ESTABLISHMENT OF TECHNICAL BASIS FOR THE NUCLEAR EMERGENCY PLANNING AND PREPAREDNESS PROGRAMME FOR THE PEBBLE BED MODULAR REACTOR (PBMR) NUCLEAR POWER STATION

by

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DECLARATION

I, the undersigned, hereby declare that the research in this thesis is my own original work, which has not partly or in full been submitted to any other University in order to obtain a degree

Signature: 

SYNOPSIS

In this work, description and explanation for the conditions of emergency preparedness is given. The aim was to establish the technical basis for emergency response plans in the event of a nuclear incident that might occur at the PBMR nuclear power station. The Koeberg Nuclear Power Station Technical Basis for Emergency Planning was basically used as a guideline and PC COSYMA, a programme that runs on PC, was used to help model the release as described or specified by the regulations set in [5] for South Africa. PC COSYMA runs were done to calculate doses to specific organs and to the whole body. These runs were done considering two weather categories (Pasquill stability category D and F) for neutral and moderately stable weather conditions. Wind speed of 2m/s was used for exposure dose integration periods 1, 10, 30 and 70 days. All dose results (organ and effective) were given by pathways: groundshine, cloudshine and inhalation, except thyroid doses whereby it was assumed that all doses are essentially committed through inhalation. A run for Thyroid including inhalation only as a pathway was also done and a run for iodine prophylaxis as protective action to see the effectiveness of the countermeasures.

All the calculated doses were lower than the individual radiation dose limit (50mSv) set by the regulator (NNR) for PBMR [20]. The implementation of countermeasures prevented a further dose accrual. Therefore, there is no need for implementation of countermeasures at PBMR, since they are well below the set criterions. But it will be a good safety culture and Defense in Depth to make an allowance for an emergency plan. Since Defense in Depth is a principle that requires that there should be multiple layers of overlapping safety provision and good safety culture looks at the behaviour on doing things.

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CHAPTER 1 :INTRODUCTION

1.1 Emergency

An emergency can be described as a major event which requires a coordinated response from a number of agencies [1]. It is a non-routine situation or event that necessitates prompt action to mitigate the danger, hazard or adverse consequences for human health and safety, property or the environment, such as nuclear or radiological emergencies [2].

There are number of different types of emergencies that can occur anytime at any place. But, this study concentrates on nuclear or radiological emergencies, and the effects that can result from conventional emergencies such as fires, storm, and earthquakes at a nuclear power plant. Nuclear or radiological emergencies are emergencies for which the principal cause of the actual or perceived hazard involves a nuclear chain reaction or involves the energy resulting from a nuclear chain reaction or from the decay of the products of a chain reaction, or exposure outside the site area (off-site) and within the site area (on-site) [3]. This study specifically examines an emergency involving the accidental release of radioactivity from the pressure boundary, and from the reactor building for the Pebble Bed Modular Reactor (PBMR) nuclear power station.

1.2 Emergency Conditions (classification system)

Rapid and coordinated response to an emergency is achieved by the use of an emergency classification system that is applicable to operating, standby, and shutdown modes. The bases for the proposed emergency classification for the PBMR are to consider the threats to the operation of the reactor, the safety of site personnel and the general public, and the integrity of the site, and to classify abnormal plant, radiological and environmental conditions to enable the application of the appropriate emergency response procedures [4]. The emergency conditions for use at the PBMR are:

1.2.1 Unusual Event

It is an abnormal occurrence which indicates an unplanned deviation from normal operations, the consequences of which may require a partial activation of the emergency plan **[5]**. This class includes occurrences onsite in which emergency treatment of one or more individuals is required. It includes those situations that have no potential for escalation to more severe emergency conditions. There may be no effect on the plant, and immediate operator action to alter plant status is not necessarily required. This type of event does not activate the entire emergency organization but may activate such teams as the first aid team. It may also require special local services such as ambulance and medical.

Implementing procedures for the handling of this class of event may also be incorporated in the plant's radiation protection procedures and general industrial safety procedures. Included in this class are events that may be complicated by contamination problems or excessive radiation exposure to onsite personnel.

The recognition of this class of emergency is primarily a judgment matter for the plant supervisory or management personnel. Its importance as part of the classification scheme rests to some extent on its negative information content, namely, that the incident giving rise to the emergency is restricted in its scope of involvement. This section of the plan designates the classification criteria and should enumerate discrete situations that could give rise to this class **[6]**.

1.2.2 Site Alert

It is an existing situation that could develop into a SITE EMERGENCY or GENERAL EMERGENCY and therefore requires notification of all emergency personnel in order to obtain a state of readiness to respond **[5]**. This class involves specific situations that can be recognized as creating a hazard potential that were previously nonexistent or latent. The situation has not yet caused damage to the plant or harm to personnel and does not necessarily require an immediate change in plant operating status. Inherently, however, this is a situation in which time is available to take precautionary and constructive steps to prevent an accident and to mitigate the consequences

should it occur. A Site Alert situation may be brought on by either man-made or natural phenomena.

SITE ALERT conditions imply a rapid transition to a state of readiness by the plant personnel, the possible cessation of certain routine functions or activities within the plant that are not immediately essential, and possible precautionary actions that a specific situation may require. Examples of situations that might be placed in this class are threats to or breaches of plant security measures such as bomb threats or civil disturbance, severe natural phenomena in the plant environment such as floods, earthquakes, tsunami, hurricanes, or tornadoes, emergency situations such as fires at adjacent locations, or release of a toxic noxious gas in or near the plant locations. This section of the emergency plan should identify specific candidate situations for SITE ALERT and the quantitative criteria that would guide the decision to implement each. Qualitative criteria should be added for other candidate situations to guide the decisions of onsite supervisory personnel [**6**].

1.2.3 Site Emergency

It is an existing emergency condition that poses a serious radiological hazard on-site, but poses no serious hazard to the public off-site [**5**]. This class includes physical occurrences within the plant requiring full plant staff emergency organizations response. The initial information and assessment indicates that it is very unlikely that an off-site hazard will be created. However, substantial modifications of plant operating status is a highly probable corrective action if this has not already taken place by the actions of automatic protective systems. Although it is judged that the emergency situation can be corrected and controlled by the plant staff, notification of corporate headquarters staff and appropriate offsite agencies as to the nature and extend of the incident is required. Evacuation of the plant is not anticipated in this class of emergency, although protective evacuations or isolations of certain plant areas may be necessary.

Examples of situations that might fall into this class are those accidents analysed in the FSAR (Final Safety Analysis Report) as events that are predicted to have no radiological consequences offsite. Fires, explosions or explosive gas release, or in-plant flooding conditions may fall into this class.

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Activation levels for declaring Site Emergencies should be based on the recognition of an immediate need to implement in-plant emergency measures to protect or provide aid to affected persons in the plant or to mitigate the consequences of damage to plant equipment, coupled with a positive observation that:

(a). effluent and other radiological monitors do not indicate the possibility of General Emergency; and

(b). there is no apparent breach of any primary system boundary. This section should describe the alarm conditions or combinations of alarm conditions and the emergency action levels for initiating Site Emergency **[6]**.

1.2.4 General Emergency

It is an existing emergency condition that poses or potentially poses a serious radiological hazard off-site **[5]**. This class involves an uncontrolled release of radioactive materials into the air, water, or ground to the extent that initial information and assessment indicate protective actions offsite may be required. Mobilization and coordinated response of offsite emergency organization is necessary. Protective actions are likely to include evacuation of plant areas other than control rooms and emergency stations, and evacuation or other protective actions for offsite areas. Assessment actions will include monitoring of the environment.

Situations likely to fall into this class include those accidents analysed in the FSAR that are predicted to have small to moderate radiological consequences at the exclusion radius. It should be anticipated that General Emergencies would not normally be preceded by Site Emergency, although the possibility of this evolution should not be excluded.

Action levels for declaring the General Emergency case should be defined. The action levels should recognize both short-term and long-term hazards. The selection of action levels for the former should be guided by direct radiation hazards and inhalation hazards that may be presented by the passage of a cloud of radioactive material release from the plant. The selection of action levels for

the long-term hazards should be guided by contamination hazards that could result from fallout or deposition of radioactive materials released from the plant.

Protective actions should be planned and implemented at the prescribed action levels. Action levels for severe short-term situations requiring rapid implementation of protective actions should be defined in terms of readily available information such as readings of effluent monitors or other onsite monitor indications. Implementation of protective actions may also be based on confirmatory measurements taken in the field to the extent it can be shown that field measurements can be taken and evaluated rapidly enough to permit adequate time for the protective actions to be accomplished. In either event, the basis and criteria used to define the action levels should be described in the plan **[6]**.

1.3 Emergency Planning/Co-ordination

An emergency plan is a document describing the organizational structures, roles and responsibility, concepts of operation, means and principle for intervention during an emergency or a set of procedures to be implemented in the event of an accident **[7]**. An effective emergency plan is not a static written document that is produced once and forgotten forever but rather, is a dynamic document that demands foresight and imagination in foreseeing the risks the public realistically faces, and the countermeasures that might help to overcome those situations **[1]**.

Emergency plans are prepared at different levels: national, local and facility. They may include all activities planned to be carried out by all relevant organizations and authorities, or may be primarily concerned with the actions to be carried out by a particular organization. Emergency planning is the process of developing and maintaining the capability to take actions that will mitigate the impact of an emergency on human health and safety **[2]**.

An important element of emergency planning is the recognition of the need to prepare to cope with a very broad spectrum of potential consequences. Emergency plans should be directed towards mitigating the consequences of emergencies and should provide reasonable assurance that

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appropriate measures can and will be taken to protect health and safety, and prevent damage to property in the event of an emergency [6].

1.4 Emergency planning categories

International guidance [8] recommends that, as a prelude to emergency planning the practices and activities for which emergency response could be required must be identified. This is simplified by grouping these practices and activities into five categories, each presenting common features in terms of the magnitude and timing of the hazard [4]. These categories are described in ***Table 1-1***.

Table 1-1: Emergency Planning Categories

CATEGORY	HAZARD
I	Installation with the potential for very large releases resulting in serious deterministic effects off-site.
II	Installation with the potential for release resulting in off-site doses above the urgent generic intervention levels but with little or no threat of doses resulting in deterministic health effects off-site.
III	Installation with no significant off-site risk but with the potential for accidents resulting in deterministic health effects on-site.
IV	Activities or events with little or unknown threat, including lost or stolen sources, and the transportation of radioactive material.
V	Installation outside the country with the potential for releases resulting in contamination within the country above the generic action levels related to food.

Table 1-2: Generic Intervention Levels for Urgent Protective Actions and Calculated doses due to DBE for expected and design values of release

Protective Action	Generic Intervention Level (a, b)	Expected Dose for any DBE (Design Basis Events)	DBD (Design Basis Dose) for any DBE (Design Basis Events)
Sheltering	10mSv	3.75mSv or less	4.95mSv or less
Evacuation	50mSv	3.75mSv or less	4.95mSv or less
Iodine Prophylaxis	100mSv	3.75mSv or less	4.95mSv or less

[5], [9]

Table 1-2 provides the generic intervention levels for urgent protective actions recommended for South African nuclear installations by the National Nuclear Regulator (NNR), and the calculated doses due to DBE for expected and design values of releases for the PBMR.

(a). the intervention levels are of avertable dose, that is, the action should be taken if the dose can be averted by the action, taking into account the loss of effectiveness due to delays or for other practical reasons; and

(b). the levels in all cases refer to the average over suitably chosen samples of the population, not to the most exposed individuals.

Calculated doses due to DBE for expected and design values of releases for the PBMR are below the recommended intervention levels, meaning there are no significant off-site risks. Therefore, in terms of the emergency planning categories listed in ***Table 1-1***, only category III will fit to the emergency planning status of the PBMR if it were to be sited on its own. However, because it is situated adjacent to the Koeberg Nuclear Power Station, the emergency planning requirements associated with Koeberg will dominate.

Emergency plans for a particular type of nuclear installation should take into account operating experience, exercises and accidents associated with similar nuclear installations.

The plan should define on-site responsibilities and take account of off-site responsibilities and provide for the implementation of appropriate protective actions.

Planning can create a high order of preparedness and ensure an orderly and timely decision-making process at times of stress, as well as the availability of necessary equipment, supplies and services **[6]**.

Proper planning can reduce the impact of both "human caused" and natural disasters and help the public to recover faster. It can also help to avoid mistakes that are often made when an emergency strikes.

1.5 Emergency preparedness

Emergency preparedness is the capability to promptly take actions that will effectively mitigate the impact of an emergency on human health and safety, property or the environment **[7]**. It generally refers to actions which can and should be performed prior to an emergency. Such actions include planning and coordination meetings, procedure writing, team training, emergency drills and exercises and preposition of emergency equipment.

The NNR requires that comprehensive emergency plans be prepared and periodically exercised to assure that actions can and will be taken to notify and protect citizens in the vicinity of a nuclear facility. Citizens living near a nuclear power plant must be advised periodically of the procedures that will be used to notify them of a problem at the facility and the actions that citizens should take if protective measures (such as evacuation or sheltering) are required **[10]**.

An emergency preparedness programme is purposely meant to make an organization ready to respond to emergency situations. Such a programme minimizes potential loss to people, property and the environment, helps restore normal business operations as quickly as possible, and ensure all necessary equipment and systems are in place to deal with the emergency. The shortage of time, lack of resources, untrained personnel, and urgent need for rapid decisions can lead to disorder when emergencies such as explosions and major releases of hazardous material occur **[11]**. Its

practical goal may be expressed as to ensure that arrangements are in place for a timely, managed, controlled, coordinated and effective response at the scene and at the local, regional, national and international level, to any nuclear or radiological emergency [2].

1.5.1 Emergency Preparedness Requirements

These are the requirements set out by the NNR for an adequate level of nuclear and radiological emergency preparedness and response for the licensing of PBMR nuclear power station [5].

(a). Authority.

(b). Organizational responsibilities.

(c). Response coordination.

(d). Plans and procedures.

(e). Emergency classification.

(f). Assessment of facility conditions.

(g). Notification and activation.

(h). Mitigation.

(i). Urgent protective action.

(j). Protection of emergency workers.

(k). Medical assistance.

(l). Longer term protective actions.

(m). Logistic support.

(n). Training.

1.5.2 Emergency preparedness maintenance

A programme of nuclear emergency preparedness is established in order to ensure that the plan will continue to be effective throughout the lifetime of the nuclear facility and the following steps will be taken into account:

1.5.2.1 Training of all members of the emergency response organization

This includes a description of specialized initial training and periodic retraining programs to be provided to each of the following categories of emergency personnel:

(a). Directors or coordinators of the plant emergency organization.

(b). Personnel responsible for accident assessment, including control room shift personnel.

(c). Radiological monitoring teams.

(d). Fire control teams (fire brigades).

(e). Repair and damage control teams.

(f). First aid and rescue teams.

(g). Local services personnel.

(h). Medical support personnel.

(i). Licensee's headquarters support personnel.

1.5.2.2 Periodic exercising of the entire plan or specific parts as required (drills and exercises) and provision of functional equipment

This includes provisions for the conduct of periodic drills and exercises to test the adequacy of timing and content of implementing procedures and methods, to test emergency equipment, and to ensure that emergency organization personnel are familiar with their duties. Preplanned descriptions, simulations, accidents, or similar events should be used to prepare scenarios appropriate to the objectives of each drill or exercise.

The plan should provide for an initial exercise prior to loading of fuel at any nuclear site and for annual exercises thereafter using scenarios appropriate to the Site Emergency or General Emergency. Each of these exercises should contain provisions for coordination with and participation of offsite emergency personnel, including those of national, provincial, or local government agencies. Each exercise should test, as minimum, the communications links and

notification procedures with those offsite agencies to demonstrate that capability for early warning of the public is maintained.

This plan should also provide for quarterly drills for fire team members, annual fire emergency drills containing provisions for participation by an offsite fire department, and annual drills of repair and damage control teams. These should be conducted as realistically as is reasonably possible and provisions should be made for critiques of all drills and exercises. Training includes delineation of methods to evaluate its effectiveness and to correct weak areas through feedback with emphasis on schedules, lesson plans, practical training, and periodic examinations.

1.5.2.3 Emergency Planning Coordinator

It is suggested that licensees establish and maintain on the normal plant operating staff an Emergency Planning Coordinator whose responsibility should include the coordination of offsite emergency planning efforts **[12]**, **[6]**.

1.6 Emergency Response

Emergency response is the performance of actions to mitigate the impact of an emergency on human health and safety, the quality of life, property or the environment. It may also provide a basis for the resumption of social and economic activity. In the context of a nuclear or radiological emergency, the practical goals of emergency response are to:

(a). take mitigatory action at the scene;

(b). prevent the occurrence of deterministic effects in workers and the public;

(c). render first aid and to manage the treatment of radiation injuries;

(d). reduce, to the extent practicable, the occurrence of non-radiological effects in the population;

(e). limit, to the extent practicable, the occurrence of non-radiological effects in individuals and in the population;

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(f). protect, to the extent practicable, the environment and property; and

(g). prepare, to the extent practicable, for the resumption of normal social and economic activity **[2]**.

1.6.1 Emergency planning zone

Emergency planning zone is defined as the off-site area around a facility for which planning and preparations are made in advance to ensure that necessary and effective protective actions are taken to protect the public, property or the environment in the case of an accident. Emergency planning zone represents the areas in which planning for given protective actions should take place based on health risk. A zone is based on the assessment that the health risk in those areas is sufficiently large to warrant the investment of resources and efforts required for detailed planning **[13]**.

With regard to the area over which planning efforts should be carried out, "Emergency Planning Zones" (EPZs) about each nuclear facility must be defined both for the short term "plume exposure pathway" and for longer term "ingestion exposure pathways".

The choice of the size of the EPZ represents a judgment on the extent of detailed planning which must be performed to assure an adequate response base **[14]**.

In South Africa, three planning zones are considered. These zones are consistent with international guidance [8], which is described below:

1.6.1.1 Precautionary action zone

A precautionary action zone (PAZ) is an area around a facility in which plans and preparations have been made to implement urgent protective actions to reduce the risk of serious deterministic effects in the event of an accident.

In this area, preparations should be made to quickly alert the public and workers and instruct them on the urgent protective actions to take. Protective actions such as sheltering, evacuation and distribution of stable iodine should be recommended immediately when severe conditions are

detected in the facility, without waiting for monitoring. The size of the PAZ is based on a best estimate of the consequences in the case of a worst accident and on the consideration that urgent protective actions taken before or shortly after a release within this zone will significantly reduce the risk of doses above the early death threshold in the worst case severe accidents. Action should be implemented immediately based on the plant conditions, before or shortly after the release.

1.6.1.2 Urgent protective action zone

An urgent protective zone is an area around a facility in which plans and preparations have been made to promptly implement urgent protective actions in the event of an accident, based on environmental monitoring. Plans and capabilities should be developed to implement sheltering or evacuation and distribute stable iodine (if appropriate). Plans should also reflect that evacuation may be required up to the boundary of the zones (e.g. reception centers for evacuees should be sited outside that zone).

The size of the UPZ represents a judgment on the extent of detailed planning required in order to ensure an effective response. It is based on the following considerations: urgent actions may need to be taken in 4 to 12 hours within the zone to significantly reduce the risk of doses above the early death threshold for the worst case severe accidents, the size provides approximately a factor of 10 reduction in concentrations (and thus risk) compared with the PAZ boundary, and detailed planning within this zone provides a substantial base for the expansion of response efforts in the event of the worst case accidents.

Hence, the UPZ should not be seen as the zone beyond which no emergency actions will be required, but rather as the zone in which detailed plans are developed to optimize the prompt response and to provide the basis for an expanded response.

1.6.1.3 Longer-term protective action zone

This is a zone around a facility in which plans and procedures are in place for taking effective protective actions to reduce the longer-term exposure due to deposited radionuclides in the event of

an accident. The LPZ is defined as the zone where, if there is an accident with a major release, protective actions such as relocation, resettlement and long-term agriculture countermeasures may be required [7],[13].

For most emergency types, response takes place in two distinct areas:

(a). On-site area

The area surrounding the facility within the security perimeter, fence or other designed property marker.

(b). Off-site area.

The area beyond that under the control of the facility or user. For facilities with the potential for emergencies involving major off-site releases, the level of planning will vary depending on the distance from the facility [3].

1.6.2 Protective action zones

Based on the worst possible meteorological conditions that may occur around a nuclear installation power station, the risk of early morbidity or mortality can be reduced or eliminated by evacuating the population around the station when an accidental release takes place.

Based on the full spectrum of postulated accidents, the risk of long-term health effects might be further reduced by sheltering the population in the downwind sector followed by an evacuation if environmental measurements justify it.

In accordance with international guidance provided by the International Atomic Energy Agency, the following protective action zones are recommended:

(a). a precautionary action zone around the station, where plans should be developed to automatically carry out a precautionary evacuation of the population as soon as plant conditions indicate the possibility of significant radiological release;

(b). an urgent protective action zone around the station, where plans should be developed for prompt sheltering, evacuation and administration of stable iodine; and

(c). a longer term protective action zone around the station, where plans should be developed to conduct environmental surveys and food sampling to determine the need to implement longer term protective actions **[13]**.

1.6.3 Protective action strategies

In the context of nuclear emergencies, protective actions include measures to limit the exposure of the public to radioactive contamination through external exposure, inhalation and ingestion **[13]**. When emergency plans are prepared for any given nuclear installation or potential accidents, account should be taken of, inter alia, the nature and magnitude of possible doses and practicability of implementing each countermeasure or combination of countermeasures in order to select specific intervention levels which could be used in most circumstances **[15]**.

The objectives of protective actions are to prevent deterministic effects (early mortality and morbidity) and to reduce stochastic effects (cancer) as much as reasonable. Nuclear emergency protection actions include:

1.6.3.1 Sheltering

Sheltering involves keeping members of the population indoors to reduce radiation exposure from cloud and ground shine and from inhalation. In addition to protecting the population, sheltering allows better and more effective communication with the affected population. For the average dwelling in South Africa, the following dose reduction factors will be assumed:

(a). dose reduction factor for cloud shine: 0.8;

(b). dose reduction factor for ground shine: 0.5; and

(c). dose reduction factor against inhalation: 0.5.

The methodology used to establish these values is consistent with international recommendations and with the results of international measurements following Chernobyl.

1.6.3.2 Evacuation

Evacuation is the prompt removal of the population from the affected areas. It is generally the most effective protective action against major airborne releases of radioactivity. Mass care facilities must be available for a substantial fraction of the evacuated population.

1.6.3.3 Administration of stable iodine tablets

Radioactive iodine has tendency of being more concentrated in the thyroid gland and that can cause early or latent effects such as thyroid cancer. Ingesting stable, non-radioactive iodine, before or immediately after exposure to radioactive iodine saturates the thyroid gland and prevents the absorption of radioactive iodine in the body.

1.6.3.4 Temporary relocation and resettlement

Temporary relocation is used when there is a need to keep the population out of the affected area for a period exceeding approximately seven days but not more than a few months. This measure requires that mass care facilities be provided to the affected population. It is expected that the temporarily relocated population will be able to return to their homes.

Resettlement is, by definition, permanent. It is adopted when the dose to the affected population over a lifetime would exceed a certain criterion.

Both relocation and resettlement are determined on the basis of ground contamination.

1.6.3.5 Food ban and food control

Protective actions related to food include:

(a). the protection of local food and water supplies by, for example, covering open wells and sheltering animals and animal feed;

(b). the long-term sampling and control of locally grown food and feed; and

(c). an immediate ban on the consumption of locally grown food and feed.

Control of milk is generally considered particularly important because it is a significant part of the diet for children.

There is also an inclusion of:

(a). urgent protective actions, which must be taken within hours of an accident to be effective. These includes: evacuation, intake of stable iodine tablets and sheltering; and

(b). longer-term protective actions, which may need to be adopted in a matter of days following an accident. These include: analysis and control of foodstuffs, relocation and resettlement.

During emergency response, best efforts are made making use of plan action criteria without regard to whether particular areas are inside or outside zones. Planning and preparedness are cooperative efforts by state agencies, local jurisdiction and the utilities. These efforts result in integrated and refined plans for emergency response and a cadre of trained emergency responders **[16]**.

1.7 Justification

For the purpose of identifying radiation fields and designing the radiation protection programme for the PBMR, the following nuclear systems have been considered as the main sources of radiation:

(a). reactor and Power Convention Unit (PCU);

(b). fuel handling equipment;

(c). primary coolant-conveying systems; and

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(d). water-carrying systems which interface with radiologically active systems, or those which are exposed to the neutron flux.

The strongest radiation field is that around the reactor during operation. The source of other radiation fields also originates from the reactor. They are products either of nuclear fission in the fuel, or of activation in the radiation field of the reactor. Other radiation fields are primarily caused by:

(a). fission products – in the fuel elements and as contaminants in the primary coolant; and

(b). activation products – in the structural material and surrounding systems around the reactor core **[17]**.

During normal PBMR operation, these radioactive materials are contained within the helium pressure boundary and support system pressure boundaries. While very small well-controlled discharges are anticipated for any nuclear plant, safety systems are required to help ensure a very low probability of a significant radiological release.

An emergency preparedness and response plan can:

(a). cover emergencies that may arise off-site from the PBMR nuclear power station and radioactive emission that affect the public;

(b). provide guidance on the specific levels of radiation at which action should be initiated to protect against exposure from contaminated air, water, soil and food;

(c). indicate what support and resources provinces would need in the event of a nuclear accident and where such resources might be obtained;

(d). give guidelines in dealing with late stages of a nuclear emergency; and

(e). provide guidance for assessing the radiological situation and give advice for intervention to interact with decision makers and executors, monitor team and the public.

1.8 Objectives of this study

The basic objective of this study is to describe and explain the conditions of emergency preparedness and to establish the technical basis for emergency response plans in the event of a nuclear incident occurring at the PBMR Nuclear Power Station.

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CHAPTER 2 : METHODOLOGY

2.1 Materials and Methods

Initially, Koeberg Nuclear Power Station's technical basis for emergency planning **[13]** were examined. The Koeberg Nuclear Power Station is designed, built and operated to some of the most stringent safety standards. The possibility of a major accident is extremely remote [13]. However, effective emergency response plans are an inherent part of the management of nuclear power station safety **[13]**. The national nuclear safety regulatory authority, the NNR, is responsible for the establishment of nuclear safety standards and requires that the station operators continually demonstrate through their safety management practices that the station is operated within the approved safety envelope. In addition, the NNR requires that safety reviews be conducted on a periodic basis to verify that the station does not pose undue health risks to the public in the light of component ageing, design modifications, changes in the local population and new or planned urban developments. Hence, the potential for serious accidents which could pose a serious threat to the health of the public around the Koeberg station is reduced, but not eliminated. History has shown that accidents can happen and, to limit their impact and protect the public, adequate emergency response plans should be in place **[18]**. The suggested technical basis for emergency planning around the Koeberg nuclear power station were:

(a). consideration of postulated accidents;

(b). the areas that are most likely to be affected (protective action zone) and the planning required to minimize the risk of early mortality and morbidity, even in the most severe accidents; and

(c). the most effective protective action strategy based on the entire postulated accident spectrum.

Postulated accidents considered in the technical planning basis for Koeberg include:

(a). design basis accidents, with limited off-site consequences, these are accidents with a higher probability of occurrence;

(b). severe accidents with no, or late, containment failure; and

(c). severe accidents with early containment failures and rapid releases to the environment. These are accidents with very low probability of occurrence and potentially worse consequences than for design basis accidents.

These accidents were analysed by ESKOM as part of safety studies carried out for regulatory review by the NNR **[13]**.

Since the Koeberg nuclear power station technical basis for emergency planning has already been approved by the regulator (NNR), PBMR is going to follow the same procedure to establish its technical basis for emergency planning.

The PBMR is a graphite moderated helium cooled reactor using a direct gas turbine cycle to convert the heat, generated by nuclear fission in the reactor and transferred to the coolant gas, into electrical energy by means of a helium turbo-generator **[19]**. The PBMR plant shall be designed, built and operated according to good engineering practice. The principles of defense-in-depth and ALARA (As Low As Reasonably Achievable) will be adopted. Furthermore, the plant and its proposed operation shall be demonstrated to meet the fundamental risk criteria and the accident management requirements **[20]**.

Areas that are most likely to be affected by postulated accidents will be identified from the accident consequence studies that will describe the variation of consequence with respect to distance. This will help in the identification of formalized emergency planning zone. The required distance from the PBMR to the formal emergency planning zone would be determined by considering the consequence resulting from the most restrictive Licensing Basis Events (LBE) tabulated below, In this case LBE 10 as described in the PBMR Safety Analysis Report (SAR) **[9]** will be considered.

Table 2-1: Licensing Basis Events

EVENTS	DESCRIPTION
LBE 1	Loss of Power Convention Unit
LBE 2	Control rod group withdrawal
LBE 3	Small isolated helium Pressure Boundary break
LBE 4	Small unisolated helium Pressure Boundary break
LBE 5	Heat exchanger tube leak isolated
LBE 6	Heat exchanger tube leak unisolated
LBE 7	Medium isolated helium Pressure Boundary break
LBE 8	Medium unisolated helium Pressure Boundary break
LBE 9	Large isolated helium Pressure Boundary break
LBE 10	Large unisolated helium Pressure Boundary break
LBE 11	Safe Shutdown Earthquake

[21]

The consequence to be determined would include:

(a). The effective dose as a measure of the mortality risk due to stochastic effects (not taking into account the frequency of the accidents). International Commission on Radiological Protection (ICRP 40) will be used. ICRP 40 **[22]**, establishes the basic principle on which the emergency preparedness for any type of accident should be based: "*the preparation of emergency plans should be based on consideration of a wide range of potential accidents, including those having low probabilities of occurrence...[but]...the degree of details in plans should decreases as the probability of the accident decreases*".

ICRP-60 **[23]** will also be considered since it elaborates on this principle and state that organizations should plan in detail for probable events in order to prevent stochastic effects, and make provisions (less detailed plans) for less probable events in order to

prevent deterministic effects, or death. This does not mean that accidents with lower probabilities should not be seriously considered, but rather that the emergency preparedness efforts and resources should be invested wisely **[13]**. And it also contains the dose data files used in PC COSYMA calculations.

(b). The (effective) whole-body dose, the absorbed dose to lung, red bone marrow and skin as a measure of deterministic effects. Nuclear Regulator (NUREG) 0654 **[14]**, Regulatory Guide (REG. GUIDE) 1.101 **[6]** and PC COSYMA (**Co**de **SY**stem from **MARIA**, of which **MARIA** is **M**ethod for **A**ssessing the **R**adiological **I**mpact of **A**ccidents) **[24]** will be used. NUREG is a regulatory guidance which helps to model effects of accidents release, and PC COSYMA is a programme which helps to model the release as described or specified by the regulations. PC COSYMA, which runs on the PC, is a probabilistic accident consequence assessment (ACA) system, for use in calculating the risk posed by potential nuclear accidents giving rise to release to atmosphere. It takes into account the range of conditions which may prevail should an accident occur. For the PBMR nuclear power station technical basis for emergency planning this is what we will input into the PC COSYMA.

In consequence analysis, it is often necessary to group event sequences that have similar consequences, together. These groups of event sequences are called release categories. Because of the large number of event sequences involved, it is impracticable to calculate the consequence of each event sequence, therefore the grouping of event sequences is necessary. For the PBMR, six release categories have been identified and are described below:

(a). RC-1 – grouping of all small breaks which are isolatable. The small breaks are breaks with equivalent area of a 10mm diameter pipe which are assumed to be within the capacity of the containment system filtration system. Thus the release to the environment is filtered through the system. Only circulating fission products are available for release. About 10% of the gas will have escaped before isolation.

(b). RCF-1 – consists of all small breaks where the break is not isolatable. Pumpdown is assumed and since this is a small pipe break no lift-off of plate-out fission products is assumed. However, there is a delayed release due to subsequent core heat-up. In

this event, about 50% of the gas is assumed to have been released before pumpdown is complete.

(c). RCF-2 – consists of all small breaks where the break was not isolatable but for which no pumpdown is assumed. Since this is a small pipe break no lift-off of plate-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.

(d). RCP-1 – consists of medium and large breaks that have been isolated. 100% of the circulating gas is assumed released before isolation is effected. The release is unfiltered and is exhausted through vent into the atmosphere. Only circulating activity and lifted-off activity form part of the source term.

(e). RCPF-1 – consists of medium breaks which are not isolatable. The whole circulating inventory and fraction of plated-out material is released immediately. The vent is assumed to be closed after the initial puff. Delayed release is assumed to occur after 32 hours.

(f). RCPF-2 – consists of large breaks which are not isolatable. The whole circulating inventory and lift-off of plated-out material is released. The vent is assumed to not be close after the initial puff. Delayed release occurs after 32 hours.

The RCPF – 2 category involves the largest radiological source term, and will be used to examine the dose to specified organs, as noted in ***Table 2-2***.

Table 2-2: Summary of Dose results required

Dose Type	Source Release Category	Distance (km)	Integration Time	Weather Stability Category	All Pathway Contribution (yes/no)
Effective dose	RC-1, RCF-1, RCF-2, RCP-1, RCPF-1, RCPF-2	0-40	1, 10, 30 & 70 days	D, F	Yes
Skin	RCPF-2	0-40	1, 10, 30 & 70 days	D, F	Yes
Lungs	RCPF-2	0-40	1, 10, 30 & 70 days	D, F	Yes
Red Bone Marrow	RCPF-2	0-40	1, 10, 30 & 70 days	D, F	Yes
Thyroid	RCPF-2	0-40	30 days	D, F	Inhalation only

- Source Term – a description of the type, quantity, radionuclide species, chemical form, and timing of the release of radioactive material from the plant during an accident **[25]**. It is specified for the calculation of events of the consequences. Source Term and dispersion parameters are generally characterized by the following parameters:

  (a). Release fraction - description of the fraction of the initial available inventory that is released to the atmosphere.

  (b). Energy of release – the energy associated with the release directly influences radiological consequences.

  (c). Release height – it is the elevation in which the source term leaves the building and enters the atmosphere.

  (d). Timing of release – description of the time after nuclear fission stops at which the release occurs.

  (e). Release duration – description of the duration of the release into the atmosphere.

Preliminary estimation of PBMR source terms used in this study is provided in ***Table 2-3***. This source term description will be refined as design and safety analysis progresses.

Table 2-3: Design Source Term [Bq]

Nuclide	Circulating Activity (gas & dust)	Lift-off Activity (gas & dust)	Delayed Activity (gas & dust)	Total Activity (Circ + Lift) Unfiltered	Total Activity (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

- Accident Descriptions – design basis and beyond design basis accidents.

- Meteorological Data files – the meteorological parameters presented in the data are as follows:
  (a) wind direction;
  (b) atmospheric stability category;
  (c) rainfall rate;
  (d) wind speed; and
  (e) mixing layer depth.
- Population Distribution – this is generally specified as a function of distance and direction from the plant.

For each accident, the PC COSYMA runs were done and the results will determine whether there is a need for inclusion of countermeasures or not. If there is a need to implement protective actions, their impact on the mitigation of consequences was assessed looking ideally at the following intervention measures:

(a). potassium iodate prophylaxis;

(b). sheltering;

(c). evacuation; and

(d). food banning.

These intervention levels are clearly defined in ***chapter 1***. However, for the PBMR technical basis, only administration of the iodate prophylaxis, sheltering and food ban will be considered. PBMR source terms are much smaller compared to Koeberg nuclear power station and Koeberg does not plan to evacuation. Therefore, evacuation is not a feasible option for PBMR also.

For PC COSYMA a run including iodine as a countermeasure was performed, iodine was assumed to be distributed at a distance of 40km within sheltered area after 2 hours of release.

Table 2-4: Summary of Dose results required including iodine as a countermeasure

Dose Type	Source Release Category	Distance (km)	Integration Time	Weather Stability Category	Pathway Contribution
Effective dose	RCPF - 2	0 - 40	30 days	F	Inhalation Only
Thyroid	RCPF - 2	0 - 40	30 days	F	Inhalation Only

Steps to be performed, if required, will include:

(a) Calculation of precautionary action zone (PAZ) radius – this represents the distance beyond which the risk of receiving an exposure exceeding the threshold for early deterministic effects is extremely small. The radius will be determined on the basis of beyond design basis accidents, with a major emphasis placed on the consequences resulting from the worst accident coincidental with the worst weather scenario.

(b) Determination of the urgent protective action zone (UPZ) radius – this is the area where the risk justifies detailed planning for urgent protective actions. Several factors will be considered in the determination of the UPZ radii:

- Design basis accident: the UPZ will include areas where the committed effective dose resulting from design basis accidents exceeds the lower intervention level for evacuation or the higher intervention level for sheltering (50mSv in both cases).
- Beyond design basis accidents: the UPZ will consider areas where serious deterministic effects for beyond design basis accidents after one day exposure could occur unless sheltering is implemented, or stable iodine is administered.
- Risk: one way to consider risk is through the use of a probability-weighted dose consequence which considers all accidents and weather scenario. Probability-weighted dose is defined as the probabilistic dose which could be received by an individual as the results of an accident.
- Probability of exceeding intervention levels: this probability decreases with distance for ground or near-ground release. When this probability drops significantly, the benefit ratio of planning also decreases significantly. The probability of exceeding

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50mSv as a function of distance from the plant may help determine where planning would be most effective. This value is chosen because it represents the upper and lower intervention levels for sheltering and evacuation, respectively, chosen by South Africa.

(c) Determination of the longer-term protective action zone radius – is not easy to determine, but it can be implemented on the basis of careful measurement and analysis.

CHAPTER 3 : RESULTS

3.1 Weather Used

For the PC COSYMA runs that were done, two weather categories were considered, Pasquill stability categories D and F. In accordance with generally accepted International practice, Pasquill D and F with a wind speed of 2m/s were used for neutral and moderately stable weather conditions.

70 days exposure shows slightly higher effective doses compared to 30 days exposure, but 30 days exposure is selected for detailed evaluation since countermeasures would normally be implemented to prevent further dose accrual. But still the radiological dose from 70 days exposure is below the regulatory guidance for requiring countermeasures.

Sixteen radial sectors are modeled with PC COSYMA. Sector 9 results are used since they are the highest dose values representing the plume center-line.

Table 3-1: 30 days Effective Dose (Sv), Weather Category D

Distance (km)	Circulating	Delayed	Plate – Out
	Sector 9	Sector 9	Sector 9
0.4	1.48E-06	2.47E-04	1.41E-07
1.65	3.54E-07	3.17E-05	1.89E-08
3.75	1.23E-07	8.81E-06	5.39E-09
6.25	6.01E-08	3.92E-06	2.43E-09
8.75	3.60E-08	2.27E-06	1.42E-09
11.25	2.22E-08	1.51E-06	9.41E-10
13.75	1.55E-08	1.11E-06	6.92E-10
16.25	1.33E-08	9.41E-07	5.93E-10
18.75	1.05E-08	8.28E-07	5.21E-10
21.25	9.17E-09	7.27E-07	4.60E-10
23.75	8.25E-09	6.48E-07	4.15E-10
26.25	7.73E-09	5.94E-07	3.86E-10
28.75	5.74E-09	5.34E-07	3.46E-10
31.25	5.33E-09	4.86E-07	3.19E-10
33.75	5.06E-09	4.51E-07	3.01E-10
36.25	3.87E-09	4.15E-07	2.77E-10
38.75	3.65E-09	3.83E-07	2.59E-10

Table 3-2: Doses per Release Categories – Effective (D30)

Distance (km)	Dose (Sv)																			NNR
	RC-1	RCF-1			RCF-2			RCP-1			RCPF-1				RCPF-2				Criteria
	Circulation	Circulation	Delayed	Total	Circulation	Delayed	Total	Circulation	Plate-out	Total	Circulation	Delayed	Plate-out	Total	Circulation	Delayed	Plate-out	Total	Total
0.4	1.48E-06	1.48E-06	2.47E-04	2.49E-04	1.48E-06	2.47E-04	2.49E-04	1.48E-06	1.41E-07	1.62E-06	1.48E-06	2.47E-04	1.41E-07	2.49E-04	1.48E-06	2.47E-04	1.41E-07	2.49E-04	5.00E-02
1.65	3.54E-07	3.54E-07	3.17E-05	3.21E-05	3.54E-07	3.17E-05	3.21E-05	3.54E-07	1.89E-08	3.73E-07	3.54E-07	3.17E-05	1.89E-08	3.21E-05	3.54E-07	3.17E-05	1.89E-08	3.21E-05	5.00E-02
3.75	1.23E-07	1.23E-07	8.81E-06	8.93E-06	1.23E-07	8.81E-06	8.93E-06	1.23E-07	5.39E-09	1.28E-07	1.23E-07	8.81E-06	5.39E-09	8.94E-06	1.23E-07	8.81E-06	5.39E-09	8.94E-06	5.00E-02
6.25	6.01E-08	6.01E-08	3.92E-06	3.98E-06	6.01E-08	3.92E-06	3.98E-06	6.01E-08	2.43E-09	6.25E-08	6.01E-08	3.92E-06	2.43E-09	3.98E-06	6.01E-08	3.92E-06	2.43E-09	3.98E-06	5.00E-02
8.75	3.60E-08	3.60E-08	2.27E-06	2.30E-06	3.60E-08	2.27E-06	2.30E-06	3.60E-08	1.42E-09	3.74E-08	3.60E-08	2.27E-06	1.42E-09	2.30E-06	3.60E-08	2.27E-06	1.42E-09	2.30E-06	5.00E-02
11.25	2.22E-08	2.22E-08	1.51E-06	1.53E-06	2.22E-08	1.51E-06	1.53E-06	2.22E-08	9.41E-10	2.32E-08	2.22E-08	1.51E-06	9.41E-10	1.53E-06	2.22E-08	1.51E-06	9.41E-10	1.53E-06	5.00E-02
13.75	1.55E-08	1.55E-08	1.11E-06	1.12E-06	1.55E-08	1.11E-06	1.12E-06	1.55E-08	6.92E-10	1.62E-08	1.55E-08	1.11E-06	6.92E-10	1.12E-06	1.55E-08	1.11E-06	6.92E-10	1.12E-06	5.00E-02
16.25	1.33E-08	1.33E-08	9.41E-07	9.55E-07	1.33E-08	9.41E-07	9.55E-07	1.33E-08	5.93E-10	1.39E-08	1.33E-08	9.41E-07	5.93E-10	9.55E-07	1.33E-08	9.41E-07	5.93E-10	9.55E-07	5.00E-02
18.75	1.05E-08	1.05E-08	8.28E-07	8.39E-07	1.05E-08	8.28E-07	8.39E-07	1.05E-08	5.21E-10	1.10E-08	1.05E-08	8.28E-07	5.21E-10	8.39E-07	1.05E-08	8.28E-07	5.21E-10	8.39E-07	5.00E-02
21.25	9.17E-09	9.17E-09	7.27E-07	7.36E-07	9.17E-09	7.27E-07	7.36E-07	9.17E-09	4.60E-10	9.63E-09	9.17E-09	7.27E-07	4.60E-10	7.36E-07	9.17E-09	7.27E-07	4.60E-10	7.36E-07	5.00E-02
23.75	8.25E-09	8.25E-09	6.48E-07	6.57E-07	8.25E-09	6.48E-07	6.57E-07	8.25E-09	4.15E-10	8.67E-09	8.25E-09	6.48E-07	4.15E-10	6.57E-07	8.25E-09	6.48E-07	4.15E-10	6.57E-07	5.00E-02
26.25	7.73E-09	7.73E-09	5.94E-07	6.02E-07	7.73E-09	5.94E-07	6.02E-07	7.73E-09	3.86E-10	8.12E-09	7.73E-09	5.94E-07	3.86E-10	6.02E-07	7.73E-09	5.94E-07	3.86E-10	6.02E-07	5.00E-02
28.75	5.74E-09	5.74E-09	5.34E-07	5.39E-07	5.74E-09	5.34E-07	5.39E-07	5.74E-09	3.46E-10	6.08E-09	5.74E-09	5.34E-07	3.46E-10	5.40E-07	5.74E-09	5.34E-07	3.46E-10	5.40E-07	5.00E-02
31.25	5.33E-09	5.33E-09	4.86E-07	4.92E-07	5.33E-09	4.86E-07	4.92E-07	5.33E-09	3.19E-10	5.64E-09	5.33E-09	4.86E-07	3.19E-10	4.92E-07	5.33E-09	4.86E-07	3.19E-10	4.92E-07	5.00E-02
33.75	5.06E-09	5.06E-09	4.51E-07	4.56E-07	5.06E-09	4.51E-07	4.56E-07	5.06E-09	3.01E-10	5.36E-09	5.06E-09	4.51E-07	3.01E-10	4.57E-07	5.06E-09	4.51E-07	3.01E-10	4.57E-07	5.00E-02
36.25	3.87E-09	3.87E-09	4.15E-07	4.19E-07	3.87E-09	4.15E-07	4.19E-07	3.87E-09	2.77E-10	4.15E-09	3.87E-09	4.15E-07	2.77E-10	4.19E-07	3.87E-09	4.15E-07	2.77E-10	4.19E-07	5.00E-0
38.75	3.65E-09	3.65E-09	3.83E-07	3.87E-07	3.65E-09	3.83E-07	3.87E-07	3.65E-09	2.59E-10	3.91E-09	3.65E-09	3.83E-07	2.59E-10	3.87E-07	3.65E-09	3.83E-07	2.59E-10	3.87E-07	5.00E-0

Table 3-3: 30 days Effective Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate – Out
	Sector 9	Sector 9	Sector 9
0.4	2.57E-06	4.95E-04	3.24E-07
1.65	7.44E-07	7.48E-05	5.20E-08
3.75	2.85E-07	2.06E-05	1.50E-08
6.25	1.47E-07	8.93E-06	6.72E-09
8.75	1.07E-07	6.28E-06	4.83E-09
11.25	8.42E-08	4.83E-06	3.81E-09
13.75	6.63E-08	3.88E-06	3.14E-09
16.25	5.33E-08	3.18E-06	2.65E-09
18.75	4.40E-08	2.67E-06	2.29E-09
21.25	4.52E-08	2.27E-06	2.03E-09
23.75	4.08E-08	1.95E-06	1.81E-09
26.25	3.26E-08	1.69E-06	1.62E-09
28.75	2.80E-08	1.48E-06	1.47E-09
31.25	2.62E-08	1.30E-06	1.35E-09
33.75	2.13E-08	1.15E-06	1.24E-09
36.25	1.88E-08	1.02E-06	1.15E-09
38.75	1.78E-08	9.09E-07	1.07E-09

3.2 Consequences of the Worst Accidents

The dose results presented above are plume centreline effective doses, and therefore represent the maximum calculated doses at various distances away from the reactor. For compliance with NNR regulations, doses at the site boundary (0.4 km) were also considered because they represent the closest point to the plant where the public might be located.

It must be demonstrated that the dose accumulated by members of the public for Category A and B events shown below are less than 250 μSv per year and 50 mSv per event **[21]**, respectively.

Table 3-5: Licensing Requirements for the PBMR

EVENT FREQUENCY	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 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 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.	Limitation of risk to the values set by the risk criteria. Plant Personnel - 5 x 10^{-5}.y^{-1} peak individual risk and - 10^{-5}.y^{-1} average risk Members of The Public - 5 x 10^{-6}.y^{-1} peak individual risk and - 10^{-8}.y^{-1} average population risk per site

Looking at both stability category D (***Table 3-2***) and category F (***Table 3-4***) results, Category F results are slightly higher than the category D, but still they are below the criterions set by the NNR. Below is the clear graphical representation of the results of accidental doses for ***Table 3-2*** and ***Table 3-4*** respectively.

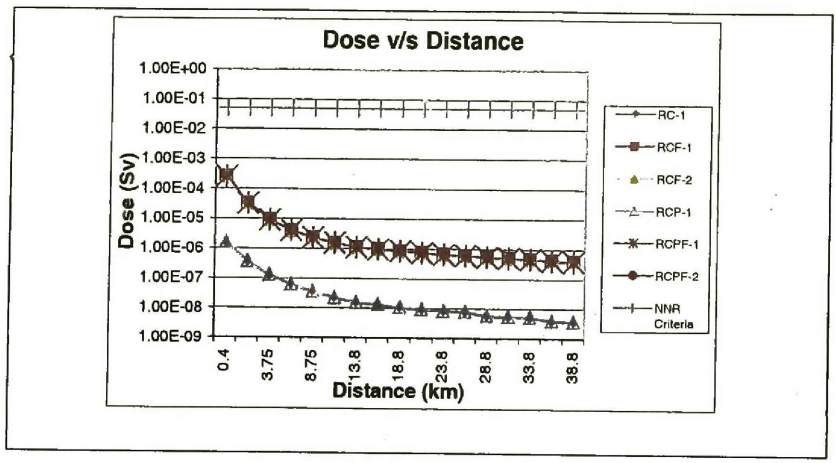


Figure 3-1: Doses per Release Categories – Effective (D30)

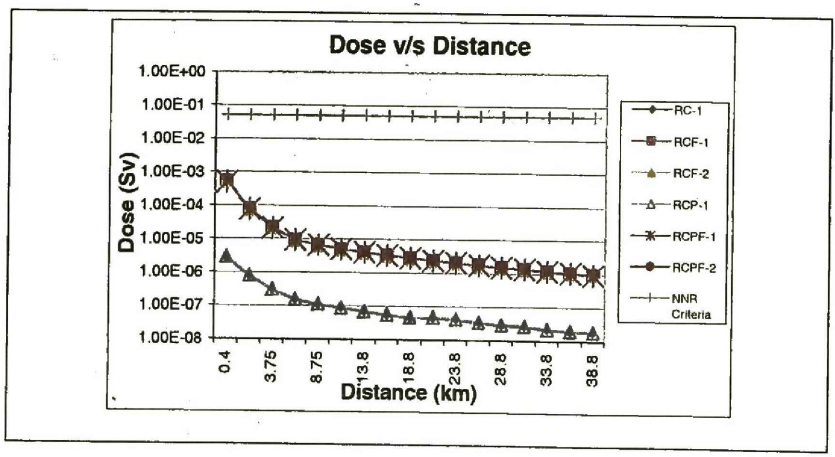


Figure 3-2: Doses per Release Categories – Effective (F30)

For the remainder of this study, we will only consider the Pasquill F category results since it is regarded as the weather condition that could lead to the worst accident scenario, that is, no rain, minimum mixing layer-depth and variability in wind direction. But still it produces results that are below the set criterions by the NNR.

Represented below are the Pasquill F results for exposure dose integration periods 1, 10, 30, and 70 respectively. Results for target organs, and the effective dose are provided, and shown for individual source term components (circulating, plate-out, and delayed activity releases) and summed for release categories. And also short–term dose calculations were done for Thyroid considering inhalation only as a pathway.

Table 3-6: 1 day Effective Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate -out
	Sector 9	Sector 9	Sector 9
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 3-7: Doses per Release Categories (Sv) – Effective (F1)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
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 3-8: 1 day Lung Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-out
	Sector 9	Sector 9	Sector 9
0.4	2.74E-06	3.14E-05	7.26E-08
1.65	7.81E-07	4.85E-06	1.16E-08
3.75	2.97E-07	1.37E-06	3.21E-09
6.25	1.53E-07	6.02E-07	1.36E-09
8.75	1.11E-07	4.27E-07	9.10E-10
11.25	8.74E-08	3.31E-07	6.71E-10
13.75	6.88E-08	2.67E-07	5.16E-10
16.25	5.53E-08	2.19E-07	4.07E-10
18.75	4.56E-08	1.84E-07	3.32E-10
21.25	4.67E-08	1.61E-07	2.89E-10
23.75	4.22E-08	1.40E-07	2.52E-10
26.25	3.36E-08	1.22E-07	2.09E-10
28.75	2.89E-08	1.07E-07	1.80E-10
31.25	2.70E-08	9.44E-08	1.62E-10
33.75	2.19E-08	8.37E-08	1.40E-10
36.25	1.94E-08	7.49E-08	1.25E-10
38.75	1.83E-08	6.70E-08	1.14E-10

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Table 3-9: Doses per Release Categories (Sv) – Lung (F1)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.74E-06	3.42E-05	3.42E-05	2.82E-06	3.42E-05	3.42E-05
1.65	7.81E-07	5.63E-06	5.63E-06	7.93E-07	5.65E-06	5.65E-06
3.75	2.97E-07	1.66E-06	1.66E-06	3.01E-07	1.67E-06	1.67E-06
6.25	1.53E-07	7.55E-07	7.55E-07	1.54E-07	7.56E-07	7.56E-07
8.75	1.11E-07	5.38E-07	5.38E-07	1.12E-07	5.39E-07	5.39E-07
11.25	8.74E-08	4.18E-07	4.18E-07	8.81E-08	4.19E-07	4.19E-07
13.75	6.88E-08	3.36E-07	3.36E-07	6.93E-08	3.36E-07	3.36E-07
16.25	5.53E-08	2.74E-07	2.74E-07	5.57E-08	2.75E-07	2.75E-07
18.75	4.56E-08	2.30E-07	2.30E-07	4.60E-08	2.30E-07	2.30E-07
21.25	4.67E-08	2.08E-07	2.08E-07	4.69E-08	2.08E-07	2.08E-07
23.75	4.22E-08	1.82E-07	1.82E-07	4.24E-08	1.82E-07	1.82E-07
26.25	3.36E-08	1.55E-07	1.55E-07	3.38E-08	1.55E-07	1.55E-07
28.75	2.89E-08	1.35E-07	1.35E-07	2.91E-08	1.36E-07	1.36E-07
31.25	2.70E-08	1.21E-07	1.21E-07	2.72E-08	1.22E-07	1.22E-07
33.75	2.19E-08	1.06E-07	1.06E-07	2.21E-08	1.06E-07	1.06E-07
36.25	1.94E-08	9.43E-08	9.43E-08	1.95E-08	9.44E-08	9.44E-08
38.75	1.83E-08	8.53E-08	8.53E-08	1.84E-08	8.54E-08	8.54E-08

Table 3-10: 1 day Red Bone Marrow Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	1.96E-06	2.90E-05	6.52E-08
1.65	6.25E-07	4.48E-06	1.04E-08
3.75	2.47E-07	1.26E-06	2.89E-09
6.25	1.29E-07	5.54E-07	1.22E-09
8.75	9.38E-08	3.93E-07	8.20E-10
11.25	7.42E-08	3.04E-07	6.05E-10
13.75	5.84E-08	2.45E-07	4.64E-10
16.25	4.69E-08	2.01E-07	3.66E-10
18.75	3.87E-08	1.69E-07	2.97E-10
21.25	4.01E-08	1.48E-07	2.59E-10
23.75	3.62E-08	1.28E-07	2.25E-10
26.25	2.88E-08	1.11E-07	1.86E-10
28.75	2.47E-08	9.76E-08	1.61E-10
31.25	2.31E-08	8.64E-08	1.44E-10
33.75	1.87E-08	7.66E-08	1.24E-10
36.25	1.65E-08	6.85E-08	1.10E-10
38.75	1.56E-08	6.13E-08	1.00E-10

Table 3-11: Doses per Release Categories (Sv) – Red Bone Marrow (F1)

Distance (km)	RC - 1	RCF -1	RCF -2	RCP -1	RCPF -1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	1.96E-06	3.10E-05	3.10E-05	2.02E-06	3.10E-05	3.10E-05
1.65	6.25E-07	5.10E-06	5.10E-06	6.36E-07	5.11E-06	5.11E-06
3.75	2.47E-07	1.51E-06	1.51E-06	2.49E-07	1.51E-06	1.51E-06
6.25	1.29E-07	6.83E-07	6.83E-07	1.30E-07	6.84E-07	6.84E-07
8.75	9.38E-08	4.87E-07	4.87E-07	9.46E-08	4.87E-07	4.87E-07
11.25	7.42E-08	3.79E-07	3.79E-07	7.48E-08	3.79E-07	3.79E-07
13.75	5.84E-08	3.04E-07	3.04E-07	5.88E-08	3.04E-07	3.04E-07
16.25	4.69E-08	2.48E-07	2.48E-07	4.72E-08	2.49E-07	2.49E-07
18.75	3.87E-08	2.08E-07	2.08E-07	3.90E-08	2.08E-07	2.08E-07
21.25	4.01E-08	1.88E-07	1.88E-07	4.03E-08	1.88E-07	1.88E-07
23.75	3.62E-08	1.64E-07	1.64E-07	3.64E-08	1.65E-07	1.65E-07
26.25	2.88E-08	1.40E-07	1.40E-07	2.90E-08	1.40E-07	1.40E-07
28.75	2.47E-08	1.22E-07	1.22E-07	2.49E-08	1.22E-07	1.22E-07
31.25	2.31E-08	1.10E-07	1.10E-07	2.32E-08	1.10E-07	1.10E-07
33.75	1.87E-08	9.54E-08	9.54E-08	1.89E-08	9.55E-08	9.55E-08
36.25	1.65E-08	8.51E-08	8.51E-08	1.67E-08	8.52E-08	8.52E-08
38.75	1.56E-08	7.69E-08	7.69E-08	1.57E-08	7.70E-08	7.70E-08

Table 3-12: 1 day Skin Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	1.27E-05	3.09E-03	2.88E-06
1.65	1.89E-06	4.66E-04	4.27E-07
3.75	4.97E-07	1.28E-04	1.14E-07
6.25	2.02E-07	5.55E-05	4.77E-08
8.75	1.34E-07	3.90E-05	3.26E-08
11.25	9.73E-08	3.00E-05	2.45E-08
13.75	7.45E-08	2.41E-05	1.93E-08
16.25	5.84E-08	1.97E-05	1.56E-08
18.75	4.70E-08	1.65E-05	1.29E-08
21.25	3.85E-08	1.40E-05	1.09E-08
23.75	3.36E-08	1.21E-05	9.47E-09
26.25	2.69E-08	1.05E-05	8.05E-09
28.75	2.28E-08	9.13E-06	7.02E-09
31.25	2.05E-08	8.05E-06	6.29E-09
33.75	1.68E-08	7.11E-06	5.50E-09
36.25	1.46E-08	6.32E-06	4.93E-09
38.75	1.33E-08	5.62E-06	4.47E-09

Table 3-13: Doses per Release Categories (Sv) – Skin (F1)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF- 2
	Circulation	Total	Total	Total	Total	Total
0.4	1.27E-05	3.11E-03	3.11E-03	1.56E-05	3.11E-03	3.11E-03
1.65	1.89E-06	4.68E-04	4.68E-04	2.32E-06	4.69E-04	4.69E-04
3.75	4.97E-07	1.29E-04	1.29E-04	6.11E-07	1.29E-04	1.29E-04
6.25	2.02E-07	5.57E-05	5.57E-05	2.50E-07	5.58E-05	5.58E-05
8.75	1.34E-07	3.92E-05	3.92E-05	1.66E-07	3.92E-05	3.92E-05
11.25	9.73E-08	3.01E-05	3.01E-05	1.22E-07	3.01E-05	3.01E-05
13.75	7.45E-08	2.42E-05	2.42E-05	9.37E-08	2.42E-05	2.42E-05
16.25	5.84E-08	1.98E-05	1.98E-05	7.39E-08	1.98E-05	1.98E-05
18.75	4.70E-08	1.66E-05	1.66E-05	5.99E-08	1.66E-05	1.66E-05
21.25	3.85E-08	1.41E-05	1.41E-05	4.94E-08	1.41E-05	1.41E-05
23.75	3.36E-08	1.21E-05	1.21E-05	4.31E-08	1.21E-05	1.21E-05
26.25	2.69E-08	1.05E-05	1.05E-05	3.50E-08	1.05E-05	1.05E-05
28.75	2.28E-08	9.15E-06	9.15E-06	2.98E-08	9.16E-06	9.16E-06
31.25	2.05E-08	8.07E-06	8.07E-06	2.68E-08	8.07E-06	8.07E-06
33.75	1.68E-08	7.12E-06	7.12E-06	2.23E-08	7.13E-06	7.13E-06
36.25	1.46E-08	6.34E-06	6.34E-06	1.96E-08	6.34E-06	6.34E-06
38.75	1.33E-08	5.63E-06	5.63E-06	1.78E-08	5.64E-06	5.64E-06

Table 3-14: 10 days Effective Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.55E-06	3.51E-04	1.90E-07
1.65	7.40E-07	5.31E-05	3.00E-08
3.75	2.84E-07	1.47E-05	8.48E-09
6.25	1.46E-07	6.36E-06	3.71E-09
8.75	1.06E-07	4.47E-06	2.61E-09
11.25	8.39E-08	3.44E-06	2.02E-09
13.75	6.61E-08	2.76E-06	1.63E-09
16.25	5.31E-08	2.26E-06	1.35E-09
18.75	4.39E-08	1.90E-06	1.14E-09
21.25	4.51E-08	1.62E-06	1.00E-09
23.75	4.07E-08	1.39E-06	8.87E-10
26.25	3.25E-08	1.21E-06	7.77E-10
28.75	2.80E-08	1.05E-06	6.94E-10
31.25	2.61E-08	9.27E-07	6.31E-10
33.75	2.12E-08	8.18E-07	5.69E-10
36.25	1.88E-08	7.28E-07	5.21E-10
38.75	1.77E-08	6.48E-07	4.80E-10

Table 3-15: Doses per Release Categories (Sv) – Effective (F10)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF -1	RCPF -2
	Circulation	Total	Total	Total	Total	Total
0.4	2.55E-06	3.54E-04	3.54E-04	2.74E-06	3.54E-04	3.54E-04
1.65	7.40E-07	5.39E-05	5.39E-05	7.70E-07	5.39E-05	5.39E-05
3.75	2.84E-07	1.50E-05	1.50E-05	2.92E-07	1.50E-05	1.50E-05
6.25	1.46E-07	6.50E-06	6.50E-06	1.50E-07	6.51E-06	6.51E-06
8.75	1.06E-07	4.58E-06	4.58E-06	1.09E-07	4.58E-06	4.58E-06
11.25	8.39E-08	3.52E-06	3.52E-06	8.59E-08	3.53E-06	3.53E-06
13.75	6.61E-08	2.83E-06	2.83E-06	6.77E-08	2.83E-06	2.83E-06
16.25	5.31E-08	2.32E-06	2.32E-06	5.45E-08	2.32E-06	2.32E-06
18.75	4.39E-08	1.94E-06	1.94E-06	4.50E-08	1.94E-06	1.94E-06
21.25	4.51E-08	1.66E-06	1.66E-06	4.61E-08	1.66E-06	1.66E-06
23.75	4.07E-08	1.43E-06	1.43E-06	4.16E-08	1.43E-06	1.43E-06
26.25	3.25E-08	1.24E-06	1.24E-06	3.32E-08	1.24E-06	1.24E-06
28.75	2.80E-08	1.08E-06	1.08E-06	2.86E-08	1.08E-06	1.08E-06
31.25	2.61E-08	9.53E-07	9.53E-07	2.67E-08	9.54E-07	9.54E-07
33.75	2.12E-08	8.40E-07	8.40E-07	2.18E-08	8.40E-07	8.40E-07
36.25	1.88E-08	7.47E-07	7.47E-07	1.93E-08	7.48E-07	7.48E-07
38.75	1.77E-08	6.65E-07	6.65E-07	1.82E-08	6.66E-07	6.66E-07

Table 3-16: 10 days Lung Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.80E-06	2.21E-04	1.59E-07
1.65	7.89E-07	3.34E-05	2.54E-08
3.75	3.00E-07	9.24E-06	7.25E-09
6.25	1.54E-07	4.01E-06	3.19E-09
8.75	1.12E-07	2.82E-06	2.25E-09
11.25	8.79E-08	2.17E-06	1.75E-09
13.75	6.92E-08	1.75E-06	1.42E-09
16.25	5.56E-08	1.43E-06	1.18E-09
18.75	4.59E-08	1.20E-06	1.00E-09
21.25	4.69E-08	1.02E-06	8.84E-10
23.75	4.24E-08	8.82E-07	7.87E-10
26.25	3.38E-08	7.63E-07	6.93E-10
28.75	2.91E-08	6.66E-07	6.22E-10
31.25	2.71E-08	5.87E-07	5.69E-10
33.75	2.20E-08	5.18E-07	5.16E-10
36.25	1.95E-08	4.61E-07	4.75E-10
38.75	1.84E-08	4.10E-07	4.40E-10

Table 3-17: Doses per Release Categories (Sv) – Lung (F10)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.80E-06	2.23E-04	2.23E-04	2.96E-06	2.23E-04	2.23E-04
1.65	7.89E-07	3.42E-05	3.42E-05	8.15E-07	3.42E-05	3.42E-05
3.75	3.00E-07	9.54E-06	9.54E-06	3.07E-07	9.54E-06	9.54E-06
6.25	1.54E-07	4.16E-06	4.16E-06	1.57E-07	4.17E-06	4.17E-06
8.75	1.12E-07	2.93E-06	2.93E-06	1.14E-07	2.94E-06	2.94E-06
11.25	8.79E-08	2.26E-06	2.26E-06	8.97E-08	2.26E-06	2.26E-06
13.75	6.92E-08	1.81E-06	1.81E-06	7.06E-08	1.82E-06	1.82E-06
16.25	5.56E-08	1.48E-06	1.48E-06	5.68E-08	1.48E-06	1.48E-06
18.75	4.59E-08	1.24E-06	1.24E-06	4.69E-08	1.24E-06	1.24E-06
21.25	4.69E-08	1.07E-06	1.07E-06	4.78E-08	1.07E-06	1.07E-06
23.75	4.24E-08	9.24E-07	9.24E-07	4.31E-08	9.25E-07	9.25E-07
26.25	3.38E-08	7.97E-07	7.97E-07	3.45E-08	7.97E-07	7.97E-07
28.75	2.91E-08	6.95E-07	6.95E-07	2.97E-08	6.95E-07	6.95E-07
31.25	2.71E-08	6.14E-07	6.14E-07	2.77E-08	6.15E-07	6.15E-07
33.75	2.20E-08	5.40E-07	5.40E-07	2.25E-08	5.41E-07	5.41E-07
36.25	1.95E-08	4.81E-07	4.81E-07	2.00E-08	4.81E-07	4.81E-07
38.75	1.84E-08	4.29E-07	4.29E-07	1.89E-08	4.29E-07	4.29E-07

Table 3-18: 10 days Red Bone Marrow Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.01E-06	2.08E-04	1.44E-07
1.65	6.33E-07	3.14E-05	2.31E-08
3.75	2.49E-07	8.69E-06	6.58E-09
6.25	1.30E-07	3.77E-06	2.90E-09
8.75	9.44E-08	2.65E-06	2.05E-09
11.25	7.47E-08	2.04E-06	1.58E-09
13.75	5.88E-08	1.64E-06	1.28E-09
16.25	4.72E-08	1.34E-06	1.06E-09
18.75	3.89E-08	1.13E-06	9.07E-10
21.25	4.03E-08	9.60E-07	8.00E-10
23.75	3.64E-08	8.28E-07	7.12E-10
26.25	2.90E-08	7.17E-07	6.26E-10
28.75	2.49E-08	6.25E-07	5.62E-10
31.25	2.32E-08	5.51E-07	5.14E-10
33.75	1.88E-08	4.87E-07	4.65E-10
36.25	1.66E-08	4.33E-07	4.28E-10
38.75	1.57E-08	3.85E-07	3.96E-10

Table 3-19: Doses per Release Categories (Sv) – Red Bone Marrow (F10)

Distance (km)	RC - 1	RCF - 1	RCF 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.01E-06	2.10E-04	2.10E-04	2.15E-06	2.10E-04	2.10E-04
1.65	6.33E-07	3.21E-05	3.21E-05	6.56E-07	3.21E-05	3.21E-05
3.75	2.49E-07	8.94E-06	8.94E-06	2.55E-07	8.94E-06	8.94E-06
6.25	1.30E-07	3.90E-06	3.90E-06	1.32E-07	3.90E-06	3.90E-06
8.75	9.44E-08	2.75E-06	2.75E-06	9.64E-08	2.75E-06	2.75E-06
11.25	7.47E-08	2.12E-06	2.12E-06	7.62E-08	2.12E-06	2.12E-06
13.75	5.88E-08	1.70E-06	1.70E-06	6.00E-08	1.70E-06	1.70E-06
16.25	4.72E-08	1.39E-06	1.39E-06	4.82E-08	1.39E-06	1.39E-06
18.75	3.89E-08	1.16E-06	1.16E-06	3.98E-08	1.16E-06	1.16E-06
21.25	4.03E-08	1.00E-06	1.00E-06	4.11E-08	1.00E-06	1.00E-06
23.75	3.64E-08	8.64E-07	8.64E-07	3.71E-08	8.65E-07	8.65E-07
26.25	2.90E-08	7.46E-07	7.46E-07	2.96E-08	7.46E-07	7.46E-07
28.75	2.49E-08	6.50E-07	6.50E-07	2.54E-08	6.51E-07	6.51E-07
31.25	2.32E-08	5.74E-07	5.74E-07	2.37E-08	5.75E-07	5.75E-07
33.75	1.88E-08	5.05E-07	5.05E-07	1.93E-08	5.06E-07	5.06E-07
36.25	1.66E-08	4.50E-07	4.50E-07	1.71E-08	4.50E-07	4.50E-07
38.75	1.57E-08	4.01E-07	4.01E-07	1.61E-08	4.01E-07	4.01E-07

Table 3-20: 10 days Skin Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate -out
	Sector 9	Sector 9	Sector 9
0.4	1.68E-05	2.17E-02	8.16E-06
1.65	2.50E-06	3.27E-03	1.27E-06
3.75	6.64E-07	9.00E-04	3.56E-07
6.25	2.74E-07	3.89E-04	1.57E-07
8.75	1.84E-07	2.74E-04	1.12E-07
11.25	1.36E-07	2.10E-04	8.73E-08
13.75	1.05E-07	1.69E-04	7.15E-08
16.25	8.33E-08	1.38E-04	5.99E-08
18.75	6.78E-08	1.16E-04	5.13E-08
21.25	5.60E-08	9.84E-05	4.47E-08
23.75	4.87E-08	8.48E-05	3.97E-08
26.25	3.98E-08	7.35E-05	3.53E-08
28.75	3.40E-08	6.41E-05	3.17E-08
31.25	3.04E-08	5.65E-05	2.89E-08
33.75	2.54E-08	4.99E-05	2.63E-08
36.25	2.22E-08	4.44E-05	2.41E-08
38.75	2.01E-08	3.95E-05	2.23E-08

Table 3-21: Doses per Release Categories (Sv) – Skin (F10)

Distance (km)	RC - 1	RCF -1	RCF - 2	RCP - 1	RCPF - 1	RCPF -2
	Circulation	Total	Total	Total	Total	Total
0.4	1.68E-05	2.17E-02	2.17E-02	2.49E-05	2.17E-02	2.17E-02
1.65	2.50E-06	3.27E-03	3.27E-03	3.76E-06	3.27E-03	3.27E-03
3.75	6.64E-07	9.00E-04	9.00E-04	1.02E-06	9.01E-04	9.01E-04
6.25	2.74E-07	3.89E-04	3.89E-04	4.30E-07	3.90E-04	3.90E-04
8.75	1.84E-07	2.74E-04	2.74E-04	2.95E-07	2.74E-04	2.74E-04
11.25	1.36E-07	2.10E-04	2.10E-04	2.23E-07	2.11E-04	2.11E-04
13.75	1.05E-07	1.69E-04	1.69E-04	1.77E-07	1.69E-04	1.69E-04
16.25	8.33E-08	1.38E-04	1.38E-04	1.43E-07	1.39E-04	1.39E-04
18.75	6.78E-08	1.16E-04	1.16E-04	1.19E-07	1.16E-04	1.16E-04
21.25	5.60E-08	9.84E-05	9.84E-05	1.01E-07	9.85E-05	9.85E-05
23.75	4.87E-08	8.49E-05	8.49E-05	8.84E-08	8.49E-05	8.49E-05
26.25	3.98E-08	7.35E-05	7.35E-05	7.51E-08	7.35E-05	7.35E-05
28.75	3.40E-08	6.41E-05	6.41E-05	6.57E-08	6.42E-05	6.42E-05
31.25	3.04E-08	5.65E-05	5.65E-05	5.92E-08	5.65E-05	5.65E-05
33.75	2.54E-08	4.99E-05	4.99E-05	5.17E-08	4.99E-05	4.99E-05
36.25	2.22E-08	4.44E-05	4.44E-05	4.64E-08	4.44E-05	4.44E-05
38.75	2.01E-08	3.95E-05	3.95E-05	4.23E-08	3.95E-05	3.95E-05

Table 3-22: 30 days Lung Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate - out
	Sector 9	Sector 9	Sector 9
0.4	2.82E-06	3.03E-04	2.92E-07
1.65	7.92E-07	4.58E-05	4.73E-08
3.75	3.00E-07	1.26E-05	1.38E-08
6.25	1.54E-07	5.47E-06	6.21E-09
8.75	1.12E-07	3.85E-06	4.49E-09
11.25	8.81E-08	2.96E-06	3.56E-09
13.75	6.94E-08	2.38E-06	2.95E-09
16.25	5.57E-08	1.95E-06	2.50E-09
18.75	4.60E-08	1.63E-06	2.17E-09
21.25	4.70E-08	1.39E-06	1.93E-09
23.75	4.24E-08	1.20E-06	1.74E-09
26.25	3.38E-08	1.04E-06	1.56E-09
28.75	2.91E-08	9.05E-07	1.42E-09
31.25	2.72E-08	7.97E-07	1.31E-09
33.75	2.21E-08	7.04E-07	1.21E-09
36.25	1.95E-08	6.27E-07	1.12E-09
38.75	1.84E-08	5.57E-07	1.05E-09

Table 3-23: Doses per Release Categories (Sv) – Lung (F30)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.82E-06	3.06E-04	3.06E-04	3.11E-06	3.06E-04	3.06E-04
1.65	7.92E-07	4.66E-05	4.66E-05	8.39E-07	4.66E-05	4.66E-05
3.75	3.00E-07	1.29E-05	1.29E-05	3.14E-07	1.29E-05	1.29E-05
6.25	1.54E-07	5.62E-06	5.62E-06	1.60E-07	5.63E-06	5.63E-06
8.75	1.12E-07	3.96E-06	3.96E-06	1.16E-07	3.97E-06	3.97E-06
11.25	8.81E-08	3.05E-06	3.05E-06	9.16E-08	3.05E-06	3.05E-06
13.75	6.94E-08	2.45E-06	2.45E-06	7.23E-08	2.45E-06	2.45E-06
16.25	5.57E-08	2.00E-06	2.00E-06	5.82E-08	2.01E-06	2.01E-06
18.75	4.60E-08	1.68E-06	1.68E-06	4.82E-08	1.68E-06	1.68E-06
21.25	4.70E-08	1.44E-06	1.44E-06	4.89E-08	1.44E-06	1.44E-06
23.75	4.24E-08	1.24E-06	1.24E-06	4.42E-08	1.24E-06	1.24E-06
26.25	3.38E-08	1.07E-06	1.07E-06	3.54E-08	1.07E-06	1.07E-06
28.75	2.91E-08	9.34E-07	9.34E-07	3.05E-08	9.36E-07	9.36E-07
31.25	2.72E-08	8.24E-07	8.24E-07	2.85E-08	8.26E-07	8.26E-07
33.75	2.21E-08	7.26E-07	7.26E-07	2.33E-08	7.28E-07	7.28E-07
36.25	1.95E-08	6.46E-07	6.46E-07	2.06E-08	6.47E-07	6.47E-07
38.75	1.84E-08	5.75E-07	5.75E-07	1.95E-08	5.76E-07	5.76E-07

Table 3-24: 30 days Red Bone Marrow Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.03E-06	2.86E-04	2.65E-07
1.65	6.36E-07	4.32E-05	4.30E-08
3.75	2.49E-07	1.19E-05	1.25E-08
6.25	1.30E-07	5.16E-06	5.65E-09
8.75	9.46E-08	3.63E-06	4.08E-09
11.25	7.48E-08	2.79E-06	3.24E-09
13.75	5.89E-08	2.24E-06	2.68E-09
16.25	4.73E-08	1.84E-06	2.27E-09
18.75	3.90E-08	1.54E-06	1.97E-09
21.25	4.03E-08	1.31E-06	1.75E-09
23.75	3.64E-08	1.13E-06	1.58E-09
26.25	2.90E-08	9.78E-07	1.42E-09
28.75	2.49E-08	8.53E-07	1.29E-09
31.25	2.33E-08	7.51E-07	1.19E-09
33.75	1.89E-08	6.64E-07	1.10E-09
36.25	1.67E-08	5.90E-07	1.02E-09
38.75	1.58E-08	5.24E-07	9.50E-10

Table 3-25: Doses per Release Categories (Sv) – Red Bone Marrow (F30)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.03E-06	2.88E-04	2.88E-04	2.29E-06	2.88E-04	2.88E-04
1.65	6.36E-07	4.38E-05	4.38E-05	6.79E-07	4.39E-05	4.39E-05
3.75	2.49E-07	1.22E-05	1.22E-05	2.62E-07	1.22E-05	1.22E-05
6.25	1.30E-07	5.29E-06	5.29E-06	1.35E-07	5.29E-06	5.29E-06
8.75	9.46E-08	3.73E-06	3.73E-06	9.87E-08	3.73E-06	3.73E-06
11.25	7.48E-08	2.87E-06	2.87E-06	7.80E-08	2.87E-06	2.87E-06
13.75	5.89E-08	2.30E-06	2.30E-06	6.16E-08	2.30E-06	2.30E-06
16.25	4.73E-08	1.88E-06	1.88E-06	4.95E-08	1.89E-06	1.89E-06
18.75	3.90E-08	1.58E-06	1.58E-06	4.10E-08	1.58E-06	1.58E-06
21.25	4.03E-08	1.35E-06	1.35E-06	4.21E-08	1.35E-06	1.35E-06
23.75	3.64E-08	1.17E-06	1.17E-06	3.80E-08	1.17E-06	1.17E-06
26.25	2.90E-08	1.01E-06	1.01E-06	3.04E-08	1.01E-06	1.01E-06
28.75	2.49E-08	8.78E-07	8.78E-07	2.62E-08	8.79E-07	8.79E-07
31.25	2.33E-08	7.74E-07	7.74E-07	2.44E-08	7.76E-07	7.76E-07
33.75	1.89E-08	6.82E-07	6.82E-07	2.00E-08	6.83E-07	6.83E-07
36.25	1.67E-08	6.07E-07	6.07E-07	1.77E-08	6.08E-07	6.08E-07
38.75	1.58E-08	5.40E-07	5.40E-07	1.67E-08	5.41E-07	5.41E-07

Table 3-26: 30 days Skin Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	1.77E-05	2.68E-02	1.35E-05
1.65	2.64E-06	4.04E-03	2.13E-06
3.75	7.03E-07	1.11E-03	6.14E-07
6.25	2.91E-07	4.81E-04	2.75E-07
8.75	1.96E-07	3.39E-04	1.99E-07
11.25	1.45E-07	2.60E-04	1.58E-07
13.75	1.13E-07	2.09E-04	1.31E-07
16.25	8.94E-08	1.72E-04	1.11E-07
18.75	7.29E-08	1.44E-04	9.64E-08
21.25	6.04E-08	1.22E-04	8.50E-08
23.75	5.24E-08	1.05E-04	7.61E-08
26.25	4.31E-08	9.12E-05	6.85E-08
28.75	3.69E-08	7.96E-05	6.22E-08
31.25	3.29E-08	7.02E-05	5.71E-08
33.75	2.76E-08	6.20E-05	5.26E-08
36.25	2.42E-08	5.52E-05	4.87E-08
38.75	2.18E-08	4.91E-05	4.53E-08

Table 3-27: Doses per Release Categories (Sv) – Skin (F30)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	1.77E-05	2.68E-02	2.68E-02	3.12E-05	2.68E-02	2.68E-02
1.65	2.64E-06	4.04E-03	4.04E-03	4.78E-06	4.04E-03	4.04E-03
3.75	7.03E-07	1.11E-03	1.11E-03	1.32E-06	1.11E-03	1.11E-03
6.25	2.91E-07	4.81E-04	4.81E-04	5.66E-07	4.82E-04	4.82E-04
8.75	1.96E-07	3.39E-04	3.39E-04	3.95E-07	3.39E-04	3.39E-04
11.25	1.45E-07	2.61E-04	2.61E-04	3.03E-07	2.61E-04	2.61E-04
13.75	1.13E-07	2.09E-04	2.09E-04	2.44E-07	2.10E-04	2.10E-04
16.25	8.94E-08	1.72E-04	1.72E-04	2.01E-07	1.72E-04	1.72E-04
18.75	7.29E-08	1.44E-04	1.44E-04	1.69E-07	1.44E-04	1.44E-04
21.25	6.04E-08	1.22E-04	1.22E-04	1.45E-07	1.22E-04	1.22E-04
23.75	5.24E-08	1.05E-04	1.05E-04	1.29E-07	1.05E-04	1.05E-04
26.25	4.31E-08	9.12E-05	9.12E-05	1.12E-07	9.13E-05	9.13E-05
28.75	3.69E-08	7.96E-05	7.96E-05	9.91E-08	7.97E-05	7.97E-05
31.25	3.29E-08	7.02E-05	7.02E-05	9.00E-08	7.02E-05	7.02E-05
33.75	2.76E-08	6.20E-05	6.20E-05	8.02E-08	6.21E-05	6.21E-05
36.25	2.42E-08	5.52E-05	5.52E-05	7.30E-08	5.53E-05	5.53E-05
38.75	2.18E-08	4.91E-05	4.91E-05	6.71E-08	4.91E-05	4.91E-05

Table 3-28: 70 days Effective Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-out
	Sector 9	Sector 9	Sector 9
0.4	2.58E-06	5.11E-04	5.08E-07
1.65	7.44E-07	7.72E-05	8.25E-08
3.75	2.85E-07	2.13E-05	2.42E-08
6.25	1.47E-07	9.22E-06	1.10E-08
8.75	1.07E-07	6.49E-06	8.01E-09
11.25	8.42E-08	4.99E-06	6.39E-09
13.75	6.63E-08	4.01E-06	5.34E-09
16.25	5.33E-08	3.28E-06	4.55E-09
18.75	4.40E-08	2.75E-06	3.98E-09
21.25	4.52E-08	2.34E-06	3.54E-09
23.75	4.08E-08	2.02E-06	3.19E-09
26.25	3.26E-08	1.75E-06	2.89E-09
28.75	2.80E-08	1.52E-06	2.64E-09
31.25	2.62E-08	1.34E-06	2.44E-09
33.75	2.13E-08	1.19E-06	2.26E-09
36.25	1.88E-08	1.06E-06	2.10E-09
38.75	1.78E-08	9.38E-07	1.96E-09

Table 3-29: Doses per Release Categories (Sv) – Effective (F70)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.58E-06	5.14E-04	5.14E-04	3.08E-06	5.14E-04	5.14E-04
1.65	7.44E-07	7.79E-05	7.79E-05	8.27E-07	7.80E-05	7.80E-05
3.75	2.85E-07	2.16E-05	2.16E-05	3.09E-07	2.16E-05	2.16E-05
6.25	1.47E-07	9.36E-06	9.36E-06	1.58E-07	9.37E-06	9.37E-06
8.75	1.07E-07	6.59E-06	6.59E-06	1.15E-07	6.60E-06	6.60E-06
11.25	8.42E-08	5.07E-06	5.07E-06	9.06E-08	5.08E-06	5.08E-06
13.75	6.63E-08	4.07E-06	4.07E-06	7.17E-08	4.08E-06	4.08E-06
16.25	5.33E-08	3.34E-06	3.34E-06	5.79E-08	3.34E-06	3.34E-06
18.75	4.40E-08	2.80E-06	2.80E-06	4.80E-08	2.80E-06	2.80E-06
21.25	4.52E-08	2.38E-06	2.38E-06	4.87E-08	2.39E-06	2.39E-06
23.75	4.08E-08	2.06E-06	2.06E-06	4.40E-08	2.06E-06	2.06E-06
26.25	3.26E-08	1.78E-06	1.78E-06	3.55E-08	1.78E-06	1.78E-06
28.75	2.80E-08	1.55E-06	1.55E-06	3.07E-08	1.55E-06	1.55E-06
31.25	2.62E-08	1.37E-06	1.37E-06	2.86E-08	1.37E-06	1.37E-06
33.75	2.13E-08	1.21E-06	1.21E-06	2.35E-08	1.21E-06	1.21E-06
36.25	1.88E-08	1.07E-06	1.07E-06	2.09E-08	1.08E-06	1.08E-06
38.75	1.78E-08	9.56E-07	9.56E-07	1.98E-08	9.58E-07	9.58E-07

Table 3-30: 70 days Lung Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.82E-06	3.18E-04	4.85E-07
1.65	7.92E-07	4.80E-05	7.94E-08
3.75	3.00E-07	1.33E-05	2.35E-08
6.25	1.54E-07	5.74E-06	1.07E-08
8.75	1.12E-07	4.04E-06	7.83E-09
11.25	8.81E-08	3.11E-06	6.28E-09
13.75	6.94E-08	2.50E-06	5.26E-09
16.25	5.57E-08	2.04E-06	4.50E-09
18.75	4.60E-08	1.71E-06	3.95E-09
21.25	4.70E-08	1.46E-06	3.53E-09
23.75	4.25E-08	1.26E-06	3.19E-09
26.25	3.39E-08	1.09E-06	2.89E-09
28.75	2.91E-08	9.49E-07	2.65E-09
31.25	2.72E-08	8.36E-07	2.46E-09
33.75	2.21E-08	7.39E-07	2.28E-09
36.25	1.95E-08	6.57E-07	2.13E-09
38.75	1.85E-08	5.84E-07	1.99E-09

Table 3-31: Doses per Release Categories (Sv) – Lung (F70)

Distance (km)	RC - 1	RCF - 1	RCF- 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.82E-06	3.21E-04	3.21E-04	3.30E-06	3.21E-04	3.21E-04
1.65	7.92E-07	4.88E-05	4.88E-05	8.72E-07	4.89E-05	4.89E-05
3.75	3.00E-07	1.36E-05	1.36E-05	3.24E-07	1.36E-05	1.36E-05
6.25	1.54E-07	5.89E-06	5.89E-06	1.65E-07	5.90E-06	5.90E-06
8.75	1.12E-07	4.15E-06	4.15E-06	1.20E-07	4.16E-06	4.16E-06
11.25	8.81E-08	3.20E-06	3.20E-06	9.44E-08	3.20E-06	3.20E-06
13.75	6.94E-08	2.57E-06	2.57E-06	7.47E-08	2.57E-06	2.57E-06
16.25	5.57E-08	2.10E-06	2.10E-06	6.02E-08	2.10E-06	2.10E-06
18.75	4.60E-08	1.76E-06	1.76E-06	5.00E-08	1.76E-06	1.76E-06
21.25	4.70E-08	1.50E-06	1.50E-06	5.05E-08	1.51E-06	1.51E-06
23.75	4.25E-08	1.30E-06	1.30E-06	4.56E-08	1.30E-06	1.30E-06
26.25	3.39E-08	1.12E-06	1.12E-06	3.67E-08	1.12E-06	1.12E-06
28.75	2.91E-08	9.78E-07	9.78E-07	3.18E-08	9.81E-07	9.81E-07
31.25	2.72E-08	8.63E-07	8.63E-07	2.96E-08	8.66E-07	8.66E-07
33.75	2.21E-08	7.61E-07	7.61E-07	2.44E-08	7.63E-07	7.63E-07
36.25	1.95E-08	6.77E-07	6.77E-07	2.16E-08	6.79E-07	6.79E-07
38.75	1.85E-08	6.02E-07	6.02E-07	2.04E-08	6.04E-07	6.04E-07

Table 3-32: 70 days Red Bone Marrow Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-out
	Sector 9	Sector 9	Sector 9
0.4	2.03E-06	3.00E-04	4.46E-07
1.65	6.36E-07	4.53E-05	7.30E-08
3.75	2.50E-07	1.25E-05	2.16E-08
6.25	1.30E-07	5.41E-06	9.85E-09
8.75	9.46E-08	3.81E-06	7.21E-09
11.25	7.48E-08	2.93E-06	5.78E-09
13.75	5.89E-08	2.35E-06	4.84E-09
16.25	4.73E-08	1.93E-06	4.14E-09
18.75	3.90E-08	1.62E-06	3.63E-09
21.25	4.04E-08	1.37E-06	3.25E-09
23.75	3.64E-08	1.18E-06	2.93E-09
26.25	2.90E-08	1.03E-06	2.66E-09
28.75	2.49E-08	8.95E-07	2.44E-09
31.25	2.33E-08	7.88E-07	2.26E-09
33.75	1.89E-08	6.96E-07	2.10E-09
36.25	1.67E-08	6.19E-07	1.96E-09
38.75	1.58E-08	5.50E-07	1.83E-09

Table 3-33: Doses per Release Categories (Sv) – Red Bone Marrow (F70)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.03E-06	3.02E-04	3.02E-04	2.47E-06	3.03E-04	3.03E-04
1.65	6.36E-07	4.60E-05	4.60E-05	7.09E-07	4.60E-05	4.60E-05
3.75	2.50E-07	1.27E-05	1.27E-05	2.71E-07	1.28E-05	1.28E-05
6.25	1.30E-07	5.54E-06	5.54E-06	1.40E-07	5.55E-06	5.55E-06
8.75	9.46E-08	3.90E-06	3.90E-06	1.02E-07	3.91E-06	3.91E-06
11.25	7.48E-08	3.00E-06	3.00E-06	8.06E-08	3.01E-06	3.01E-06
13.75	5.89E-08	2.41E-06	2.41E-06	6.37E-08	2.42E-06	2.42E-06
16.25	4.73E-08	1.97E-06	1.97E-06	5.14E-08	1.98E-06	1.98E-06
18.75	3.90E-08	1.65E-06	1.65E-06	4.27E-08	1.66E-06	1.66E-06
21.25	4.04E-08	1.41E-06	1.41E-06	4.36E-08	1.42E-06	1.42E-06
23.75	3.64E-08	1.22E-06	1.22E-06	3.94E-08	1.22E-06	1.22E-06
26.25	2.90E-08	1.06E-06	1.06E-06	3.17E-08	1.06E-06	1.06E-06
28.75	2.49E-08	9.20E-07	9.20E-07	2.74E-08	9.22E-07	9.22E-07
31.25	2.33E-08	8.11E-07	8.11E-07	2.55E-08	8.14E-07	8.14E-07
33.75	1.89E-08	7.15E-07	7.15E-07	2.10E-08	7.17E-07	7.17E-07
36.25	1.67E-08	6.36E-07	6.36E-07	1.86E-08	6.38E-07	6.38E-07
38.75	1.58E-08	5.66E-07	5.66E-07	1.76E-08	5.67E-07	5.67E-07

Table 3-34: 70 days skin Dose (Sv), Weather Category F

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	1.79E-05	2.78E-02	1.80E-05
1.65	2.66E-06	4.19E-03	2.88E-06
3.75	7.08E-07	1.15E-03	8.39E-07
6.25	2.93E-07	4.99E-04	3.80E-07
8.75	1.97E-07	3.51E-04	2.77E-07
11.25	1.46E-07	2.70E-04	2.21E-07
13.75	1.14E-07	2.17E-04	1.85E-07
16.25	9.02E-08	1.78E-04	1.58E-07
18.75	7.36E-08	1.49E-04	1.38E-07
21.25	6.09E-08	1.27E-04	1.22E-07
23.75	5.29E-08	1.09E-04	1.10E-07
26.25	4.35E-08	9.46E-05	9.94E-08
28.75	3.72E-08	8.26E-05	9.07E-08
31.25	3.32E-08	7.28E-05	8.36E-08
33.75	2.79E-08	6.44E-05	7.74E-08
36.25	2.45E-08	5.73E-05	7.20E-08
38.75	2.20E-08	5.09E-05	6.71E-08

Table 3-35: Doses per Release Categories (Sv) – Skin (F70)

Distance (km)	RC –1	RCF - 1	RCF - 2	RCP –1	RCPF - 1	RCPF – 2
	Circulation	Total	Total	Total	Total	Total
0.4	1.79E-05	2.78E-02	2.78E-02	3.58E-05	2.78E-02	2.78E-02
1.65	2.66E-06	4.19E-03	4.19E-03	5.54E-06	4.19E-03	4.19E-03
3.75	7.08E-07	1.15E-03	1.15E-03	1.55E-06	1.16E-03	1.16E-03
6.25	2.93E-07	5.00E-04	5.00E-04	6.73E-07	5.00E-04	5.00E-04
8.75	1.97E-07	3.52E-04	3.52E-04	4.74E-07	3.52E-04	3.52E-04
11.25	1.46E-07	2.70E-04	2.70E-04	3.67E-07	2.71E-04	2.71E-04
13.75	1.14E-07	2.17E-04	2.17E-04	2.98E-07	2.17E-04	2.17E-04
16.25	9.02E-08	1.78E-04	1.78E-04	2.48E-07	1.78E-04	1.78E-04
18.75	7.36E-08	1.49E-04	1.49E-04	2.11E-07	1.49E-04	1.49E-04
21.25	6.09E-08	1.27E-04	1.27E-04	1.83E-07	1.27E-04	1.27E-04
23.75	5.29E-08	1.09E-04	1.09E-04	1.63E-07	1.09E-04	1.09E-04
26.25	4.35E-08	9.47E-05	9.47E-05	1.43E-07	9.48E-05	9.48E-05
28.75	3.72E-08	8.26E-05	8.26E-05	1.28E-07	8.27E-05	8.27E-05
31.25	3.32E-08	7.28E-05	7.28E-05	1.17E-07	7.29E-05	7.29E-05
33.75	2.79E-08	6.44E-05	6.44E-05	1.05E-07	6.45E-05	6.45E-05
36.25	2.45E-08	5.73E-05	5.73E-05	9.65E-08	5.74E-05	5.74E-05
38.75	2.20E-08	5.10E-05	5.10E-05	8.92E-08	5.10E-05	5.10E-05

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Table 3-36: 30 days Thyroid Dose (Sv), Weather Category F, Inhalation only as a pathway

Distance (km)	Circulating	Delayed	Plate-Out
	Sector 9	Sector 9	Sector 9
0.4	2.20E-06	4.09E-03	9.97E-07
1.65	3.28E-07	6.17E-04	1.50E-07
3.75	8.87E-08	1.70E-04	4.10E-08
6.25	3.75E-08	7.36E-05	1.76E-08
8.75	2.58E-08	5.18E-05	1.23E-08
11.25	1.95E-08	3.98E-05	9.35E-09
13.75	1.53E-08	3.20E-05	7.46E-09
16.25	1.23E-08	2.62E-05	6.07E-09
18.75	1.02E-08	2.20E-05	5.06E-09
21.25	8.49E-09	1.87E-05	4.28E-09
23.75	7.31E-09	1.61E-05	3.69E-09
26.25	6.15E-09	1.39E-05	3.17E-09
28.75	5.29E-09	1.22E-05	2.75E-09
31.25	4.67E-09	1.07E-05	2.44E-09
33.75	4.01E-09	9.48E-06	2.13E-09
36.25	3.52E-09	8.43E-06	1.89E-09
38.75	3.13E-09	7.50E-06	1.69E-09

Table 3-37: Doses per Release Categories (Sv) – Thyroid (F30)

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP – 1	RCPF - 1	RCPF –2
	Circulation	Total	Total	Total	Total	Total
0.4	2.20E-06	4.10E-03	4.10E-03	3.20E-06	4.10E-03	4.10E-03
1.65	3.28E-07	6.18E-04	6.18E-04	4.78E-07	6.18E-04	6.18E-04
3.75	8.87E-08	1.70E-04	1.70E-04	1.30E-07	1.70E-04	1.70E-04
6.25	3.75E-08	7.36E-05	7.36E-05	5.51E-08	7.36E-05	7.36E-05
8.75	2.58E-08	5.18E-05	5.18E-05	3.81E-08	5.18E-05	5.18E-05
11.25	1.95E-08	3.98E-05	3.98E-05	2.88E-08	3.98E-05	3.98E-05
13.75	1.53E-08	3.20E-05	3.20E-05	2.28E-08	3.20E-05	3.20E-05
16.25	1.23E-08	2.62E-05	2.62E-05	1.84E-08	2.62E-05	2.62E-05
18.75	1.02E-08	2.20E-05	2.20E-05	1.52E-08	2.20E-05	2.20E-05
21.25	8.49E-09	1.87E-05	1.87E-05	1.28E-08	1.87E-05	1.87E-05
23.75	7.31E-09	1.61E-05	1.61E-05	1.10E-08	1.61E-05	1.61E-05
26.25	6.15E-09	1.39E-05	1.39E-05	9.32E-09	1.39E-05	1.39E-05
28.75	5.29E-09	1.22E-05	1.22E-05	8.04E-09	1.22E-05	1.22E-05
31.25	4.67E-09	1.07E-05	1.07E-05	7.10E-09	1.07E-05	1.07E-05
33.75	4.01E-09	9.48E-06	9.48E-06	6.14E-09	9.48E-06	9.48E-06
36.25	3.52E-09	8.44E-06	8.44E-06	5.42E-09	8.44E-06	8.44E-06
38.75	3.13E-09	7.50E-06	7.50E-06	4.83E-09	7.50E-06	7.50E-06

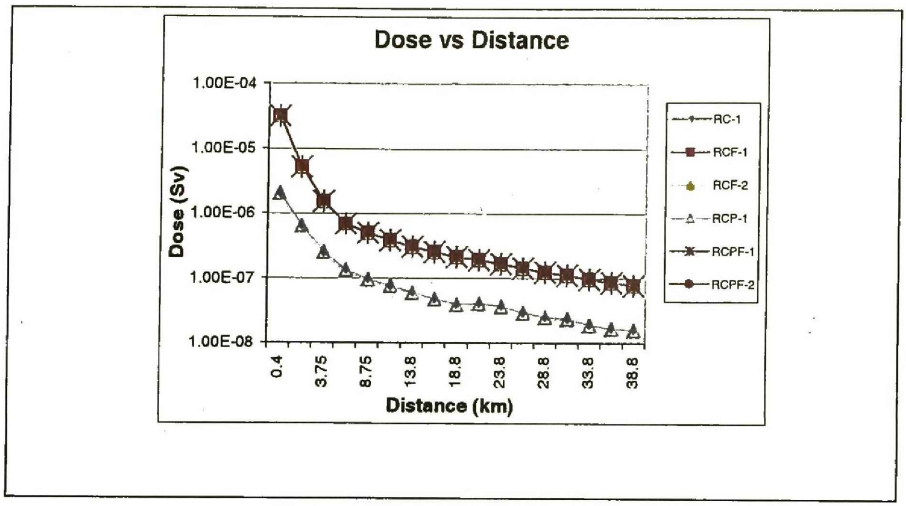


Figure 3-5: Doses per Release Categories – Red Bone Marrow (F1)

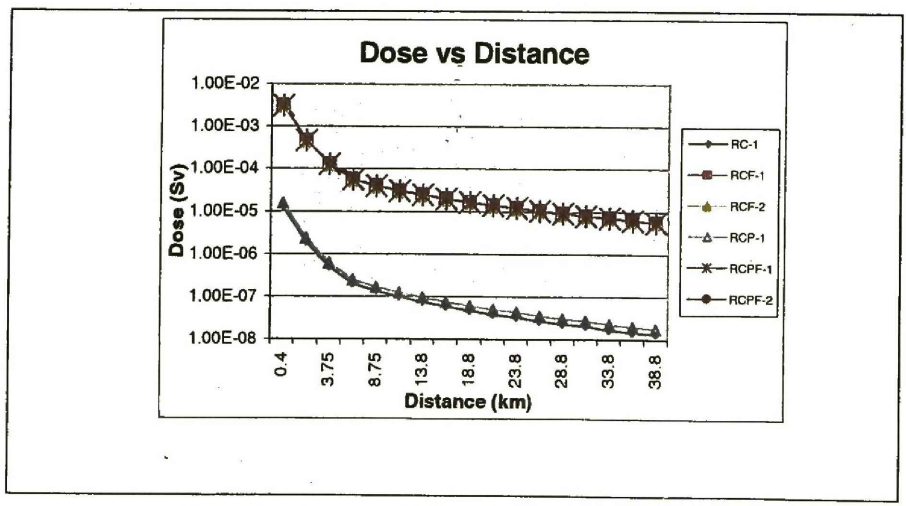


Figure 3-6: Doses per Release Categories – Skin (F1)

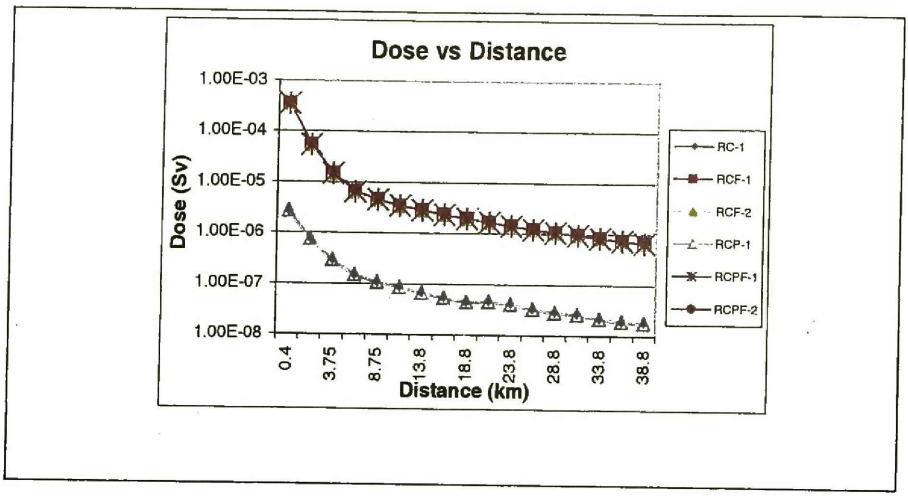


Figure 3-7: Doses per Release Categories – Effective (10)

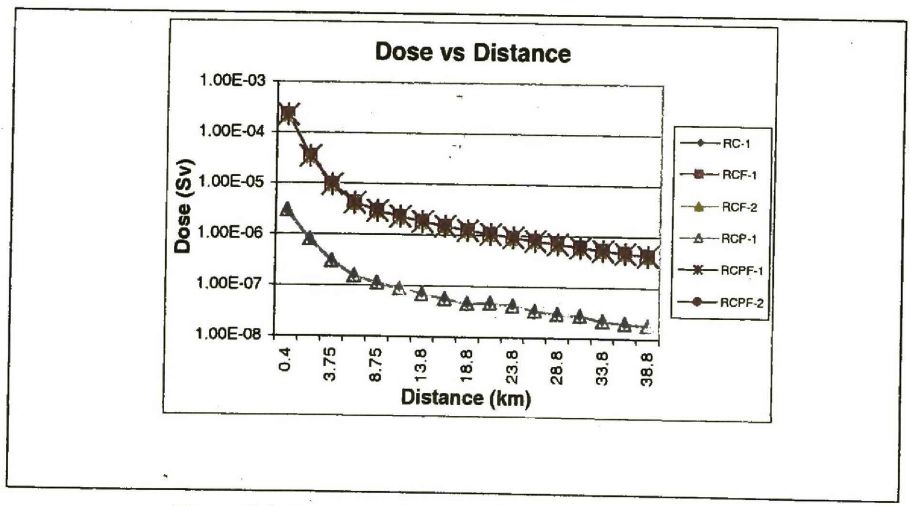


Figure 3-8: Doses per Release Categories – Lung (F10)

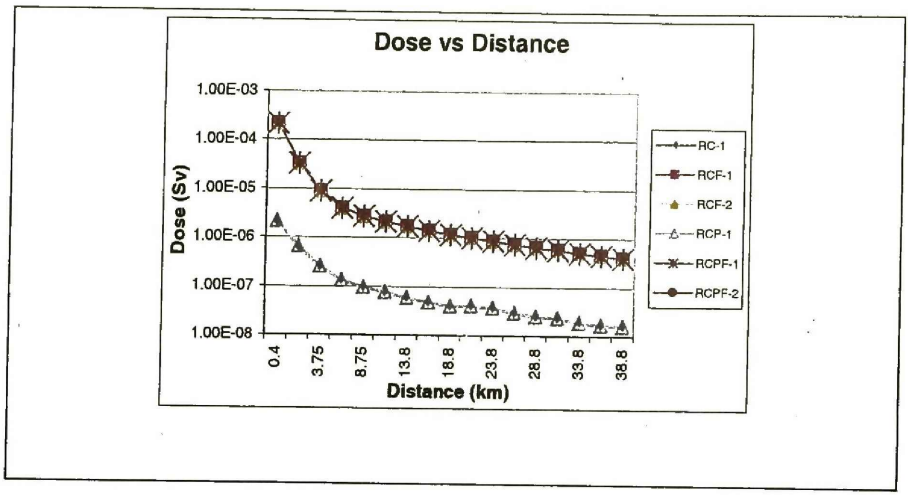


Figure 3-9: Doses per Release Categories – Red Bone Marrow (F10)

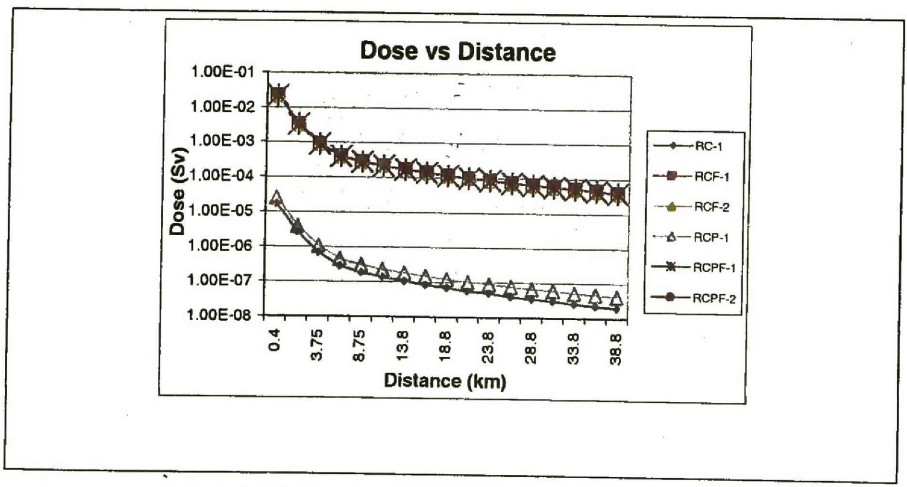


Figure 3-10: Doses per Release Categories – Skin (F10)

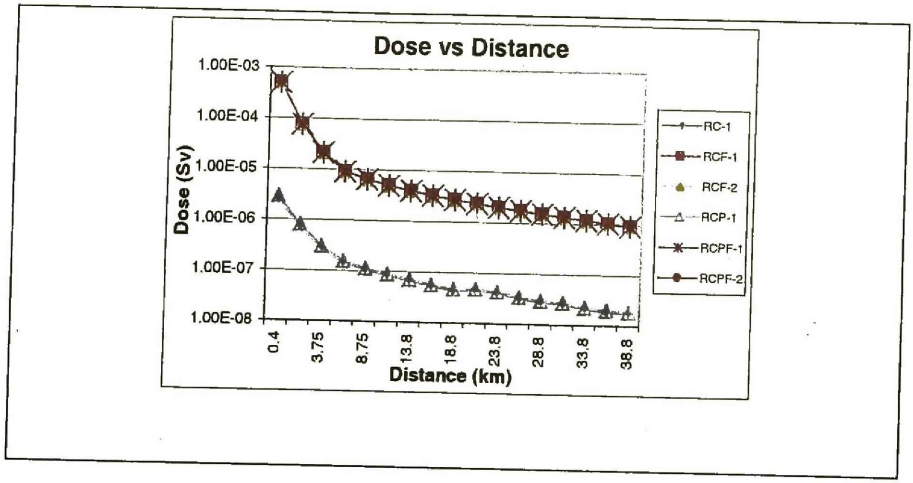


Figure 3-11: Doses per Release Categories – Effective (F30)

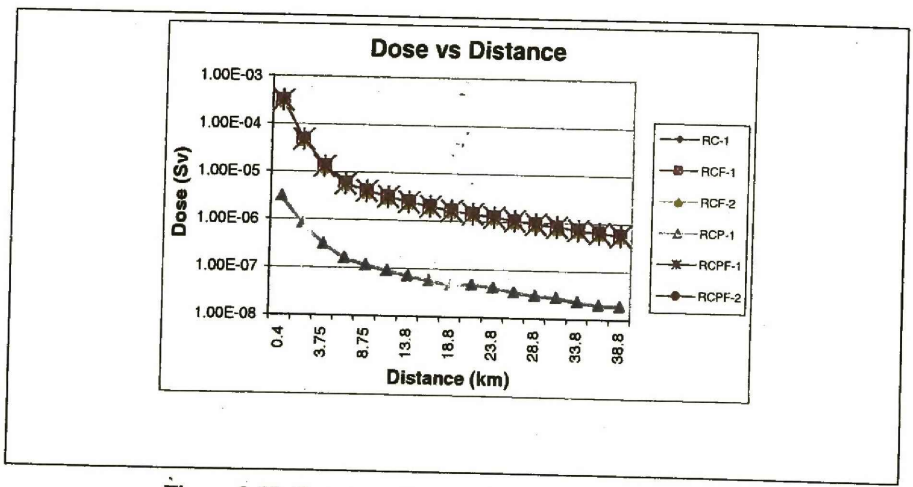


Figure 3-12: Doses per Release Categories – Lung (F30)

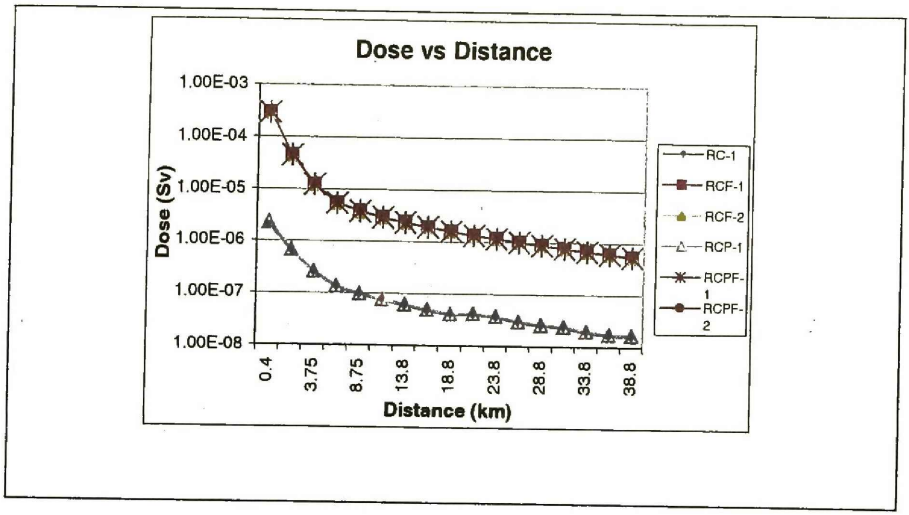


Figure 3-13: Doses per Release Categories – Red Bone Marrow (F30)

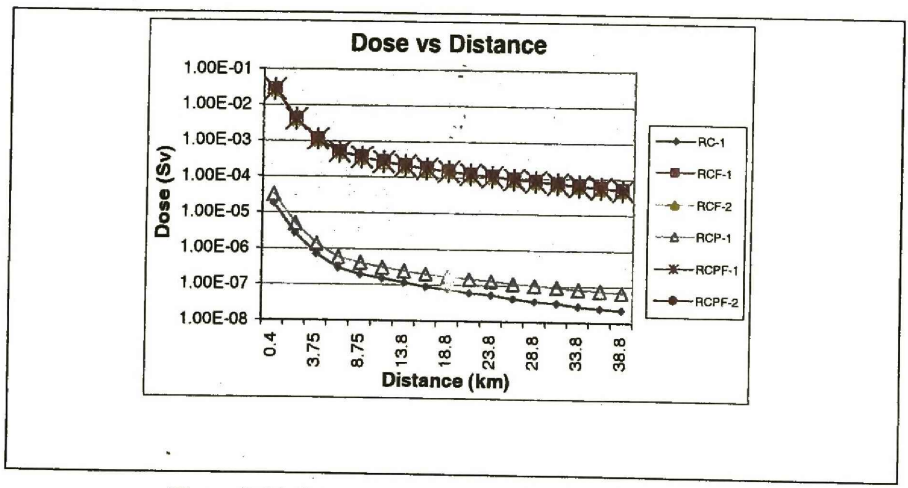


Figure 3-14: Doses per Release Categories – Skin (F30)

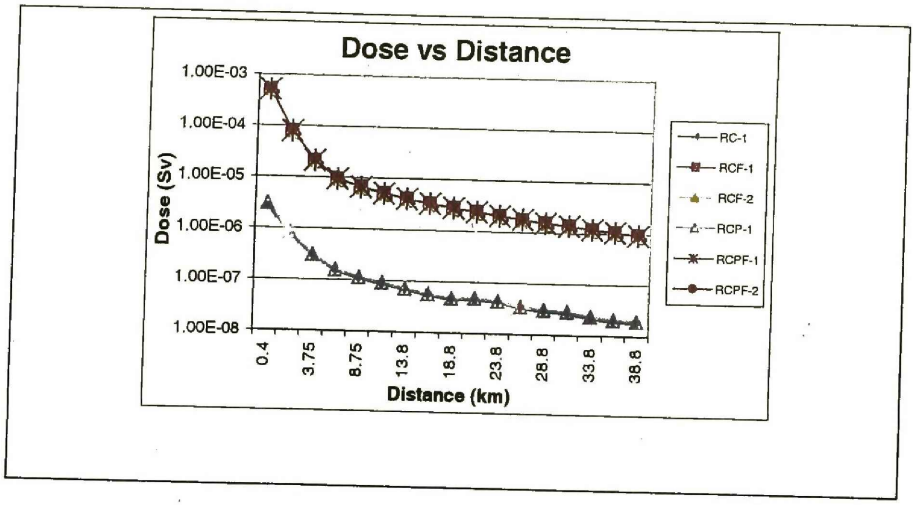


Figure 3-15: Doses per Release Categories – Effective (F70)

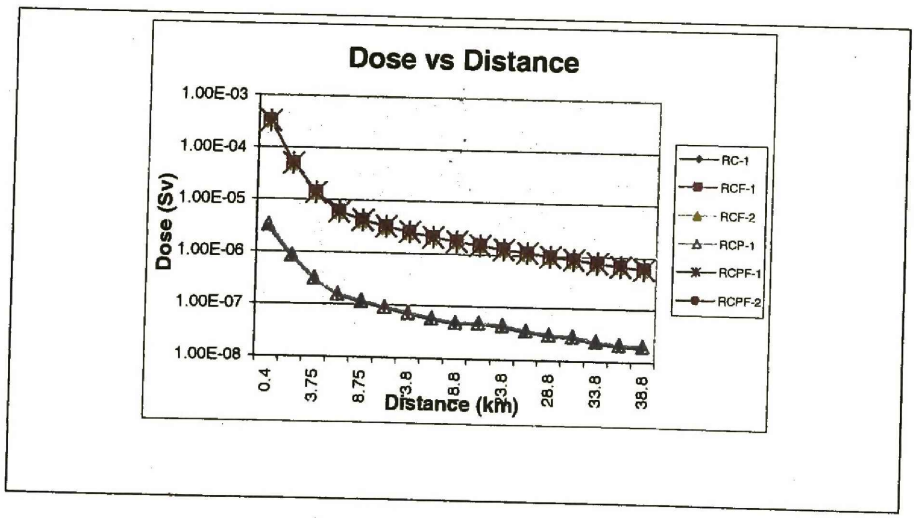


Figure 3-16: Doses per Release Categories – Lung (F70)

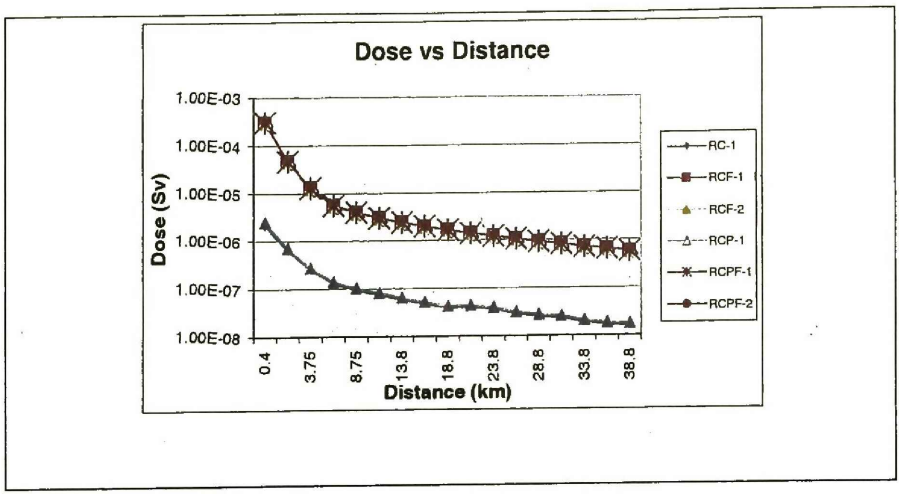


Figure 3-17: Doses per Release Categories – Red Bone Marrow (F70)

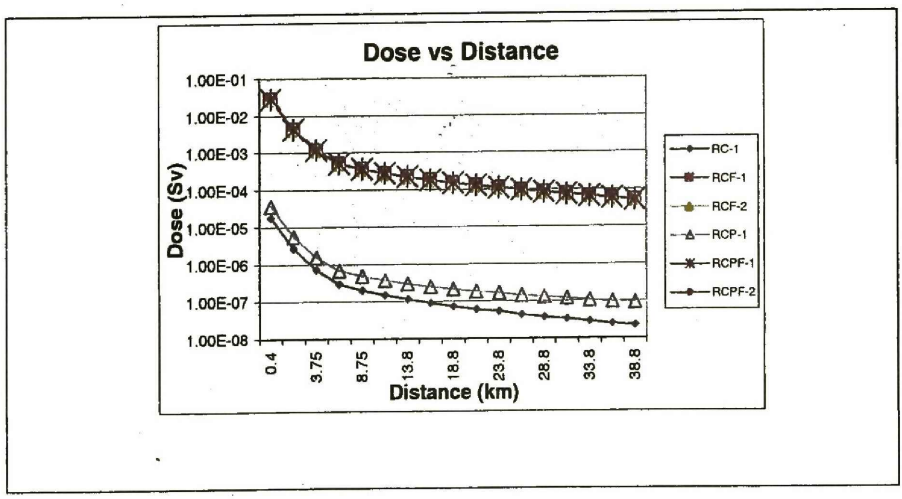


Figure 3-18: Doses per Release Categories – Skin (F70)

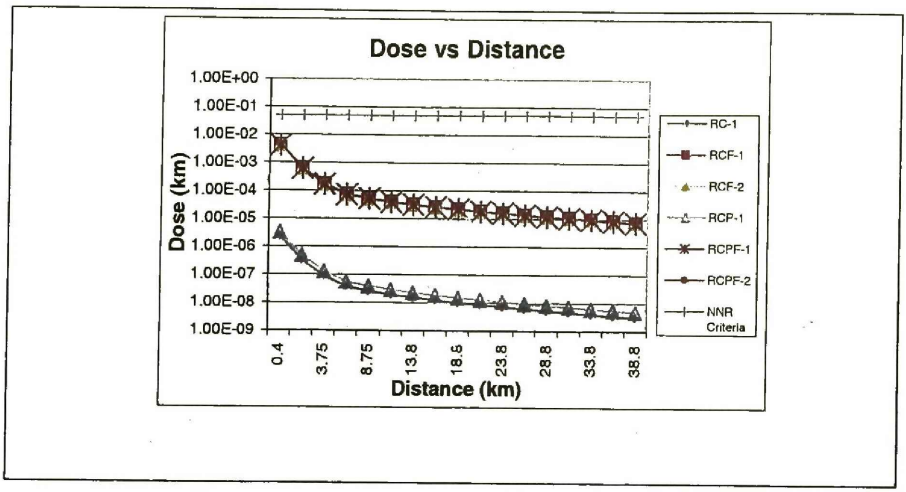


Figure 3-19: Doses per Release Categories – Thyroid including inhalation only as a pathway (F30)

For each accident run done for 1, 10, 30, and 70 days exposure periods, none of them involved exceedence of threshold for activation of countermeasures.

3.3 Countermeasures, Protective Actions

PBMR considered implementation of countermeasures and their descriptions are clearly defined in section *1.6.3*. Only PC COSYMA runs including iodine prophylaxis as a countermeasure were done to show the reduction of dose accumulation that can result from countermeasures. Below is the summary of the results and graphical representation when such a countermeasure is implemented.

Table 3-38: 30 days Thyroid Dose (Sv), Weather Category F, including iodine prophylaxis as a countermeasure and inhalation as a pathway

Distance (km)	Circulating	Delayed	Plate - Out
	Sector 9	Sector 9	Sector 9
0.4	2.44E-07	0.00E+00	1.14E-07
1.65	3.18E-08	0.00E+00	1.51E-08
3.75	6.39E-09	0.00E+00	3.17E-09
6.25	1.59E-09	0.00E+00	8.65E-10
8.75	3.39E-10	0.00E+00	2.67E-10
11.25	1.93E-10	0.00E+00	1.89E-10
13.75	1.49E-10	0.00E+00	1.61E-10
16.25	1.18E-10	0.00E+00	1.39E-10
18.75	9.59E-11	0.00E+00	1.23E-10
21.25	7.93E-11	0.00E+00	1.11E-10
23.75	7.16E-11	0.00E+00	1.01E-10
26.25	5.62E-11	0.00E+00	9.26E-11
28.75	4.79E-11	0.00E+00	8.56E-11
31.25	4.47E-11	0.00E+00	7.96E-11
33.75	3.56E-11	0.00E+00	7.45E-11
36.25	3.12E-11	0.00E+00	7.00E-11
38.75	2.95E-11	0.00E+00	6.58E-11

Table 3-39: Doses per Release Categories (Sv) – Thyroid (countermeasure) F30

Distance (km)	RC - 1	RCF - 1	RCF - 2	RCP - 1	RCPF - 1	RCPF - 2
	Circulation	Total	Total	Total	Total	Total
0.4	2.44E-07	2.44E-07	2.44E-07	3.58E-07	3.58E-07	3.58E-07
1.65	3.18E-08	3.18E-08	3.18E-08	4.68E-08	4.68E-08	4.68E-08
3.75	6.39E-09	6.39E-09	6.39E-09	9.55E-09	9.55E-09	9.55E-09
6.25	1.59E-09	1.59E-09	1.59E-09	2.45E-09	2.45E-09	2.45E-09
8.75	3.39E-10	3.39E-10	3.39E-10	6.06E-10	6.06E-10	6.06E-10
11.25	1.93E-10	1.93E-10	1.93E-10	3.82E-10	3.82E-10	3.82E-10
13.75	1.49E-10	1.49E-10	1.49E-10	3.10E-10	3.10E-10	3.10E-10
16.25	1.18E-10	1.18E-10	1.18E-10	2.57E-10	2.57E-10	2.57E-10
18.75	9.59E-11	9.59E-11	9.59E-11	2.19E-10	2.19E-10	2.19E-10
21.25	7.93E-11	7.93E-11	7.93E-11	1.90E-10	1.90E-10	1.90E-10
23.75	7.16E-11	7.16E-11	7.16E-11	1.72E-10	1.72E-10	1.72E-10
26.25	5.62E-11	5.62E-11	5.62E-11	1.49E-10	1.49E-10	1.49E-10
28.75	4.79E-11	4.79E-11	4.79E-11	1.33E-10	1.33E-10	1.33E-10
31.25	4.47E-11	4.47E-11	4.47E-11	1.24E-10	1.24E-10	1.24E-10
33.75	3.56E-11	3.56E-11	3.56E-11	1.10E-10	1.10E-10	1.10E-10
36.25	3.12E-11	3.12E-11	3.12E-11	1.01E-10	1.01E-10	1.01E-10
38.75	2.95E-11	2.95E-11	2.95E-11	9.53E-11	9.53E-11	9.53E-11

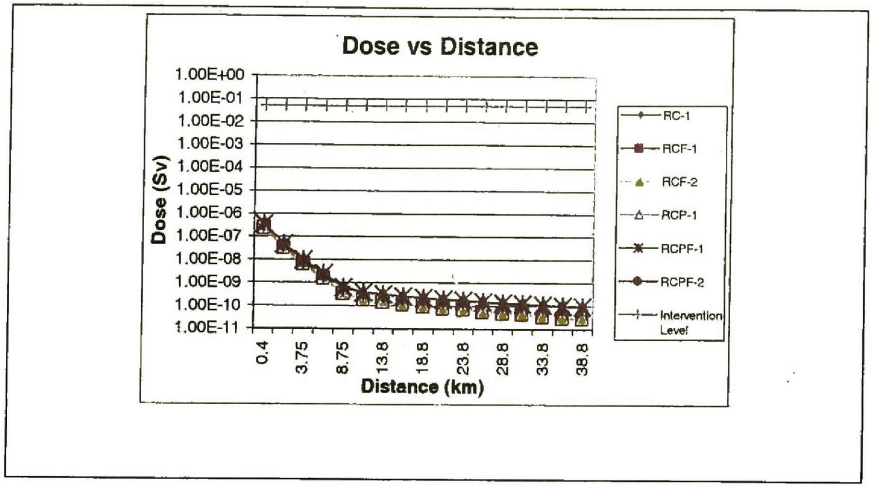


Figure 3-20: Doses per Release Categories – Thyroid including iodine as a countermeasure

Below is a clear graphical representation of summary of ***Figure 3-19*** and ***Figure 3-20*** together. It is a match up to thyroid doses with inhalation only as a pathway and with inclusion of iodine prophylaxis as a countermeasure.

We used C to denote countermeasure iodine prophylaxis for thyroid and P for thyroid with inhalation only as a pathway.

LIBRA...

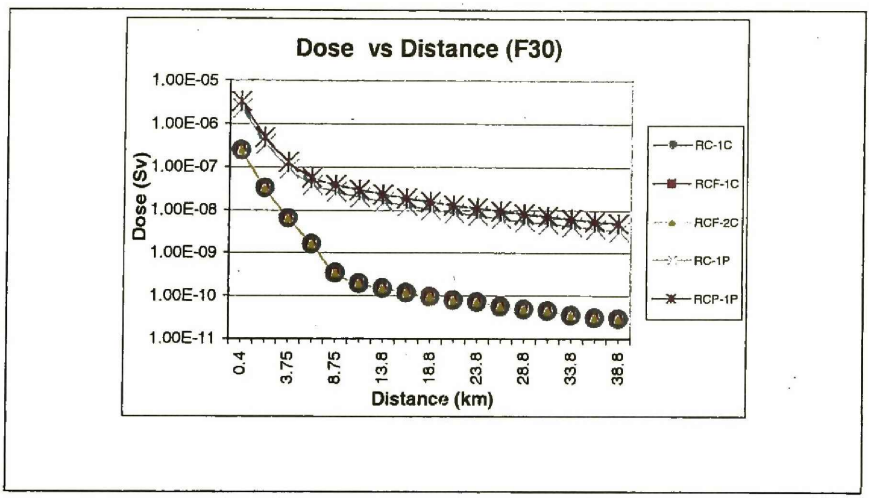


Figure 3-21: Doses per Release Categories – Thyroid with source term without delayed activity (with and without Iodine Prophylaxis)

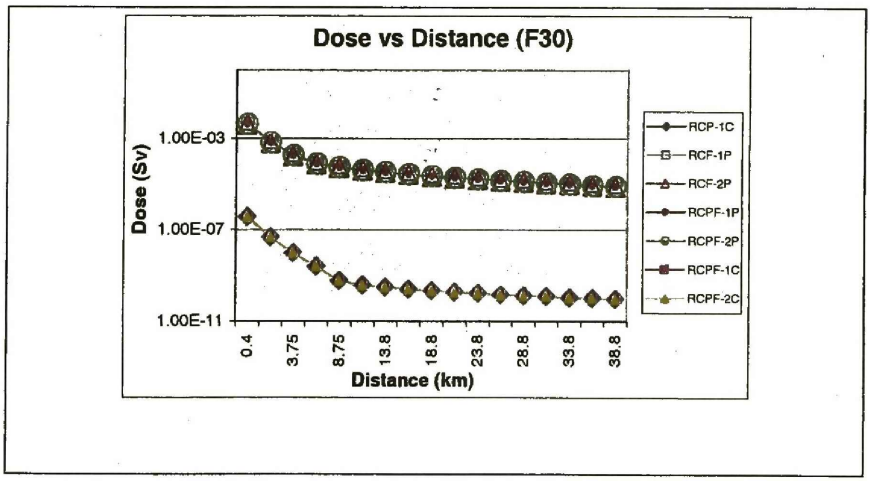


Figure 3-22: Doses per Release Categories – Thyroid with source term including delayed activity (with and without Iodine Prophylaxis)

Figure 3-21 and *Figure 3-22* clearly show that within the area where iodine is distributed there is a further reduction in dose received by the public.

Below are the intervention levels in use in South Africa. The implementation of protective actions is to prevent deterministic effects and to reduce as much as possible, stochastic effects. But for this study we put more concentration on the deterministic effects. Deterministic effects are prevented by implementing protective actions, which limit the exposure to levels which are below the deterministic thresholds. Deterministic effects include early morbidity (illness) and early mortality (death) but it occurs above the certain threshold.

Above the lower intervention level, introduction of the protective action should be considered unless there are practical reasons, which make the action difficult or detrimental. If the action would avert a dose greater than the upper intervention level, the protective action is almost always justified.

Table 3-40: Intervention levels in use in South Africa

Protective actions	Whole body dose (mSv)	Lung, Thyroid or any single organ dose (mSv)
Sheltering and Stable Iodine administration		
Upper dose level	50	500
Lower dose level	5	50
Evacuation		
Upper dose level	500	5000
Lower dose level	50	500

For this study, we only considered stable iodine administration with sheltering for thyroid with inhalation only as a pathway. The results show that we are below the deterministic threshold, that is, below the lower dose level (5.00E-02Sv) for thyroid, with or without administration of iodine prophylaxis.

CHAPTER 4 : DISCUSSION AND CONCLUSIONS

4.1 Consequences of Design Basis Accidents

However unlikely, should an accident occur at the PBMR Power Station, the consequences are not likely to exceed those of design basis accidents. Design basis accidents are licensing basis events with a frequency of occurrence that places them into the category "B" type events described in ***Table 3-5*** of ***chapter 3***. They are the type of accidents predicted to occur between once in a hundred years and once in a million years, and on the basis of which the plant systems have been designed.

The whole body dose to the closest members of the public, for weather category F for 30 days exposure period in ***Figure 3-11*** is 4.98E-04Sv, which does not exceed the public dose limit of 5.00E-02Sv *Table 3-5*. That is, doses decreases with increasing distance. Therefore, based on design basis accidents, protective intervention would not be necessary.

4.2 Consequences of Beyond Design Basis Accidents

LBE – 10 in *Table 2-1* has a predicted frequency of less than once in a million years, and is thus considered beyond design basis [9]. It is release category RCPF – 2.

RCPF – 2 is the worst accident category in terms of dose consequences and timing of release. It is a very low probability event and, emergency plans are aimed at preventing deterministic effects for this type of accidents.

The calculated doses that are presented in ***chapter 3*** are only the center-line values with pathways (inhalation, cloudshine and groundshine) contributions. These values apply only to a very limited geographic area, and doses have fallen rapidly a few tens of meters off the center-line, particularly for the very stable weather condition such as Pasquill F.

Table 3-4 presents doses that were calculated using Pasquill F stability. Pasquill F stability occurs only 2% of the time and that result in very narrow plumes **[13]**. The peak center-line values presented are not for the average doses in the downwind sector. They represent the worst-case values.

Figure 3-11 presents the worst-case results, and the dose received by the whole body is 4.98E-04Sv, that is below the set limit to the members of the public for category B (***Table 3-5***).

4.3 Consequences to the Whole Body and to Specific Organs (Lungs, Skin and Red Bone Marrow)

Since RCPF – 2 category involves the largest radiological source term, it will be used to examine the effective dose and dose to specific organs. The whole body dose for integration time 10days, 30days and 70days is 3.54E-04Sv, 4.98E-04Sv and 5.14E-04Sv respectively. Except for 1 day exposure that is slightly less by dose of 4.74E-05Sv due to the fact that the people are exposed for a very short time. Therefore, the doses are well below the deterministic threshold level. For red bone marrow, doses that can be received for 10days, 30days and 70 days are approximately 2.10E-04Sv, 2.88E-04Sv and 3.03E-04Sv respectively and for 1 day exposure is 3.10E-05Sv. For integration time 10, 30 and 70 for skin dose that can be received are approximately 2.17E-02Sv, 2.68E-02Sv and 2.78E-02 respectively and for 1 day exposure is 3.11E-03Sv. For lungs doses that were received for 10, 30, and 70 are 2.23E-04Sv, 3.06E-04Sv and 3.21E-04Sv, for 1 day exposure is 3.42E-05Sv. All these doses are below the set criterions (***Table 3-5***).

Deterministic effects have a threshold dose, and the severity of the effect is dose related. At low doses there appears to be a threshold dose below which no radiation effects is observed. The sensitivity of different organs and their consequences vary very much between organs and also depend on the overall exposure time. Therefore, the probability of developing a so-called deterministic radiation effect becomes relevant only after high radiation doses. The radiation dose limit for the members of the public is 50mSv, and this level of exposure is considered safe. In

general, it is safe to say that all calculated doses for this study are not significant from the standpoint of health effects.

4.4 Contribution of Pathways

All the runs were done including all pathways, except for 30 days runs that looked specifically at inhalation dose to thyroid. Comparing ***Figure 3-19*** for thyroid dose and other Figures where runs were done including all pathways (for example, ***Figure 3-11***), it can be seen that for both graphs we observe a decrease in dose as distance increases. ***Figure 3-11*** shows a larger decrease in the effective dose compared to ***Figure 3-19*** thyroid dose. This is due to the assumption that all thyroid doses are essentially committed through inhalation, therefore, in this case, inhalation acts as a major contributor to dose.

4.5 Effectiveness of Countermeasures

PBMR considered inclusion of countermeasures, and determined they were not required since expected radiation doses are still below the criterions set for PBMR. The effectiveness of countermeasures was tested by applying Iodine Prophylaxis on thyroid where runs were done considering inhalation only as a pathway.

Figure 3-21 and ***Figure 3-22*** show the effect of countermeasures without delayed activity and with delayed activity, respectively. Without delayed activity, the dose reduction between thyroid with and without a countermeasure is approximately a factor of 10 at 0.4 km, and a factor of 100 for distances under 8 km and for the range 8 – 40km is approximately lowered by a factor of 1000 Sv.

With delayed activity, the dose reduction difference is lower by approximately a factor of 10E4 Sv beyond 0.4 km and for the range 8 - 40km is 10E5Sv. These doses are very much lower than the set intervention levels (***Table 3-40***).

4.6 Conclusions and Recommendations

All calculated doses for both Pasquill stability D and F are lower than the doses set for PBMR by the regulator (NNR). The introduction of countermeasure showed a further reduction in doses.

Administration of stable iodine tablets can be a very effective protective action against thyroid exposure, especially when combined with sheltering, provided it is administered before or soon after the release. If taken at the time of the release, it can practically eliminate the absorption of iodine by the thyroid. Even when administered some hours later following exposure, the stable iodine taken will retain some effectiveness.

The main problem in implementing the administration of stable iodine tablets as a protective action is in distribution. Various countries have adopted different models for distribution of iodine to the population, including the following:

(a) Pre-distribution: stable iodine tablets are distributed to the general population or selectively to special populations such as school children as part of the on-going emergency preparedness program, and

(b) Distribution at the time of the emergency: emergency staff to the general population at the time of the emergency distributes stable iodine tablets. Distribution can be door-to-door, to centralized distribution and pick up centers, or at the mass care following an evacuation.

The first option requires tracking the population and planned regular re-supply to ensure that all new and transient members of the public have access to stable iodine. Tablets need to be replaced at their end of life or when lost. The second option requires significant human resources and may introduce delays, which could substantially reduce the effectiveness of the stable iodine against radioactive iodine intake.

Accident timing will influence how much time is available to implement protective actions, depending on the time at which the operator is able to recognize the seriousness of an accident and declare a general emergency. This might sounds like an easy practice but it is not. If the operator

waits until elevated radiation readings are detected off-site, meaning that a release has already started, then they may not be enough time to implement effective urgent protective actions.

For PBMR, there is no need for inclusion of countermeasures since the radiological doses due to an accidental release are well below the set criterions. But still it will be a good Safety Culture and Defense in Depth to make an allowance for an emergency plan.

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