DETERMINISTIC ANALYSIS FOR THE SENSITIVITY OF LICENSING BASIS EVENTS (LBE) RADIOLOGICAL CONSEQUENCES TO VARIOUS EXPOSURE PATHWAYS FOR THE PEBBLE BED MODULAR REACTOR (PBMR)

BY

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P B M R

PREFACE

The dissertation presents the work done at Nuclear Safety and Licensing Department of the Pebble Bed Modular Reactor in Centurion, Pretoria in the Republic of South Africa from March 2002 - Dec 2002 under the supervision of Mrs. Marilyn Norris.

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ABSTRACT

Nuclear safety is the main concern for the licensing of nuclear power plants, not only in the Republic of South Africa but also worldwide. The design of the nuclear power plant plays an important role in the licensing process, which includes probabilistic and deterministic analysis of a set of design or Licensing basis events. This study was about the deterministic analysis for the sensitivity of licensing basis events radiological consequences to different radiological pathways. The study was done for the Pebble Bed Modular Reactor (PBMR), which is a nuclear power plant, still in its early phase of design approaching its detailed design phase.

An abnormal event or an accident could lead to a release of radioactive particles and gases from a Pebble Bed Modular Reactor and could give rise to radiation exposure to workers and the surrounding population. Therefore nuclear events due to PBMR, which are Licensing Basis Events or Design Basis Accidents, must be analyzed in order to demonstrate that accidental and routine releases of radioactivity are kept As Low As Reasonably Achievable (ALARA) and that the design basis meets offsite dose requirements with adequate safety margins.

In this work, it is also shown that collectively the risk criteria are satisfied in the fundamental safety requirements of National Nuclear Regulator (NNR) of the Republic of South Africa (RSA) and similar risk criteria of the other countries in which it has to be employed.

Furthermore the various pathways through which radioactivity can reach the public are analysed. The focus of the study was to determine which pathways deliver the greatest radiation exposure if there is an accident due to an event happening in PBMR and also to provide a LBE analysis process as a step in confirming that the design meets the licensing requirements.

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List of Abbreviations

ABBREVIATION	DESCRIPTION
PBMR	Pebble Bed Modular Reactor
MPS	Main Power System
MARIA	Method of Assessing Radiological Impacts on Accidents
LWR	Light Water Reactor
KNPS	Koeberg Nuclear Power Station
HTGR	High Temperature Gas Cooled Reactors
LBE	Licensing Basis Events
DBA	Design Basis Accidents
COSYMA	Code System from Maria
SAR	Safety Analysis Report
ALARA	As Low As Reasonably Achievable
PyC	Pyrolitic Carbon
SiC	Silicon Carbide
PRA	Probabilistic Risk Assessment
GDC	General Design Criteria
LG 1037	Licensing Guidance 1037
PFSDP	PBMR Fundamental Safety Design Philosophy
PCU	Power Conversion Unit
RCS	Reactivity Control System
OCS	Operational Control System
SSC	Systems Structures and Components
HPB	Helium Pressure Boundary
EPS	Equipment Protection System
HVAC	Heat, Ventilation and Air Conditioning
FHSS	Fuel Handling and Storage System
RPV	Reactor Pressure Vessel
SSE	Safe Shutdown Earthquake
PPB	Primary Pressure Boundary

CHAPTER 1: INTRODUCTION

1.1 Overview

This study was done for the PBMR, which is a high temperature gas cooled reactor, still in the preliminary design stage. Design plays a very important role in the safety of a nuclear power plant. Safety in general must always be a major consideration. Nuclear energy is advantageous in a way that , when it is compared to other energy sources such as coal, it can preserve the environment, can be employed safely for medical diagnosis and treatment. Unlike coal industries, it cannot emit greenhouse gases and can also isolate its waste from the environment.

PBMR uses a closed Brayton cycle to generate electricity by converting nuclear energy into electrical energy as shown in **Figure 1**.

PBMR consists of two parts, the reactor core, where nuclear fission takes place and the Main Power System (MPS), where nuclear energy is converted to electrical energy. Operation of a PBMR starts with the production of heat and radionuclides (fission products, which are highly radioactive) due to the fission reaction in the reactor core. A small fraction of the fission products will migrate through the fuel to the MPS. If a break occurs in the MPS, radioactivity could be released to the environment and poses radiation exposure risk to the public and plant personnel. Public and environment will obtain radioactivity via different radiation exposure pathways.

The goal of nuclear safety is to protect the most exposed individual member of the public and to provide sufficient protection for the society at large and for the environment. In this research project, protection of the workers is excluded. Therefore the potential radioactive release from a nuclear power plant has to be minimized since it is a major concern to the public and is directly related to health effects on the people. A safe design must be used in order to lower the risk, and maximize the benefits of nuclear power at an acceptable cost, so that the nuclear facility can meet the acceptance criteria set by the nuclear regulatory authority. This goal can be achieved by looking at previous experiences of other Nuclear Power Stations. Lessons can be learned from the Chernobyl accident, which occurred in 1986, so that a safer nuclear energy industry can be created. The Chernobyl accident resulted from a flawed reactor design. Reckless operation compounded by unacceptable design and bad reactor management. A plant design must be analyzed thoroughly from

both a performance and a safety perspective. With proper examination of potential hazards, and potential weaknesses areas of improvement can be identified.

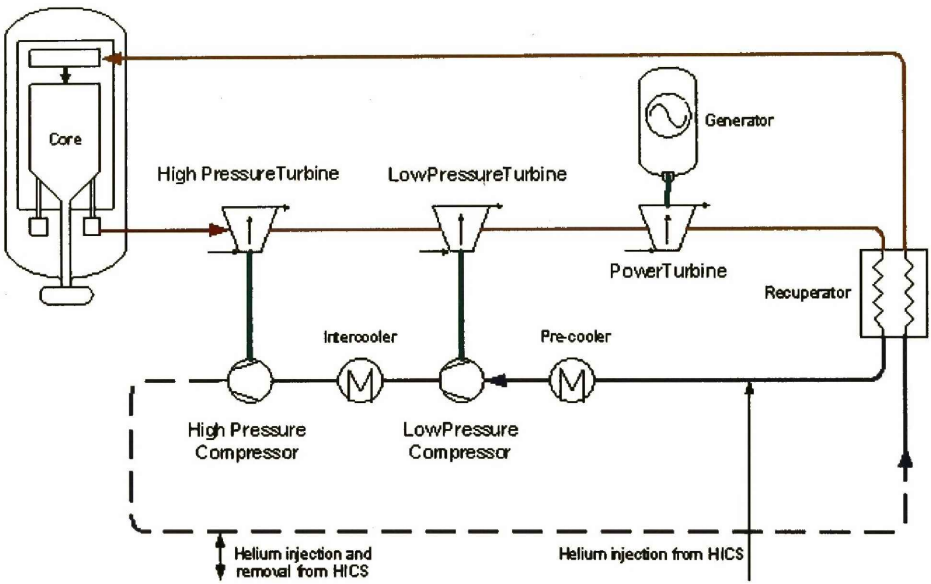

Figure 1: Brayton cycle (Helium Flow)

Acceptance criteria refer to the safety criteria, which require the early coordination between design process and hazard analyses so that the structures, systems and components necessary to prevent or mitigate hazards are identified and incorporated in the early design phase.

For the PBMR, which has not yet been built and is still in its early basic phase of design, approaching its detailed design phase, only a limited amount of historical data is available. There is limited information concerning operation or accidental release of radioactivity from High Temperature Gas Cooled Reactors (HTGR) using graphite as a moderator and gas (such as helium or air) as a coolant. HTGR have been in existence for only a few tens of years in the United Kingdom, Germany, China, Japan, and the United States. When compared with thousands of total reactor years of operation for light water reactors, the data on High Temperature Gas Cooled Reactors is very limited. Analyses, tests and experiments must be carried out to validate the design of the PBMR. In the present analysis being done for the PBMR, it has to be demonstrated that the design is safe.

Uncertainties are expected to play a major role in establishing the licensing basis for the PBMR.

The safety assessment is done in order to review the design and to determine if the design is within the safety limits and licensing basis for the reactor design is established against the regulatory criteria and fundamental safety standards. Safety limits, regulatory criteria and fundamental safety standards refer to the regulatory limits that PBMR has to comply with in order to ensure that its operation does not expose the public and the environment to unacceptable high risk. These are shown in **Table 5.** Safety analysis is also done to provide predictions of accident consequences , so that if the design is based on the safety analyses, it will be able to withstand a real accident with some margin at least as far as the public safety is concerned.

Safety analysis involves certain approaches to quantify Design basis accidents, which are accidents PBMR is designed to withstand. Various codes are available for quantification of accident consequences. Such approaches include Deterministic analysis, which is the assessment of design according to a prescribed list of failures based on past experiences. Deterministic analysis requires the use of conservative input parameters which will make the results more pessimistic with respect to safety acceptance criteria in order to give a conservative, but reasonable, prediction of accidents. The other approach is the Probabilistic Analysis, which provides insights into the safety aspect of plant design, performance and the potential environmental impacts of postulated accidents, including the identification of dominant risk contributors. The latter approach is not used in this study.

The code used for this research is PC COSYMA, which is the code system from MARIA, of which MARIA is the Methods Of Assessing Radiological Impacts on Accidents. MARIA is a project from the European commission that was developed primarily in 1983 by the National Radiation Protection Board (NRPB) with contributions from the other organizations to build on the nuclear Accident Consequence Assessment (ACA) methods in use within European Union. The objective of the project was to develop a computer program system for use in ACA, i.e. COSYMA. PC COSYMA is a highly modularized code, with each module addressing part of the analysis. Different modules describe the transfer of released activity through the atmosphere and can also be interlinked and run in combination by the system.

From a deterministic assessment which traces the migration of radioactivity from its point of origin, to a point at which it can be discharged, all radionuclides and their associate discharge quantities can be identified using limiting assumptions which are chosen judiciously in order not to compromise operational flexibility.

Doses and health risks for all identified radionuclides discharged from the reactor building can be calculated by use of atmospheric dispersion codes and site-specific input data. Then the impact of radioactive discharges would have been assessed at the design stage and compared to the annual dose limit to determine whether they are acceptable, based on the results of the safety assessment that would have been performed. When the nuclear regulator is satisfied that the PBMR complies with the safety criteria, a license can be granted **[2]**.

1.2 Problem Statement and the Importance of the study

In order for the PBMR to be licensed, it has to comply with the safety and licensing criteria set by the nuclear regulatory authority of the country in which it is to be built and operated.

One of the major components of the licensing process, which needs to be thoroughly considered in the PBMR, is the credibility of its design basis. The fundamental concept of the design of the PBMR is aimed at achieving a plant that has no physical process that could cause a significant radiation-induced hazard outside the site boundary.

The problem with the PBMR design criteria is that it does not have a broad international consensus that has been developed compared to a LWR such as Koeberg Nuclear Power Station (KNPS), which is well researched and has documented design rules, which are readily available.

Although there have been similar designs of High Temperature Gas Cooled Reactors (HTGR) which have been licensed and operated elsewhere, there are not yet detailed national rules or international standards available for defining PBMR design basis. Therefore the documentation of the PBMR design basis is an important step in the licensing process and is currently receiving major attention by its designers.

Completion of a PBMR design with full documentation of design rules will lead to a design that is expected to achieve the goals of being a safe, efficient, environmentally acceptable and economically viable, high temperature energy source for the generation of electricity. PBMR efficient use of natural resources and the inherent safety of its design, coupled with

the increasing demand for electricity will create a potential market for nuclear power, in particular the PBMR concept. As the world economy continues to expand due to the increased use of the new technologies, so will the demand for electricity. As the electricity demand increases, new plants will be needed both to accommodate the new demand and to replace plants build 40 to 50 years ago **[14]**. The project is also important as it demonstrates that design safety plays a very important role in the safety of the public and the environment. It is for this reason that we determine the sensitivity of the predicted LBE radiological consequences to various exposure pathways.

1.3 Objective

In the event of a release of radioactivity from PBMR, members of the public will be exposed to external dose and internal dose. The level of dose, the rate of dose accumulated and the organs of the body, which are exposed, will determine the risk of health effects. They can either be deterministic effects (for instance vomiting, nausea and diarrhea) or stochastic effects such as cancer.

The main goal of nuclear regulator and the government is to protect the most exposed individual member of the public and provide sufficient protection for society at large and for the environment. This project does not deal with the critical group. This study contributes to achievement of that goal by evaluating how sensitive the different radioactivity exposure pathways are to the Licensing Basis Event (Design Basis Accidents).

This can be achieved by:

(1). Identification of the assumptions used in the input to PC COSYMA for the calculation of LBE consequences.

(2). Examining the variation in the consequences with variation in the input parameters (exposure pathways) and the assessment of the effect on the dose. It has to be ensured that even if conservatively pessimistic assumptions are taken into account the doses fall within the regulatory dose limit.

1.4 Layout of the Study

In the present chapter, a brief overview that describes the status of the PBMR is given. The status of the PBMR is its licensing process and its design. The goal/ aim of the study is identified and explained how it should be addressed by describing the software to be used. Lastly the objective of the study and the importance of the study are explained.

In **Chapter 2**, a detailed theoretical background of the study is explained. Full details of the PBMR'S nuclear safety and licensing are explained. Details of achieving a safe design, i.e. by consequence analysis that determines the consequences due to the Design Basis Accident using sensitivity analysis and deterministic analysis are discussed.

In **Chapter 3**, the methods used for achieving the objectives are explained. Description of how PC COSYMA works is given and how the deterministic and sensitivity analysis are performed on this software. The inputs and assumptions to PC COSYMA are specified. Calculation methodology is given with description of how outputs are presented.

In **Chapter 4**, results of the calculations, which were performed, are presented. They are presented in form of spreadsheet tables.

Chapter 5, Discussion of the results is presented in this chapter.

Chapter 6, The output of the PC COSYMA (calculations) are compared with the design data from Safety Analysis Report (SAR) to determine if they fall under the regulatory dose criteria and finally conclusions are drawn from the outcome of the results. Recommendations for future research are given.

Chapter 7 deals with the references.

CHAPTER 2: LITERATURE REVIEW/THEORETICAL BACKGROUND

All nuclear power plants are required to have a license in order to operate. A nuclear regulatory authority, whose main objective is to protect the public from the consequences of nuclear event, grants the operating license. In order for a nuclear power plant to be licensed, it must demonstrate that its operation does not expose the workers, the public and environment to an unacceptably high risk by demonstrating compliance with safety criteria set by the nuclear regulatory authority. This project does not deal with the workforce exposure to ionizing radiation, nor the environmental effect but only the radiological dose to the public.

The safety criteria are based upon normal operation (start up, power operation, shut down, maintenance, testing and refueling), anticipated operational events (such as loss of normal electrical power) and accidental releases of radioactivity **[1]**. They spell out the maximum allowable dose, dose rate or risk to the public and plant personnel **[2].**

Safety and licensing requirements are based upon conditions that the plant's design, construction, and operation will be according to good engineering practice and that the power plant will provide a safety analysis in support of license application, which shall demonstrate the adequacy of plant, design and operational procedures against the nuclear regulator's requirements.

Principles such as defense-in-depth and ALARA must be adopted. Defense-in-depth requires that there should be multiple layers of overlapping safety provisions to help ensure accidents will be prevented and mitigated. Application of the ALARA principle involves selection of design and operational features providing the optimum level of safety and it ensures that risk and radiation doses to members of the public and plant personnel must be maintained as low as reasonably achievable.

Risk criteria are established according to the following principles which are the under – pinning philosophy for the design and the operation of the PBMR and the principles upon which the fundamental safety standards are based.

- The risk presented by a nuclear site shall not increase significantly the total risks to which the population is exposed. This means that the background radiation from terrestrial and cosmic sources cannot be avoided. A nuclear site should not add significantly to this routine exposure to radiation.

- The nuclear risk shall compare favourably with those associated with other major industrial enterprises. The risk of injury or death to workers or the public should be less than that from the mining or chemical industry.
- Allowance shall be made for possible demands by society for greater standards of safety over the period (assumed to be several decades) of the working life of the facility i.e. targets are set for the designer and operator to achieve in terms of reducing to as low as reasonable the dose received by the workers and members of the public and to reduce the risk to which the worker and public are exposed. To demonstrate that the reactor will be acceptably safe, the applicant is required to demonstrate that the design of the plant:
    - Respects good nuclear safety design practice;
    - Will make use of appropriate internationally recognised design and operational rules; and
    - Will comply with the risk and radiation dose limitation criteria **[14].**

2.1 Overview of Nuclear Safety and Licensing for PBMR

The PBMR is a graphite moderated helium cooled power reactor using a Brayton direct gas cycle to convert the heat, which is generated in the core by nuclear fission and transferred to the coolant gas, into electrical energy by means of a turbo- generator. The PBMR core is based on the German High Temperature Gas Cooled Reactor technology and uses spherical fuel elements **[5]** as shown in **Figure 2**. Each fuel particle consists of a small uranium dioxide kernel, coated with a porous carbon buffer to accommodate gaseous fission products. Around this is a coating of pyrolitic carbon, a silicon carbide layer, and a further layer of pyrolitic carbon. These layers provide the primary barriers to fission product release. The coated fuel particles are moulded into graphite spheres, each containing thousands of coated particles. This 50mm graphite sphere is then coated in a further 5mm thick, fuel free, graphite layer. The core consists of several hundred thousand of these fuel spheres.

The overall safety philosophy of the PBMR is to produce a safe plant design that meets all statutory, licensing and user requirements, by providing protection against radionuclide release through the application of the safety design concept.

For the PBMR, safety by design is aimed at preventing accidents, where an accident is defined as 'an unlikely event (natural or unnatural), which results in the release of radioactive substances'.

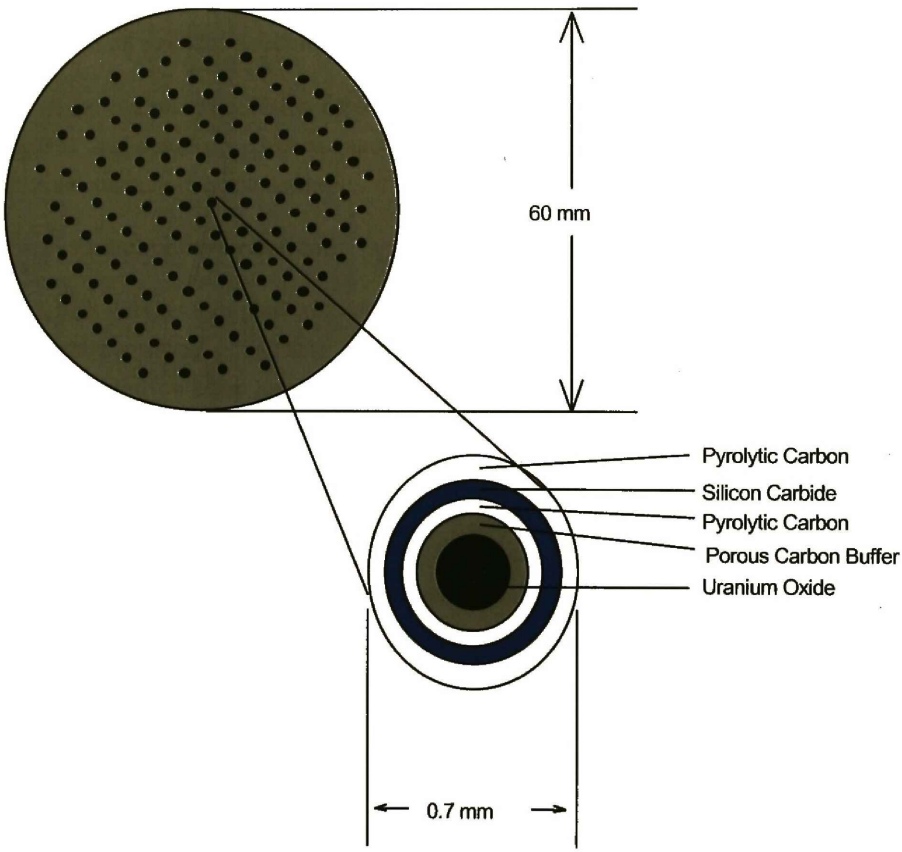

Figure 2: Coated fuel particles within graphite matrix sphere

The PBMR is designed to derive maximum safety benefits from its natural characteristics by the achievement of proper operating conditions, prevention of accidents or mitigation of accidents consequences, resulting in protection of workers, the public and the environment from undue radiation hazards. This is an advantage over other reactor designs, which rely on extensive engineered safety systems to achieve acceptable levels of safety **[6]**. Its inherent safety characteristics enable the meeting of stringent safety requirements while

achieving a competitive economic performance. The inherent safety is a result of the design, the materials used, the fuel and the natural physics involved.

The Inherent safety characteristics are:

2.1.1 Small excess reactivity

Small excess reactivity of the core at operating conditions is a result of using continuous fuelling and defueling. Excess reactivity is therefore only necessary to allow for xenon fluctuations during load following.

2.1.2 Radionuclides retention

The high temperature radionuclide retention capability is provided by the fuel kernel coatings consisting of multiple layers of Pyrolitic carbon and of Silicon Carbide (SiC). These coated particles have been demonstrated by German tests to contain nearly all radiologically significant gaseous or solid fission products up to temperatures of at least 1650 ° C **[13].**

2.1.3 Negative temperature coefficient

The large negative temperature coefficient of the core is a result of using low enriched uranium fuel in a graphite matrix. Design phase plans include a start-up core loaded with fuel with less than 5% U-235 enrichment and equilibrium core with 8% or 9% enrichment **[6].** This is largely determined by the temperature dependence of the resonance absorption in the fertile material U-238. This together with the negative temperature coefficient, results in a high overall negative temperature reactivity coefficient. This means that the reactor would counteract a rise in temperature with a reduction in power.

2.1.4 Neutron transparency and chemical inertness of helium

Neutron–transparency of helium means that the void-coefficient of reactivity of the helium coolant is zero and that a loss of coolant cannot cause a reactivity increase. The chemical inertness of helium, even at very high temperature, implies that it will not react chemically with the graphite or fuel. The use of helium, a single-phase coolant, eliminates the possibility of a change of phase of the reactor coolant (i.e., liquid to vapour) under accident conditions. Thus, complex semi-empirical relationships for analysis of two phase flow and heat transfer characteristics as functions of geometry, boiling regime, etc, are avoided **[6].**

2.1.5 Inherent heat removal capability

The slender design of the reactor vessel allows for optimal passive heat removal from the core even under conditions of "no forced coolant flow", with the reactor depressurized. Heat flow by conduction and radiation to the reactor pressure vessels and subsequent removal by the system in the reactor cavity, would limit the maximum fuel and vessel temperature, so that both remain in the safe region.

The designers and developers of the PBMR must have a structured process to develop a safety case, which will provide a logical link between various steps of design process, safety assessment and development of operational support programmes. As not all licensing requirements have been defined for PBMR modules which might be built in the Republic of South Africa or in the United States, the current focus of PBMR designers is to quantify these risks to the public and to the plant personnel due to normal operations and nuclear accidents, and to compare these risks with the safety criteria that have been established by the nuclear regulator to determine compliance.

2.2 Consequence analysis

Consequence analysis is done to determine compliance of the design to the safety criteria of the nuclear regulatory authority. It is done using the processes of predicting the consequences of various nuclear accident release sequences in order to support the evaluation of accident risks and to evaluate compliance with the regulatory criteria in PBMR design using systematic and comprehensive analysis , which uses a deterministic and probabilistic approach to safety.

2.2.1 Licensing Basis Events (LBE)

Consequence analysis to demonstrate compliance with the regulatory requirements applies to all those events of importance to the Designer (PBMR) and the Regulator in defining the licensing basis for Systems, Structures and Components (SSC). These events are called Licensing Basis Event (LBE). Licensing Basis Events (LBE) is a term used by the PBMR company and are also those events or combination of events that can occur on a PBMR, for which it shall be demonstrated that the design of the PBMR meets all the regulatory, safety and risk criteria. LBE are selected on PBMR by identifying those SSC that could potentially help to mitigate or reduce the frequency of an LBE **[4]**.

2.2.1.1 LBE identification

The Licensing Basis Events listing documents the inputs considered from all relevant technological sources, including operating experience, safety and licensing documents from similar gas cooled reactors, RSA NNR and United States Nuclear Regulatory Commission (NRC) regulatory guidance, related experience from light water reactors, experience and judgment of nuclear industry consultants and results from previous PBMR safety analyses. The Licensing Basis Events can be screened to modify or exclude events that cannot physically happen due to design differences between the PBMR and other reactors for which an event might have been applicable.

Events shown to have no radiological consequences, without reliance on a safety structure, system, or component to prevent or mitigate the effects of the initiating event, may also be screened out. Events retained in the deterministic set of potential LBE shall be grouped together under a set of headings defined by types of initiating events, and potential radiological consequences to public and plant personnel. After listing, screening and final deterministic derivation of the LBE by the PBMR engineers, managers, and safety analysts, they are independently reviewed and included in the quality record. The independent review may be conducted by any competent organization either internal or external to the licensee's organization, but who are not immediately responsible for the document being reviewed. A safety assessment is then carried out for each LBE by execution of initial deterministic safety analyses of the LBE for the evaluation of their consequences in terms of the plant behavior and fuel radionuclide retention.

After deterministic assessment of the LBE, the Probabilistic Risk Assessment (PRA) is performed and the probabilistic results evaluated. The results from the probabilistic assessment are compared with the LBE list from deterministic analysis to ensure that PBMR LBE list includes all the LBE on the two lists. The LBE are then grouped according to their categories of events (Licensing Guidance (LG) 1037), which are Basic licensing requirements for PBMR after being assembled **[2]**. After independent review of the LBE, consequence determination and categorization, the LBE are evaluated against the regulatory risk and safety criteria and against the PBMR General Design Criteria (GDC) to establish that the PBMR design is adequate **[4]**.

2.2.1.2 LBE classification

Licensing Basis Events can be classified in two ways:

(a) According to probability of occurrence which is according to their category of events (as in LG 1037) **[2]** as follows:

- Category A events, those events that could lead to exposure and could occur with a frequency of more than one in hundred years and such events are treated as part of the normal operation, or anticipated operational occurrences.
- Category B events, those events leading to exposure and which could occur with a frequency of between one in hundred years and one in one million years.
- Category C events, all possible events that could lead to exposure. Category C includes category A and B events as well as events which occur with annual frequency less than 10E-06. Consideration is given to the exclusion of very low frequency events in the range below 10E-06 per year because including them is not cost effective.

(b) According to the challenges to their safety function, specifically to the fuel integrity that could result from:

- Undesirable Reactivity Excursions and power distributions.
- Challenges to Heat Removal capability.
- Possibility of chemical attack.

Listed below are eleven LBE categorized according to their challenge to safety functions

1) Loss Of Power Conversion Unit (PCU)

This LBE encompasses a large number of initiators such as Power Conversion Unit upsets and station blackout. This class of LBE has no offsite release. However, it sets the design basis for a number of SSC that are relied on to perform required functions in order to meet the offsite top level regulatory requirements.

2) Control Rod Group withdrawal

This LBE starts with a withdrawal of one group of control rods in the RCS used for the operation and the other available for reactor shutdown. In this event a malfunction in the OCS withdraws a group of inserted rods. The intrinsic negative temperature coefficient of the core reacts to the temperature increase and begins to shut the reactor down. This

class of LBE also does not have an offsite release. However it sets the design basis for a number of SSC that are relied on to perform required functions in order to meet the offsite top level regulatory requirements.

3) Small isolated Helium Pressure Boundary Break

This is a small helium pressure boundary break, equivalent in area to 10mm diameter pipe or less, while the reactor is at operating power, resulting in the helium outflow from the HPB into the reactor building. The break can be isolated from the MPS upon detection either automatically by the Equipment Protection System (EPS) or via a maintenance valve (or spade), which is inserted between the RPV and the PCU.

4) Small Unisolated Helium Pressure Boundary Break

This is also a small helium pressure boundary break, equivalent to a 10mm diameter pipe or less, while the reactor is at operating power, resulting in the helium outflow from the HPB into the reactor building. However, in this event, either the isolation fails or the break is not in the area of the HPB that can be isolated from the MPS. Isolation failure includes failure of both automatic isolation by EPS and manual isolation by spade.

5) Heat Exchanger Tube Break Isolated

This LBE is equivalent in area to a 15mm diameter or less, while the reactor is at power, resulting in the helium out flow from the HPB into the reactor building.

6) Heat Exchanger Tube Break Unisolated

A break in the heat exchanger tube that is not isolated, equivalent in area to a 15mm diameter pipe or less, while the reactor is at power, resulting in the helium outflow from the HPB into the reactor building.

7) Medium Isolatable High Pressure Boundary Break

This LBE is a break in the HPB, equivalent in area up to a 65mm diameter pipe, while the reactor is at power, resulting in helium outflow into the reactor building. The break is in an area of the HPB that can be isolated from the MPS upon detection. The isolation can be through the EPS by automatically isolating the HICS or FHSS valves or through the operator by inserting a spade to isolate the RPV from the rest of the MPS.

8) Medium Unisolated Helium Pressure Boundary Break

This LBE is also a break in the HPB, equivalent in area to a 65mm diameter pipe, while the reactor is at power, resulting in helium outflow into the reactor building. However, in this event, either the isolation fails or the break is not in an area of the HPB that can be isolated from the MPS.

9) Large Isolated Helium Pressure Boundary Break

This is a break in the HPB equivalent in area to between a 65mm and a 170mm diameter pipe, while the reactor is at power, resulting in the helium outflow into the reactor building. The break is in the area of the HPB that can be isolated from the MPS upon detection.

10) Large Unisolated Helium Pressure Boundary Break

This is also a break in the HPB; equivalent in area to a diameter between 65mm diameter pipe and 170mm, while the reactor is at operating power, resulting in the helium outflow into the reactor building. In this LBE either the isolation fails or the break is not in an area of the HPB that can be isolated from the RPV.

11) Safe Shutdown Earthquake

This LBE is a 0.27g magnitude earthquake. This magnitude earthquake is consistent with the seismology of the site at a frequency of 10E-3/ plant year; therefore it is Safe Shutdown Earthquake (SSE). The plant response to a safe shutdown earthquake is expected to be similar to that of LBE 1 **[16].**

2.2.1.3 Analysis of Licensing Basis Events

To demonstrate that the PBMR meets the required safety and risk criteria and that no event of significant consequence (exceeding dose criteria for normal operation) is overlooked, it has to be ensured that the PBMR design is safe. To demonstrate this, two types of calculations need to be performed, namely:

- Deterministic dose calculations for category A and B events.
- Probabilistic calculations for category C events.

For this study only deterministic dose calculations for category A and B events (LBE) are performed. Category A and B events are also defined as Design Basis Accidents.

Consequence assessment starts with the postulated release of radionuclides to the environment from the reactor. Radionuclide release can either be to the atmosphere or to

the aquatic environment. The focus of this study is on dispersion of and exposure to radiological release to the atmosphere.

Atmospheric releases results from those LBE, which involve a break in the pressure boundary. It is customary to group event sequences (LBE) with similar consequences into groups called release categories. Each release category is characterized by a source term describing the quantity of radioactive material released, release timing and duration, release frequency, release height, and thermal energy of the gas released.

For each release category, a distribution of consequences is calculated. The grouping of event sequences (LBE) is necessary because it is not practical to determine the consequences of each event sequence, due to the large number of event sequences involved.

PBMR has six release categories as shown in **Table 1** small, medium and large breaks, which are divided for the purpose of the analysis and classified according to the size of the pipes. Releases from the reactor core can be terminated by closure of the valves for certain breaks, depending on the location of pressure boundary break relative to pressure vessel.

For a more thorough understanding of the release categories, all the activity in (Bq) from the PBMR is split into three source terms, which are characterized as the circulating activity, delayed activity, and the plated out activity. They are fully explained below.

- Circulating activity

  There will be some activity within the helium coolant pressure boundary during normal operation, due to fission products released from initially- failed or defective coated particles, and from activation of dust or impurities within the helium gas. Most of this activity circulates with the coolant, and would be released along with the helium in the event of the pipe break. Any helium release from the main power system would include circulating activity.

- Lift off of dust or plated out activity

  Lift off of plated out activity refers to some fission products circulating with the hot helium during normal operation, which will plate out on cooler surfaces of pipes and vessels within the pressure boundary. Additionally, some contaminated dust particles might settle out inside pipes in areas where the coolant flow tends to be laminar. In the event of sufficiently large pipe breaks, the turbulence of the rapidly escaping helium may resuspend some dust, or lift some plated material from the pipe surface near the break. These particles would be carried out with the helium and the circulating activity.

- Delayed release from fuel

  If the flow path between the reactor core and the break in the piping could not be isolated, and all normally available systems which could provide available systems which could provide forced circulation of helium through the core were unavailable for tens of hours, the decay heat could cause the peak fuel temperatures to exceed those for normal operation. If forced cooling continued to be unavailable, peak temperatures could increase enough to cause coating failure and release of fission products from a small fraction of initially intact fuel particles. This delayed release could continue for a few hours until the decay heat subsided and fuel temperatures decreased to operating temperature and below. A delayed release would involve a larger source term than that from the circulating and lift off activity releases.

They release category are identified and are denoted as follows where RC is an abbreviation for Release Category.

2.2.1.3.1 RC-1

RC-1 are Small breaks, which are isolatable. The small breaks are breaks with equivalent area as a 10mm diameter pipe, which are assumed to be within the capacity of the containment filtration system. Thus the release to the environment is filtered through the system. Only circulating fission products in the Primary pressure boundary (pipes circulating helium around the MPS) are available for release. Because small breaks would not create much turbulence due to the size, lift off of plated out activity is not expected. About 10% of the gas will have escaped before isolation.

2.2.1.3.2 RCF-1

This release category consists of all small breaks in the primary pressure boundary, which is not isolatable. Pump down is assumed and since this is a small pipe break, no lift off of plated-out fission products is assumed. Pump down is a process whereby if there is a break in the PPB, the gas that circulates within the PPB will be taken out and stored in the inventory control tanks. This is normally done when we have a small break, then at least a certain percentage activity of the circulating gas will be retained. However, there could be a delayed release due to subsequent core heat up. This is explained in section 2.2.1.3. In this event, about 50% of the gas is assumed to have been released before pump down is complete.

2.2.1.3.3 RCF-2

This category consists of all small breaks where the break is not isolatable but for which no pump down is assumed. Since this is a small pipe break, no lift off of plated-out fission products is assumed. However there is a delayed release due to subsequent core heat-up. In this event, about 100% of the gas will have been released.

2.2.1.3.4 RCP-1

This category consists of medium and large breaks (breaks with the size between medium 10 to 65mm and large breaks between 65 to 170mm in diameters as described in **Table 1**) that have been isolated.100% of the circulating gas is assumed released. The release is unfiltered and is exhausted through vent into the atmosphere. Only circulating activity and lift off of plated out form part of the source term.

2.2.1.3.5 RCPF-1

This category is of medium breaks, which are not isolatable. The whole circulating inventory and fraction of plate out material is released immediately. The vent is assumed to reclose after the initial puff. A puff refers to a brief, sudden emission of gas. Delayed release is assumed to occur after 32 hours as described in section 2.2.1.3.

Table 1: Release categories for the PBMR

Release category	Description	Source Term
RC1	Small breaks, including ruptures in the heat exchangers of 10mm in diameter; Isolated; Filtered vent; immediate circulation inventory released; no lift off; 10% gas released.	Circulating
RCF-1	Small break, including ruptures in the heat exchangers; not isolated; with pump down; filtered vent; immediate circulating inventory released; delayed fuel release; 50% gas released	Circulating and fuel or Delayed release
RCF-2	Small break, including ruptures in the heat exchangers; not isolated; without pump down; filtered vent; immediate circulating inventory released; delayed fuel release; 100% gas released	Circulating and fuel
RCP-1	Medium and large breaks- include ruptures in the heat exchangers of between 65mm and 170mm in diameter; isolated; Unfiltered vent, Immediate circulating inventory released, with immediate circulating and plate out released. In the event of a medium break 90% of the gas is released.100% is assumed released in the case of large breaks.	Circulating and Lift off of Plated out
RCPF-1	Medium break; Not isolated; Unfiltered vent; immediate circulating inventory released, with immediate plate out and delayed release; Vent closed; 100% gas released.	Circulating and Lift –off and fuel
RCPF-2	Large break; Not Isolated; Unfiltered vent; Immediate circulating inventory released, with immediate plate out and delayed release; Vent open; 100%gas released.	Circulating and lift off and fuel

2.2.1.3.6 RCPF-2

This category consists of large breaks, which are not isolatable. The whole circulating Inventory and 5% of plate out material is released. The vent is assumed to not reclose after the initial puff. Delayed release occurs after 32 hours.

Radiological consequences of each release are evaluated using PC COSYMA version 2. To perform the evaluation, a large amount of input data is required and it also needs to be specified in PC COSYMA as summarized in **Table 4**.

The main types of data that need to be specified during consequence analysis are:

2.2.1.4 Source term data

The source term data describes amount and isotopic composition of the radionuclides released or the strength and timing of the release. For the dose calculations, source term used is the design source term and it is specified. Source term represents design and expected source term, respectively. The design source term is as shown in **Table 2.** This design source term has been split into activities from different contributions, namely circulating inventory, lift-off of plated out activity and delayed activity. For more details of the activities see section 2.2.1.3. For each type of nuclide, PC COSYMA is run for only one type of source term at a time, namely circulating activity only, lift off of plate out activity only, and delayed activity only. The source term is generally characterized by the following parameters:

2.2.1.4.1 Release fraction

The release fraction describes the fraction of the initial available inventory that is released to the atmosphere. For the determination of the release fraction, the transport and deposition within, and release of radioactivity from the containment are typically taken into account. At this stage of design and analysis, they are not considered. It has been conservatively assumed that what is released from the PPB into the containment system is released into the environment. No credit was taken for any hold up (radioactivity deposited or clinged to the surface of the pipes) in the reactor building. In the PBMR for each release category, the amount of activity for each radionuclide available for release is determined by the neutronics and thermohydraulics calculations provided as inputs by the PBMR engineering group for the source term. It is then specified as a source term available for release.

Three sources of radioactivity are considered in the PBMR source term, namely,

- Those that are contained in the helium circuit during normal operation,
- That plated out on, then detached from various surfaces in the primary circuit, including dust,
- And that contained in defective fuel particles (from the manufacturing process) and tramp Uranium (contaminated uranium) that may be released during heat up events.

These were described more fully in section 2.2.1.3

Licensing basis Events may have one, two or all of these sources present.

2.2.1.4.2 Frequency of occurrence

The frequency of occurrence (release frequency) of an event sequence leading to a particular release of radioactivity into the atmosphere describes the expected frequency of that particular accident sequence occurring per year.

2.2.1.4.3 Energy of release

This is the energy content of the release. It can be calculated from the sensible heat of the helium in the primary circuit and from the decay heat of the radionuclides. It depends on the time at which the release from the pressure boundary occurs. It may influence radiological consequences, as it may cause the plume to rise substantially into the atmosphere before a significant dispersion takes place and that is going to result in a reduction of exposure of population located downwind. In the PBMR, a value for energy corresponding to decay heat 2 hours after fission reaction has stopped is used. It is 1.06 MW. This is an assumed value, obtained by multiplying the decay heat for a single fuel element two hours after fission has stopped by the number of fuel balls in the core which is assumed to be 330 000. It is conservative to use a lower decay heat because the lower energy limits the effective release height and minimizes the volume of air mixing with the radioactive plume as it is dispersed. Less mixing leads to higher predicted concentration and dose to receptors at ground level.

Table 2: Design source term in bequerel (Bq)

Nuclide	Circulating (Gas & dust)	Lift-off (gas & Dust)	Delayed	Total (Circ + Lift) (Unfiltered)	Total (Circ + Lift) (Filtered)	Delayed (Filtered)
Kr-83m	6.00E+10		4.85E+08	6.00E+10	6.00E+10	4.85E+08
Kr-85m	1.77E+11		1.58E+10	1.77E+11	1.77E+11	1.58E+10
Kr-85	6.45E+10		4.85E+10	6.45E+10	6.45E+10	4.85E+10
Kr-87	2.44E+11		3.80E+08	2.44E+11	2.44E+11	3.80E+08
Kr-88	4.20E+11		1.39E+10	4.20E+11	4.20E+11	1.39E+10
Kr-89	1.45E+11			1.45E+11	1.45E+11	
Kr-90	7.23E+10			7.23E+10	7.23E+10	
Kr-91	3.45E+10		7.14E+10	3.45E+10	3.45E+10	7.14E+10
Xe-131m	1.22E+10		2.03E+11	1.22E+10	1.22E+10	2.03E+11
Xe-133m	3.43E+10		1.17E+13	3.43E+10	3.43E+10	1.17E+13
Xe-133	1.49E+12			1.49E+12	1.49E+12	
Xe-135m	5.84E+10		4.70E+10	5.84E+10	5.84E+10	4.70E+10
Xe-135	2.30E+11			2.30E+11	2.30E+11	
Xe-137	1.53E+11			1.53E+11	1.53E+11	
Xe-138	2.81E+11			2.81E+11	2.81E+11	
Xe-139	4.42E+10		6.02E+12	4.42E+10	4.42E+10	6.02E+12
Xe-140	1.95E+10		1.19E+10	1.95E+10	1.95E+10	1.19E+10
Br-83	4.07E+08	9.08E+07		4.98E+08	4.98E+05	
Br-84	2.09E+09	4.50E+08		2.54E+09	2.54E+06	
Br-85	1.17E+10	2.49E+09		1.42E+10	1.42E+07	
I-131	6.36E+07	6.79E+07	6.02E+11	1.31E+08	1.31E+05	6.02E+08
I-132	2.66E+09	5.66E+08	1.19E+09	3.23E+09	3.23E+06	1.19E+06
I-133	6.97E+08	2.12E+08	2.01E+11	9.09E+08	9.09E+05	2.01E+08
I-134	9.32E+09	2.02E+09	9.03E+06	1.13E+10	1.13E+07	9.03E+03
I-135	1.62E+09	3.93E+08	1.95E+10	2.02E+09	2.02E+06	1.95E+07
I-136	1.86E+08	3.95E+07		2.25E+08	2.25E+05	
Cs-134	3.61E+05	2.84E+07		2.88E+07	2.88E+04	
Cs-137	2.28E+06	5.49E+08		5.51E+08	5.51E+05	
Sr-90	4.56E+03	1.09E+06		1.10E+06	1.10E+03	
Ag-110m	4.54E+05	1.22E+07		1.26E+07	1.26E+04	
C-14	8.60E+12	0.00E+00		8.60E+12	8.60E+09	

Note: Blank spaces indicate zero activity

2.2.1.4.4 Release height

Release height is very important as it influences the exposure of the population near the plant. The actual plume height may not be the physical stack height. Plume rise can occur because of the velocity of stack emission, and the temperature differential between the stack effluent (energy of the release) and the surrounding air. The rise of the plume results in an increase in the release height, and allows for greater mixing for lower integrated concentrations at ground level. **Figure 3** shows atmospheric dispersion of the plume. There are two predetermined release routes in the event of a depressurization. For small pressure boundary break, which is assumed to be within the capacity of the containment filtration system, the release is filtered through the system and exhausted to the atmosphere at the top of the reactor building. The exhaust point is at a height of 23 meters, where HVAC vents are located.

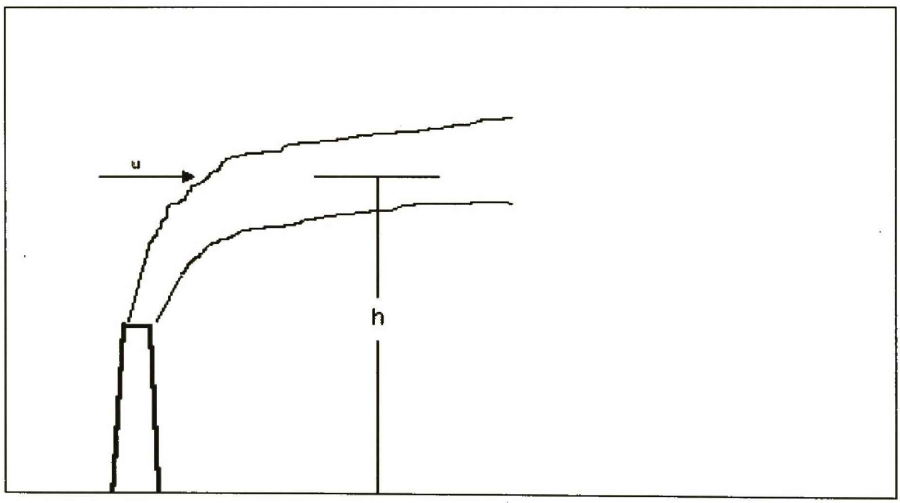

Figure 3: Dispersion of Plume (u=windspeed, h=effective height of release)

This is the only release route in the event of a small pressure boundary break. The second scenario involves medium releases, which have a dedicated shaft interconnecting with other cavities, and reclosable vents at the roof, as in the case of a small break. Larger break release is through same route as the medium releases except that the blast panels, located at a height of 23 meters are assumed not to reclose after the initial release.

2.2.1.4.5 Timing of release

The time at which the release occurs is immediately after nuclear fission stops. This conservative assumption does not allow for activity reduction through radioactive decay prior to release. The decay heat for 2 hours after fission stopped is used for reducing energy and release height, but the zero time inventories is assumed to maximize the quantity of short–lived fission products in the source term.

2.2.1.4.6 Release duration

It is the duration of the release into the atmosphere. It influences horizontal dispersion of the released material. PC COSYMA models releases as puffs lasting for one hour. This is conservative, as most releases will last longer than one hour releasing the same quantity over a longer period of time could allow greater mixing and lower dose predictions. All releases are modeled as short duration releases except for those which have delayed release, in which case they are represented as two puffs lasting one hour each but separated by the time at which the delayed release is supposed to start.

2.2.1.5 Meteorological data

Data being used for the PBMR is data used by KNPS, since the PBMR does not yet have its own data. The meteorological data is based on data for the years 1998 and 1999. The meteorological data file contains 17520 hours of data. 17520 hours is obtained by multiplying 2 years by 365 days per year, multiply by 24 hours per day.

The following information is included in the Koeberg NPS data:

- Wind direction
- Atmospheric stability category.
- Rainfall rate.
- Wind speed.
- Mixing layer depth.

They all affect the concentration of radioactivity to a person exposed.

It is a common practice in probabilistic consequence to perform calculations for a smaller representative set of weather data because a large amount of data involved during calculations makes it impractical to calculate consequences for each hour of data. To

achieve this, a sampling technique called stratified sampling is used. In stratified sampling, weather data that will result in similar consequences are grouped together under one class by PC COSYMA using weather data sampling scheme. Several of these groups are created. They are groups of meteorological conditions, which would lead to comparable radiological consequences in the near range for a given release **[11]**. Weather sequences are then randomly selected for analysis by randomly selecting one or more hours per group. In this way a full range of weather conditions is considered. The sampling scheme used for this evaluation of weather data is the default scheme that comes with PC COSYMA.

2.2.1.6 Population distribution data

Population data used for this evaluation represents the population distribution within 50 km radius of the site. The data used are the same as that used by KNPS. The data is based on the 1991 government census but were adjusted to reflect 1996 conditions. The data is in the format used by PC COSYMA. The population is generally spatially distributed on sectors with 16 directions (each described by an angle of 22.5^{0}). The radial grid used has 22 distances bands up to 50 km. The grid is centred on the facility from which the radionuclides are assumed to be released.

2.2.1.7 Agricultural production

The agricultural production data are also an important element of consequence analysis. Agricultural production is important, since the food grown in an area is affected by the release of radioactivity. For the current evaluation, a total food ban was assumed. Agricultural data would be generally specified in PC COSYMA in the same format as the population data.

2.2.1.8 Radionuclide grouping

It is a standard practice in consequences analysis to group radionuclides according to their chemical and physical properties. The chemical and physical properties impact the manner in which nuclides are transported in the atmosphere up to the various organs of the body via various pathways. Nuclides with similar properties are grouped together because they behave similarly. PC COSYMA allows for nuclide groups of up to 14. A default-grouping scheme of 7 nuclide groups is commonly used for consequence analysis as shown in **Table 3**.

Nuclide Group Number	Elements In The Group
1	Kr, Xe, Ar (Noble gases)
2	I, Br (Halogens)
3	Rb, Cs (Alkali Metals)
4	Sb, Te (Tellurium Group)
5	Sr, Ba (Tellurium group)
6	Co, Mo, Tc, Ru, Rh (Noble metals)
7	Y, Zr, Ce, Pr, Nd, Np, Pu, Am, Cm (Lanthanides)

Table 3: Radionuclide grouping considered in consequence analysis

This grouping is appropriate for the PBMR because of the limited number of nuclides that are released. The release fraction for each of these groups is taken to be unity. This means that the initial inventory specified in the PC COSYMA input is assumed to be released in its entirety.

2.2.1.9 Main Endpoints to PC Cosyma

Descriptions of consequences from accidental release are called endpoints as referred in PC COSYMA. For the current analysis, the effective dose is the endpoint that is determined. The main endpoints that can be calculated by PC COSYMA are as follows:

2.2.1.9.1 Concentration

Concentration and deposition of nuclides at selected points refers to the concentration of activity in the air and also deposition of nuclides at selected points.

2.2.1.9.2 Dose

Dose received at various distance away from site, which referred to the dose accumulated by different organs (effective dose), which can also be obtained at each distance considered. They can be short or long term doses. Short-term doses are doses over a maximum of 30 days, while long-term doses assume a dose integration period of 50 years.

Information about contributions to doses by different nuclides and different exposure pathways can also be obtained. They are discussed later on.

2.2.1.9.3 Numbers of early and late fatal and non fatal health effects

The early health effects are those that appear within a few weeks after the accident. They result due to a large release over a very short time because there are thresholds that must be exceeded to produce these effects. For the PBMR it is irrelevant since the ranges of possible dose consequence are one or two orders of magnitude lower than the thresholds based on the analysis already performed and expected. The effects can include loss or impairment of various vital organs. Late health effects also include hereditary effects in the descendants of the exposed public.

Further information on health effects can be obtained in terms of the risk 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 sites. For purpose of this assessment, the results presented only include doses at distances away from the reactor.

Other probabilistic effects that could be modeled with PC COSYMA include:

- Short term and long term risk of morbidity and mortality for various health effects and CCDF for early and late health effects were not evaluated in this assessment.
- Effects of countermeasures, including amount of food banned

  It is assumed in consequence analysis that after an accident release, protective measures are generally taken to mitigate the release. These measures are called countermeasures. These vary from distribution of stable iodine tablets, to relocation of the affected population and food banning.
- Economic costs include the contribution from application of countermeasures and health effects **[7]**.

CHAPTER 3: METHODOLOGY

Included in PC COSYMA calculation of LBE consequences of the current study are various exposure pathways to humans, which are external and internal and can be split into Cloud shine, Ground shine, Inhalation, Resuspension, Skin and Clothing. The inputs are identified from previous safety studies, similar HTGR and some relevant past experience from currently operating Light water Reactors and also from events that have been prescribed by the US NRC [11]. They are to be explained later on. The following are assumptions, which are used as inputs to PC COSYMA:

- During calculations, it is assumed that all the radioactive materials circulating in the helium circuit at a time of the pressure boundary failure are released in the first hour of the event. For medium and large breaks, a fraction of the material plated out on piping and vessels is assumed to be lifted off by the turbulent outflow of helium, and released along with the circulating activity
- It is also assumed that after a break in the primary pressure boundary, that cannot be isolated, there's a release that is going to commence after 32 hours which is called Delayed release. The value of 32 hours was taken from High temperature modular reactor SAR. Delayed release occurs due to events where active core cooling is not assumed, where there will be additional releases from the fuel due to the slow heat up of the fuel beyond normal operating temperatures. When the core is isolated from the break, the activity from a delayed release from the fuel is contained so there will be no delayed release.
- Due to the low driving force behind this delayed release, there will be a number of mechanisms that could remove, in particular, the halogens from the release before partial escape from the building. Since all the gas will have been lost during a depressurization event, the only driving force to this delayed release is gas expansion as a result of high temperatures. The inventory used as the delayed source term was a fraction of the activity released from the core into the reactor building, which was released into the environment. All of the noble gases are assumed to be released.
- For the circulating, and plate out activity release categories, the activity inventory specified is the one that is released; therefore the release fractions are all unity.

- For the accident source term, the initial inventory for the release category, the activity inventory for the release used as input to PC COSYMA is the sum of the activity circulating in the Helium inventory at the time of the event, plus the accumulated plate-out activity that may be lifted off. Plate out radioactivity will only play a role in the event of medium and large pressure boundary breaks. No lift off is assumed for small breaks. The reason for this is that a small pipe break will not generate high enough flow forces to dislodge plated-out activity. For purpose of demonstrating compliance with the NNR regulations, it is conservatively assumed that in the event of an unisolatable break, the entire primary inventory is released. Therefore, the initial inventory available for the release is calculated where applicable.
- Another assumption is that for medium and large breaks, no credit is taken for filtration by the HVAC. For small breaks, non noble gas activity filtration occurs and a factor of 0.001 is used to reduce the doses appropriately. Noble gases don't filter. (The halogens elements that are Cl, Fl, Br, I are not necessarily gaseous. They may occur as particulates or gases. Particulate forms may be filtered. Noble gases which are He, Ne, Ar, Kr, Xe are the last column in the periodic table. They are not captured by HEPA filters.). No deposition within the reactor building is assumed for either case. This is conservative and overestimates the Offsite consequences.

3.1 Additional Inputs

For calculating the radiation dose from inhalation of radioactive aerosols, gases, and vapors, PC COSYMA requires three site-specific parameters, which have to be specified. These are the surface roughness (terrain type), breathing rate, and shielding factors.

3.1.1 Surface roughness

Terrain irregularities generally affect the wind and air temperature. The irregularities usually include building structures, hills, valleys, and other obstacles. The presence of building structures and other line of sight obstructions can significantly effect the ground contamination dose rate by attenuation of the gamma ray so to provide shielding. However, the effect of these irregularities is much smaller high up in the atmosphere.

PC COSYMA can allow only two choices of surface roughness i.e. smooth and rough surfaces. The smooth terrain choice is appropriate for rural areas, while the rough terrain is appropriate for sites with large forested areas in the vicinity of the release point, or for

sites located near urban centers where there are relatively tall building structures. The current evaluation covers an area of 50 km radius around the site. This area includes both the big metropolitan areas such as Cape Town, and the rural farms in the vicinity of the sites. A smooth terrain type of calculations is assumed because most of the area near the site can be considered 'smooth terrain'.

3.1.2 Breathing rate

PC COSYMA requires the breathing rate to be specified for calculating both short term and long-term radioactive consequence. For the current analysis, a moderate value of 3.333 x 10^{-4} m^3/s is used. This value is chosen because it is higher than the "average" breathing rate for the full duration, and much higher (more conservative) for the longer term delayed release. Higher breathing rate means you take a greater volume of air and radioactivity into your lungs over a given period of time. The following values are suggested by US NRC in Reg Guide 1.3, where they use a slightly higher rate initially, then a much lower rate until the end of the accident.

- "For the first 8 hours, the breathing rate of persons offsite is assumed to be 3.47 x 10^{-4} cubic meters per second. From 8 to 24 hours following the accident, the breathing rate is assumed to be 1.75 x 10^{-4} cubic meters per second. After that, until the end of the accident, the rate is assumed to be 2.32 x 10^{-4} cubic meters per second. (These values were developed from and correspond to the average daily breathing rate 2 x 10^7 $cm^3.day^{-1}$ assumed in the report of ICRP, Committee II-1959.)"

3.1.3 Shielding factors

It is assumed in consequence assessment that people are outside and unprotected when the event happens. Essentially, it is conservatively assumed that they are naked and remain at the same location for 30 days. Thus, the location factors specified in PC COSYMA are all unity.

3.1.4 Reactor building dimensions

Dimensions of the reactor building also have to be specified. For the current PBMR design, the dimensions are described.

- Length of the reactor building is 54.65m.

- Width of the reactor building is 32.9m.
- Height of the reactor is 42m, but much of the building is below ground level.

The roof is at level 23m, which is the release height for the PBMR. PC COSYMA requires, in addition to release height, the diameter of the reactor building to be specified. This is because PC COSYMA is designed for the LWR, which has cylindrical containment buildings. The dimensions of the building are important since the volume into which the gas will expand into must be known. For the PBMR, the above dimensions must be converted to that of cylindrical structure with the same volume. This gives a radius of 24m, thus, the building width is 48m for PC COSYMA input.

In addition to site-specific data that the user must provide as input, PC COSYMA also requires values for various quantities, including dose per intake, or concentration in food per unit deposit for calculations of various radiological consequences. Since a food ban is assumed, this information was not required for the current assessment. Dose conversion factors are built into the PC COSYMA code and do not have to be entered by the user. PC COSYMA incorporates biokinetics models recommended in ICRP 56, 67, and 69.

For consequence analysis, models are used to perform calculations. These models are created by PC COSYMA software to simulate the atmospheric dispersion. For the determination of doses resulting from a release, the atmospheric and ground concentration of every radionuclide that is deposited by the passing plume has to be calculated. Once the concentrations are known, the whole body dose due to various exposure pathways can be calculated.

PC COSYMA uses the atmospheric dispersion model called the Gaussian Plume Model to describe the movement of radionuclides through the atmosphere. It allows for the hourly changes in the meteorological conditions affecting the plume. It also takes into account the terrain type over which the plume is traveling. It can allow for the plume to deplete by various processes and build up of radioactive isotopes. It can further allow for material released over a long period by describing the release as a series of hourly phases, which are treated separately.

3.2 Exposure Pathways

Different exposure pathways are the routes in which the public can accumulate a radiation dose after a release to the atmosphere. These exposure pathways are taken into account

by PC COSYMA when determining the radiation dose. The doses calculated by PC COSYMA are those for an average individual. The individual is based on a healthy 70 kg reference man.

The pathways are:

- External exposure to gamma and beta radiation from activity in the passing plume or cloud of radioactive material called cloud shine.
- External exposure to gamma and beta radiation from activity deposited on the ground called ground shine.
- Internal exposure to activity due to inhalation of activity directly from the passing plume.
- Internal irradiation due to inhalation of activity from resuspended ground deposit. (Resuspension)
- Internal exposure following ingestion of food contaminated by activity deposited from the plume. (It is not calculated for this study due to assumed food ban including water next to the plant.)
- External gamma and Beta irradiation from activity deposited onto the skin and clothing.

For each pathway, the dosimetric models are used to evaluate not only the effective dose, but also the dose in each of a number of organs and tissues (equivalent dose) that are of significance for evaluating the health impact in the exposed population. These organs include the bone marrow, lung, thyroid, breast, liver, GI tract, skin and the average dose in the remainder of the body **[7]**.

The importance of these different pathways is that they can be used to make recommendations on which exposure pathway are most important for longer or short term doses for emergency planning or which pathways should be considered in the assessment. Recommendations are based on calculations to investigate the relative importance of different exposure pathways following particular discharges to atmosphere. It is important to take account of local and regional factors in determining which pathways to consider.

For the variation in the consequences with the variation in the input parameters, the sensitivity analysis of LBE is performed by varying exposure pathways (as inputs) using deterministic analysis by PC COSYMA. The purpose of sensitivity study is to address modeling assumptions suspected of having significant impacts on the results i.e. to identify

input parameters and assumptions, which have the greatest influence on the doses. For this, various parameter values and assumptions are altered and the effects of these changes on the calculated doses are studied.

In order to assist the interpretation of the results, deterministic analysis should be associated with an estimate of uncertainties. In stating what is uncertain, it is necessary to check which uncertainties are important to the final results and how much do the final results change if a parameter is varied. Sensitivity analysis is performed on PC COSYMA, which is used for assessment of the off-site consequences of accidental release of radioactive material to the atmosphere.

Sensitivity study is performed by carrying out runs on the system repeatedly with a parameter value changed each time during this repetition. In the analysis, a first run is carried out, changing the desired parameter values in all sections of the interface, for which a .SAV FILE is created. A .SAV FILE is a file containing the first calculation with the extension name .SAV. This file will then be used as the basis for the second run, in which parameter values for some of the sections from the main menu are not required, because the run has only a selection of endpoints.

The .SAV file for the second run is also created to be used as the basis for a third run, in which the endpoints or options are the same as the first run. Analysis is carried on until all parameters of interest are varied, with the cycle repeated for the next parameter (pathway).

Sensitivity study was performed on the exposure pathways for early dose calculations for the different pathways mentioned in section **3.2**.

For each run that is performed, only one pathway is considered as an input and its effect on the result is observed i.e. only one pathway is included as an input parameter excluding the other four pathways.

3.3 Three Major Sections Of PC Cosyma Program

3.3.1 Input interface

In the input interface, a series of menus are used to guide the user through the process of identifying the required endpoints. Every menu is included in the input interface so that the user can enter information. Endpoints are specified and values are set for the input parameters needed in the calculation of the endpoints. The interface also determines which of the calculation programs are required and a system is set up to run the data without further intervention from the user. When running the input interface, it must be selected from the three major subsections (PC COSYMA main menu on screen).

Once the input interface is selected, there will be a presentation of menus relating to the input parameters for a part of the PC COSYMA. An ASCII text file is written which gives a summary of all the parameter values entered. The user may wish to exit from PC COSYMA to check the input values before proceeding. If necessary, the user can again enter the Input interface to correct input parameter values. Once the input values have been double checked, they can be transferred to a calculations program through a file. All the values are written to this file and also used in writing to the .SAV file so that values are used again in the system. Once all the parameters have been set, OK TO RUN option must be selected in order to proceed with the calculations. When exiting from input interface, the file is overwritten.

Table 4 provides an illustration of input parameters required for performing PC COSYMA Calculations.

3.3.2 Calculations programme

The calculation package consists of a number of programs, which implement PC COSYMA to run the required calculations. The programme can be run by selecting calculations from the main menu. When starting the calculations, the few remaining parts of the interface must be completed before running the programs to ensure that the correct file is used for the calculations. A COSYMA session must not begin by running the calculation programs. PC COSYMA uses a number of files to pass information between e various programs, which are used for the calculations specified.

3.3.3 Results interface

The interface allows the user to see the results of the calculations, which have been performed. The results interface uses a series of menus to guide the user through the presentation of the results. It allows the detailed representation of results and incorporates an interface allowing graphical representation of the results.

To run the results interface, the user must select results from the main menu of PC COSYMA. The results interface can be used in two ways referred to as interactive or automatic mode. In the interactive mode, the user has control over the order in which the results for the various endpoints are displayed, and does not have to examine all the results generated. The automatic mode gives the user a simple means of generating printed tables or graphs of a selection of the calculated endpoints. The user has no influence over the choice of results for presentation, as the selection is made by the system, but the two modes can be combined to give a rapid presentation of the main results and allow a more detailed examination of the other results.

The results interface is divided into a series of sections for the different endpoints of COSYMA. For the current study, endpoints calculated are short term and long term individual doses. The options for short and long term doses are identical when doses by grid point is selected, a presentation of the dose for the various organs considered in each sector at a chosen distance are given.

Once the user has selected the required endpoint, the system presents the results, on the screen. There are options for examining the results including a table and a graph displayed together. For many of the endpoints, the results (dose) are presented in terms of the mean value as a function of distance.

When the screen is first displayed, the data in the distance and dose columns are presented graphically. For deterministic runs, the mean value as a function of distance is presented. The y values are the variation of the quantity in one direction versus distance. This value is averaged over all sectors for the single set of conditions considered. After observing the results on PC COSYMA screen, the results can be moved from the textfile in PC COSYMA (file name. TXT)) to the Spreadsheet (Filenames.SPS) [7].

This is called extracting the results from COSYMA to Excel. For the current study, the endpoint of interest is the dose and therefore the filename given to the Excel spreadsheet is the dose. After the filename has been chosen, PC COSYMA is then closed.

After that, in the computer, you have to go to the hard drive and open the Excel files in the PC COSYMA, Results directory. The Excel spreadsheets allow more options for arrangements and display of results in tabular and graphical form.

Table 4: Summary of Inputs to PC COSYMA

Source Term	Release & Site Parameters	Meteorological Conditions	Countermeasures Strategies
Circulating activity	Release Height (23m)	Ambient Temperature (Koeberg Meteorological data files 1998-99)	Sheltering (Not credited)
Dust and Plateout activity	Release Energy (1.06 MW)	Wind Speed (Koeberg Met data)	Evacuation (Not credited)
Delayed release Activity	Distance to receptors (400m to x)	Wind Direction (Koeberg Met data)	Food Banning (100% food ban)
Form (noble gases, aerosols, elemental, or organically bound iodine.(PC COSYMA default)	Surface Roughness (Smooth Terrain)	Atmospheric Stability (Koeberg Met data)	Iodine Prophylaxis (Not Credited)
Release Fractions (1.0)	Population Distribution (Koeberg Data)	Inversion Layer (Koeberg Met data)	Relocation (Not Credited)
Phases and Timing Circulating + Dust Activity = 0	Agricultural land use data (Not used as food ban assumed)	Deposition (PC COSYMA default)	Decontamination (Not credited)
Delayed Release- 32 hrs	Breathing Rate (3.33 E-4 m^3/s	Dispersion (PC COSYMA default)	
		Precipitation (Koeberg Met data)	
		Sampling Scheme (probabilistic)—PC COSYMA Default	

CHAPTER 4: RESULTS

4.1 Introduction

This chapter presents the various results obtained from using PC COSYMA for the deterministic analysis of the sensitivity of Licensing Basis Event consequences due to various exposure pathways. The results have been calculated at the middle of each distance band. For the specified distance band around the release source, the results are presented at the midpoints of two bands. Source term used is the design source term, from **Table 2**, which is the source term used for dose calculations.

Data for the contribution made by different exposure pathways to the dose is presented, specifically individual effective dose for 1 day, 7 days and 30 days integration time reported in Sv. The dose values presented are plume centreline doses, which are doses at sector 9 of the 16 sectors in the population distribution data. Plume centreline dose represents the maximum doses an individual would receive. The doses have been determined at 400m, which is a distance to the PBMR site boundary that is the nearest place where the public may be found and that is where the maximum effective dose is obtained.

Plume centreline dose is due to the fact that the plume dispersion does not occur along a straight line even for short distance, even when the wind blows in one direction. Wind meander (the slight change in the direction of the wind) would spread the dose over a large area, reducing the peak values, particularly at large distances from the release point.

All the activity in (Bq) from the reactor that is calculated is split into three source terms, which are characterized as the circulating activity, delayed activity, and the plated out activity. They are fully explained in chapter 2. For each release category, the effective doses at the plume center line for circulating, delayed, and plate-out activity (as shown in **Table A-1**), have been added together into release categories to determine the total effective dose and the class under which the effective dose will fall.

Effective doses of all release categories have been presented in **Table A-2** and rranged in **Table A-3.** Table A-3 is also the final dose obtained that will be compared the dose regulatory limit of 50mSv per event for members of the public as it can be n in **Table 5.** The effective dose due to the contribution of all the pathways for the

1-day, 7 days and 30-days dose integration time or exposure time are also presented in **Table A-1**, **Table A4** and **Table A7**.

Meteorologists distinguish several states of the atmospheric surface layer as unstable, neutral, and stable. The amount of turbulence in the ambient air has a major effect upon the rise and dispersion of air pollutant plumes. The amount of turbulence can be categorized into defined increments or "stability classes". The most commonly used categories are the Pasquill stability classes A, B, C, D, E, and F. Class A denotes the most unstable or most turbulent conditions and Class F denotes the most stable or least turbulent conditions.

All the dose results mentioned above are calculated using weather conditions of category F stability with a wind velocity of 2 m/sec. The weather of category F stability is those conditions, which are moderately stable conditions with no rain and minimum variability in the wind direction. They are based on meteorological measurements and plume behaviors. Stable conditions occur mainly during the nighttime.

For an elevated release, the location of the maximum concentration depends on the stability class chosen. For materials with a deposition velocity of zero and a release point at or very near GROUND LEVEL, the maximum concentration is always associated with "F" stability. Probabilistic analyses typically look at thousand of hours of meteorological data for a given site, but deterministic analyses are typically performed for one or more stability category or wind speed combinations specified by the regulator. Category F with low wind speed is often used for the relatively conservative dose calculations.

4.2 Effective Doses for all Events for Short-term individual Doses of 1 day, 7 days and 30 days Dose Integration Time

Presented below are the results of the effective doses of the 1-day, 7 -days and 30 days dose integration time. The results are calculated the same way with only different integration time and the same weather category. The graphs of RC-1 and RCP-1 from **Figure 4**, **Figure 5** and **Figure 6** follow the same pattern, Doses due to RC-1 and RCP-1 increase very slightly with an increase in the dose integration time and an increase in the distance. The graphs are combined to give the graph in **Figure 7**. For the graphs of RCF-1 & 2 and RCFP-1 & 2 from **Figure 4**, **Figure 5** and **Figure 6**, the dose is time sensitive i.e. the dose increases much more rapidly with an increase in the dose integration time. The graphs are also combined to give the graph in **Figure 8**.

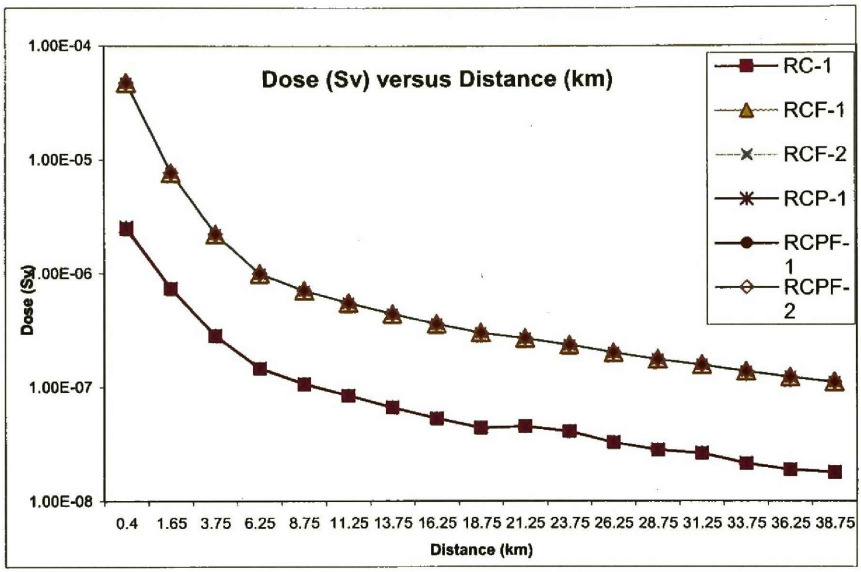

Figure 4: Graphs of Dose (Sv) vs. Distance (km) due to RC-1, RCP-1, RCF and RCPF activities for 1-day integration time

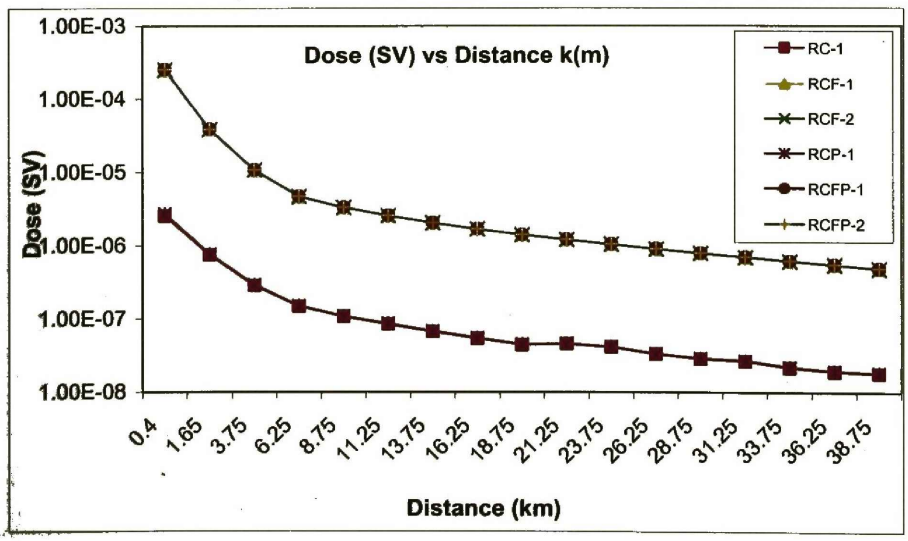

Figure 5: Graphs of Dose (Sv) vs. Distance (km) due to RC-1, RCP-1, RCF and RCPF activities for 7 days integration time

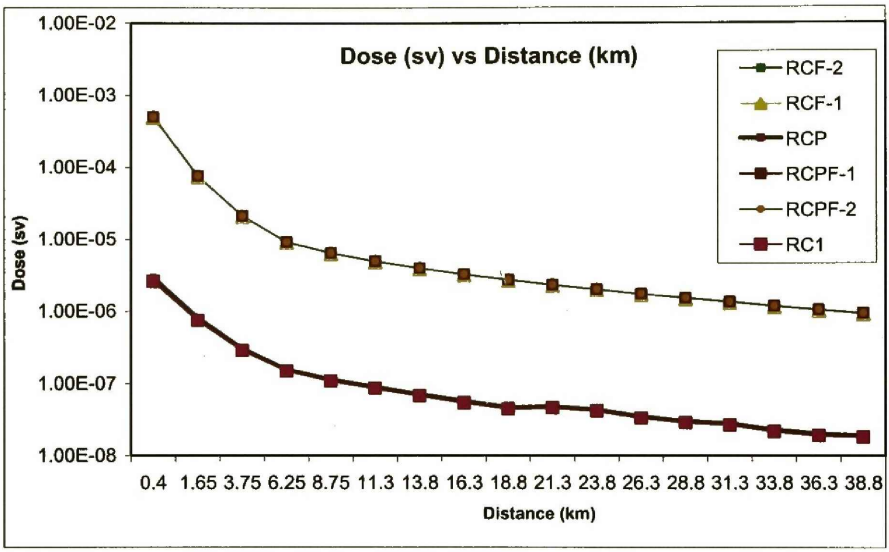

Figure 6: Graphs of Dose (Sv) vs. Distance (km) due to RC-1, RCP-1, RCF and RCPF activities for 30 days integration time

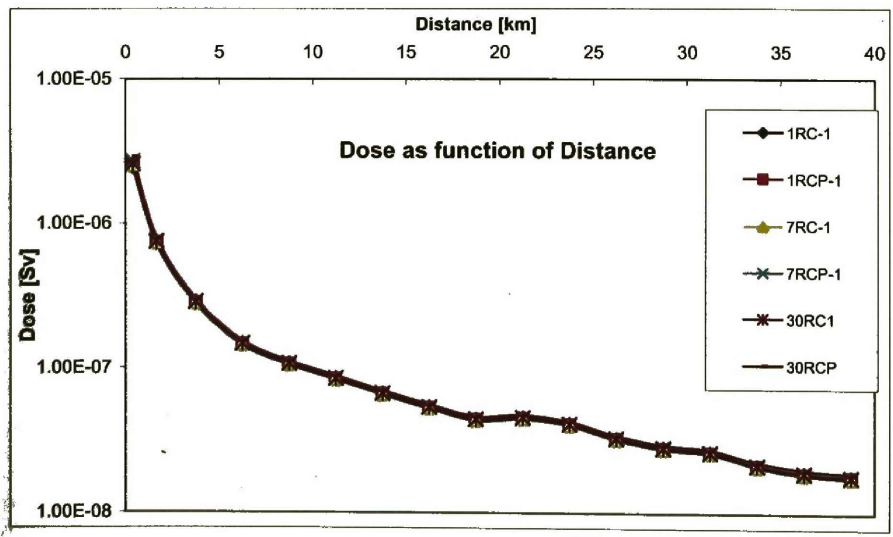

Figure 7: Graph of dose due to RC-1 and RCP-1 combined for 1, 7 and 30 days dose integration time

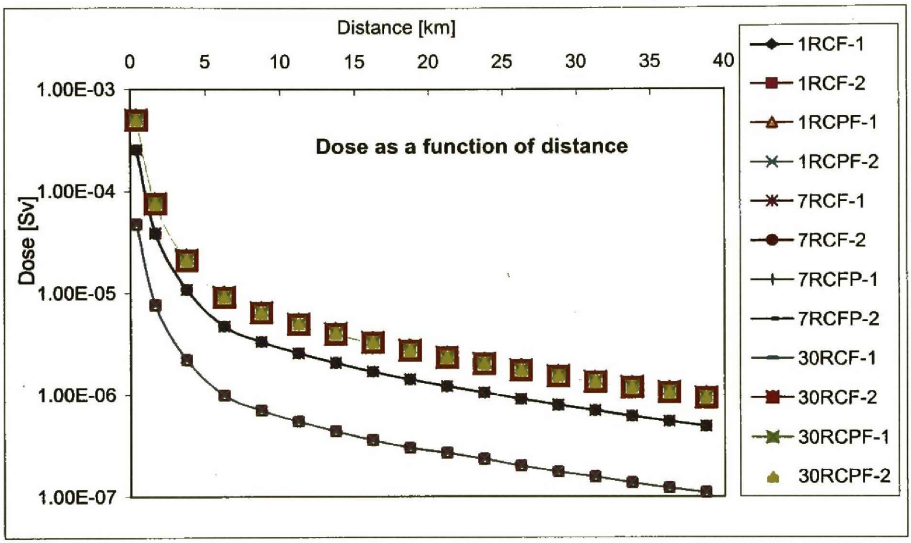

Figure 8: Graph of dose due to RCF-1 & 2 & RCFP-1 & 2 combined for 1, 7 and 30 days dose integration time

4.3 The Contribution by Exposure Pathway to the Effective Doses for 1 day, 7 days and 30 Days Dose Integration Time per percentages

The section provides the results of the contribution of each pathway to the effective dose. The contribution of each exposure pathway to the effective dose for 1, 7 and 30 days dose integration time shown by percentages.

For the following results the contribution of each pathway to the dose for each organ is shown by percentages. The effective dose in these results is presented as the mean effective dose at 0.4 km. The contribution of different source terms (circulating, plate out, or delayed) to the dose from each pathway is also presented. Dose by pathway percentage contribution is also presented by pie charts. **Note that,** PC COSYMA presents the results of both equivalent and effective dose. (From the dose shown in appendix tables, only the graphical representation of the dose is of interest, which is the effective dose, will be shown underneath. The graphs of the equivalent dose are not shown). The effective dose obtained is also given for the circulating activity, delayed release activity and lift off of plate out for different integration time.

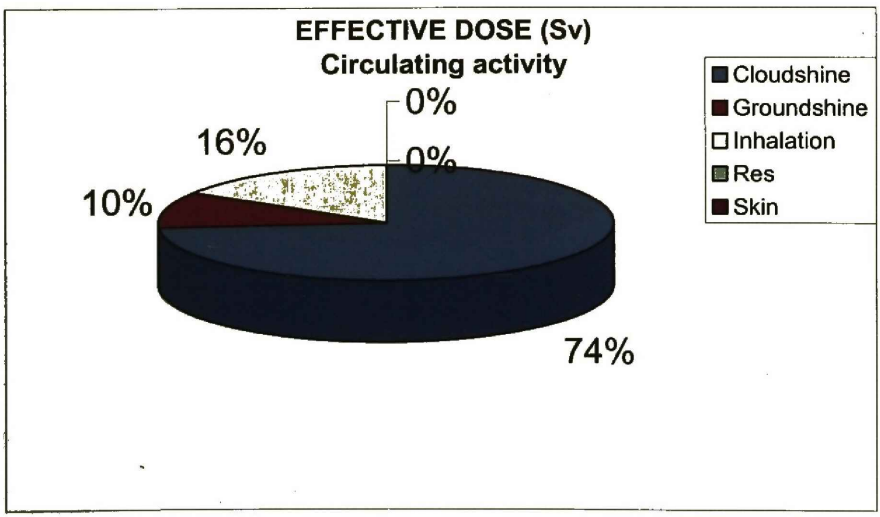

Figure 9: Graph of individual 1-day dose integration time and percentage contribution by pathway at 0.4km for circulating activity

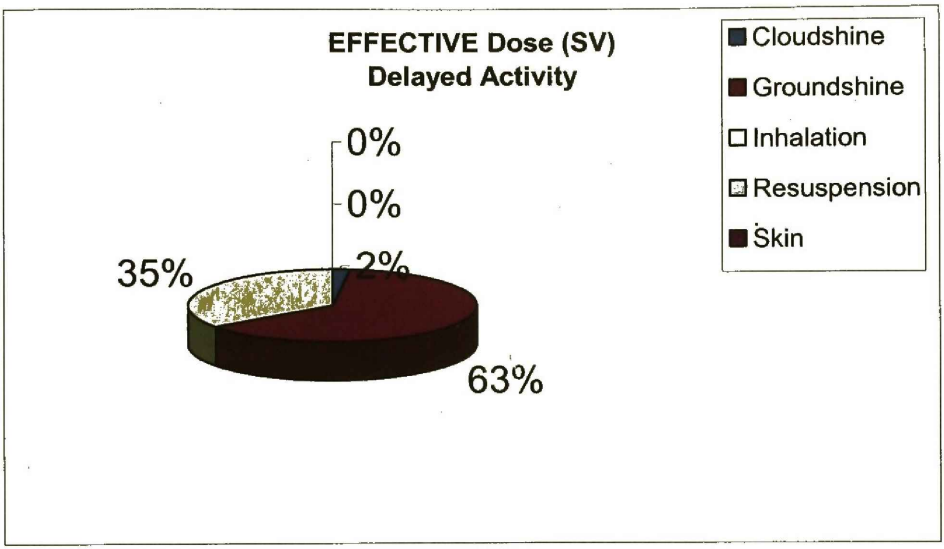

Figure 10: Graph of individual 1-day dose integration time and percentage contribution by pathway at 0.4km for delayed activity

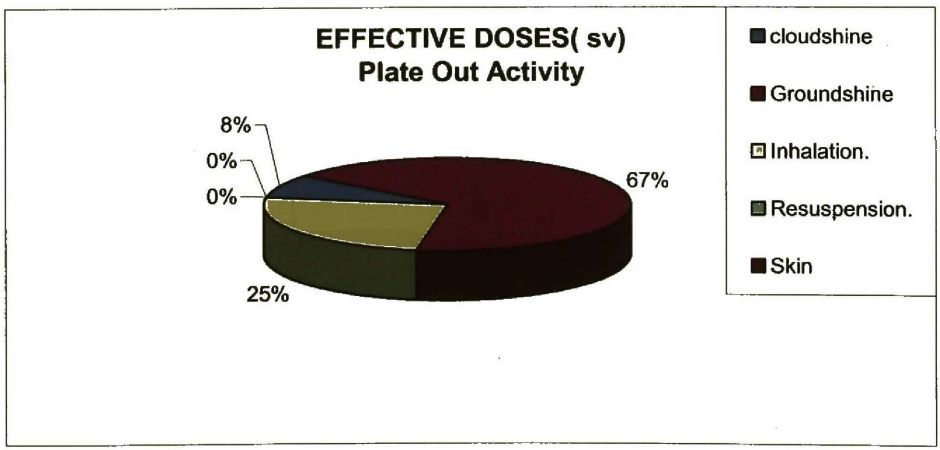

Figure 11: Graph of individual 1 day dose integration time and percentage contribution by pathway at 0.4 km for Lift off of plate out activity

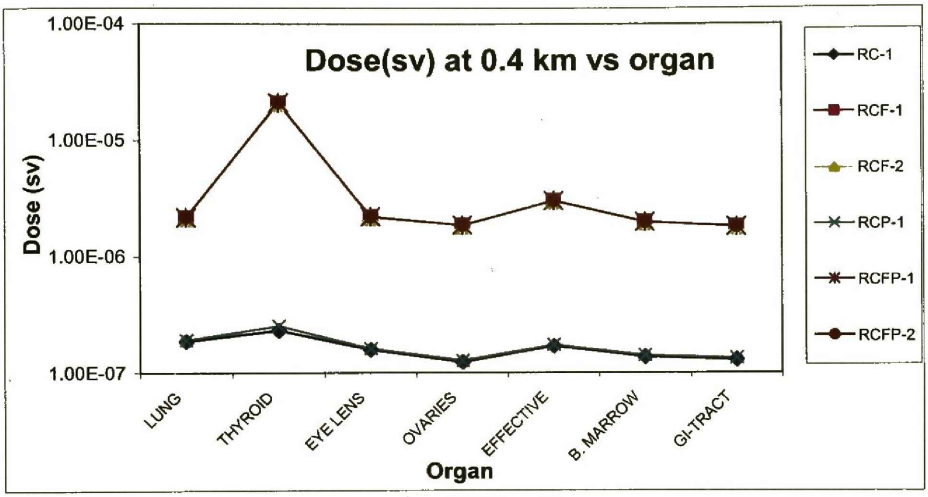

Figure 12: Graph of the total effective dose contribution release category for 1 day dose integration time

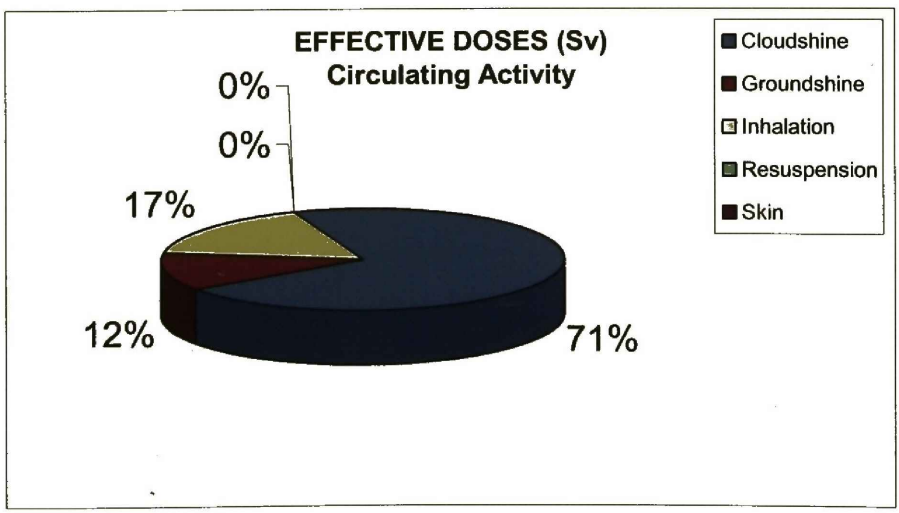

Figure 13: Graph of individual 7 days dose integration time and percentage contribution by pathway at 0.4 km for circulating activity

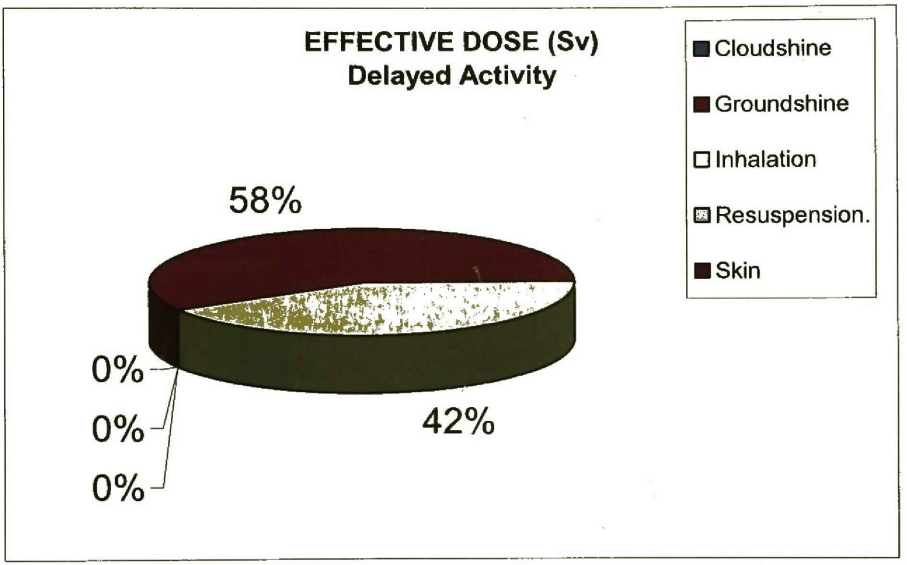

Figure 14: Graph of individual 7 days dose integration time and percentage contribution by pathway at 0.4 km for Delayed release activity

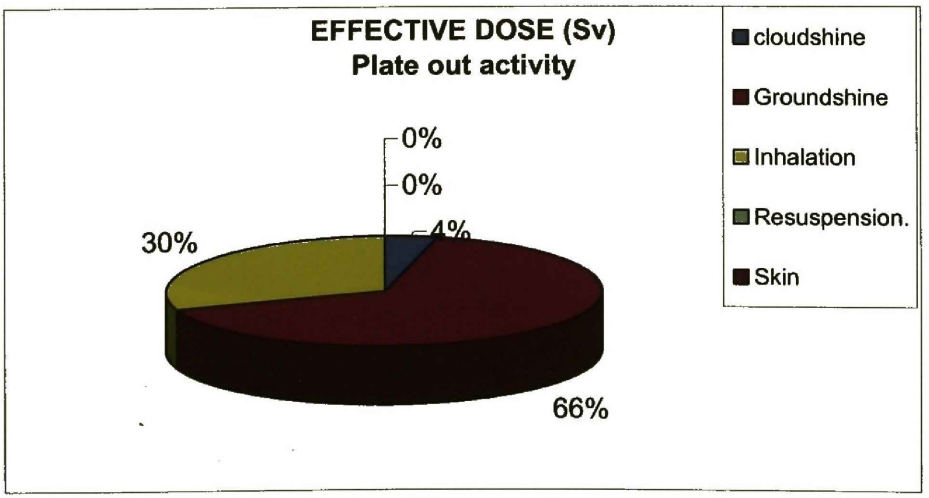

Figure 15: Graph of individual 7 days dose integration time and percentage contribution by pathway at 0.4 km for Lift off of Plate out activity

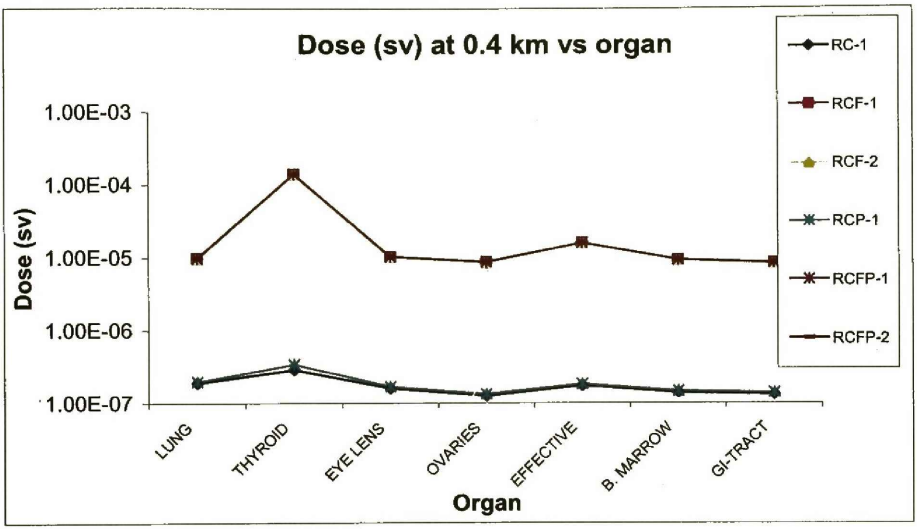

Figure 16: Graph of the total effective dose contribution release category for 7 days dose integration time

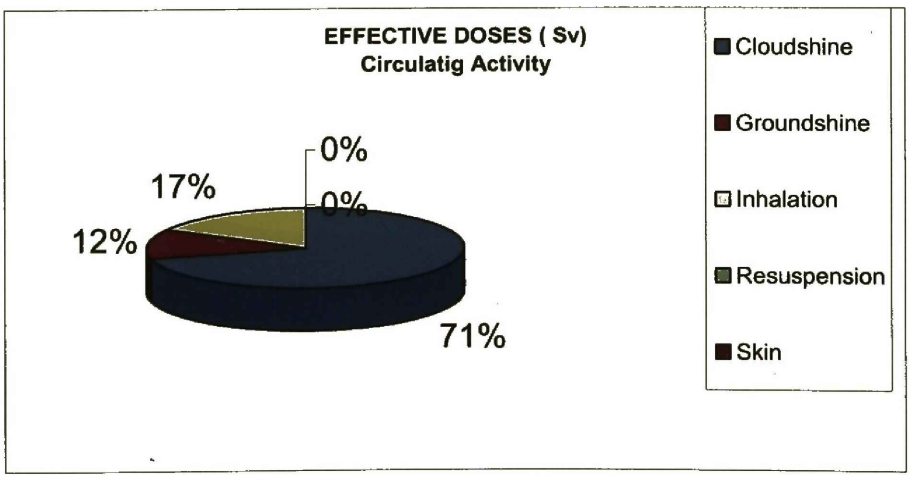

Figure 17: Graph of individual 30 days dose integration time and percentage contribution by pathway at 0.4 km for circulating activity

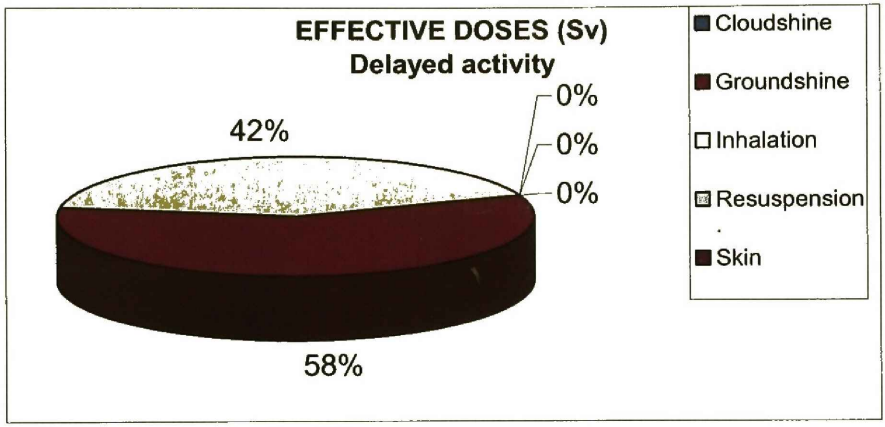

Figure 18: Graph of individual 30 days dose integration time and percentage contribution by pathway at 0.4 km for Delayed release activity

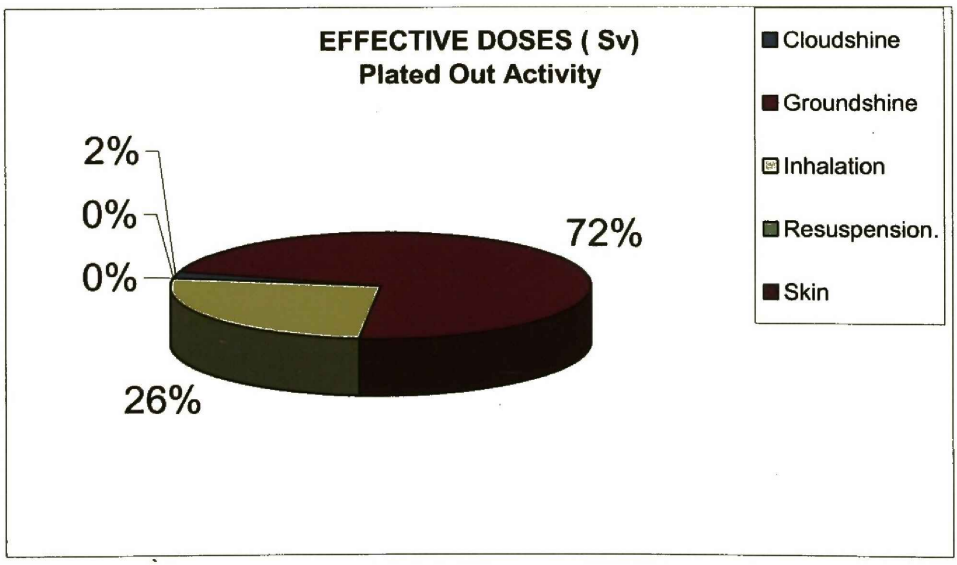

Figure 19: Graph of individual 30 days dose integration time and percentage contribution by pathway at 0.4 km for Lift off of Plate Out activity

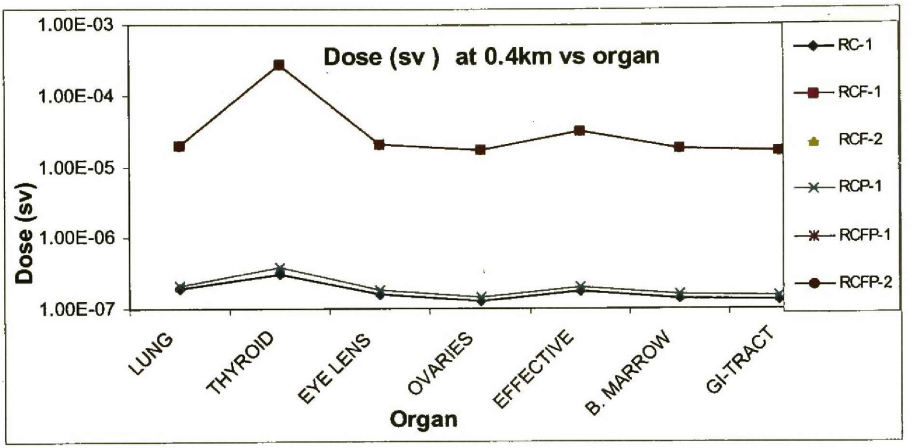

Figure 20: Graph of the total effective dose contribution release category for 30 days dose integration time

CHAPTER 5 DISCUSSION

This chapter discusses the results obtained from the deterministic analysis for the sensitivity of Licensing basis event (LBE) consequences to various exposure pathways. The results are the effective doses of 1-day, 7days and 30 days dose integration time and the doses by their dominant activity type (Circulating, delayed, and lift off of plated out material) are also discussed for each different pathway.

Radioactivity from a nuclear power plant lead to external dose due to the ambient radiation level and internal dose due to the inhaled species. The external and internal dose are discussed below.

Cloud shine dose depends on the predicted distribution of air borne activity. The semi–infinite plume of uniform radionuclide concentration is assumed. For ground shine, the material deposited on different surfaces (such as walls, roofs, grass in the residential areas) and the movement of activity into the ground is taken into consideration, Ground shine dose obtained is dependent on the amount of time spent outdoors.

For inhalation, which causes the internal exposure, it is calculated by taking the product of the time, exposed air concentration, breathing rate and dose per unit activity inhaled. It is the most significant route of internal exposure. The nature and magnitude of the dose depends on the particle size distribution and nuclide, which governs how it penetrates into and subsequently deposited into the respiratory tract, the airborne concentration, governing how much is deposited and the chemical and physical form governing fate and biological response to the contaminant within the respiratory tract and other organs of the body.

The skin and clothing pathway assumes that the dose is a multiple of the dose due to dry deposition on the ground at the same location. The contribution of Resuspension on the dose to skin and clothing is very small compared with other exposure pathways due to the shielding effect of the clothing though clothing is not going to prevent inhalation of resuspended dust. For each release the aim is to see how the relative contributions change as the dose integration time increases or how the absolute magnitude of the dose due to each pathway change with increasing dose-integration time. Finally the results are compared with the requirements of the nuclear regulatory authority in the Licensing guidance (LG)-1037 in **Table 5**.

5.1 Effective Doses for 1 day, 7 days and 30 days Exposure Time

For 1, 7, and 30 day's exposure time, the effective doses follow the same pattern for the dominant dose by activity type of each release category, for all of the exposure time. RC-1 involves only circulating activity, RCP-1 shows circulating being the dominant. RC-1 and RCP-1 have the same pattern for three different exposure times. The dose of RC-1 and RCP-1 increases very slightly with an increase in the dose integration time (exposure time) and decreases when moving away from the point source, the dose decreases as observed from **Figure 7**.

For RCF-1 & 2 and RCFP-1 & 2, it is shown that delayed release is the dominant activity type. This applies for 1, 7, 30 days exposure time. The dose due to RCF-1 and RCFP-1 are time sensitive i.e. the dose increases with exposure time from 1 day to 30 days but the dose decreases with an increase in the distance, by moving away from the point source the dose is minimized.

5.2 Contribution by Pathway to the Effective Dose for each Release Category for 1 day, 7 days and 30 days Exposure Time by Percentages

For 1, 7, and 30 days, cloud shine is the most contributing pathway, followed by inhalation, then ground shine pathway for the circulating activity. Cloud shine dose percentage decreases as exposure time increases, ground shine and inhalation dose percentage increases with increasing exposure time. This is because in the first hours or a day of the release the activity in the plume is still more concentrated because it is not yet deposited to the ground. As time increases, after some few days, there is then less activity in the atmosphere since it has deposited hence the higher ground shine as time went by.

For the delayed activity, the ground shine pathway is the most contributing, followed by inhalation and then cloud shine. For delayed release, ground shine and cloud shine percentage decreases with exposure time but inhalation percentage increases with exposure time.

For the lift off of plated out activity for all the exposure time, ground shine is the most contributing. Inhalation pathway follows as the second contributing and cloud shine is the least contributing. Inhalation dose percentage increases with an increase in exposure time.

5.3 Pathway Contribution by dominant Activity type for 1, 7 and 30 days

The pathway contribution by dominant activity type follows the same pattern for 1 day, 7 days, and 30 days integration time. For one-day integration time, cloud shine is the highest dose contributor for circulating activity. Ground shine is dominant dose contributor for delayed activity and plate out activity. The same pattern applies for 7 days and 30 days. Cloud shine is dominant for circulating activity, Ground shine is the dominant for delayed and plate out activity.

5.3.1 Cloud shine being the dominant pathway for circulating activity

For circulating activity, all the fission products that circulate during normal operation are released immediately in the first hour of the event. The higher driving force of the energy content of the release will influence the plume to rise high up into the atmosphere therefore increasing airborne concentration which contributes to cloud shine before deposition to the ground takes place.

5.3.2 Ground shine being the dominant pathway in delayed release and plated out activity

For the delayed release, which is due to the slow heat up of fuel, there is a low driving force of energy since all the helium gas is released with the first puff and then a smaller fraction of activity is released. Low energy release does not influence the plume to rise and allows less dispersion before the activity is deposited to the ground leading to an increase in ground shine.

The plate out activity is a small fraction of material plated out from piping and vessels. It is lifted off and released by the outflow of helium. The lift off of plated out material is carried out the roof with the helium and the circulated activity. The activity is probably in the form of larger, heavier particles than the circulating activity and that is why it can deposit on the ground more quickly. The pattern will follow for, 7 and 30 day's exposure time.

Table 5: The nuclear regulatory licensing criteria from (LG 1037) compared to dose obtained

EVENT FREQUENCY	SAFETY REQUIREMENTS	SAFETY CRITERIA
Category A Category A events (or combinations of events) are those which lead to exposure and which could occur with a frequency of more than one in one hundred years ($\geq 10^{-2}$ y^{-1}). Such events are treated as part of normal operation.	The design shall be such to ensure that under anticipated conditions of normal operation, there shall be no radiation hazard to the workforce and members of the public. Normal operation includes exposures resulting from minor mishaps and misjudgements in operations, maintenance and decommissioning, In addition all doses shall be kept ALARA and the principle of defence-in-depth shall be applied	The individual radiation dose limit shall be: -20 mSv.y^{-1} to plant personnel and - 250 µSv.y^{-1} to members of the public
Category B Category B events (or combinations of events) are those which lead to exposure and which could occur with a frequency of between one in one hundred years (10^{-2} y^{-1}) and one in one million years (10^{-6} y^{-1}).	The design shall be such to prevent and mitigate potential equipment failure or withstand externally or internally originating events, which could give, rise to plant damage leading to radiation hazards to plant personnel and members of the public in excess of the safety criteria. The analysis performed to demonstrate compliance with this requirement shall be conservative. In addition radiation doses and risks associated with these events shall be kept ALARA and the principle of defence-in-depth shall be applied.	The individual radiation dose limit shall be: - 500 mSv to plant personnel and - 50 mSv to members of the public for one single event or combination of events in this category
Category C Category C events (or combinations of events) are all possible events that could lead to exposure. As such, Category C events will include Category A and B events as well as events which occur with an annual frequency of less than 10^{-6}. Consideration may be given to the exclusion of very low frequency events in the range below 10^{-6} per year.	The design shall be demonstrated to respect the risk criteria for plant personnel and members of the public The analysis performed to demonstrate compliance with this requirement may use best estimate data provided it is supported by an appropriate uncertainty analysis. The analysis must also demonstrate a bias against larger accidents. See appendix E. In addition radiation doses and risks associated with these events shall be kept ALARA and the principle of defence-in-depth shall be applied.	Limitation of risk to the values set by the risk criteria. Plant Personnel - $5 \times 10^{-5}.y^{-1}$ peak individual risk and - $10^{-5}.y^{-1}$ average risk Members of The Public - $5 \times 10^{-6}.y^{-1}$ peak individual risk and - $10^{-6}.y^{-1}$ average population risk per site

CHAPTER 6: CONCLUSION REMARKS

This study indicates that the criteria set by nuclear regulator for dose to the public from accident due to PBMR are met, for short-term individual effective dose of 1 day, 7 days and 30 days exposure time due to contribution of each pathway to the dose. The results are calculated by making several conservative assumptions. Such necessary assumptions are:

- That people are outdoors at the time of the accident and long after the accident and they receive no protective benefit from clothing.
- It was assumed that what was released from the Primary Pressure Boundary (pipes) into the containment will be released to the environment. No credit was taken for any hold up of radioactivity in the reactor.

The COSYMA code was used for the assessment of the dose to the public from an accident due to the PBMR. The dominant pathways in the total dose were different depending on the activity type and percentage contribution. For percentage contribution, in some cases ground shine and cloud shine pathway were found to be major contributors by giving the greatest radiation dose, followed by Inhalation pathway. Skin and clothing and Resuspension pathway were found to be minor contributors.

Surprisingly Inhalation was found not to be the major contributor to the dose and it was expected to be the major contributor because of its radiological significance. What is inhaled into the respiratory tract may continue to irradiate inside the body for the rest of the life. Dose from inhalation of released noble gases, are often small compared to via external exposure. Inhalation is not usually the determinant in quantifying the radiological hazards for noble gases. For the noble gases what is inhaled into the lungs is exhaled back out of the body unlike aerosols and particulates like ^{137}Cs, ^{90}Sr, $^{110}Ag_m$ and ^{131}I. When they are inhaled, they attach to different organs in the body and continue to have a long-term impact in the body. Dose due to Groundside pathway and cloud shine pathway were expected to give a lower contribution than inhalation pathway. For both ground shine and cloud shine pathway, minimizing exposure time, using shielding and maximizing the distance from the source can minimize the dose.

For Ground shine, there's a default deposition rate from PC COSYMA. If a slower settling rate for deposition is assumed, there will be less concentration on the ground and therefore leading to the ground shine pathway being reduced.

CHAPTER 7: REFERENCES

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APPENDIX A: DOSE RESULTS

Table A-1: Doses at sector 9 for 1-day integration time

Distance (km)	Doses (Sv)		
	Circulating activity dose	Delayed release	Lift off of plated out activity
0.4	2.45E-06	4.49E-05	8.56E-08
1.65	7.25E-07	6.89E-06	1.35E-08
3.75	2.80E-07	1.93E-06	3.73E-09
6.25	1.45E-07	8.44E-07	1.58E-09
8.75	1.05E-07	5.97E-07	1.06E-09
11.25	8.30E-08	4.62E-07	7.88E-10
13.75	6.54E-08	3.72E-07	6.08E-10
16.25	5.25E-08	3.05E-07	4.82E-10
18.75	4.34E-08	2.56E-07	3.93E-10
21.25	4.46E-08	2.23E-07	3.41E-10
23.75	4.03E-08	1.93E-07	2.97E-10
26.25	3.22E-08	1.67E-07	2.46E-10
28.75	2.77E-08	1.46E-07	2.13E-10
31.25	2.59E-08	1.30E-07	1.91E-10
33.75	2.10E-08	1.15E-07	1.65E-10
36.25	1.86E-08	1.03E-07	1.47E-10
38.75	1.76E-08	9.16E-08	1.34E-10

Table A-2: Doses for each release category for 1-day integration time

Doses (SV)																		
Distance (km)	RC-1	RCF-1			RCF-2			RCP-1			RCPF-1				RCPF-2			
	Circulating	Circulating	Delayed	Total	Circulating	Delayed	Total	Circulating	Plate out	Total	Circulating	Plate out	Delayed	Total	Circulating	Plate out	Delayed	Total
0.4	2.45E-06	2.45E-06	4.49E-05	4.73E-05	2.45E-06	4.49E-05	4.73E-05	2.45E-06	8.56E-08	2.54E-06	2.45E-06	8.56E-08	4.49E-05	4.74E-05	2.45E-06	8.56E-08	4.49E-05	4.74E-05
1.65	7.25E-07	7.25E-07	6.89E-06	7.61E-06	7.25E-07	6.89E-06	7.61E-06	7.25E-07	1.35E-08	7.39E-07	7.25E-07	1.35E-08	6.89E-06	7.63E-06	7.25E-07	1.35E-08	6.89E-06	7.63E-06
3.75	2.80E-07	2.80E-07	1.93E-06	2.21E-06	2.80E-07	1.93E-06	2.21E-06	2.80E-07	3.73E-09	2.83E-07	2.80E-07	3.73E-09	1.93E-06	2.21E-06	2.80E-07	3.73E-09	1.93E-06	2.21E-06
6.25	1.45E-07	1.45E-07	8.44E-07	9.89E-07	1.45E-07	8.44E-07	9.89E-07	1.45E-07	1.58E-09	1.46E-07	1.45E-07	1.58E-09	8.44E-07	9.90E-07	1.45E-07	1.58E-09	8.44E-07	9.90E-07
8.75	1.05E-07	1.05E-07	5.97E-07	7.02E-07	1.05E-07	5.97E-07	7.02E-07	1.05E-07	1.06E-09	1.06E-07	1.05E-07	1.06E-09	5.97E-07	7.03E-07	1.05E-07	1.06E-09	5.97E-07	7.03E-07
11.25	8.30E-08	8.30E-08	4.62E-07	5.45E-07	8.30E-08	4.62E-07	5.45E-07	8.30E-08	7.88E-10	8.38E-08	8.30E-08	7.88E-10	4.62E-07	5.45E-07	8.30E-08	7.88E-10	4.62E-07	5.45E-07
13.75	6.54E-08	6.54E-08	3.72E-07	4.37E-07	6.54E-08	3.72E-07	4.37E-07	6.54E-08	6.08E-10	6.60E-08	6.54E-08	6.08E-10	3.72E-07	4.38E-07	6.54E-08	6.08E-10	3.72E-07	4.38E-07
16.25	5.25E-08	5.25E-08	3.05E-07	3.58E-07	5.25E-08	3.05E-07	3.58E-07	5.25E-08	4.82E-10	5.30E-08	5.25E-08	4.82E-10	3.05E-07	3.58E-07	5.25E-08	4.82E-10	3.05E-07	3.58E-07
18.75	4.34E-08	4.34E-08	2.56E-07	3.00E-07	4.34E-08	2.56E-07	3.00E-07	4.34E-08	3.93E-10	4.38E-08	4.34E-08	3.93E-10	2.56E-07	3.00E-07	4.34E-08	3.93E-10	2.56E-07	3.00E-07
21.25	4.46E-08	4.46E-08	2.23E-07	2.67E-07	4.46E-08	2.23E-07	2.67E-07	4.46E-08	3.41E-10	4.50E-08	4.46E-08	3.41E-10	2.23E-07	2.68E-07	4.46E-08	3.41E-10	2.23E-07	2.68E-07
23.75	4.03E-08	4.03E-08	1.93E-07	2.33E-07	4.03E-08	1.93E-07	2.33E-07	4.03E-08	2.97E-10	4.06E-08	4.03E-08	2.97E-10	1.93E-07	2.33E-07	4.03E-08	2.97E-10	1.93E-07	2.33E-07
26.25	3.22E-08	3.22E-08	1.67E-07	1.99E-07	3.22E-08	1.67E-07	1.99E-07	3.22E-08	2.46E-10	3.24E-08	3.22E-08	2.46E-10	1.67E-07	2.00E-07	3.22E-08	2.46E-10	1.67E-07	2.00E-07
28.75	2.77E-08	2.77E-08	1.46E-07	1.74E-07	2.77E-08	1.46E-07	1.74E-07	2.77E-08	2.13E-10	2.79E-08	2.77E-08	2.13E-10	1.46E-07	1.74E-07	2.77E-08	2.13E-10	1.46E-07	1.74E-07
31.25	2.59E-08	2.59E-08	1.30E-07	1.55E-07	2.59E-08	1.30E-07	1.55E-07	2.59E-08	1.91E-10	2.60E-08	2.59E-08	1.91E-10	1.30E-07	1.56E-07	2.59E-08	1.91E-10	1.30E-07	1.56E-07
33.75	2.10E-08	2.10E-08	1.15E-07	1.36E-07	2.10E-08	1.15E-07	1.36E-07	2.10E-08	1.65E-10	2.12E-08	2.10E-08	1.65E-10	1.15E-07	1.36E-07	2.10E-08	1.65E-10	1.15E-07	1.36E-07
36.25	1.86E-08	1.86E-08	1.03E-07	1.21E-07	1.86E-08	1.03E-07	1.21E-07	1.86E-08	1.47E-10	1.87E-08	1.86E-08	1.47E-10	1.03E-07	1.21E-07	1.86E-08	1.47E-10	1.03E-07	1.21E-07
38.75	1.76E-08	1.76E-08	9.16E-08	1.09E-07	1.76E-08	9.16E-08	1.09E-07	1.76E-08	1.34E-10	1.77E-08	1.76E-08	1.34E-10	9.16E-08	1.09E-07	1.76E-08	1.34E-10	9.16E-08	1.09E-07

Table A-3: Total Effective doses per release category for 1 day dose integration time

Distance (km)	Doses (SV)					
	RC-1	RCF-1	RCF-2	RCP-1	RCPF-1	RCPF-2
0.4	2.45E-06	4.73E-05	4.73E-05	2.54E-06	4.74E-05	4.74E-05
1.65	7.25E-07	7.61E-06	7.61E-06	7.39E-07	7.63E-06	7.63E-06
3.75	2.80E-07	2.21E-06	2.21E-06	2.83E-07	2.21E-06	2.21E-06
6.25	1.45E-07	9.89E-07	9.89E-07	1.46E-07	9.90E-07	9.90E-07
8.75	1.05E-07	7.02E-07	7.02E-07	1.06E-07	7.03E-07	7.03E-07
11.25	8.30E-08	5.45E-07	5.45E-07	8.38E-08	5.45E-07	5.45E-07
13.75	6.54E-08	4.37E-07	4.37E-07	6.60E-08	4.38E-07	4.38E-07
16.25	5.25E-08	3.58E-07	3.58E-07	5.30E-08	3.58E-07	3.58E-07
18.75	4.34E-08	3.00E-07	3.00E-07	4.38E-08	3.00E-07	3.00E-07
21.25	4.46E-08	2.67E-07	2.67E-07	4.50E-08	2.68E-07	2.68E-07
23.75	4.03E-08	2.33E-07	2.33E-07	4.06E-08	2.33E-07	2.33E-07
26.25	3.22E-08	1.99E-07	1.99E-07	3.24E-08	2.00E-07	2.00E-07
28.75	2.77E-08	1.74E-07	1.74E-07	2.79E-08	1.74E-07	1.74E-07
31.25	2.59E-08	1.55E-07	1.55E-07	2.60E-08	1.56E-07	1.56E-07
33.75	2.10E-08	1.36E-07	1.36E-07	2.12E-08	1.36E-07	1.36E-07
36.25	1.86E-08	1.21E-07	1.21E-07	1.87E-08	1.21E-07	1.21E-07
38.75	1.76E-08	1.09E-07	1.09E-07	1.77E-08	1.09E-07	1.09E-07

Table A-4: Doses at sector 9 for 7 days integration time

Distance (km)	Doses (SV)		
	Circulating activity dose	Delayed release dose	Lift off of plated out activity
0.4	2.54E-06	2.51E-04	1.67E-07
1.65	7.39E-07	3.80E-05	2.63E-08
3.75	2.83E-07	1.05E-05	7.40E-09
6.25	1.46E-07	4.55E-06	3.22E-09
8.75	1.06E-07	3.20E-06	2.25E-09
11.25	8.39E-08	2.46E-06	1.72E-09
13.75	6.61E-08	1.98E-06	1.38E-09
16.25	5.31E-08	1.62E-06	1.14E-09
18.75	4.38E-08	1.36E-06	9.58E-10
21.25	4.50E-08	1.16E-06	8.36E-10
23.75	4.07E-08	9.98E-07	7.37E-10
26.25	3.25E-08	8.65E-07	6.41E-10
28.75	2.79E-08	7.55E-07	5.69E-10
31.25	2.61E-08	6.66E-07	5.16E-10
33.75	2.12E-08	5.88E-07	4.62E-10
36.25	1.88E-08	5.24E-07	4.21E-10
38.75	1.77E-08	4.65E-07	3.87E-10

Table A-5: Effective dose for each event category for 7 days integration doses

Distance (km)	Doses (SV)																	
	RC-1	RCF-1			RCF-2			RCP-1			RCFP-1				RCPF-2			
	Circulating	Circulating	Delayed	Total	Circulating	Delayed	Total	Circulating	plate out	Total	Circulating	Delayed	Plate out	Total	Circulating	Delayed	Plate out	Total
0.4	2.54E-06	2.54E-06	2.51E-04	2.54E-04	2.54E-06	2.51E-04	2.54E-04	2.54E-06	1.67E-07	2.71E-06	2.54E-06	2.51E-04	1.67E-07	2.54E-04	2.51E-04	2.71E-06	1.67E-07	2.54E-04
1.65	7.39E-07	7.39E-07	3.80E-05	3.87E-05	7.39E-07	3.80E-05	3.87E-05	7.39E-07	2.63E-08	7.65E-07	7.39E-07	3.80E-05	2.63E-08	3.87E-05	3.80E-05	7.65E-07	2.63E-08	3.88E-05
3.75	2.83E-07	2.83E-07	1.05E-05	1.08E-05	2.83E-07	1.05E-05	1.08E-05	2.83E-07	7.40E-09	2.91E-07	2.83E-07	1.05E-05	7.40E-09	1.08E-05	1.05E-05	2.91E-07	7.40E-09	1.08E-05
6.25	1.46E-07	1.46E-07	4.55E-06	4.69E-06	1.46E-07	4.55E-06	4.69E-06	1.46E-07	3.22E-09	1.49E-07	1.46E-07	4.55E-06	3.22E-09	4.69E-06	4.55E-06	1.49E-07	3.22E-09	4.70E-06
8.75	1.06E-07	1.06E-07	3.20E-06	3.31E-06	1.06E-07	3.20E-06	3.31E-06	1.06E-07	2.25E-09	1.08E-07	1.06E-07	3.20E-06	2.25E-09	3.31E-06	3.20E-06	1.08E-07	2.25E-09	3.31E-06
11.25	8.39E-08	8.39E-08	2.46E-06	2.55E-06	8.39E-08	2.46E-06	2.55E-06	8.39E-08	1.72E-09	8.56E-08	8.39E-08	2.46E-06	1.72E-09	2.55E-06	2.46E-06	8.56E-08	1.72E-09	2.55E-06
13.75	6.61E-08	6.61E-08	1.98E-06	2.05E-06	6.61E-08	1.98E-06	2.05E-06	6.61E-08	1.38E-09	6.74E-08	6.61E-08	1.98E-06	1.38E-09	2.05E-06	1.98E-06	6.74E-08	1.38E-09	2.05E-06
16.25	5.31E-08	5.31E-08	1.62E-06	1.67E-06	5.31E-08	1.62E-06	1.67E-06	5.31E-08	1.14E-09	5.42E-08	5.31E-08	1.62E-06	1.14E-09	1.68E-06	1.62E-06	5.42E-08	1.14E-09	1.68E-06
18.75	4.38E-08	4.38E-08	1.36E-06	1.40E-06	4.38E-08	1.36E-06	1.40E-06	4.38E-08	9.58E-10	4.48E-08	4.38E-08	1.36E-06	9.58E-10	1.40E-06	1.36E-06	4.48E-08	9.58E-10	1.40E-06
21.25	4.50E-08	4.50E-08	1.16E-06	1.20E-06	4.50E-08	1.16E-06	1.20E-06	4.50E-08	8.36E-10	4.59E-08	4.50E-08	1.16E-06	8.36E-10	1.20E-06	1.16E-06	4.59E-08	8.36E-10	1.20E-06
23.75	4.07E-08	4.07E-08	9.98E-07	1.04E-06	4.07E-08	9.98E-07	1.04E-06	4.07E-08	7.37E-10	4.14E-08	4.07E-08	9.98E-07	7.37E-10	1.04E-06	9.98E-07	4.14E-08	7.37E-10	1.04E-06
26.25	3.25E-08	3.25E-08	8.65E-07	8.97E-07	3.25E-08	8.65E-07	8.97E-07	3.25E-08	6.41E-10	3.31E-08	3.25E-08	8.65E-07	6.41E-10	8.98E-07	8.65E-07	3.31E-08	6.41E-10	8.99E-07
28.75	2.79E-08	2.79E-08	7.55E-07	7.83E-07	2.79E-08	7.55E-07	7.83E-07	2.79E-08	5.69E-10	2.85E-08	2.79E-08	7.55E-07	5.69E-10	7.83E-07	7.55E-07	2.85E-08	5.69E-10	7.84E-07
31.25	2.61E-08	2.61E-08	6.66E-07	6.92E-07	2.61E-08	6.66E-07	6.92E-07	2.61E-08	5.16E-10	2.66E-08	2.61E-08	6.66E-07	5.16E-10	6.92E-07	6.66E-07	2.66E-08	5.16E-10	6.93E-07
33.75	2.12E-08	2.12E-08	5.88E-07	6.09E-07	2.12E-08	5.88E-07	6.09E-07	2.12E-08	4.62E-10	2.17E-08	2.12E-08	5.88E-07	4.62E-10	6.10E-07	5.88E-07	2.17E-08	4.62E-10	6.10E-07
36.25	1.88E-08	1.88E-08	5.24E-07	5.42E-07	1.88E-08	5.24E-07	5.42E-07	1.88E-08	4.21E-10	1.92E-08	1.88E-08	5.24E-07	4.21E-10	5.43E-07	5.24E-07	1.92E-08	4.21E-10	5.43E-07
38.75	1.77E-08	1.77E-08	4.65E-07	4.83E-07	1.77E-08	4.65E-07	4.83E-07	1.77E-08	3.87E-10	1.81E-08	1.77E-08	4.65E-07	3.87E-10	4.84E-07	4.65E-07	1.81E-08	3.87E-10	4.84E-07

Table A-6: Total effective doses per release category for 7 days integration time

Distance (km)	Doses (SV)					
	RC-1	RCF-1	RCF-2	RCP-1	RCFP-1	RCFP-2
0.4	2.54E-06	2.54E-04	2.54E-04	2.71E-06	2.54E-04	2.54E-04
1.65	7.39E-07	3.87E-05	3.87E-05	7.65E-07	3.87E-05	3.88E-05
3.75	2.83E-07	1.08E-05	1.08E-05	2.91E-07	1.08E-05	1.08E-05
6.25	1.46E-07	4.69E-06	4.69E-06	1.49E-07	4.69E-06	4.70E-06
8.75	1.06E-07	3.31E-06	3.31E-06	1.08E-07	3.31E-06	3.31E-06
11.25	8.39E-08	2.55E-06	2.55E-06	8.56E-08	2.55E-06	2.55E-06
13.75	6.61E-08	2.05E-06	2.05E-06	6.74E-08	2.05E-06	2.05E-06
16.25	5.31E-08	1.67E-06	1.67E-06	5.42E-08	1.68E-06	1.68E-06
18.75	4.38E-08	1.40E-06	1.40E-06	4.48E-08	1.40E-06	1.40E-06
21.25	4.50E-08	1.20E-06	1.20E-06	4.59E-08	1.20E-06	1.20E-06
23.75	4.07E-08	1.04E-06	1.04E-06	4.14E-08	1.04E-06	1.04E-06
26.25	3.25E-08	8.97E-07	8.97E-07	3.31E-08	8.98E-07	8.99E-07
28.75	2.79E-08	7.83E-07	7.83E-07	2.85E-08	7.83E-07	7.84E-07
31.25	2.61E-08	6.92E-07	6.92E-07	2.66E-08	6.92E-07	6.93E-07
33.75	2.12E-08	6.09E-07	6.09E-07	2.17E-08	6.10E-07	6.10E-07
36.25	1.88E-08	5.42E-07	5.42E-07	1.92E-08	5.43E-07	5.43E-07
38.75	1.77E-08	4.83E-07	4.83E-07	1.81E-08	4.84E-07	4.84E-07

Table A-7: Doses received at sector 9 versus the distance in km for 30 days integration time

Distance	Dose (Sv)		
	Circulating activity	Plate-out activity	Delayed
0.4	2.57E-06	3.24E-07	4.95E-04
1.65	7.44E-07	5.20E-08	7.48E-05
3.75	2.85E-07	1.50E-08	2.06E-05
6.25	1.47E-07	6.72E-09	8.93E-06
8.75	1.07E-07	4.83E-09	6.28E-06
11.25	8.42E-08	3.81E-09	4.83E-06
13.75	6.63E-08	3.14E-09	3.88E-06
16.25	5.33E-08	2.65E-09	3.18E-06
18.75	4.40E-08	2.29E-09	2.67E-06
21.25	4.52E-08	2.03E-09	2.27E-06
23.75	4.08E-08	1.81E-09	1.95E-06
26.25	3.26E-08	1.62E-09	1.69E-06
28.75	2.80E-08	1.47E-09	1.48E-06
31.25	2.62E-08	1.35E-09	1.30E-06
33.75	2.13E-08	1.24E-09	1.15E-06
36.25	1.88E-08	1.15E-09	1.02E-06
38.75	1.78E-08	1.07E-09	9.09E-07

Table A-8: Effective doses for each event category for short-term individual doses for 30 days integration time

Distance	Dose (Sv)																	
	RC1	RCF-1			RCF-2			RCP-1			RCPF-1				RCPF-2			
	Circulating	Circulating	Delayed	Total	Circulating	Delayed	Total	Circulating	Plate-out	Total	Circulating	Plate-out	Delayed	Total	Circulating	Plate-out	Delayed	Total
0.4	2.57E-06	2.57E-06	4.95E-04	4.98E-04	2.57E-06	4.95E-04	4.98E-04	2.57E-06	3.24E-07	2.90E-06	2.57E-06	3.24E-07	4.95E-04	4.98E-04	2.57E-06	3.24E-07	4.95E-04	4.98E-04
1.65	7.44E-07	7.44E-07	7.48E-05	7.55E-05	7.44E-07	7.48E-05	7.55E-05	7.44E-07	5.20E-08	7.96E-07	7.44E-07	5.20E-08	7.48E-05	7.56E-05	7.44E-07	5.20E-08	7.48E-05	7.56E-05
3.75	2.85E-07	2.85E-07	2.06E-05	2.09E-05	2.85E-07	2.06E-05	2.09E-05	2.85E-07	1.50E-08	3.00E-07	2.85E-07	1.50E-08	2.06E-05	2.09E-05	2.85E-07	1.50E-08	2.06E-05	2.09E-05
6.25	1.47E-07	1.47E-07	8.93E-06	9.07E-06	1.47E-07	8.93E-06	9.07E-06	1.47E-07	6.72E-09	1.53E-07	1.47E-07	6.72E-09	8.93E-06	9.08E-06	1.47E-07	6.72E-09	8.93E-06	9.08E-06
8.75	1.07E-07	1.07E-07	6.28E-06	6.39E-06	1.07E-07	6.28E-06	6.39E-06	1.07E-07	4.83E-09	1.11E-07	1.07E-07	4.83E-09	6.28E-06	6.40E-06	1.07E-07	4.83E-09	6.28E-06	6.40E-06
11.25	8.42E-08	8.42E-08	4.83E-06	4.92E-06	8.42E-08	4.83E-06	4.92E-06	8.42E-08	3.81E-09	8.80E-08	8.42E-08	3.81E-09	4.83E-06	4.92E-06	8.42E-08	3.81E-09	4.83E-06	4.92E-06
13.75	6.63E-08	6.63E-08	3.88E-06	3.95E-06	6.63E-08	3.88E-06	3.95E-06	6.63E-08	3.14E-09	6.94E-08	6.63E-08	3.14E-09	3.88E-06	3.95E-06	6.63E-08	3.14E-09	3.88E-06	3.95E-06
16.25	5.33E-08	5.33E-08	3.18E-06	3.23E-06	5.33E-08	3.18E-06	3.23E-06	5.33E-08	2.65E-09	5.59E-08	5.33E-08	2.65E-09	3.18E-06	3.24E-06	5.33E-08	2.65E-09	3.18E-06	3.24E-06
18.75	4.40E-08	4.40E-08	2.67E-06	2.71E-06	4.40E-08	2.67E-06	2.71E-06	4.40E-08	2.29E-09	4.63E-08	4.40E-08	2.29E-09	2.67E-06	2.71E-06	4.40E-08	2.29E-09	2.67E-06	2.71E-06
21.25	4.52E-08	4.52E-08	2.27E-06	2.31E-06	4.52E-08	2.27E-06	2.31E-06	4.52E-08	2.03E-09	4.72E-08	4.52E-08	2.03E-09	2.27E-06	2.31E-06	4.52E-08	2.03E-09	2.27E-06	2.31E-06
23.75	4.08E-08	4.08E-08	1.95E-06	1.99E-06	4.08E-08	1.95E-06	1.99E-06	4.08E-08	1.81E-09	4.26E-08	4.08E-08	1.81E-09	1.95E-06	2.00E-06	4.08E-08	1.81E-09	1.95E-06	2.00E-06
26.25	3.26E-08	3.26E-08	1.69E-06	1.73E-06	3.26E-08	1.69E-06	1.73E-06	3.26E-08	1.62E-09	3.42E-08	3.26E-08	1.62E-09	1.69E-06	1.73E-06	3.26E-08	1.62E-09	1.69E-06	1.73E-06
28.75	2.80E-08	2.80E-08	1.48E-06	1.51E-06	2.80E-08	1.48E-06	1.51E-06	2.80E-08	1.47E-09	2.95E-08	2.80E-08	1.47E-09	1.48E-06	1.51E-06	2.80E-08	1.47E-09	1.48E-06	1.51E-06
31.25	2.62E-08	2.62E-08	1.30E-06	1.33E-06	2.62E-08	1.30E-06	1.33E-06	2.62E-08	1.35E-09	2.75E-08	2.62E-08	1.35E-09	1.30E-06	1.33E-06	2.62E-08	1.35E-09	1.30E-06	1.33E-06
33.75	2.13E-08	2.13E-08	1.15E-06	1.17E-06	2.13E-08	1.15E-06	1.17E-06	2.13E-08	1.24E-09	2.25E-08	2.13E-08	1.24E-09	1.15E-06	1.17E-06	2.13E-08	1.24E-09	1.15E-06	1.17E-06
36.25	1.88E-08	1.88E-08	1.02E-06	1.04E-06	1.88E-08	1.02E-06	1.04E-06	1.88E-08	1.15E-09	2.00E-08	1.88E-08	1.15E-09	1.02E-06	1.04E-06	1.88E-08	1.15E-09	1.02E-06	1.04E-06
38.75	1.78E-08	1.78E-08	9.09E-07	9.27E-07	1.78E-08	9.09E-07	9.27E-07	1.78E-08	1.07E-09	1.88E-08	1.78E-08	1.07E-09	9.09E-07	9.28E-07	1.78E-08	1.07E-09	9.09E-07	9.28E-07

Table A-9: Total effective dose for all release categories for 30 days dose integration time

Distance (km)	DOSES (Sv)					
	RC-1	RCF-1	RCF-2	RCP-1	RCPF-1	RCPF-2
0.4	2.57E-06	4.98E-04	4.98E-04	2.90E-06	4.98E-04	4.98E-04
1.65	7.44E-07	7.55E-05	7.55E-05	7.96E-07	7.56E-05	7.56E-05
3.75	2.85E-07	2.09E-05	2.09E-05	3.00E-07	2.09E-05	2.09E-05
6.25	1.47E-07	9.07E-06	9.07E-06	1.53E-07	9.08E-06	9.08E-06
8.75	1.07E-07	6.39E-06	6.39E-06	1.11E-07	6.40E-06	6.40E-06
11.25	8.42E-08	4.92E-06	4.92E-06	8.80E-08	4.92E-06	4.92E-06
13.75	6.63E-08	3.95E-06	3.95E-06	6.94E-08	3.95E-06	3.95E-06
16.25	5.33E-08	3.23E-06	3.23E-06	5.59E-08	3.24E-06	3.24E-06
18.75	4.40E-08	2.71E-06	2.71E-06	4.63E-08	2.71E-06	2.71E-06
21.25	4.52E-08	2.31E-06	2.31E-06	4.72E-08	2.31E-06	2.31E-06
23.75	4.08E-08	1.99E-06	1.99E-06	4.26E-08	2.00E-06	2.00E-06
26.25	3.26E-08	1.73E-06	1.73E-06	3.42E-08	1.73E-06	1.73E-06
28.75	2.80E-08	1.51E-06	1.51E-06	2.95E-08	1.51E-06	1.51E-06
31.25	2.62E-08	1.33E-06	1.33E-06	2.75E-08	1.33E-06	1.33E-06
33.75	2.13E-08	1.17E-06	1.17E-06	2.25E-08	1.17E-06	1.17E-06
36.25	1.88E-08	1.04E-06	1.04E-06	2.00E-08	1.04E-06	1.04E-06
38.75	1.78E-08	9.27E-07	9.27E-07	1.88E-08	9.28E-07	9.28E-07

Table A-10: Individual dose and percentage contribution by pathway for 1 day dose integration time for circulating activity at 0.4 km

ORGANS	Dose (Sv)	Cloudshine	Groundshine	Inhalation	Resuspension	Skin
LUNG	1.87E-07	68	10	22	0	0
THYROID	2.31E-07	62	9	30	0	0
EYE LENS	1.57E-07	88	12	0	0	0
OVARIES	1.23E-07	85	13	2	0	0
EFFECTIVE	1.68E-07	74	10	16	0	0
B. MARROW	1.36E-07	85	12	2	0	0
GI-TRACT	1.29E-07	86	12	2	0	0

Table A-11: Individual dose and percentage contribution by pathway for 1-day dose integration time for delayed release activity at 0.4 km

Organ	Percentage					
Organ	Dose (Sv)	Cloudshine	Groundshine	Inhalation	Resuspension	Skin
LUNG	1.97E-06	2	94	3	0	0
THYROID	2.08E-05	0	10	90	0	0
EYE LENS	2.03E-06	3	97	0	0	0
OVARIES	1.72E-06	2	96	2	0	0
EFFECTIVE	2.81E-06	2	63	35	0	0
B. MARROW	1.82E-06	2	97	1	0	0
GI-TRACT	1.66E-06	2	96	2	0	0

Table A-12: Individual dose and percentage contribution by pathway for 1-day dose integration time for lift off of plated out activity

Organ	Percentage					
	Dose (Sv)	Cloud shine	Ground shine	Inhalation.	Resuspension.	Skin
LUNG	4.59E-09	9	83	8	0	0
THYROID	2.36E-08	2	18	80	0	0
EYE LENS	4.50E-09	10	90	0	0	0
OVARIES	3.88E-09	9	87	4	0	0
EFFECTIVE	5.40E-09	8	67	25	0	0
B. MARROW	4.12E-09	9	87	3	0	0
GI-TRACT	3.81E-09	9	86	5	0	0

Table A-13: Total effective dose contribution by pathway for 1-day dose integration time

	Doses per category (Sv)					
Organ	RC-1	RCF-1	RCF-2	RCP-1	RCFP-1	RCFP-2
LUNG	1.87E-07	2.16E-06	2.16E-06	1.92E-07	2.16E-06	2.16E-06
THYROID	2.31E-07	2.10E-05	2.10E-05	2.55E-07	2.10E-05	2.10E-05
EYE LENS	1.57E-07	2.18E-06	2.18E-06	1.61E-07	2.19E-06	2.19E-06
OVARIES	1.23E-07	1.84E-06	1.84E-06	1.27E-07	1.85E-06	1.85E-06
EFFECTIVE	1.68E-07	2.98E-06	2.98E-06	1.73E-07	2.98E-06	2.98E-06
B. MARROW	1.36E-07	1.95E-06	1.95E-06	1.40E-07	1.96E-06	1.96E-06
GI-TRACT	1.29E-07	1.79E-06	1.79E-06	1.33E-07	1.79E-06	1.79E-06

Table A-14: Individual doses and percentage contribution by pathway for 7 days dose integration time for circulating activity at 0.4 km

Organ	Percentage					
	Dose (Sv)	Cloud shine	Ground shine	Inhalation	Resuspension	Skin
LUNG	1.90E-07	67	11	22	0	0
THYROID	2.89E-07	49	8	42	0	0
EYE LENS	1.60E-07	86	14	0	0	0
OVARIES	1.26E-07	83	15	2	0	0
EFFECTIVE	1.74E-07	71	12	17	0	0
MARROW	1.39E-07	84	14	2	0	0
GI-TRACT	1.32E-07	84	14	2	0	0

Table A-15: Individual dose and percentage contribution by pathway for 7 days dose integration time for delayed release activity at 0.4 km

	Percentage					
ORGAN	Dose (Sv)	Cloud shine	Ground shine	Inhalation	Resuspension.	Skin
LUNG	9.61E-06	0	99	1	0	0
THYROID	1.41E-04	0	7	92	0	0
EYE LENS	1.01E-05	1	99	0	0	0
OVARIES	8.54E-06	0	99	0	0	0
EFFECTIVE	1.57E-05	0	58	42	0	0
B. MARROW	9.05E-06	0	99	0	0	0
GI-TRACT	8.21E-06	0	99	1	0	0

Table A-16: Individual dose and percentage contribution by pathway for 7 days dose integration time for lift off of plate out activity at 0.4 km

Organ	Percentage					
	Dose (Sv)	Cloud shine	Ground shine	Inhalation	Resuspension	Skin
LUNG	8.56E-09	5	85	10	0	0
THYROID	5.37E-08	1	15	84	0	0
EYE LENS	8.17E-09	6	94	0	0	0
OVARIES	7.38E-09	5	88	8	0	0
EFFECTIVE	1.05E-08	4	66	30	0	0
B. MARROW	7.75E-09	5	88	7	0	0
GI-TRACT	7.45E-09	5	83	12	0	0

Table A-17: Total effective dose contribution per release category for all the activity above for 7 days dose integration time at 0.4 km

		Dose per release category (Sv)				
ORGANS						
	RC-1	RCF-1	RCF-2	RCP-1	RCFP-1	RCFP-2
LUNG	1.90E-07	9.80E-06	9.80E-06	1.98E-07	9.81E-06	9.81E-06
THYROID	2.89E-07	1.41E-04	1.41E-04	3.42E-07	1.41E-04	1.41E-04
EYE LENS	1.60E-07	1.03E-05	1.03E-05	1.69E-07	1.03E-05	1.03E-05
OVARIES	1.26E-07	8.66E-06	8.66E-06	1.33E-07	8.67E-06	8.67E-06
EFFECTIVE	1.74E-07	1.59E-05	1.59E-05	1.84E-07	1.59E-05	1.59E-05
B. MARROW	1.39E-07	9.19E-06	9.19E-06	1.47E-07	9.20E-06	9.20E-06
GI-TRACT	1.32E-07	8.34E-06	8.34E-06	1.40E-07	8.35E-06	8.35E-06

Table A-18: Individual dose and percentage contribution by pathway for 30 days dose integration time for circulating activity at 0.4 km

Organ	Percentage					
	Dose (Sv)	Cloud shine	Groundshine	Inhalation	Resuspension	Skin
LUNG	1.91E-07	66	12	22	0	0
THYROID	3.05E-07	47	8	45	0	0
EYE LENS	1.62E-07	85	15	0	0	0
OVARIES	1.27E-07	82	16	2	0	0
EFFECTIVE	1.76E-07	71	12	17	0	0
B. MARROW	1.41E-07	83	15	2	0	0
GI-TRACT	1.33E-07	83	14	2	0	0

Table A-19: Individual dose and percentage contribution by pathway for 30 days dose integration time for Delayed release activity at 0.4 km

Organ	Percentage					
	Dose (Sv)	Cloud shine	Groundshine	Inhalation	Resuspension.	Skin
LUNG	1.89E-05	0	99	1	0	0
THYROID	2.77E-04	0	8	92	0	0
EYE LENS	2.00E-05	0	100	0	0	0
OVARIES	1.69E-05	0	100	0	0	0
EFFECTIVE	3.10E-05	0	58	42	0	0
B. MARROW	1.79E-05	0	99	0	0	0
GI-TRACT	1.62E-05	0	99	0	0	0

Table A-20: Individual dose and percentage by pathway for 30 days dose integration time for lift off of plate out activity at 0.4 km

Organ	Percentage					
	Dose (Sv)	Cloud shine	Ground shine	Inhalation	Resuspension.	Skin
LUNG	1.83E-08	2	84	14	0	0
THYROID	7.98E-08	1	21	78	0	0
EYE LENS	1.68E-08	3	97	0	0	0
OVARIES	1.60E-08	2	86	12	0	0
EFFECTIVE	2.03E-08	2	72	26	0	0
B. MARROW	1.66E-08	2	87	11	0	0
GI-TRACT	1.60E-08	2	83	15	0	0

Table A-21: Total effective doses and percentage per category for all the activity for 30 days dose integration time at distance 0.4 km

	Dose per category (Sv)					
Organ	RC-1	RCF-1	RCF-2	RCP-1	RCFP-1	RCFP-2
LUNG	1.91E-07	1.91E-05	1.91E-05	2.09E-07	1.91E-05	1.91E-05
THYROID	3.05E-07	2.77E-04	2.77E-04	3.85E-07	2.77E-04	2.77E-04
EYE LENS	1.62E-07	2.02E-05	2.02E-05	1.79E-07	2.02E-05	2.02E-05
OVARIES	1.27E-07	1.70E-05	1.70E-05	1.43E-07	1.70E-05	1.70E-05
EFFECTIVE	1.76E-07	3.11E-05	3.11E-05	1.96E-07	3.12E-05	3.12E-05
B. MARROW	1.41E-07	1.80E-05	1.80E-05	1.57E-07	1.80E-05	1.80E-05
GI-TRACT	1.33E-07	1.63E-05	1.63E-05	1.49E-07	1.64E-05	1.64E-05