72E-11	1.16E-11	1.36E-10	1.17E-10	7.46E-13
58.75	2.16E-09	1.23E-10	8.88E-11	5.26E-11	1.42E-09	1.33E-10	1.33E-10	6.75E-11	2.91E-11	1.24E-11	1.44E-10	1.25E-10	7.34E-13

Table F27: Mean Long Term Individual Risk of Mortality for MC_SFB1

Distance (km)	TOTAL	b.marrow	b.surface	breast	lung	stomach	colon	liver	pancreas	thyroid	Hered.Eff	remainder	skin
0.5	5.00E-08	7.70E-09	1.05E-08	1.12E-09	1.78E-08	2.90E-09	2.23E-09	4.66E-09	6.38E-10	2.58E-10	5.73E-09	2.76E-09	3.02E-11
1.75	7.15E-09	1.09E-09	1.45E-09	1.76E-10	2.50E-09	4.54E-10	3.48E-10	6.50E-10	9.98E-11	4.05E-11	8.42E-10	4.32E-10	4.17E-12
3.75	1.97E-09	2.97E-10	3.90E-10	5.11E-11	6.79E-10	1.32E-10	1.01E-10	1.76E-10	2.89E-11	1.18E-11	2.35E-10	1.25E-10	1.12E-12
6.25	9.69E-10	1.46E-10	1.91E-10	2.55E-11	3.34E-10	6.57E-11	5.03E-11	8.62E-11	1.44E-11	5.88E-12	1.16E-10	6.25E-11	5.48E-13
8.75	6.30E-10	9.53E-11	1.26E-10	1.61E-11	2.18E-10	4.15E-11	3.18E-11	5.66E-11	9.11E-12	3.70E-12	7.50E-11	3.94E-11	3.62E-13
11.25	2.85E-10	4.18E-11	5.19E-11	8.77E-12	9.44E-11	2.25E-11	1.71E-11	2.40E-11	4.94E-12	2.02E-12	3.59E-11	2.13E-11	1.48E-13
13.75	2.32E-10	3.45E-11	4.40E-11	6.69E-12	7.84E-11	1.72E-11	1.31E-11	2.01E-11	3.77E-12	1.54E-12	2.87E-11	1.63E-11	1.26E-13
16.25	1.88E-10	2.80E-11	3.57E-11	5.37E-12	6.36E-11	1.38E-11	1.05E-11	1.63E-11	3.03E-12	1.24E-12	2.32E-11	1.31E-11	1.02E-13
18.75	1.51E-10	2.25E-11	2.88E-11	4.25E-12	5.11E-11	1.09E-11	8.34E-12	1.31E-11	2.40E-12	9.78E-13	1.85E-11	1.04E-11	8.24E-14
21.25	1.32E-10	1.99E-11	2.60E-11	3.51E-12	4.54E-11	9.04E-12	6.91E-12	1.17E-11	1.98E-12	8.08E-13	1.59E-11	8.58E-12	7.45E-14
23.75	1.12E-10	1.70E-11	2.23E-11	2.92E-12	3.88E-11	7.51E-12	5.75E-12	1.01E-11	1.65E-12	6.71E-13	1.34E-11	7.14E-12	6.41E-14
26.25	1.04E-10	1.56E-11	2.02E-11	2.82E-12	3.55E-11	7.27E-12	5.55E-12	9.14E-12	1.60E-12	6.50E-13	1.26E-11	6.90E-12	5.78E-14
28.75	9.82E-11	1.45E-11	1.80E-11	3.00E-12	3.27E-11	7.70E-12	5.86E-12	8.31E-12	1.69E-12	6.90E-13	1.24E-11	7.29E-12	5.15E-14
31.25	9.44E-11	1.35E-11	1.57E-11	3.37E-12	3.00E-11	8.65E-12	6.55E-12	7.46E-12	1.89E-12	7.78E-13	1.26E-11	8.17E-12	4.45E-14
33.75	7.79E-11	1.13E-11	1.37E-11	2.57E-12	2.54E-11	6.59E-12	5.01E-12	6.39E-12	1.44E-12	5.92E-13	1.01E-11	6.24E-12	3.89E-14
36.25	6.42E-11	9.66E-12	1.26E-11	1.70E-12	2.21E-11	4.38E-12	3.35E-12	5.70E-12	9.62E-13	3.92E-13	7.72E-12	4.16E-12	3.62E-14
38.75	6.95E-11	1.06E-11	1.42E-11	1.67E-12	2.44E-11	4.29E-12	3.30E-12	6.36E-12	9.43E-13	3.83E-13	8.11E-12	4.09E-12	4.10E-14
41.25	8.32E-11	1.28E-11	1.73E-11	1.91E-12	2.94E-11	4.93E-12	3.79E-12	7.70E-12	1.08E-12	4.39E-13	9.60E-12	4.70E-12	4.99E-14
43.75	9.11E-11	1.40E-11	1.91E-11	2.07E-12	3.23E-11	5.34E-12	4.11E-12	8.46E-12	1.18E-12	4.75E-13	1.05E-11	5.09E-12	5.50E-14
46.25	7.70E-11	1.18E-11	1.60E-11	1.79E-12	2.72E-11	4.61E-12	3.55E-12	7.11E-12	1.01E-12	4.11E-13	8.91E-12	4.39E-12	4.60E-14
48.75	6.02E-11	9.21E-12	1.24E-11	1.44E-12	2.12E-11	3.70E-12	2.84E-12	5.52E-12	8.13E-13	3.30E-13	7.02E-12	3.52E-12	3.57E-14
51.25	4.36E-11	6.65E-12	8.91E-12	1.05E-12	1.53E-11	2.70E-12	2.08E-12	3.98E-12	5.95E-13	2.41E-13	5.09E-12	2.57E-12	2.57E-14
53.75	3.63E-11	5.54E-12	7.44E-12	8.65E-13	1.27E-11	2.23E-12	1.71E-12	3.32E-12	4.90E-13	1.99E-13	4.23E-12	2.12E-12	2.14E-14
56.25	3.45E-11	5.25E-12	7.01E-12	8.44E-13	1.21E-11	2.17E-12	1.67E-12	3.14E-12	4.78E-13	1.94E-13	4.05E-12	2.07E-12	2.02E-14
58.75	3.49E-11	5.27E-12	6.93E-12	9.04E-13	1.21E-11	2.33E-12	1.78E-12	3.12E-12	5.11E-13	2.08E-13	4.17E-12	2.21E-12	1.99E-14

Table F28: Mean Long Term Individual Risk of Mortality for MC_SFPL1

Distance (km)	TOTAL	b.marrow	b.surface	breast	lung	stomach	colon	liver	pancreas	thyroid	Hered.Eff	remainder	skin
0.5	3.42E-02	1.46E-02	1.67E-03	1.23E-02	1.99E-02	2.13E-02	1.86E-02	4.47E-03	7.16E-03	3.05E-03	9.23E+00	2.06E-02	1.33E-04
1.75	3.79E-02	1.94E-02	2.32E-03	1.67E-02	2.57E-02	2.71E-02	2.44E-02	6.20E-03	9.93E-03	4.22E-03	1.46E+00	2.65E-02	1.77E-04
3.75	3.88E-02	1.77E-02	2.07E-03	1.51E-02	2.37E-02	2.53E-02	2.23E-02	5.53E-03	8.85E-03	3.76E-03	4.43E-01	2.46E-02	1.61E-04
6.25	4.21E-02	1.96E-02	2.36E-03	1.70E-02	2.61E-02	2.77E-02	2.45E-02	6.32E-03	1.01E-02	4.29E-03	2.12E-01	2.70E-02	1.80E-04
8.75	4.39E-02	1.85E-02	2.21E-03	1.59E-02	2.55E-02	2.72E-02	2.39E-02	5.89E-03	9.44E-03	3.99E-03	1.41E-01	2.64E-02	1.67E-04
11.25	4.25E-02	1.58E-02	1.81E-03	1.32E-02	2.32E-02	2.53E-02	2.12E-02	4.84E-03	7.75E-03	3.28E-03	1.12E-01	2.43E-02	1.39E-04
13.75	4.02E-02	1.44E-02	1.69E-03	1.22E-02	2.10E-02	2.28E-02	1.93E-02	4.51E-03	7.22E-03	3.05E-03	8.91E-02	2.20E-02	1.28E-04
16.25	3.88E-02	1.34E-02	1.51E-03	1.13E-02	1.99E-02	2.16E-02	1.82E-02	4.04E-03	6.48E-03	2.73E-03	5.88E-02	2.08E-02	1.17E-04
18.75	3.56E-02	1.28E-02	1.48E-03	1.09E-02	1.90E-02	2.06E-02	1.75E-02	3.96E-03	6.34E-03	2.67E-03	4.59E-02	1.99E-02	1.08E-04
21.25	3.49E-02	1.24E-02	1.39E-03	1.03E-02	1.92E-02	2.08E-02	1.74E-02	3.72E-03	5.95E-03	2.51E-03	4.48E-02	2.01E-02	1.02E-04
23.75	3.26E-02	1.09E-02	1.25E-03	9.12E-03	1.65E-02	1.80E-02	1.50E-02	3.35E-03	5.36E-03	2.26E-03	3.91E-02	1.73E-02	8.98E-05
26.25	3.18E-02	1.01E-02	1.12E-03	8.37E-03	1.56E-02	1.71E-02	1.41E-02	3.00E-03	4.81E-03	2.02E-03	3.21E-02	1.64E-02	8.27E-05
28.75	3.23E-02	1.03E-02	1.13E-03	8.48E-03	1.60E-02	1.76E-02	1.45E-02	3.03E-03	4.85E-03	2.04E-03	3.12E-02	1.69E-02	8.59E-05
31.25	3.36E-02	1.09E-02	1.23E-03	9.07E-03	1.63E-02	1.79E-02	1.48E-02	3.28E-03	5.25E-03	2.20E-03	2.97E-02	1.71E-02	9.14E-05
33.75	3.37E-02	1.03E-02	1.15E-03	8.54E-03	1.61E-02	1.78E-02	1.46E-02	3.07E-03	4.92E-03	2.06E-03	2.40E-02	1.70E-02	8.64E-05
36.25	3.64E-02	1.29E-02	1.46E-03	1.08E-02	1.89E-02	2.06E-02	1.73E-02	3.91E-03	6.26E-03	2.62E-03	2.86E-02	1.98E-02	1.11E-04
38.75	3.15E-02	1.04E-02	1.20E-03	8.64E-03	1.63E-02	1.78E-02	1.48E-02	3.21E-03	5.14E-03	2.15E-03	3.06E-02	1.71E-02	8.81E-05
41.25	2.92E-02	8.30E-03	9.20E-04	6.81E-03	1.33E-02	1.49E-02	1.19E-02	2.46E-03	3.93E-03	1.65E-03	1.98E-02	1.42E-02	6.91E-05
43.75	2.81E-02	9.88E-03	1.06E-03	8.07E-03	1.55E-02	1.67E-02	1.42E-02	2.84E-03	4.55E-03	1.90E-03	2.09E-02	1.61E-02	8.31E-05
46.25	2.69E-02	9.51E-03	1.09E-03	8.07E-03	1.38E-02	1.50E-02	1.28E-02	2.90E-03	4.65E-03	1.94E-03	2.31E-02	1.45E-02	8.32E-05
48.75	2.49E-02	7.00E-03	7.97E-04	5.80E-03	1.14E-02	1.27E-02	1.02E-02	2.13E-03	3.41E-03	1.42E-03	1.89E-02	1.21E-02	5.78E-05
51.25	2.28E-02	6.14E-03	6.69E-04	5.01E-03	9.99E-03	1.12E-02	8.95E-03	1.79E-03	2.86E-03	1.20E-03	1.36E-02	1.06E-02	4.91E-05
53.75	2.01E-02	4.75E-03	5.17E-04	3.88E-03	8.01E-03	9.05E-03	7.07E-03	1.38E-03	2.21E-03	9.26E-04	1.10E-02	8.56E-03	3.64E-05
56.25	1.85E-02	4.31E-03	4.75E-04	3.55E-03	7.21E-03	8.16E-03	6.36E-03	1.27E-03	2.03E-03	8.50E-04	9.71E-03	7.71E-03	3.26E-05
58.75	1.78E-02	3.75E-03	4.04E-04	3.06E-03	6.40E-03	7.27E-03	5.64E-03	1.08E-03	1.73E-03	7.24E-04	8.54E-03	6.86E-03	2.88E-05

Table F29: Mean Long Term Individual Risk of Mortality for MC_SEAL1

Distance (km)	TOTAL	b.marrow	b.surface	breast	lung	stomach	colon	liver	pancreas	thyroid	Hered.Eff	remainder	skin
0.5	1.28E-09	2.16E-10	3.42E-10	6.28E-12	5.18E-10	1.66E-11	1.43E-11	1.43E-10	3.78E-12	1.37E-12	1.15E-10	1.72E-11	6.90E-13
1.75	1.63E-10	2.75E-11	4.36E-11	8.49E-13	6.60E-11	2.24E-12	1.91E-12	1.82E-11	5.07E-13	1.85E-13	1.48E-11	2.31E-12	8.78E-14
3.75	4.43E-11	7.47E-12	1.18E-11	2.46E-13	1.79E-11	6.45E-13	5.47E-13	4.93E-12	1.46E-13	5.37E-14	4.03E-12	6.63E-13	2.38E-14
6.25	1.84E-11	3.10E-12	4.87E-12	1.10E-13	7.41E-12	2.87E-13	2.41E-13	2.04E-12	6.47E-14	2.40E-14	1.68E-12	2.93E-13	9.81E-15
8.75	1.06E-11	1.79E-12	2.82E-12	6.24E-14	4.28E-12	1.63E-13	1.37E-13	1.18E-12	3.69E-14	1.37E-14	9.70E-13	1.67E-13	5.67E-15
11.25	8.37E-12	1.41E-12	2.21E-12	5.34E-14	3.36E-12	1.39E-13	1.16E-13	9.24E-13	3.14E-14	1.17E-14	7.71E-13	1.42E-13	4.44E-15
13.75	5.75E-12	9.64E-13	1.51E-12	3.78E-14	2.31E-12	9.84E-14	8.18E-14	6.34E-13	2.21E-14	8.30E-15	5.31E-13	9.97E-14	3.04E-15
16.25	4.68E-12	7.86E-13	1.23E-12	3.03E-14	1.88E-12	7.90E-14	6.58E-14	5.17E-13	1.78E-14	6.66E-15	4.32E-13	8.02E-14	2.48E-15
18.75	3.87E-12	6.50E-13	1.02E-12	2.43E-14	1.56E-12	6.34E-14	5.30E-14	4.28E-13	1.43E-14	5.33E-15	3.56E-13	6.45E-14	2.06E-15
21.25	3.54E-12	5.93E-13	9.30E-13	2.31E-14	1.42E-12	6.03E-14	5.02E-14	3.90E-13	1.36E-14	5.08E-15	3.27E-13	6.10E-14	1.87E-15
23.75	3.18E-12	5.34E-13	8.38E-13	2.03E-14	1.28E-12	5.30E-14	4.42E-14	3.51E-13	1.19E-14	4.46E-15	2.93E-13	5.37E-14	1.69E-15
26.25	2.88E-12	4.84E-13	7.62E-13	1.77E-14	1.16E-12	4.63E-14	3.88E-14	3.19E-13	1.04E-14	3.88E-15	2.65E-13	4.71E-14	1.54E-15
28.75	2.32E-12	3.90E-13	6.13E-13	1.48E-14	9.34E-13	3.87E-14	3.23E-14	2.57E-13	8.71E-15	3.25E-15	2.14E-13	3.92E-14	1.23E-15
31.25	2.10E-12	3.52E-13	5.52E-13	1.33E-14	8.42E-13	3.48E-14	2.91E-14	2.31E-13	7.84E-15	2.93E-15	1.93E-13	3.53E-14	1.11E-15
33.75	2.00E-12	3.36E-13	5.29E-13	1.23E-14	8.05E-13	3.23E-14	2.71E-14	2.21E-13	7.27E-15	2.71E-15	1.84E-13	3.28E-14	1.07E-15
36.25	1.89E-12	3.18E-13	5.01E-13	1.11E-14	7.62E-13	2.91E-14	2.46E-14	2.10E-13	6.58E-15	2.43E-15	1.73E-13	2.98E-14	1.01E-15
38.75	1.70E-12	2.87E-13	4.51E-13	1.00E-14	6.87E-13	2.62E-14	2.22E-14	1.89E-13	5.93E-15	2.19E-15	1.56E-13	2.68E-14	9.10E-16
41.25	1.47E-12	2.47E-13	3.89E-13	8.60E-15	5.91E-13	2.25E-14	1.90E-14	1.63E-13	5.09E-15	1.88E-15	1.34E-13	2.30E-14	7.84E-16
43.75	1.33E-12	2.24E-13	3.54E-13	7.67E-15	5.37E-13	2.01E-14	1.70E-14	1.48E-13	4.54E-15	1.68E-15	1.22E-13	2.06E-14	7.13E-16
46.25	1.24E-12	2.10E-13	3.31E-13	7.04E-15	5.02E-13	1.84E-14	1.57E-14	1.38E-13	4.17E-15	1.54E-15	1.13E-13	1.89E-14	6.67E-16
48.75	1.23E-12	2.07E-13	3.28E-13	6.80E-15	4.97E-13	1.78E-14	1.52E-14	1.37E-13	4.04E-15	1.48E-15	1.12E-13	1.83E-14	6.61E-16
51.25	1.15E-12	1.93E-13	3.05E-13	6.33E-15	4.63E-13	1.66E-14	1.41E-14	1.28E-13	3.76E-15	1.38E-15	1.04E-13	1.71E-14	6.16E-16
53.75	1.02E-12	1.72E-13	2.71E-13	5.94E-15	4.11E-13	1.56E-14	1.32E-14	1.13E-13	3.52E-15	1.30E-15	9.32E-14	1.59E-14	5.46E-16
56.25	9.61E-13	1.61E-13	2.54E-13	5.98E-15	3.87E-13	1.56E-14	1.31E-14	1.06E-13	3.52E-15	1.31E-15	8.83E-14	1.59E-14	5.11E-16
58.75	9.08E-13	1.52E-13	2.39E-13	5.99E-15	3.64E-13	1.56E-14	1.31E-14	1.00E-13	3.52E-15	1.32E-15	8.40E-14	1.58E-14	4.81E-16

Table F30: Mean Long Term Individual Risk of Mortality for MC_FIRE1

Distance (km)	TOTAL	b.marrow	b.surface	breast	lung	stomach	colon	liver	pancreas	thyroid	Hered.Eff	remainder	skin
0.5	2.02E-02	3.57E-03	5.21E-03	5.94E-04	9.00E-03	1.52E-03	1.16E-03	2.35E-03	3.37E-04	1.37E-04	2.96E-03	1.45E-03	6.84E-06
1.75	5.23E-03	8.13E-04	1.18E-03	1.37E-04	2.05E-03	3.54E-04	2.68E-04	5.35E-04	7.78E-05	3.16E-05	6.76E-04	3.37E-04	1.55E-06
3.75	1.69E-03	2.47E-04	3.53E-04	4.44E-05	6.18E-04	1.14E-04	8.64E-05	1.61E-04	2.51E-05	1.02E-05	2.10E-04	1.09E-04	4.62E-07
6.25	7.73E-04	1.10E-04	1.53E-04	2.19E-05	2.73E-04	5.63E-05	4.25E-05	7.03E-05	1.24E-05	5.03E-06	9.72E-05	5.34E-05	2.00E-07
8.75	5.43E-04	7.69E-05	1.07E-04	1.51E-05	1.91E-04	3.90E-05	2.94E-05	4.93E-05	8.55E-06	3.49E-06	6.77E-05	3.70E-05	1.40E-07
11.25	3.81E-04	5.40E-05	7.65E-05	1.02E-05	1.35E-04	2.61E-05	1.98E-05	3.49E-05	5.74E-06	2.34E-06	4.67E-05	2.48E-05	1.00E-07
13.75	2.64E-04	3.72E-05	5.19E-05	7.34E-06	9.25E-05	1.89E-05	1.43E-05	2.39E-05	4.14E-06	1.69E-06	3.28E-05	1.79E-05	6.78E-08
16.25	2.24E-04	3.13E-05	4.34E-05	6.34E-06	7.77E-05	1.63E-05	1.23E-05	2.00E-05	3.58E-06	1.46E-06	2.79E-05	1.55E-05	5.66E-08
18.75	1.93E-04	2.69E-05	3.67E-05	5.65E-06	6.64E-05	1.45E-05	1.10E-05	1.70E-05	3.19E-06	1.30E-06	2.43E-05	1.38E-05	4.79E-08
21.25	1.93E-04	2.72E-05	3.75E-05	5.57E-06	6.73E-05	1.43E-05	1.08E-05	1.73E-05	3.14E-06	1.28E-06	2.43E-05	1.36E-05	4.89E-08
23.75	1.64E-04	2.29E-05	3.12E-05	4.87E-06	5.66E-05	1.25E-05	9.44E-06	1.45E-05	2.74E-06	1.12E-06	2.08E-05	1.19E-05	4.07E-08
26.25	1.41E-04	1.96E-05	2.67E-05	4.19E-06	4.84E-05	1.08E-05	8.12E-06	1.24E-05	2.36E-06	9.64E-07	1.78E-05	1.02E-05	3.48E-08
28.75	1.21E-04	1.70E-05	2.36E-05	3.39E-06	4.22E-05	8.72E-06	6.58E-06	1.09E-05	1.91E-06	7.80E-07	1.50E-05	8.28E-06	3.09E-08
31.25	1.07E-04	1.50E-05	2.10E-05	2.93E-06	3.73E-05	7.55E-06	5.70E-06	9.63E-06	1.66E-06	6.75E-07	1.32E-05	7.16E-06	2.74E-08
33.75	1.03E-04	1.46E-05	2.06E-05	2.74E-06	3.64E-05	7.04E-06	5.32E-06	9.42E-06	1.55E-06	6.29E-07	1.26E-05	6.69E-06	2.70E-08
36.25	1.10E-04	1.55E-05	2.22E-05	2.81E-06	3.89E-05	7.23E-06	5.47E-06	1.01E-05	1.59E-06	6.46E-07	1.32E-05	6.88E-06	2.91E-08
38.75	1.14E-04	1.62E-05	2.33E-05	2.88E-06	4.07E-05	7.42E-06	5.62E-06	1.06E-05	1.63E-06	6.62E-07	1.37E-05	7.06E-06	3.05E-08
41.25	1.03E-04	1.45E-05	2.04E-05	2.75E-06	3.61E-05	7.07E-06	5.34E-06	9.35E-06	1.55E-06	6.32E-07	1.26E-05	6.71E-06	2.67E-08
43.75	8.45E-05	1.16E-05	1.51E-05	2.78E-06	2.82E-05	7.14E-06	5.37E-06	7.11E-06	1.56E-06	6.41E-07	1.10E-05	6.75E-06	1.95E-08
46.25	7.65E-05	1.04E-05	1.31E-05	2.69E-06	2.50E-05	6.90E-06	5.19E-06	6.26E-06	1.51E-06	6.20E-07	1.02E-05	6.52E-06	1.69E-08
48.75	7.22E-05	9.82E-06	1.26E-05	2.47E-06	2.38E-05	6.34E-06	4.77E-06	5.98E-06	1.39E-06	5.70E-07	9.57E-06	6.00E-06	1.63E-08
51.25	7.37E-05	1.01E-05	1.33E-05	2.39E-06	2.47E-05	6.15E-06	4.63E-06	6.25E-06	1.35E-06	5.52E-07	9.60E-06	5.82E-06	1.72E-08
53.75	6.75E-05	9.33E-06	1.26E-05	2.05E-06	2.30E-05	5.27E-06	3.97E-06	5.86E-06	1.16E-06	4.72E-07	8.58E-06	4.99E-06	1.64E-08
56.25	5.54E-05	7.72E-06	1.06E-05	1.60E-06	1.91E-05	4.10E-06	3.10E-06	4.91E-06	9.01E-07	3.68E-07	6.93E-06	3.89E-06	1.39E-08
58.75	4.97E-05	6.93E-06	9.61E-06	1.40E-06	1.72E-05	3.59E-06	2.71E-06	4.43E-06	7.88E-07	3.21E-07	6.16E-06	3.41E-06	1.26E-08

Table F31: Early Fatalities per Distance Band

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Deaths per Year
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
1.75	0.00E+00	0.00E+00	1.41E+02	0.00E+00	0.00E+00	**3.15E-05**
3.75	0.00E+00	0.00E+00	5.73E+01	0.00E+00	0.00E+00	**1.28E-05**
6.25	0.00E+00	0.00E+00	2.37E+01	0.00E+00	0.00E+00	**5.31E-06**
8.75	0.00E+00	0.00E+00	9.35E+00	0.00E+00	0.00E+00	**2.09E-06**
11.25	0.00E+00	0.00E+00	2.02E+02	0.00E+00	0.00E+00	**4.52E-05**
13.75	0.00E+00	0.00E+00	2.04E+03	0.00E+00	0.00E+00	**4.56E-04**
16.25	0.00E+00	0.00E+00	3.93E+02	0.00E+00	0.00E+00	**8.80E-05**
18.75	0.00E+00	0.00E+00	1.29E+02	0.00E+00	0.00E+00	**2.89E-05**
21.25	0.00E+00	0.00E+00	5.10E+01	0.00E+00	0.00E+00	**1.14E-05**
23.75	0.00E+00	0.00E+00	1.68E+02	0.00E+00	0.00E+00	**3.76E-05**
26.25	0.00E+00	0.00E+00	3.62E+02	0.00E+00	0.00E+00	**8.12E-05**
28.75	0.00E+00	0.00E+00	3.51E+02	0.00E+00	0.00E+00	**7.86E-05**
31.25	0.00E+00	0.00E+00	4.20E+02	0.00E+00	0.00E+00	**9.40E-05**
33.75	0.00E+00	0.00E+00	5.22E+02	0.00E+00	0.00E+00	**1.17E-04**
36.25	0.00E+00	0.00E+00	3.54E+02	0.00E+00	0.00E+00	**7.93E-05**
38.75	0.00E+00	0.00E+00	1.82E+02	0.00E+00	0.00E+00	**4.07E-05**
41.25	0.00E+00	0.00E+00	9.09E+01	0.00E+00	0.00E+00	**2.04E-05**
43.75	0.00E+00	0.00E+00	7.84E+01	0.00E+00	0.00E+00	**1.76E-05**
46.25	0.00E+00	0.00E+00	1.34E+02	0.00E+00	0.00E+00	**2.99E-05**
48.75	0.00E+00	0.00E+00	3.39E+01	0.00E+00	0.00E+00	**7.59E-06**
51.25	0.00E+00	0.00E+00	1.44E+01	0.00E+00	0.00E+00	**3.22E-06**
53.75	0.00E+00	0.00E+00	4.39E+01	0.00E+00	0.00E+00	**9.82E-06**
56.25	0.00E+00	0.00E+00	4.74E+01	0.00E+00	0.00E+00	**1.06E-05**
58.75	0.00E+00	0.00E+00	1.64E+01	0.00E+00	0.00E+00	**3.67E-06**
Total Deaths	**0.00E+00**	**0.00E+00**	**5.86E+03**	**0.00E+00**	**0.00E+00**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Table F32: Late Fatalities per Distance Band

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Deaths per Year
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
1.75	3.70E-04	6.04E-06	9.03E+01	3.46E-07	1.58E+01	**2.16E-05**
3.75	1.72E-04	2.81E-06	3.80E+01	1.12E-07	3.46E+00	**8.82E-06**
6.25	2.30E-04	3.90E-06	2.04E+02	3.60E-08	6.15E-01	**4.58E-05**
8.75	2.44E-05	4.01E-07	7.95E+01	1.19E-08	1.37E+00	**1.79E-05**
11.25	5.53E-05	8.88E-07	2.64E+02	4.57E-08	1.54E+00	**5.92E-05**
13.75	6.59E-04	1.07E-05	2.66E+03	4.20E-07	1.15E+01	**5.98E-04**
16.25	1.05E-03	1.72E-05	2.83E+03	6.53E-07	3.11E+01	**6.37E-04**
18.75	5.88E-04	9.69E-06	1.89E+03	7.31E-07	1.41E+01	**4.24E-04**
21.25	2.88E-04	4.74E-06	8.23E+02	2.25E-07	1.36E+01	**1.86E-04**
23.75	7.16E-04	1.18E-05	2.60E+03	3.59E-07	3.84E+01	**5.85E-04**
26.25	1.62E-03	2.67E-05	6.14E+03	6.42E-07	4.13E+01	**1.38E-03**
28.75	1.96E-03	3.26E-05	8.26E+03	6.32E-07	3.78E+01	**1.85E-03**
31.25	2.17E-03	3.66E-05	1.49E+04	1.01E-06	5.19E+01	**3.34E-03**
33.75	1.89E-03	3.13E-05	1.52E+04	9.86E-07	4.66E+01	**3.41E-03**
36.25	1.51E-03	2.43E-05	1.32E+04	5.98E-07	4.21E+01	**2.96E-03**
38.75	1.49E-03	2.41E-05	8.13E+03	3.88E-07	3.04E+01	**1.82E-03**
41.25	1.19E-03	1.94E-05	7.92E+03	4.53E-07	3.09E+01	**1.78E-03**
43.75	1.21E-03	1.99E-05	1.15E+04	5.43E-07	6.62E+01	**2.57E-03**
46.25	1.13E-03	1.85E-05	7.96E+03	4.13E-07	5.46E+01	**1.79E-03**
48.75	3.63E-04	5.90E-06	4.17E+03	1.09E-07	4.47E+01	**9.39E-04**
51.25	3.30E-04	5.31E-06	3.78E+03	1.13E-07	1.41E+01	**8.47E-04**
53.75	2.68E-04	4.34E-06	2.99E+03	8.34E-08	1.03E+01	**6.71E-04**
56.25	3.99E-05	6.48E-07	9.81E+02	1.66E-08	2.53E+00	**2.20E-04**
58.75	4.44E-05	7.45E-07	1.49E+03	1.21E-08	2.35E+00	**3.35E-04**
Total Deaths	**1.94E-02**	**3.18E-04**	**1.18E+05**	**8.94E-06**	**6.07E+02**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Table F33: Total Fatalities per Distance Band

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Deaths per Year
0.5	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**
1.75	3.70E-04	6.04E-06	2.31E+02	3.46E-07	1.58E+01	**5.31E-05**
3.75	1.72E-04	2.81E-06	9.53E+01	1.12E-07	3.46E+00	**2.17E-05**
6.25	2.30E-04	3.90E-06	2.28E+02	3.60E-08	6.15E-01	**5.11E-05**
8.75	2.44E-05	4.01E-07	8.89E+01	1.19E-08	1.37E+00	**2.00E-05**
11.25	5.53E-05	8.88E-07	4.65E+02	4.57E-08	1.54E+00	**1.04E-04**
13.75	6.59E-04	1.07E-05	4.70E+03	4.20E-07	1.15E+01	**1.05E-03**
16.25	1.05E-03	1.72E-05	3.23E+03	6.53E-07	3.11E+01	**7.25E-04**
18.75	5.88E-04	9.69E-06	2.02E+03	7.31E-07	1.41E+01	**4.53E-04**
21.25	2.88E-04	4.74E-06	8.74E+02	2.25E-07	1.36E+01	**1.97E-04**
23.75	7.16E-04	1.18E-05	2.77E+03	3.59E-07	3.84E+01	**6.23E-04**
26.25	1.62E-03	2.67E-05	6.50E+03	6.42E-07	4.13E+01	**1.46E-03**
28.75	1.96E-03	3.26E-05	8.61E+03	6.32E-07	3.78E+01	**1.93E-03**
31.25	2.17E-03	3.66E-05	1.53E+04	1.01E-06	5.19E+01	**3.43E-03**
33.75	1.89E-03	3.13E-05	1.57E+04	9.86E-07	4.66E+01	**3.52E-03**
36.25	1.51E-03	2.43E-05	1.35E+04	5.98E-07	4.21E+01	**3.04E-03**
38.75	1.49E-03	2.41E-05	8.32E+03	3.88E-07	3.04E+01	**1.87E-03**
41.25	1.19E-03	1.94E-05	8.01E+03	4.53E-07	3.09E+01	**1.80E-03**
43.75	1.21E-03	1.99E-05	1.15E+04	5.43E-07	6.62E+01	**2.59E-03**
46.25	1.13E-03	1.85E-05	8.09E+03	4.13E-07	5.46E+01	**1.82E-03**
48.75	3.63E-04	5.90E-06	4.21E+03	1.09E-07	4.47E+01	**9.47E-04**
51.25	3.30E-04	5.31E-06	3.79E+03	1.13E-07	1.41E+01	**8.50E-04**
53.75	2.68E-04	4.34E-06	3.04E+03	8.34E-08	1.03E+01	**6.81E-04**
56.25	3.99E-05	6.48E-07	1.03E+03	1.66E-08	2.53E+00	**2.31E-04**
58.75	4.44E-05	7.45E-07	1.51E+03	1.21E-08	2.35E+00	**3.39E-04**
Total Deaths	**1.94E-02**	**3.18E-04**	**1.24E+05**	**8.94E-06**	**6.07E+02**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Population	**4.869E+07**
Pop within 1.75 km	**2076**

	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Deaths per Year
Av Public Risk	4.05E-16	1.83E-17	5.70E-10	1.43E-17	1.11E-12	**5.71E-10**
Peak Public Risk	1.82E-13	8.14E-15	2.49E-08	1.29E-14	6.80E-10	**2.56E-08**
Av Pblc Cond Rsk	3.97E-10	6.54E-12	2.54E-03	1.84E-13	1.25E-05	
Pk Pblc Cond Rsk	1.78E-07	2.91E-09	1.11E-01	1.67E-10	7.63E-03	

Table F34: Short Term Conditional Individual Mortality Risk

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Risk
0.5	0.00E+00	0.00E+00	8.68E-02	0.00E+00	0.00E+00	**1.94E-08**
1.75	0.00E+00	0.00E+00	4.87E-02	0.00E+00	0.00E+00	**1.09E-08**
3.75	0.00E+00	0.00E+00	3.05E-02	0.00E+00	0.00E+00	**6.83E-09**
6.25	0.00E+00	0.00E+00	1.83E-02	0.00E+00	0.00E+00	**4.11E-09**
8.75	0.00E+00	0.00E+00	1.01E-02	0.00E+00	0.00E+00	**2.27E-09**
11.25	0.00E+00	0.00E+00	7.60E-03	0.00E+00	0.00E+00	**1.70E-09**
13.75	0.00E+00	0.00E+00	5.82E-03	0.00E+00	0.00E+00	**1.30E-09**
16.25	0.00E+00	0.00E+00	3.83E-03	0.00E+00	0.00E+00	**8.59E-10**
18.75	0.00E+00	0.00E+00	3.64E-03	0.00E+00	0.00E+00	**8.16E-10**
21.25	0.00E+00	0.00E+00	2.87E-03	0.00E+00	0.00E+00	**6.44E-10**
23.75	0.00E+00	0.00E+00	2.64E-03	0.00E+00	0.00E+00	**5.92E-10**
26.25	0.00E+00	0.00E+00	2.13E-03	0.00E+00	0.00E+00	**4.76E-10**
28.75	0.00E+00	0.00E+00	1.91E-03	0.00E+00	0.00E+00	**4.27E-10**
31.25	0.00E+00	0.00E+00	1.33E-03	0.00E+00	0.00E+00	**2.97E-10**
33.75	0.00E+00	0.00E+00	8.71E-04	0.00E+00	0.00E+00	**1.95E-10**
36.25	0.00E+00	0.00E+00	8.68E-04	0.00E+00	0.00E+00	**1.94E-10**
38.75	0.00E+00	0.00E+00	2.52E-03	0.00E+00	0.00E+00	**5.65E-10**
41.25	0.00E+00	0.00E+00	1.00E-03	0.00E+00	0.00E+00	**2.24E-10**
43.75	0.00E+00	0.00E+00	7.05E-04	0.00E+00	0.00E+00	**1.58E-10**
46.25	0.00E+00	0.00E+00	1.05E-03	0.00E+00	0.00E+00	**2.36E-10**
48.75	0.00E+00	0.00E+00	1.27E-03	0.00E+00	0.00E+00	**2.84E-10**
51.25	0.00E+00	0.00E+00	5.13E-04	0.00E+00	0.00E+00	**1.15E-10**
53.75	0.00E+00	0.00E+00	4.64E-04	0.00E+00	0.00E+00	**1.04E-10**
56.25	0.00E+00	0.00E+00	2.99E-04	0.00E+00	0.00E+00	**6.70E-11**
58.75	0.00E+00	0.00E+00	2.84E-04	0.00E+00	0.00E+00	**6.35E-11**
Total Risk	**0.00E+00**	**0.00E+00**	**2.36E-01**	**0.00E+00**	**0.00E+00**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Table F35: Long Term Conditional Individual Mortality Risk

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Risk
0.5	3.09E-06	5.00E-08	3.42E-02	1.28E-09	2.02E-02	**9.47E-09**
1.75	4.42E-07	7.15E-09	3.79E-02	1.63E-10	5.23E-03	**8.95E-09**
3.75	1.22E-07	1.97E-09	3.88E-02	4.43E-11	1.69E-03	**8.84E-09**
6.25	6.01E-08	9.69E-10	4.21E-02	1.84E-11	7.73E-04	**9.51E-09**
8.75	3.91E-08	6.30E-10	4.39E-02	1.06E-11	5.43E-04	**9.88E-09**
11.25	1.76E-08	2.85E-10	4.25E-02	8.37E-12	3.81E-04	**9.55E-09**
13.75	1.44E-08	2.32E-10	4.02E-02	5.75E-12	2.64E-04	**9.03E-09**
16.25	1.16E-08	1.88E-10	3.88E-02	4.68E-12	2.24E-04	**8.72E-09**
18.75	9.33E-09	1.51E-10	3.56E-02	3.87E-12	1.93E-04	**7.98E-09**
21.25	8.18E-09	1.32E-10	3.49E-02	3.54E-12	1.93E-04	**7.84E-09**
23.75	6.96E-09	1.12E-10	3.26E-02	3.18E-12	1.64E-04	**7.31E-09**
26.25	6.41E-09	1.04E-10	3.18E-02	2.88E-12	1.41E-04	**7.14E-09**
28.75	6.04E-09	9.82E-11	3.23E-02	2.32E-12	1.21E-04	**7.25E-09**
31.25	5.75E-09	9.44E-11	3.36E-02	2.10E-12	1.07E-04	**7.54E-09**
33.75	4.77E-09	7.79E-11	3.37E-02	2.00E-12	1.03E-04	**7.55E-09**
36.25	3.97E-09	6.42E-11	3.64E-02	1.89E-12	1.10E-04	**8.15E-09**
38.75	4.32E-09	6.95E-11	3.15E-02	1.70E-12	1.14E-04	**7.06E-09**
41.25	5.18E-09	8.32E-11	2.92E-02	1.47E-12	1.03E-04	**6.55E-09**
43.75	5.68E-09	9.11E-11	2.81E-02	1.33E-12	8.45E-05	**6.29E-09**
46.25	4.79E-09	7.70E-11	2.69E-02	1.24E-12	7.65E-05	**6.02E-09**
48.75	3.75E-09	6.02E-11	2.49E-02	1.23E-12	7.22E-05	**5.58E-09**
51.25	2.71E-09	4.36E-11	2.28E-02	1.15E-12	7.37E-05	**5.12E-09**
53.75	2.25E-09	3.63E-11	2.01E-02	1.02E-12	6.75E-05	**4.51E-09**
56.25	2.14E-09	3.45E-11	1.85E-02	9.61E-13	5.54E-05	**4.16E-09**
58.75	2.16E-09	3.49E-11	1.78E-02	9.08E-13	4.97E-05	**3.99E-09**
Total Risk	**3.88E-06**	**6.28E-08**	**8.09E-01**	**1.56E-09**	**3.11E-02**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Table F37: Total Conditional Individual Mortality Risk

Distance (km)	MC_LOAD1	MC_SFB1	MC_SFPL1	MC_SEAL1	MC_FIRE1	Risk
0.5	3.09E-06	5.00E-08	1.21E-01	1.28E-09	2.02E-02	**2.89E-08**
1.75	4.42E-07	7.15E-09	8.66E-02	1.63E-10	5.23E-03	**1.99E-08**
3.75	1.22E-07	1.97E-09	6.93E-02	4.43E-11	1.69E-03	**1.57E-08**
6.25	6.01E-08	9.69E-10	6.05E-02	1.84E-11	7.73E-04	**1.36E-08**
8.75	3.91E-08	6.30E-10	5.40E-02	1.06E-11	5.43E-04	**1.21E-08**
11.25	1.76E-08	2.85E-10	5.01E-02	8.37E-12	3.81E-04	**1.12E-08**
13.75	1.44E-08	2.32E-10	4.60E-02	5.75E-12	2.64E-04	**1.03E-08**
16.25	1.16E-08	1.88E-10	4.27E-02	4.68E-12	2.24E-04	**9.58E-09**
18.75	9.33E-09	1.51E-10	3.92E-02	3.87E-12	1.93E-04	**8.80E-09**
21.25	8.18E-09	1.32E-10	3.78E-02	3.54E-12	1.93E-04	**8.48E-09**
23.75	6.96E-09	1.12E-10	3.52E-02	3.18E-12	1.64E-04	**7.90E-09**
26.25	6.41E-09	1.04E-10	3.39E-02	2.88E-12	1.41E-04	**7.61E-09**
28.75	6.04E-09	9.82E-11	3.42E-02	2.32E-12	1.21E-04	**7.67E-09**
31.25	5.75E-09	9.44E-11	3.49E-02	2.10E-12	1.07E-04	**7.83E-09**
33.75	4.77E-09	7.79E-11	3.45E-02	2.00E-12	1.03E-04	**7.75E-09**
36.25	3.97E-09	6.42E-11	3.72E-02	1.89E-12	1.10E-04	**8.35E-09**
38.75	4.32E-09	6.95E-11	3.40E-02	1.70E-12	1.14E-04	**7.63E-09**
41.25	5.18E-09	8.32E-11	3.02E-02	1.47E-12	1.03E-04	**6.77E-09**
43.75	5.68E-09	9.11E-11	2.88E-02	1.33E-12	8.45E-05	**6.45E-09**
46.25	4.79E-09	7.70E-11	2.79E-02	1.24E-12	7.65E-05	**6.26E-09**
48.75	3.75E-09	6.02E-11	2.62E-02	1.23E-12	7.22E-05	**5.86E-09**
51.25	2.71E-09	4.36E-11	2.34E-02	1.15E-12	7.37E-05	**5.24E-09**
53.75	2.25E-09	3.63E-11	2.06E-02	1.02E-12	6.75E-05	**4.61E-09**
56.25	2.14E-09	3.45E-11	1.88E-02	9.61E-13	5.54E-05	**4.22E-09**
58.75	2.16E-09	3.49E-11	1.81E-02	9.08E-13	4.97E-05	**4.05E-09**
Total Risk	**3.88E-06**	**6.28E-08**	**1.04E+00**	**1.56E-09**	**3.11E-02**	
Frequency	**1.02E-06**	**2.80E-06**	**2.24E-07**	**7.76E-05**	**8.91E-08**	

Av Site Risk	3.15E-12	1.40E-13	2.71E-08	9.90E-14	1.80E-09	**2.89E-08**
Peak Site Risk	3.15E-12	1.40E-13	2.71E-08	9.90E-14	1.80E-09	**2.89E-08**

PAIA section 44 (2)a.Redacted information could jepoardise effectiveness of testing procedure if disclosed

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17 APPENDIX I: ENVIRONMENTAL IMPACT STATEMENT

The U.S Nuclear Regulatory Commission (NRC) has conducted several risk assessments and other analyses to evaluate the safety of transportation of spent power reactor nuclear fuel during the past 35 years. The first analysis documented in NUREG-0170, "Final Environmental Statement on the Transportation of Radioactive Material by Air and Other Modes" [62], provided an environmental impact statement for transportation of all types of radioactive material by road, rail, air, and water, and concluded the following:

- The average radiation dose to members of the public from routine transportation of radioactive materials is a fraction of their background dose.

- The radiological risk from accidents in transporting radioactive material is very small compared to the non-radiological risk from accidents involving large trucks or freight trains.

On the basis of this environmental impact statement, NRC regulations in 1981 were considered "adequate to protect the public against unreasonable risk from the transport of radioactive materials". This initial study has been improved over the years to incorporate more advanced models, risk assessment methods and updated data.

The latest risk assessment NUREG-2125, "Spent Fuel Transportation Risk Assessment", 2014, estimates the risk associated with the transportation of spent nuclear fuel (SNF) by examining the behaviour of NRC-certified casks during routine transportation and in transportation accidents. The response for these casks is typical of other cask designs.

The risks associated with routine shipments (incident-free) and shipments where an accident occurs are calculated separately. During routine transportation, the risk and the consequence are the same. In this case, the dose to residents living along a transportation route, to people sharing the highway or railway, people at stops, and transportation workers are all calculated. Regulations allow limited external radiation from the cask. The dose of radiation to members of the public during routine transportation is a small fraction of the naturally occurring background radiation that individuals experience.

Accident risk is the product of the consequence of the accident and its probability. The probability of an accident that has an effect on the cask is the product of the probability that the cask is involved in an accident and the conditional probability that the accident is severe enough to reduce the shielding or containment effectiveness of the cask. The conditional probability is based on accident statistics for all types of heavy trucks and railcars. The accident probability is determined by multiplying these accident rates by the distance travelled.

In NUREG-2125, the following conclusions were reached:

- The collective dose risks from routine transportation are very small. These doses are approximately four to five orders of magnitude less than the collective background radiation dose.
- The routes selected for this study adequately represent the routes for SNF transport, and there was relatively little variation in the risks per kilometer over these routes.
- Radioactive material would not be released in an accident if the fuel is contained in an inner welded canister inside the cask.
- Only rail casks without inner welded canisters would release radioactive material, and only then in exceptionally severe accidents.
- If there were an accident during a spent fuel shipment, there is only about one in a billion chance that the accident would result in a release of radioactive material.
- If there were a release of radioactive material in a spent fuel shipment accident, the dose to the maximally exposed individual would be less than 2 Sv and would not result in an acute lethality.
- The collective dose risks for the two types of extremely severe accidents (accidents involving a release of radioactive material and loss of lead shielding accidents) are negligible compared to the risk from a no-release, no-loss of shielding accident.
- The risk of gamma shielding loss from a fire is negligible.
- None of the fire accidents investigated in this study resulted in a release of radioactive material.

Based on these findings, the radiological impacts from spent fuel transportation conducted in compliance with NRC regulations are low. They are, in fact, generally less than previous, already low, estimates. Accordingly, with respect to spent fuel transportation, NUREG-2125 reconfirms the previous NRC conclusion that regulations for transportation of radioactive material are adequate to protect the public against unreasonable risk.

PAIA section 44 (2)a. Redacted information could jepoardise effectiveness of testing procedure if disclosed