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Australian Radiation Protection and
Nuclear Safety Agency

The 2000 Reference Accident Used to Assess the Suitability of Australian Ports for Visits by Nuclear Powered Warships

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REGULATORY BRANCH, ARPANSA
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The Commonwealth Government has established an interdepartmental standing committee called the Visiting Ships Panel (Nuclear) (VSP(N)) to control arrangements for visits to Australia by Nuclear Powered warships (NPWs).

The responsibilities of the VSP(N) are to:

(i) advise the Minister of Defence on proposals for NPW visits;

(ii) develop and maintain procedures related to NPW visits; and

(iii) oversee the implementation of specific arrangements, especially safety requirements, for visits by NPWs.

This document has been prepared by the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA) Regulatory Branch for the VSP(N).

AUSTRALIAN RADIATION PROTECTION AND NUCLEAR SAFETY AGENCY

ARPANSA

Our Ref: 2000/1141-4 / RR

4 January 2001

Cmdr K Joseph
Chairman
Visiting Ships Panel (Nuclear)
Department of Defence
CP4-6-39
Campbell Park Offices
CANBERRA ACT 2600

Dear Cmdr Joseph,

2000 Reference Accident as basis of the Australian Port Assessment for Visits by Nuclear Powered Warships (NPW)

BACKGROUND

Visits by nuclear powered warships (NPWs) to Australian ports are accepted only to berths and anchorages that have been assessed against radiological criteria and approved by the Visiting Ships Panel (Nuclear) (VSP(N)). Visits must comply with conditions of entry, including the existence of satisfactory emergency arrangements, set out in the Department of Defence document 'Visits of Nuclear Powered Warships to Australian Ports (OPSMAN 1)'. Approvals of ports are revalidated about every two years.

Assessments to determine the suitability of Australian ports for visits by NPWs include evaluating the radiological consequences of a hypothetical 'reference accident' to a nuclear reactor on board a vessel in port. The scenario is modelled using conservative assumptions and is considered to represent an upper bound risk to the surrounding population for the purpose of emergency planning.

This overall approach was supported in 1989 by the Senate Standing Committee on Foreign Affairs, Defence and Trade in its report: Visits to Australia by Nuclear Powered or Armed Vessels - Contingency Planning for the Accidental Release of Ionising Radiation.

NEED FOR UPDATING REFERENCE ACCIDENT

In 1996, the VSP(N) tasked ARPANSA to update the current reference accident used in port assessments (known as the 1975 Reference Accident). The Revision was needed to take into consideration changes that have occurred, particularly in relation to the following matters:

(a) available information and data on NPWs, improvements in the capabilities for modelling the consequences of reactor accidents, updated data used for calculating radiation doses; and

(b) international recommendations for implementing countermeasures in radiation emergencies, and in particular the use of 'avertable dose' for making decisions on intervention.

THE 2000 REFERENCE ACCIDENT

The attached report, prepared by ARPANSA, documents the updated reference accident, known as the '2000 Reference Accident', and includes current information and modelling techniques. In calculating the consequences of the 2000 Reference Accident, two groups of NPWs, based on reactor power, have been considered: submarines and smaller surface vessels; and NIMITZ-class aircraft carriers.

The main changes to the models, parameters and assumptions used to calculate the consequences of the Reference Accident for both submarines and smaller surface vessels and NIMITZ class aircraft carriers are: -

(i) revised estimates of reactor power and core operating history;

(ii) revised fractions for the release of fission products from the core;

(iii) revised estimates of the containment leak rate, incorporating an allowance for the presence of a secondary containment;

(iv) inclusion of an improved fission product containment deposition model;

(v) revised atmospheric dispersion model, incorporating updated information on wind direction variability, atmospheric turbulence, and terrain roughness effects;

(vi) inclusion of a model for ground deposition of fission products;

(vii) updated radiation dose conversion factors for inhalation and cloudshine;

(viii) inclusion of a model for effective inhalation dose;

(ix) inclusion of a model for groundshine dose; and

(x) revised criteria for countermeasures following an accident.

The impact on the emergency planning zones resulting from changes incorporated in the 2000 Reference Accident model is summarised in section 8 of the report. It should be noted that collective dose is port specific and is only evaluated during the assessments of individual ports.

REFERRAL

The 2000 Reference Accident represents a significant update in assessing the suitability of ports used by visiting nuclear powered warships. State and Territory Radiation Control Officers were consulted on the basis of drafts of the report and their comments were taken into account in preparing the final report.

Subsequent to the functions of the CEO of ARPANSA under section 15 1(a) and 1(b) of the Australian Radiation Protection and Nuclear Safety Act, 1998 I advise that the Visiting Ships Panel (Nuclear) should use the 2000 Reference Accident documented in the attached report, for assessing the suitability of Australian ports for visit of nuclear powered warships.

Yours sincerely,

John Loy

John Loy
CEO of ARPANSA

EXECUTIVE SUMMARY

INTRODUCTION

One of the most visible aspects of the defence cooperation that takes place between Australia and allied nations are the visits to Australian ports by conventional and nuclear-powered warships (NPWs). The Commonwealth Government's policy is to accept these visits. Because of the nature of the of NPW propulsion plants, special procedures have been adopted to ensure that safety of the public is maintained during visits by such vessels.

Visits of NPWs to Australian ports are permitted only to berths and anchorages that have been assessed as suitable by the Visiting Ships Panel (Nuclear) (VSP(N)). In order to ensure that the members of the public are not subject to an unacceptable risk due to NPW visits, adequate emergency arrangements and contingency plans are put in place for each port visit. The arrangements are in the form of a special plan for dealing with very unlikely accidents that might result in the release of radioactivity to the environment.

BACKGROUND

To assist in planning emergency arrangements, the radiological consequences of a severe hypothetical accident scenario are calculated and compared with radiological acceptance criteria. The hypothetical accident, termed the Reference Accident, is selected to represent an upper bound risk to the surrounding population.

The consequences of this scenario are compared with port acceptability criteria to determine the impact of the Reference Accident on the surrounding population. In addition, emergency planning zones, based on the calculated consequences of the Reference Accident, are used by emergency planning authorities in developing port specific emergency arrangements.

NEW REFERENCE ACCIDENT

The Reference Accident that is currently used as the basis of port assessments was developed during the early 1970s, and was based on the information available at that time. It is referred to as the '1975 Reference Accident'. Significant changes have occurred since that development. These changes are associated with improved modelling capabilities, more information on the nuclear powered warship containment, and health physics data on intervention levels for countermeasures should an accident occur.

These changes led to a decision by the VSP(N) to review and revise the Reference Accident used for port assessments, and support was obtained from relevant agencies within the Commonwealth, State and Territories. This accident is referred to as the '2000 Reference Accident'.

In both the 1975 Reference Accident and the 2000 Reference Accident, a single accident scenario was chosen to represent an upper bound risk to the surrounding population. This accident is assumed sufficiently severe to result in a full core meltdown, that is, melting of all fuel in the reactor core. The reactor primary and secondary containments are assumed to remain intact, and thus limit the fraction of fission products released to the atmosphere. The

2000 Reference Accident scenario, therefore, describes a ‘contained accident’, in that it gives credit to the containment. For the purposes of emergency planning for NPW visits, the Senate Standing Committee on Foreign Affairs, Defence and Trade accepted in its 1989 report, that such an accident represents an upper bound in terms of risk to the surrounding population.

SUMMARY OF CHANGES

In calculating the consequences of the 2000 Reference Accident, two classes of NPW have been considered, submarines and smaller surface vessels, and NIMITZ class aircraft carriers. The consequences calculated in the 1975 Reference Accident assume a simplified and conservative model developed during the 1970s. Since that time more accurate and complex models and techniques have become available. The use of comprehensive computer models allows more detailed, but still conservative assessment of accident consequences.

The major changes to the models, parameters and assumptions used to calculate the consequences of the Reference Accident for both submarines and smaller surface vessels and NIMITZ class aircraft carriers are:

(i) revised estimates of reactor power and core operating history;

(ii) revised fractions for the release of fission products from the core;

(iii) revised estimates of the containment leak rate, incorporating an allowance for the presence of a secondary containment;

(iv) inclusion of an improved fission product containment deposition model;

(v) revised atmospheric dispersion model, incorporating updated information on wind direction variability, atmospheric turbulence, and terrain roughness effects;

(vi) inclusion of a model for ground deposition of fission products;

(vii) updated radiation dose conversion factors for inhalation and cloudshine;

(viii) inclusion of a model for effective inhalation dose;

(ix) inclusion of a model for groundshine dose; and

(x) revised criteria for countermeasures following an accident.

RESULTS OF CHANGES

The changes incorporated in the 2000 Reference Accident have had a significant impact on the calculated consequences. The changes that tend to significantly increase the consequences are the increased maximum ship power estimates, and the inclusion of more fission products in the release. Other changes that act to reduce the calculated radiation doses, are the updated atmospheric dispersion model and, in the case of thyroid inhalation dose, the reduced radiation dose conversion factors. The reduction in the magnitude of the calculated release of fission products to the atmosphere is due primarily to the revised estimate of the containment leak rate, which takes into account the presence of a secondary containment. This also leads to a significant reduction in calculated radiation doses to the public.

While some of these changes act to increase the calculated consequences and some act to reduce them, the overall effect is a significant reduction in both the calculated releases of fission products and radiation doses to the public.

INDIVIDUAL DOSE - EMERGENCY PLANNING ZONES

For NPW visits to Australia, Emergency Planning Zones (EPZs) are defined around NPW berths and anchorages. These EPZs assist in the identification of areas where hazards might arise, and ensure that appropriate and timely protective actions can be taken to control radiation doses in the event of an accident. The major impact of the 2000 Reference Accident on NPW visits is the effect on the extent of the EPZs.

Zone 1

Zone 1 is a region close to the NPW within which the surrounding population may be exposed to direct gamma shine from the vessel, as well as airborne radioactive material following an accident. The extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be required following the Reference Accident.

For submarines and smaller surface vessels, the 2000 Reference Accident estimates Zone 1 as a circle of radius 600m centred on the NPW. This is the same as estimated using the 1975 Reference Accident.

For NIMITZ-class aircraft carriers, the 2000 Reference Accident estimates Zone 1 as a circle of radius 800m centred on the NPW. This is an increase from the 600m radius estimated using the 1975 Reference Accident.

Zone 2

Zone 2 represents an area within which the projected doses do not justify evacuation, but where, subject to actual field measurements of radioactivity, the maximum avertable doses that are estimated may justify sheltering as a countermeasure. A viable emergency plan for the implementation of sheltering and distribution of stable iodine, or evacuation within this zone is established in each port special plan.

For submarines and smaller surface vessels, with a vessel removal time of 24 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.4km. This is a reduction from the 2.2km estimated by the 1975 Reference Accident.

For submarines and smaller surface vessels, with a vessel removal time of 4 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.2km. This is the same as the Zone 2 radius estimated by the 1975 Reference Accident.

For NIMITZ class aircraft carriers, with a vessel removal time of 2 hours, the 2000 Reference Accident estimates Zone 2 as a 30 degree downwind sector within a circle of radius 1.9km. This is a reduction from the 3.5km radius estimated by the 1975 Reference Accident.

Zone 3

Zone 3 represents an area within which the surrounding population may be subject to hazards associated with long term exposure to ground deposited radioactive material (groundshine), and ingestion of contaminated water, foodstuffs, milk and agricultural produce. Due to the slow rate of accrual of groundshine and ingestion doses, immediate action is not required to protect the population from these hazards. Decisions to implement protective actions, such as relocation and food restrictions, would be made based on the results of extensive radiation and contamination monitoring.

PORT ASSESSMENTS - COLLECTIVE DOSE – EMERGENCY PLANNING ZONES

Collective dose provides a measure of the societal consequences of the Reference Accident in terms of the number of health effects, which may appear over the ensuing lifetime of the surrounding population. The approach to calculating collective dose is described, however, since collective doses are port specific, they are to be calculated in future individual port assessments, and are not presented in this report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SUBMARINES AND SMALLER SURFACE VESSELS

NIMITZ CLASS AIRCRAFT CARRIERS

TECHNICAL SUMMARY

INTRODUCTION

Visits to Australian ports by conventional and nuclear-powered warships (NPWs) of allied nations are one of the most visible aspects of the defence cooperation that takes place between Australia and other countries in peacetime. The Commonwealth Government's policy is to accept these visits. Because of the nature of the of NPW propulsion plants, special procedures have been adopted to ensure that safety of the public is maintained during visits by such vessels.

These procedures include Conditions of Entry for NPWs into approved Australian ports, which are:

(a) Visits will be for purposes such as crew rest and recreation, and not for fuel handling or repairs to reactor plant (necessitating breach of reactor containment).

(b) Visits will be subject to satisfactory arrangements concerning liability and indemnity, and to provision of assurances relating to the operation and safety of the warships while they are in Australian waters.

(c) Movement of vessels must take place during daylight hours under conditions where visibility is not less than three-quarters of a nautical mile.

(d) Navigational controls on other shipping will be applied during the time that nuclear powered ships are entering or leaving port.

(e) There must be a capability to remove the vessel, either under its own power or under tow, to a designated safe anchorage or a designated distance to sea, as soon as possible within the time frame specified for the particular berth or anchorage, and in any case within 24 hours, if an incident should occur.

(f) An operating safety organisation, competent to conduct a suitable radiation monitoring program and able to initiate actions and provide services necessary to safeguard the public in the event of a release of radioactivity following an accident, must exist in the port being visited.

Other procedures involve the arrangements for visits, including contingency arrangements in the unlikely event of an accident resulting in the hazardous release of radioactivity to the environment. Visits of NPWs to Australian ports are permitted only to berths and anchorages that have been assessed as suitable by the Visiting Ships Panel (Nuclear) (VSP(N)). This is in order to ensure that the members of the public are not subject to an unacceptable risk due to NPW visits, and that adequate emergency arrangements are in place for dealing with accidents.

The primary means for judging the suitability of ports for NPW visits has been radiological port assessments performed by the Nuclear Safety Bureau (NSB), and port validations performed by the VSP(N). On February 5, 1999, the NSB became the Regulatory Branch of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

BACKGROUND

For the purposes of emergency planning, the radiological consequences of a severe hypothetical accident scenario are calculated and compared with radiological acceptance criteria. The hypothetical accident, termed the Reference Accident, is selected to represent an upper bound risk to the surrounding population, and is used to assist in planning emergency arrangements. The use of such a Reference Accident is also the basis for estimating the adequacy of emergency planning for any research reactor sites in Australia. The aim of the Reference Accident is to aid in planning emergency measures that would take effect if an accident occurred on a visiting NPW, and involved the release of radionuclides from the nuclear reactor on these vessels.

The calculated consequences of this scenario are compared with port acceptability criteria to determine, on a port specific basis, whether the impact of the Reference Accident on the surrounding population meets the criteria. In addition, emergency planning zones based on the calculated consequences of the Reference Accident are used by emergency planning authorities in developing port specific emergency arrangements. Publicly available reports documenting port assessments for approved ports have routinely been published by the NSB. The ARPANSA Regulatory Branch will publish future port assessments.

NEW REFERENCE ACCIDENT

The 1975 NPW Reference Accident used, as the basis of port assessments was developed during the early 1970s and was based on the information available at that time. During the 1980s, the Australian Atomic Energy Commission (AAEC) provided a revised accident scenario incorporating more realistic accident assumptions. However, this 1980s accident scenario was used for comparative purposes and, not for port assessments. Significant changes have occurred since the development of the 1975 Reference Accident, particularly in relation to:

(i) the availability of information and data on NPW reactor power and containment performance;

(ii) the capabilities for modelling the consequences of reactor accidents;

(iii) the data used for calculating radiation doses; and

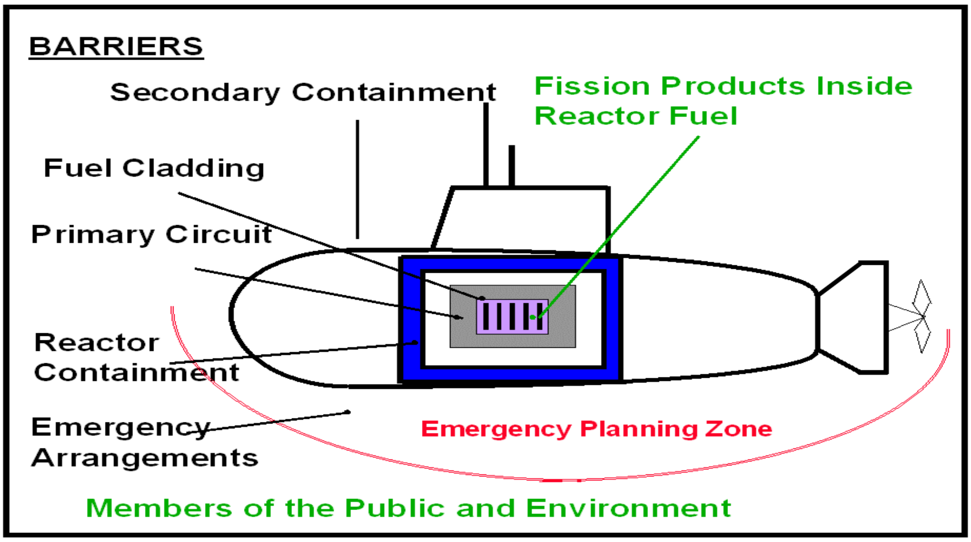
(iv) the dose or intervention levels for the implementation of countermeasures in radiation emergencies.

These changes lead to a decision by the VSP(N) to review and revise the 1975 Reference Accident used for port assessments. The VSP(N) received support from the relevant Commonwealth and States/Territories agencies on the need to review the Reference Accident scenario. The NSB (now part of ARPANSA) was tasked with defining and documenting a new Reference Accident that would incorporate current information and techniques. This is referred to in this report as the ‘2000 Reference Accident’.

ACCIDENT SCENARIO

A single accident scenario was chosen to represent an upper bound risk to the surrounding population for the purposes of emergency planning. Like the 1975 Reference Accident, the 2000 Reference Accident postulates a contained loss-of-coolant-accident (LOCA). The initiating event for this scenario is a failure of the primary cooling circuit pipework on board the NPW. This results in loss of coolant from the primary circuit, and the subsequent overheating and melting of nuclear fuel inside the reactor core. The accident is considered a 'a contained LOCA' since the primary and secondary containment are assumed to remain intact. Thus only a small fraction of the fission products released from the fuel leaks into the atmosphere (see Figure TS-1).

Figure TS-1 Barriers to Radioactivity Release



The choice of a 'contained' LOCA for the 2000 Reference Accident is supported by a Technical Safety Assessment (TSA), which has been performed for a nuclear powered submarine 'reference design' in Canada. This study examined a large number of reactor initiating events for NPW accidents. The TSA results show that the total core damage frequency is dominated by primary system failures giving rise to LOCAs.

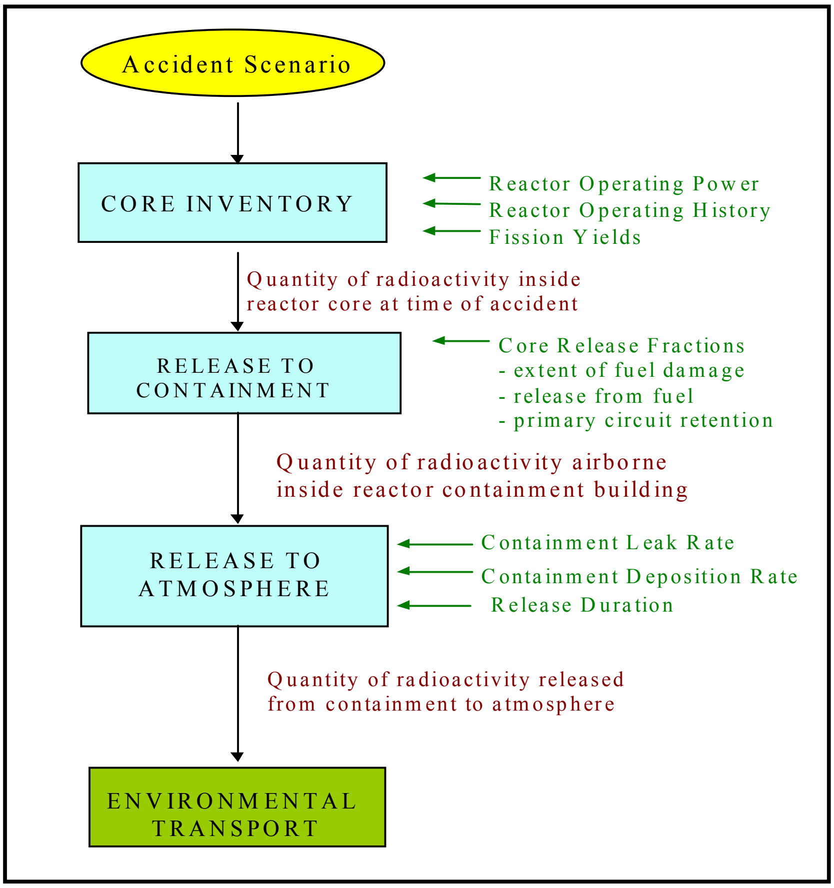
On currently available information, the 2000 Reference Accident scenario described above is an upper bound, in terms of risk to the surrounding population and for the purposes of emergency planning for NPW visits.

MODELLING AND VALIDATION

The assumptions, models and parameters used to calculate the release of radioactive material and radiation doses to the surrounding population require revision to be consistent with available information and current international best practice. The consequences of the 1975 Reference Accident are currently calculated using a simplified, but conservative model developed during the 1970s. Since that time, models and techniques that are more complex have become available, and the use of modern computer models allows more detailed and realistic assessment of accident consequences.

The computer code used for modelling the consequences of the 2000 Reference Accident is the ACCIDENT code, a generic nuclear reactor accident consequence assessment code developed by the NSB. The 2000 Reference Accident uses the ACCIDENT code process of modelling (see Figure TS-2).

Figure TS-2 2000 Reference Accident Model



MATHEMATICAL UNCERTAINTY

The 2000 Reference Accident uses a number of assumptions from the ACCIDENT code. With any calculation of this type uncertainties can exist in factors such as:

(i) estimate of the source term;
(ii) atmospheric dispersion;
(iii) individual breathing rate;
(iv) risk for intake factor;
(v) containment leak performance;
(vi) deposition half-life within the containment;
(vii) core release fractions;
(viii) averaging of exposure data; and
(ix) shielding available to individuals.

A conservative or upper value of these factors has been used since this is an accepted approach to safety planning. By using conservative values there will be an overestimation of the release, and hence the consequences. The model is suitable for planning an emergency response, provided the uncertainties discussed above are taken into account by the use of conservative assumptions.

The ACCIDENT model should not be used for the estimation of airborne radionuclide concentrations in actual emergencies, unless real-time data is available. When such data is available it can be checked against the model estimates, and used to adjust the model parameters to refine the model estimates.

A number of inter-comparison exercises have been undertaken to provide confidence in the consequence results calculated by the ACCIDENT code. The NSB and Australian Nuclear Science and Technology Organisation (ANSTO) have undertaken validation exercises on the ACCIDENT code.

The results calculated by ACCIDENT, for a specific accident scenario, were compared with those calculated by the independent internationally used computer model PCCOSYMA (See Appendix B). The comparisons have shown a high level of consistency between the two codes, and all differences have been explained and found acceptable. The validation exercises carried out on the ACCIDENT code provide a high degree of confidence that the consequence results for the 2000 Reference Accident are valid and conservative.

SUMMARY OF CHANGES

In calculating the consequences of the 2000 Reference Accident, two classes of NPW have been considered, namely submarines and smaller surface vessels, and NIMITZ-class aircraft carriers.

An important factor in estimating the consequences of an accident is the duration of a release, and this is covered in the Conditions of Entry. As a condition of entry to Australian ports, submarines and smaller surface vessels are subject to a vessel removal time of 24 hours following an accident. NIMITZ-class aircraft carriers, which have a higher reactor power, are subject to a vessel removal time of 2 hours following an accident.

The major changes to the models, parameters and assumptions used to calculate the consequences of the Reference Accident for both submarines and smaller surface vessels and NIMITZ class aircraft carriers are: -

(xi) revised estimates of reactor power and core operating history;

(xii) revised fractions for the release of fission products from the core;

(xiii) revised estimates of the containment leak rate, incorporating an allowance for the presence of a secondary containment;

(xiv) inclusion of an improved fission product containment deposition model;

(xv) revised atmospheric dispersion model, incorporating updated information on wind direction variability, atmospheric turbulence, and terrain roughness effects;

(xvi) inclusion of a model for ground deposition of fission products;

(xvii) updated radiation dose conversion factors for inhalation and cloudshine;

(xviii) inclusion of a model for effective inhalation dose;

(xix) inclusion of a model for groundshine dose; and

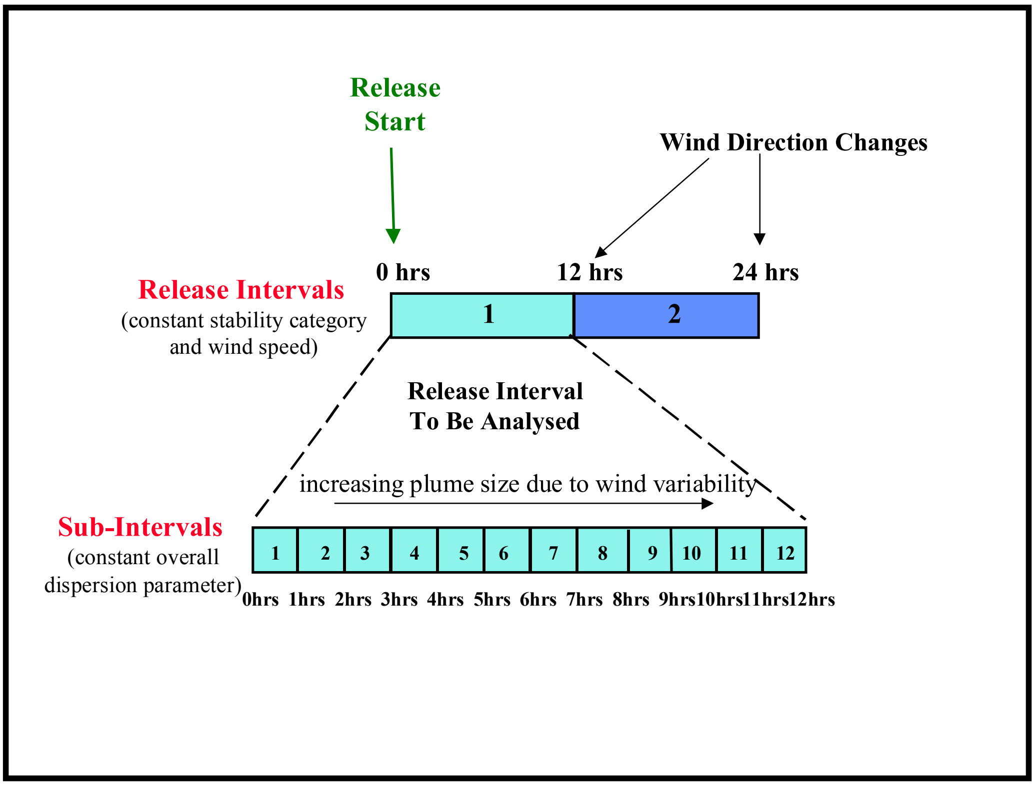
(xx) revised criteria for countermeasures following an accident.

RESULTS OF CHANGES

The changes have had a significant impact in the calculated consequences estimated in the 2000 Reference Accident. While some of the changes act to increase the calculated consequences and some act to reduce them, the overall effect is a significant reduction in both the calculated releases of fission products and radiation doses to the public. Changes that tend to increase the consequences are the increased maximum ship power estimates, and the inclusion of more fission products in the release.

The reduction in the magnitude of the calculated release of fission products to the atmosphere is due primarily to the revised estimate of the containment leak rate, which takes into account the presence of a secondary containment. This also leads to a significant reduction in calculated radiation doses. Other changes, which act to reduce calculated radiation doses are the updated atmospheric dispersion model (see Figure TS-3) and, the reduced radiation dose conversion factors in the case of thyroid inhalation dose.

Figure TS-3 Modelling of Extended Releases



The release of radioactive iodine generally dominates the immediate consequences of a reactor accident. The amount of iodine released from the containment has been significantly reduced from that in the 1975 Reference Accident. The major reason for this reduction in the iodine release are the decreased containment leak rate, which takes into account the presence of a secondary containment, and the revised fission product containment deposition model.

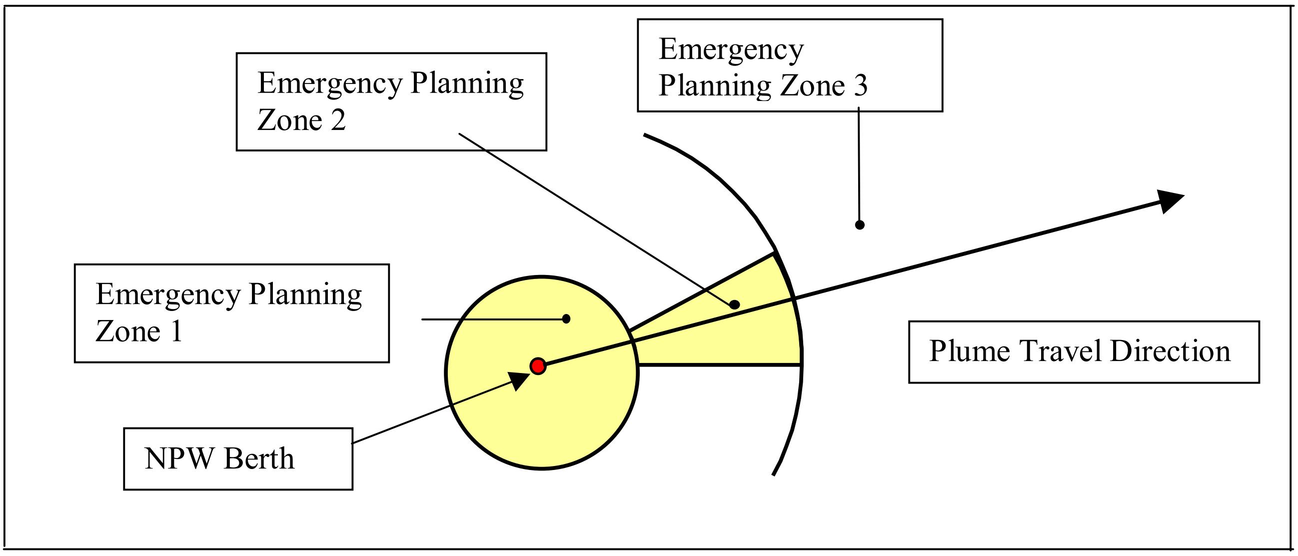
However, the effect of these changes is somewhat counteracted by the assumption of operation at maximum power immediately prior to the accident, which acts to increase the iodine release.

The total gamma energy release is also reduced due to the lower containment leak rate; however, the reduction is not as significant as for iodine due to the additional radionuclides considered in the source term for the 2000 Reference Accident model.

INDIVIDUAL DOSE - EMERGENCY PLANNING ZONES

The major impact of the 2000 Reference Accident model on NPW visits is the effect on the extent of Emergency Planning Zones (EPZs) (see Figure TS-4). EPZs are defined to assist in the identification of areas where hazards might arise, and to ensure that appropriate and timely protective actions can be taken to control radiation doses in the event of an accident. The zones are based on estimates of averted dose for implementation of appropriate countermeasures, as determined from the projected doses derived from the reference accident models.

Figure TS-4 Diagram of Zones Centred around NPW



Zone 1

Zone 1 is a region close to the NPW within which the surrounding population may be exposed to direct gamma shine from the vessel as well as airborne radioactive material following the reference accident. The extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be required following the Reference Accident, ie. the distance at which the avertable dose for an individual exceeds the Generic Intervention Level for evacuation (as defined in IAEA Safety Series 109, Intervention Criteria in a Nuclear or Radiation Emergency).
For submarines and smaller surface vessels, the 2000 Reference Accident estimates Zone 1 as a circle of radius 600m centred on the NPW. This is the same as estimated using the 1975 Reference Accident.

For NIMITZ-class aircraft carriers, the 2000 Reference Accident estimates Zone 1 as a circle of radius 800m centred on the NPW. This is an increase from the 600m radius estimated using the 1975 Reference Accident.

Zone 2

Zone 2 represents an area within which the projected doses do not justify evacuation, but where, subject to actual field measurements of radioactivity, the maximum avertable doses that are estimated may justify sheltering as a countermeasure. A viable emergency plan for the implementation of sheltering and distribution of stable iodine or evacuation within this zone should be established. The extent of Zone 2 is defined as the maximum distance to which the maximum avertable dose (taken as the full projected dose from the reference accident model) justifies the countermeasures of sheltering and/or stable iodine, ie. the distance at which the Generic Intervention Levels for these countermeasures is exceeded.

For submarines and smaller surface vessels, with a vessel removal time of 24 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.4km. This is a reduction from the 2.2km estimated by the 1975 Reference Accident.

For submarines and smaller surface vessels, with a vessel removal time of 4 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.2km. This is the same as the Zone 2 radius estimated by the 1975 Reference Accident.

For NIMITZ class aircraft carriers, with a vessel removal time of 2 hours, the 2000 Reference Accident estimates Zone 2 as a 30 degree downwind sector within a circle of radius 1.9km. This is a reduction from the 3.5km radius estimated by the 1975 Reference Accident.

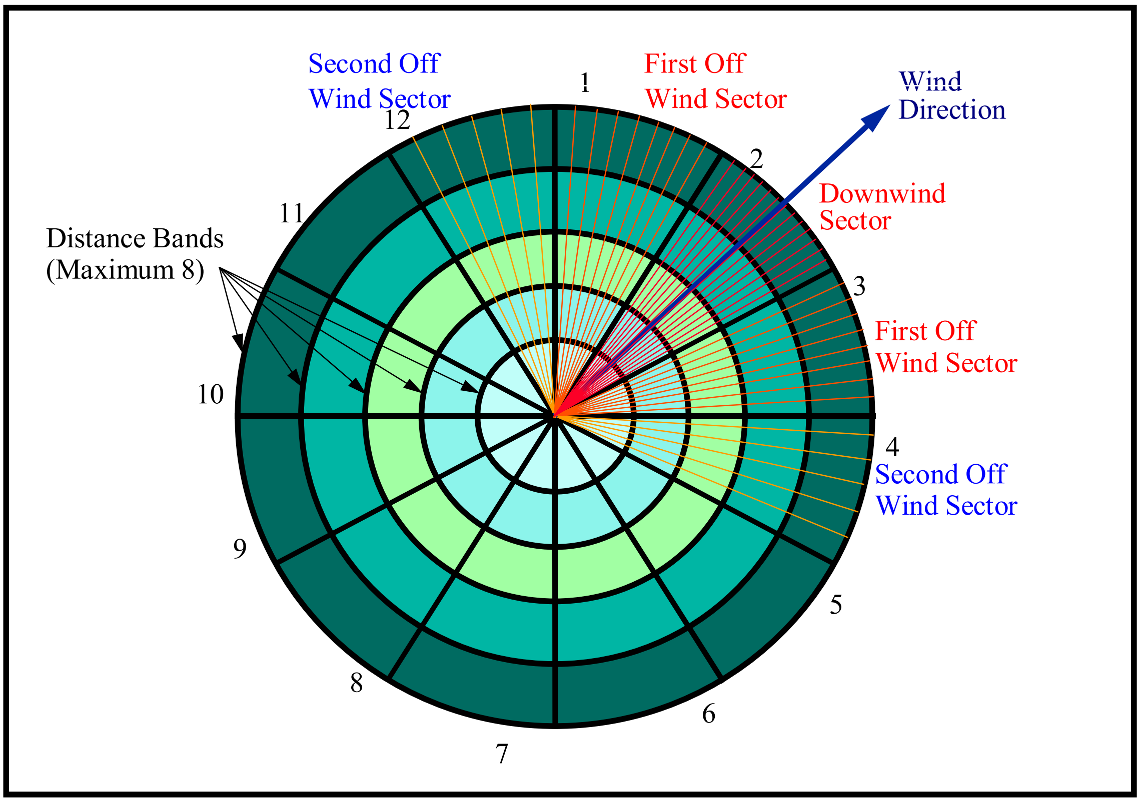
Zone 3

Zone 3 represents an area within which the surrounding population may be subject to hazards associated with long term exposure to ground deposited radioactive material (groundshine) and ingestion of contaminated water, foodstuffs, milk and agricultural produce. Due to the slow rate of accrual of groundshine and ingestion doses, immediate action is not required to protect the population from these hazards. Decisions to implement protective actions, such as relocation and food restrictions, would be made based on the results of extensive radiation and contamination monitoring.

COLLECTIVE DOSE

Collective dose provides a measure of the societal consequences of the 2000 Reference Accident in terms of the number of health effects, which may appear over the ensuing lifetime of the surrounding population. It is essentially calculated by multiplying the average individual dose received in the various distance bands by the population in the downwind sector. The collective dose is calculated, on a port specific basis for 12 different wind directions, with the direction giving the highest collective dose used to assess port acceptability (see Figure TS-5). Since collective doses are port specific they will be calculated in the individual port assessments and are not presented in this report.

Figure TS-5 Wind Variability Dose Effect on Adjacent Sectors



1. INTRODUCTION

Visits to Australian ports by conventional and nuclear-powered warships of allied nations are one of the most visible aspects of the defence cooperation that takes place between Australia and other countries in peacetime. The Commonwealth Government's policy is to welcome these visits. In view of the nature of the of NPW propulsion plants, special procedures have been adopted to ensure that the safety of the general public is maintained during visits by such vessels.

These procedures include Conditions of Entry for NPWs into approved Australian ports. These are specified in OPSMAN 1 [1] as follows:

(a) Visits will be for purposes such as crew rest and recreation, and not for fuel handling or repairs to reactor plant (necessitating breach of reactor containment).

(b) Visits will be subject to satisfactory arrangements concerning liability and indemnity, and to provision of assurances relating to the operation and safety of the warships while they are in Australian waters.

(c) Movement of vessels must take place during daylight hours under conditions where visibility is not less than three-quarters of a nautical mile.

(d) Navigational controls on other shipping will be applied during the time that nuclear powered ships are entering or leaving port.

(e) There must be a capability to remove the vessel, either under its own power or under tow, to a designated safe anchorage or a designated distance to sea, as soon as possible within the time frame specified for the particular berth or anchorage, and in any case within 24 hours, if an incident should occur.

(f) An operating safety organisation, competent to conduct a suitable radiation monitoring program and able to initiate actions and provide services necessary to safeguard the public in the event of a release of radioactivity following an accident, must exist in the port being visited.

Other procedures include arrangements for visits, and contingency arrangements in the unlikely event of an accident resulting in the hazardous release of radioactivity to the environment.

Visits of Nuclear Powered Warships (NPWs) to Australian ports are permitted only to berths and anchorages that have been assessed as suitable by the Visiting Ships Panel (Nuclear) (VSP(N)). This is in order to ensure that the members of the public are not subject to an unacceptable risk due to NPW visits, and that adequate emergency arrangements are in place for dealing with accidents. The primary means for judging the suitability of ports for NPW visits are radiological port assessments performed by the Nuclear Safety Bureau (NSB) and port validations performed by the VSP(N). On February 5, 1999, the NSB became the Regulatory Branch of the Australian Radiation Protection and Nuclear Safety Agency (ARPANSA).

For the purpose of a siting assessment [2], ARPANSA defines a Reference Accident, which is a hypothetical accident that is specific to the nuclear installation. In general terms, it assumes an initiating event such as a plant failure, and a degraded performance of one or more safety systems. This can result in a release of radioactive material to the reactor containment and a leak of radioactive material from the containment system.

The consequences of the Reference Accident are determined using conservative assumptions. ARPANSA uses the Reference Accident to determine whether:

- offsite emergency intervention would be feasible;
- whether collective effective doses would be less than the acceptable limits; and
- whether contamination of the environment would restrict the long-term use of land around the site.

This process has been used in the assessment of the siting at Lucas Heights of the proposed replacement research reactor by the Australian Nuclear Science and Technology Organisation [3].

The Reference Accident approach used for siting nuclear installations in Australia is consistent with the approach for NPW visits. For the purposes of emergency planning for NPW visits, radiological assessments of Australian ports are carried out. The process involves evaluating the radiological consequences, in terms of individual and collective dose, of a hypothetical accident scenario considered to represent an upper bound risk to the surrounding population.

The calculated consequences of this scenario, termed the Reference Accident, are compared with reference port acceptability criteria to determine, on a port specific basis, whether the impact of the Reference Accident on the surrounding population is acceptable. Emergency planning zones are defined based on the calculated consequences of the Reference Accident, which are used by emergency planning authorities in developing port specific emergency arrangements.

Publicly available reports documenting port assessments for approved ports have been routinely published by the NSB [4,5,6,7,8,9,10] and will be published in the future by ARPANSA. The 1975 Reference Accident is currently used as the basis of port assessments. The method of evaluating its consequences has not been revised since it was developed during the early 1970s. During the 1980s, the Australian Atomic Energy Commission (AAEC) provided a revised accident scenario [12] incorporating more realistic accident assumptions, however, this was used purely for comparative purposes and did not affect the 1975 Reference Accident used for port assessments.

Significant changes have occurred since the development of the1975 Reference Accident, particularly in relation to the availability of information and data on NPWs, the capabilities for modelling the consequences of reactor accidents, data used for calculating radiation doses, and intervention levels for the implementation of countermeasures in radiation emergencies. There was a change in the international recommendations for carrying out interventions in radiation emergencies, in particular the use of avertable dose criteria for the decision making process. These changes have lead to a decision by the VSP(N) to review and revise the 1975 Reference Accident used for port assessments.

In 1996, the NSB issued two working papers documenting reviews by the NSB of the method of calculating the consequences of the Reference Accident and of the radiological acceptance criteria used in assessing port suitability [13,14]. These papers were presented and discussed at the biennial national seminar on NPW visits to Australia held at the Australian Emergency Management Institute, Mt Macedon in November 1996 [15]. At this seminar, the Commonwealth, States and Territory authorities supported the need to review the 1975 Reference Accident scenario. The NSB was tasked with defining and documenting a new Reference Accident, known as '2000 Reference Accident' that incorporates current information and techniques. The purpose of this paper is to document the year 2000 Reference Accident scenario proposed for performing port assessments.

2. THE REFERENCE ACCIDENT

2.1 1975 REFERENCE ACCIDENT SCENARIO

In its submission to the Senate Standing Committee on Foreign Affairs and Defence Inquiry into safety procedures relating to nuclear powered or armed vessels in Australian waters [16], the AAEC reviewed a range of hypothetical accidents that could occur in NPWs. The hypothetical scenarios included power excursions associated with reactivity accidents, start-up accidents, loss of coolant accidents, and accidents leading to the degradation of the reactor containment. Based on its review, which estimated both the consequences and frequency of the accidents, a single accident scenario was chosen by the AAEC to represent an upper bound risk to the surrounding population for the purposes of emergency planning.

The Senate Standing Committee [17] stated ‘ The Committee accepts the overall conclusions of AAEC’s assessment as to both accident likelihood and accident consequences. The Committee has been unable to find any reason to justify substitution of an uncontained accident for the current contained reference accident’. Evaluation of the consequences of this scenario, termed the Reference Accident, was thus considered appropriate for judging the acceptability of Australian ports for visits by NPWs, and for planning emergency measures in case of accident.

The 1975 Reference Accident postulated by the AAEC was a contained loss of coolant accident (LOCA). The initiating event for this scenario is a failure of the primary cooling circuit pipework on board the NPW resulting in loss of coolant from the primary circuit, and the subsequent overheating and melting of nuclear fuel inside the reactor core. An emergency core cooling system is likely to be present to return lost coolant to the reactor core and minimise core damage. However, due to the lack of information on NPW safety systems, no credit is given to such a system. The 1975 Reference Accident LOCA is assumed sufficiently severe to result in a full core meltdown, that is, melting of all the fuel in the reactor core.

Following the 1975 Reference Accident, radioactive fission products are assumed to be released from the reactor core into the containment surrounding the reactor under the driving force of the high primary circuit pressure. The containment, which is assumed to remain intact, would become pressurised and a fraction of its contents would gradually leak to the atmosphere, until the pressure again reduces to atmospheric pressure.

Such an accident would be characterised by a direct gamma radiation field (within about 200m of the vessel), and a slow leakage of fission products at ground level, which would disperse in the atmosphere according to the prevailing meteorological conditions. A plume of radioactive material would form in the direction of the prevailing wind, and might lead to the radiation exposure of the surrounding population. The release would continue until sealing the containment controls the accident or the vessel is removed from the port.

A difference between land based reactors and NPWs is that in the case of the warship the radioactive source term can be removed from the port. The conditions of entry for NPWs into Australian ports [1] require that, if an incident should occur, there must be the capability to remove the NPW from the port as soon as possible within the time frame specified for the particular port. In all cases within 24 hours, and for NIMITZ class aircraft carriers within two hours.

It has been estimated that the likelihood of the reference accident occurring during a four or five day visit to a port would be less than one in a million per reactor [16]. The AAEC's review of NPW accident scenarios concluded that more severe NPW accidents, which might result in larger releases of radioactivity due to containment degradation (eg. high speed collisions, vessel grounding, and containment failure from over-pressurisation), need not be considered in port assessments due to their extremely low probability [16].

The choice of a contained LOCA, as the reference accident, is supported by a Technical Safety Assessment (TSA) performed in Canada for a nuclear powered submarine 'reference design '[18]. This study examined a large number of reactor initiating events for NPW accidents, including primary coolant system pipework failures (LOCAs, etc), and non-LOCA events such as reactivity transients, safety system failures, steam line failures, and flooding. Also considered were hazards that may effect the reactor such as fires, explosions, ship collisions and falling objects.

The Canadian TSA was a Probabilistic Safety Analysis (PSA) of all postulated initiating events for a submarine "reference design". The TSA considered a range of fission product release rates from the fuel, and differing containment performance, including the timing and duration of releases to the environment. The TSA results show that the total core damage frequency is dominated by primary system failures giving rise to LOCAs. The Canadian TSA estimate of the likelihood of a LOCA is consistent with the estimates in the 1975 Reference Accident and the 2000 Reference Accident (DGNS, AEMI, 1998 [19]).

The 'contained LOCA' initiating event scenario is considered to represent an upper bound in terms of risk to the surrounding population for the purposes of emergency planning for NPW visits. The 2000 Reference Accident is thus an appropriate choice for assessing the suitability of Australian ports for visits by NPWs.

2.2 MODELLING

The consequences of the 1975 Reference Accident are calculated using a simplified, conservative model developed during the 1970s [11]. The assumptions, models and parameters need revision to be consistent with current information and international practices. Improved models and techniques have become available. The improved computer modelling allows more detailed and realistic assessment of accident consequences and radiation doses to members of the surrounding population.

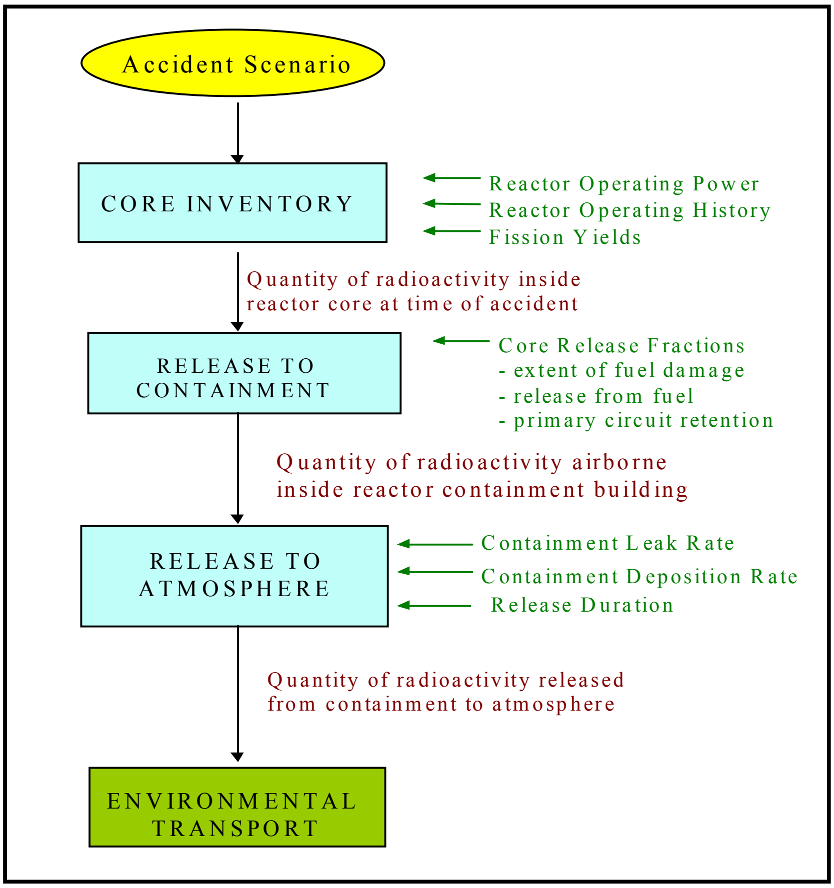
The computer code used for assessing the consequences of the 2000 Reference Accident is the ACCIDENT code, a generic nuclear reactor accident consequence assessment code developed by the NSB. In the ACCIDENT code, the process of modelling the 2000 Reference Accident is divided into the following three stages as described below (see Figure 2.2-1) and described in detail in the ACCIDENT Descriptive Manual [20]:

(i) Source Term Modelling, or modelling the transport of fission products from the reactor core to the environment to determine the magnitude, composition and timing of the release to the environment;

(ii) Environmental Transport Modelling, or modelling the transport of fission products in the environment to determine concentrations of radioactivity in the air, on the ground and in the foodchain; and

(iii) Radiation Dose Modelling or modelling of radiation doses which might be received by the surrounding population due to exposure to environmental concentrations of radioactivity.

Figure 2.2-1 Reference Accident Model



The ACCIDENT code is used by ARPANSA for the assessment because it is well documented [20]. It permits a detailed examination of the accident scenario inputs and the contributions to the calculated dose from all the fission products and dose pathways.

Sections 3 to 5 of this report gives a brief overview of the models used in the ACCIDENT code. These sections discuss the values of input parameters currently assumed, and those proposed for the new NPW Reference Accident. A summary of 1975 and 2000 Reference Accident parameters is included as Appendix A-1.

2.3 MODELLING PARAMETERS

In modelling the consequences of the Reference Accident the following considerations should be noted:

(i) Port assessments are concerned with planning for the early phase emergency response, when action must be taken rapidly to control radiation doses from a NPW accident. Therefore, only the short-term consequences of the 2000 Reference Accident, taken as the first 24 hours following the accident, are considered here in detail. The principal short-term hazards following the 2000 Reference Accident would be direct irradiation from the cloud (cloudshine); inhalation of fission products and direct irradiation from ground deposited radioactive material (groundshine). Intermediate and long term effects of ground, food and water contamination are not considered in this report.

(ii) Direct gamma shine from the vessel is neglected in the dose calculations, since distance and attenuation in air would reduce direct irradiation to insignificant levels beyond about 200m from the vessel [21,22].

(iii) Dispersion parameters are calculated assuming a ground level release and the receptor located on ground level at the centreline of the plume. For the extended release durations, credit is given to variability in the wind direction.

(iv) Direct radiation from resuspended beta and gamma emitting fission products that are deposited on the skin or inhaled are neglected since the doses resulting from these pathways are insignificant in comparison with other pathways [20,23].

(v) Aquatic dispersion of fission product releases to water are neglected since the overall hazards to the population from a release to water would be on a much smaller scale than for the same magnitude of release to the atmosphere [23].

2.4 VALIDATION OF ACCIDENT CODE

A number of validation exercises have been undertaken to provide confidence in the consequence results calculated by the ACCIDENT code. During 1995, the Australian Radiation Laboratory independently examined the models and parameters used in ACCIDENT and found them acceptable, within the limitations of the Gaussian plume model [24]. The NSB and ANSTO [25, 26] also undertook validation exercises. These validation exercises compared the results calculated by ACCIDENT for a specific accident scenario with those calculated by the independent internationally used code PCCOSYMA [27]. An inter-comparison of this type is considered in Appendix B

The comparisons show a high level of consistency between the two codes, and all differences have been explained and found acceptable. The validation exercises carried out on the ACCIDENT code provide a high degree of confidence, that the consequence results for the 2000 Reference Accident are valid and conservative.

3. SOURCE TERM

The source term refers to the magnitude, composition and timing of the release of radioactivity to the environment following the Reference Accident. In the ACCIDENT code, the process of modelling the source term is divided into the following three stages [20]:

(i) Estimate of Core Fission Product Inventory;

(ii) Release of Fission Products to the Reactor Containment; and

(iii) Release of Fission Products from the Containment to the Atmosphere.

3.1 ESTIMATE OF CORE FISSION PRODUCT INVENTORY

The core inventory refers to the quantity of each radioactive fission product inside the reactor core prior to the accident and depends on the reactor operating power and its operating history. The specific parameters that determine the core inventory of each fission product are:

- Reactor operating power parameters, consisting of:
    - (i) average reactor operating power; and
    - (ii) maximum reactor operating power.

- Refuelling cycle parameters, consisting of:
    - (i) period between refuelling; and
    - (ii) fraction of core replaced on refuelling.

- Reactor operation prior to accident, consisting of:
    - (i) operating time at maximum power prior to accident; and
    - (ii) shutdown time prior to accident.

It should be noted that precursor sources are neglected in the ACCIDENT model [20], for example, the post shutdown production of I-131 from Te-131 and Xe-135 from I-135. A special treatment of nuclides Cs-134 and Cs-136 has been necessary since the fission product yield used in ACCIDENT does not take into account activation of stable nuclides Cs-133 and Xe-136. In order to obtain conservative estimates, the fission product yields for Cs-133 and Xe-136 are used in ACCIDENT for Cs-134 and Cs-136 respectively.

3.1.1 Reactor Operating Power

Three classes of NPW are considered in calculating core inventories, namely:

(i) Submarines;

(ii) Smaller surface vessels; and

(i) NIMITZ class aircraft carriers.

In calculating the core inventories for submarines, a Los Angeles class submarine is considered since these vessels have the largest reactors. A Los Angeles class submarine has been estimated to have a maximum reactor operating power of about 160 MW(t) [22,28]. This estimate assumes the vessel can generate 38,000 shaft horsepower (28.3 MW), has a 7 MW electrical load and a nuclear power generating efficiency of 20%. The average reactor operating power has been estimated to be about 25% of maximum power, ie. 40 MW(t) [20,22].

The maximum and average reactor operating powers for smaller surface vessels (ie. vessels other than aircraft carriers) is considered similar to submarines, as these vessels typically have similar shaft horsepower [29] and electrical loads [29]. However, unlike submarines the surface vessels have two independent reactors.

In assessing the consequences of the 2000 Reference Accident, a maximum reactor operating power of 160 MW(t), and an average reactor operating power of 40 MW(t), is assumed for submarines and smaller surface vessels. The 1975 Reference Accident model also assumed an average reactor power for submarines and smaller surface vessels of 40 MW(t), however no maximum reactor power was specified [4,5,7,8,10].

NIMITZ class aircraft carriers have two reactors, which are assumed to generate 130,000 shaft horsepower (97 MW) per reactor [28]. Assuming a conservative electrical load of 50 MW (50% of shaft power) [29] and an efficiency of 25% [22], the maximum reactor operating power is estimated to be about 600 MW(t). As for submarines and smaller surface vessels, the average reactor operating power is taken as about 25% of maximum power, which for NIMITZ aircraft carriers is about 150 MW(t).

In assessing the consequences of the 2000 Reference Accident, a maximum reactor operating power of 600 MW(t) and an average reactor operating power of 150 MW(t) is assumed for NIMITZ class aircraft carriers. The 1975 Reference Accident model assumed the average reactor power for NIMITZ class aircraft carriers to be 500 MW(t) [6,9].

3.1.2 Refuelling Cycle

Due to the need to run for long periods of time without refuelling, NPW reactors have much longer refuelling cycles than land based reactors. The Senate Standing Committee into visits to Australia by nuclear powered or armed vessels [17] reported that US aircraft carriers can operate for 15 years before refuelling, at which time the whole core is replaced. The core lifetime assumed in Canada for assessing Canadian berths for NPW visits is 12 years [18]. The refuelling period assumed for assessing the consequences of the 1975 Reference Accident is not clearly specified, however, it is believed to be several years.

In assessing the consequences of the 2000 Reference Accident, a refuelling period of 15 years is assumed with 100% of the core replaced on refuelling. It is assumed that the 2000 Reference Accident occurs just prior to refuelling, when fission product core inventories are at a maximum.

3.1.3 Operation Prior to Accident

When a reactor is operated at higher power, the core inventory of short lived fission products increases significantly. These short-lived isotopes include the radioactive iodine isotopes, which are likely to be the major contributor to the consequences of a reactor accident.

To allow for the potential build up of these short-lived fission products, a period of 4 days of operation at maximum power is assumed to occur immediately prior to the accident, in addition to the 15 years operation at average power.

3.2 RELEASE OF FISSION PRODUCTS TO THE CONTAINMENT

The release of fission products from the reactor core to the containment is specified in the ACCIDENT code by a parameter termed the core release fraction [20]. This parameter represents the fraction of the core inventory of each fission product radionuclide, released into the containment atmosphere during the accident. The core release fraction takes into account factors such as the extent of fuel melting, the temperature and duration of the fuel melt, the volatility of the various fission products, and the retention of fission products in the reactor primary cooling circuit.

The core release fractions currently used for assessing the consequences of the Reference Accident are based on information from the United States Atomic Energy Commission available during the 1970s [30,31]. Nuclides that are likely to contribute significantly to the consequences of a nuclear accident are characterised by high core inventories, long half-life and/or high radiotoxicity. In the ACCIDENT code, a separate core release fraction is specified for the following nine groups of fission product radionuclides [20].

1. Xe,Kr
2. I,Br
3. Cs,Rb
4. Te,Sb
5. Ba,Sr
6. Ru
7. Mo,Tc,Rh
8. Ce,La,Pr,Y
9. Nb,Zr

More information on fission product release from nuclear reactors under severe accident conditions has become available and Table 3.2-1 show fractions for various fission product radionuclides reported in recent accident studies [22,32,33,34,35,36,37]. It is noted that these studies, with the exception of the NZ and Canada reports [22,37], are for reactors using oxide fuel, whereas NPWs are expected to use metallic fuel [22].

Table 3.2-1 Core Release Fractions Reported by Various Accident Studies

Nuclide(s)	**NZ** [22]	**UK1** [32]	**NUREG 5747 (USA)** [33]	**NUREG 1150 (USA)** [34]		**Chernobyl** [35,36]	**Canada** [37]
				95% Confidence Interval	*Mean*		
Xe,Kr	100%	90%	80%	100%	90%	80-100%	100%
I	70%	70%	40%	60%	15%	20%	70%
Cs	40%	50%	30%	40%	7%	10-17%	30%
Te	-	30%	15%	20%	4%	10-15%	10%
Ba,Sr	-	6%	3-4%	15%	3%	3-6%	5%
Ru	1%	2%	0.8%	0.4%	0.1%	3-6%	1%
Ce	-	-	1%	3%	0.4%	2%	0.1%
Zr	-	-	-	-	-	3%	0.1%

In the absence of more information specific to NPWs, the above studies are considered appropriate for defining core release fractions for the Reference Accident as shown in Table 3.2-2. Also shown for comparison are the core release fractions currently used for the 1975 Reference Accident and those that are specified for the Revised Accident [12], which took into account the release fractions of the Three Mile Island accident.

Table 3.2-2 Core Release Fractions for the Reference Accident

Nuclide(s)	**1975 Reference Accident [4,5,6,7,8,9,10]**	**1986 Revised Accident # [12]**	**2000 Reference Accident (new)**
Xe,Kr	100%	100%	100%
I,Br	50%	5%	50%*
Cs,Rb	15%	15%	30%
Te,Sb	-	-	15%
Ba,Sr	0.1%	0.1%	5%
Ru	10%	10%	2%
Mo,Tc,Rh	1%	1%	1%
Ce,La,Pr,Y	1%	1%	1%
Nb,Zr	1%	1%	1%

* *2% of iodine released is assumed to be in the form of organic iodine which does not plate out, and 98% of the iodine released is in the form of inorganic iodine. This is confirmed by comments in a New Zealand Report on Nuclear Propulsion [22].*

The AAEC Regulatory Branch provided a Revised Reference Accident model at the request of Australian Ionising Radiation Advisory Council (AIRAC).

The new core release fraction for some nuclides is higher than the value currently used while for others the new value is lower. The nuclides for which the core release fraction is increased are isotopes of caesium (increased by a factor of 2) and isotopes of barium and strontium (increased by a factor of 50). On the other hand, the core release fraction for isotopes of ruthenium is decreased by a factor of 5. A core release fraction for isotopes of tellurium, which is not currently specified for the 1975 Reference Accident, has been included in the 2000 Reference Accident.

3.3 RELEASE OF FISSION PRODUCTS FROM THE CONTAINMENT TO THE ATMOSPHERE

The leakage rate of fission products from the reactor containment to the atmosphere depends on the quantity of fission products airborne inside the containment, and the leakage performance of the containment system. In the ACCIDENT model the quantity of each fission product initially airborne, inside the containment is depleted with time after the accident, due to the processes of deposition onto surfaces inside the containment, radioactive decay and leakage from the containment [20]. The deposition rate of each radionuclide is determined from the calculated quantity of that nuclide airborne inside the containment, the containment dimensions (surface area and volume), and the rate at which the nuclide settles onto containment surfaces (specified by a parameter termed the containment deposition velocity).

The accident specific parameters involved in calculating the release of each fission product to the atmosphere are:

(i) The Containment Leak Rate;

(ii) The Containment Deposition Velocities; and

(iii) The Containment Surface Area to Volume Ratio.

3.3.1 Containment Leak Rate

The containment system provided on board an NPW, either a submarine or a surface vessel is a dual containment system consisting of a primary and a secondary containment [22,23,38]. The primary containment is provided by the reactor compartment, which is designed as a pressure vessel to house the reactor pressure vessel and primary circuit. The secondary containment surrounds the primary containment, and is provided by the internal ship bulkheads and/or the hull of the vessel. The reactor containment system is assumed functional for the duration of the accident.

3.3.1.1 Leak from Primary Containment.

Following an accident the leakage rate from the NPW primary containment has been estimated to be typically no more than 1% of the contained volume per day (%VPD), at a peak post-accident pressure of about 2 MPa [22,18]. In an actual accident, the pressure inside the primary containment, and therefore the containment leak rate, is likely to peak in the period 1 to 3 hours following the accident, after which it would gradually decay [18] due to the action of active and passive heat sinks.

The 1975 Reference Accident assumes the presence of only a primary containment, which is assumed to leak at a rate of 1.5%VPD. However, in the light of additional information available on NPW containment systems, allowance is made for a secondary containment in assessing the consequences of the 2000 Reference Accident.

For the primary containment, the design overpressure is assumed to be maintained for 24 hours following the Reference Accident, resulting in a 1%VPD primary containment leak rate over this 24 hour period. This is a conservative assumption, given that the overpressure period is likely to be much shorter. However, it does not necessarily result in a significant overestimation of fission product release. The overpressure period occurs early in the release, the time when most fission products are airborne inside the containment, and therefore available for release.

3.3.1.2 Release from Secondary Containment.

Fission products released from the primary containment leak into a secondary containment provided by bulkheads and/or the hull of the vessel. The Australian Defence Science and Technology Organisation has estimated the maximum leak rate to the atmosphere from internal compartments of a conventional naval vessel to be about 1% VPD [39].

For nuclear powered submarines, the Canadian Technical Safety Assessment (TSA) [18] has estimated that, in scenarios where the primary containment remains intact, the leakage from the secondary containment would be negligible. The TSA assumes that, to ensure secondary containment integrity, the vessel's crew follow accident management and emergency procedures. In cases where the secondary containment is breached by open personnel hatches, it is estimated that the contents of the secondary containment would be vented by diffusion to the atmosphere at a constant rate of about 1%VPD [18,22].

To allow for uncertainties regarding fission product transport processes within the secondary containment [40] and uncertainties about secondary containment provisions on board nuclear powered surface vessels, the leakage performance of the secondary containment is conservatively assumed to be degraded by an order of magnitude to 10%VPD. This is consistent with the approach taken by New Zealand in assessing the consequences of a NPW Reference Accident [22].

Taking into account the performance of both the primary and secondary containment the effective overall containment leak rate for assessing the consequences of the Reference Accident is taken to be 0.1%VPD.

3.3.2 Containment Deposition Velocities

Non-gaseous fission products trapped inside the reactor containment will gradually deposit onto surfaces within the containment, reducing the amount of activity available for release to the atmosphere. The dominant deposition processes following the 2000 Reference Accident are likely to be agglomeration, or coagulation, of particles, and gravitational settling [39,37]. The presence of steam inside the containment, which is likely following the 2000 Reference Accident, will enhance these deposition processes.

The 1975 Reference Accident includes a very simple model for containment deposition, in which 50% of the iodines released into the containment is assumed to plate out, and is therefore unavailable for release to the atmosphere. No deposition within the containment is assumed for other nuclides. The model used in the ACCIDENT code includes a more detailed containment deposition model for all fission products except noble gases, thus allowing a less conservative estimate of the release from the containment [20].

Several studies have been performed to examine the behaviour of aerosols inside reactor containment following a major reactor accident [40]. These studies involve experiments in which an aerosol is released into a containment structure, and the deposition behaviour is examined. The deposition behaviour is also assessed by the analyses of specific accident scenarios using computer codes, which have been validated using experimental data. Based on the results of seven of these studies, values for the deposition half-life of aerosols inside a reactor containment have been computed. The results are summarised in Table 3.3-1.

The results indicate that the deposition half-life for aerosols, inside a reactor containment, is generally less than about 2.5 hours. For the caesium and iodine isotopes, the deposition half-life is even shorter – of the order of 40 minutes. In assessing the consequences of the Reference Accident, the deposition half-life has been conservatively assumed to be 5 hours for fission product groups other than noble gases (which do not deposit), and organic iodine which is treated separately. This allows for uncertainties and the possibility of re-suspension of deposited material following deposition.

Due to its importance in determining accident consequences, the deposition behaviour of radioactive iodine needs to be given separate consideration. The assumption of a five hour deposition half life is very conservative for most iodine species. However, some iodine is released in the form of organic iodine that does not plate out appreciably. For this reason organic iodine is treated separately, and is assumed to have zero containment deposition [41]. Two percent of all iodine is conservatively assumed to be in organic form.

In the ACCIDENT code, the rate at which non-gaseous airborne fission products in the containment building deposit onto surfaces within the containment is specified in terms of a containment deposition velocity. The containment deposition velocity is related to the deposition half-life through the surface area to volume ratio of the containment. Assuming a containment surface area to volume ratio of 1.2m^{-1} (see Section 3.3.3), the deposition velocity corresponding to a deposition half-life of 5 hours is $30\mu\text{ms}^{-1}$.

Table 3.3-1 Data on Deposition Characteristics of Aerosols in a Reactor Containment

Study [40]	**Description of Results Used**	**Case/Figure No.**	**Deposition Half Life**
1. p27	Results of the LACE experiments LA2 and LA4 involving CsOH aerosol.	LA2 test. Figure 1.	48 min.
		LA4 test. Figure 5.	25 min.
2. p81	Calculation of the time variation of the airborne mass of radioactive aerosols CsI and CsOH using ITHACA code.	Figure 2.	41 min.
3. p101	Results of the DEMONA experiments B2, B3 and B4 involving SnO_2 aerosol.	Expt. B2 (dry). Figure 8.	80 min.
		Expt. B3/B4 (steam). Figure 8.	41 min.
4. p145	Results of the NSPP experiments 501, 502, 503, 504 and 505 involving Fe_2O_3 aerosol.	Exp. 501	110 min.
		Exp. 502	110 min.
		Exp. 503	70 min.
		Exp. 504	70 min.
		Exp. 505	38 min.
5. p159	Results of the VANAM experiment.	Figure 6. Low annulus measurement	65 min.
6. p303	Calculation of airborne radionuclide masses for LCP scenario using CONTAIN code.	Figure 17a.	
		I	67 min.
		Cs	69 min.
		Figure 17b.	
		Te	318 min.
		Sr	132 min.
		La	75 min.
		Ce	75 min.
		Nb	75 min.
		Figure 17c.	
		Ba	64 min.
7. p587	Calculation of airborne aerosol masses for AB and TMLB scenarios by AEA.	Figure 7. AB scenario (UKAEA)	67 min.
		Figure 11. TMLB scenario (UKAEA)	133 min.

3.3.3 Containment Surface Area to Volume Ratio

The internal surface area to volume ratio of the reactor containment affects the deposition rate by specifying the amount of surface area available per unit volume of airborne material. The time constant for deposition of airborne material in the containment is determined by multiplying the deposition velocity by the surface area to volume ratio [18,42].

The external surface area of the reactor compartment, (within the primary containment), on board a nuclear submarine has been estimated to be 470 m^2, while the free volume of the reactor compartment has been estimated to be 390 m^3 [39], giving a surface area to volume ratio of 1.2 m^{-1}. This value has been used for assessing the consequences of the Reference Accident. A surface area to volume ratio of $1.2m^{-1}$ has also been used for surface ships.

4. ENVIRONMENTAL TRANSPORT

Environmental transport modelling is concerned with the transport of fission products in the environment to determine the concentrations of radioactivity in the air, on the ground, and in the food chain. The process of environmental transport modelling for the Reference Accident is divided into the following stages:

(i) Atmospheric Dispersion; and

(ii) Ground Deposition.

4.1 ATMOSPHERIC DISPERSION

The release of fission products from the secondary containment to the atmosphere is assumed non-energetic and at sea level for both submarines and surface vessels. Radioactive material released from the NPW would disperse in the atmosphere according to the prevailing dispersion conditions, forming a radioactive plume in the downwind direction.

Atmospheric dispersion modelling is concerned with the dispersion of the radioactivity released from a source, and is used to determine the airborne radioactivity concentrations in the atmosphere following the 2000 Reference Accident. The dispersion conditions are influenced primarily by the meteorological conditions. In particular, the amount of atmospheric turbulence, the wind speed, the wind direction variability, and the nature of the surrounding terrain. In general, the more turbulent the atmosphere the greater the extent of atmospheric dispersion, and hence the lower resulting air concentrations of radioactivity. Stable atmospheric (strong inversion) conditions are of particular concern in assessing the consequences of nuclear accidents, as these conditions would result in higher airborne concentrations of radioactivity.

4.1.1 Gaussian Plume Model

The model used for atmospheric dispersion for the 1975 Reference Accident is a Gaussian plume model. For the purpose of emergency planning this model is commonly used for estimating the consequences of nuclear reactor accidents [11,18]. This model is generally used in preference to other more complex models because it is mathematically simple, and readily implemented in computer codes. For many applications, it produces results that agree with experimental data as well as any other model [43]. It has been found particularly useful for accident assessment studies involving atmospheric dispersal of toxic material. The validity, accuracy and limitations of the Gaussian plume model have been studied in detail elsewhere [11,44,45,46,49].

The model used in the ACCIDENT code also utilises the Gaussian plume model. The equations used in ACCIDENT are the basis of the 2000 Reference Accident analysis and are described in more detail in Appendix A-3. This model assumes that the concentration profile of material in the plume follows a Gaussian distribution in both the horizontal and vertical directions. The size of the plume, and hence the magnitude of the resulting air concentrations of radioactive material, is determined by the values of the horizontal and vertical sigma parameters and the wind speed. The horizontal and vertical sigma parameters represent the standard deviation of the Gaussian distribution of material in the horizontal and vertical directions, while the wind speed determines the size of the plume in the downwind direction. The larger the sigma parameters and wind speed, the larger the plume, and hence the lower the atmospheric concentrations of radioactivity.

The most common way of specifying the level of atmospheric turbulence is the classification scheme developed by Pasquill [47]. In this scheme, the level of atmospheric turbulence is specified as one of six stability categories, ranging from stability category A, which represents turbulent atmospheric conditions; through to stability category F, which represents stable atmospheric conditions. A seventh stability category, stability category G, has also been defined to represent very stable atmospheric conditions [48,50]. The values of the sigma parameters have been determined experimentally for each of the atmospheric stability category [50].

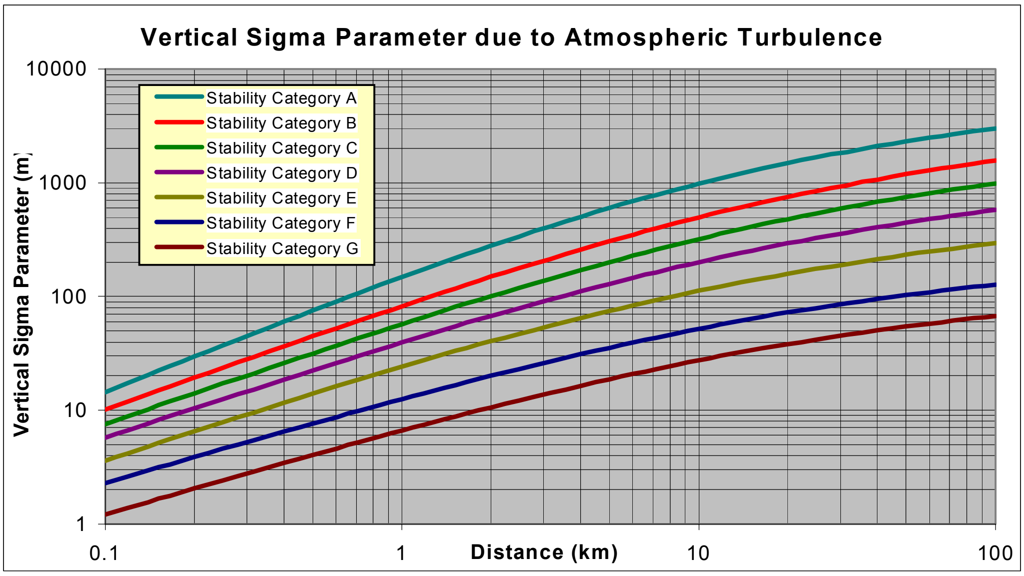
As the plume travels downwind and expands vertically, it may eventually reach and be reflected by the ground, and if one exists by an atmospheric inversion layer [11,50,51]. An atmospheric inversion layer refers to a positive temperature gradient in the lower levels of the atmosphere, which acts as a boundary to the vertical dispersion of material in the atmosphere. Inversion layers can occur at varying heights and are particularly evident during stable atmospheric conditions. The Gaussian model used in ACCIDENT allows for reflections from both the ground and an inversion layer.

Note that no allowance is made in ACCIDENT for building wake effects or plume rise due to buoyancy and/or momentum [50]. This results in conservative estimates of airborne radioactivity concentrations since these effects will only increase the values of the sigma parameters or increase the height of the plume. In addition, no allowance is made for topographic effects on atmospheric dispersion; however, this is again conservative due to the increased turbulence caused by topography.

4.1.2 Vertical Sigma Parameters

The vertical sigma parameter specifies the size of the plume in the vertical direction that depends on the level of atmospheric turbulence and the terrain roughness. These two processes are treated separately in determining the values of the vertical sigma parameter. Figure 4-1 shows the effect of atmospheric turbulence on the vertical sigma factor.

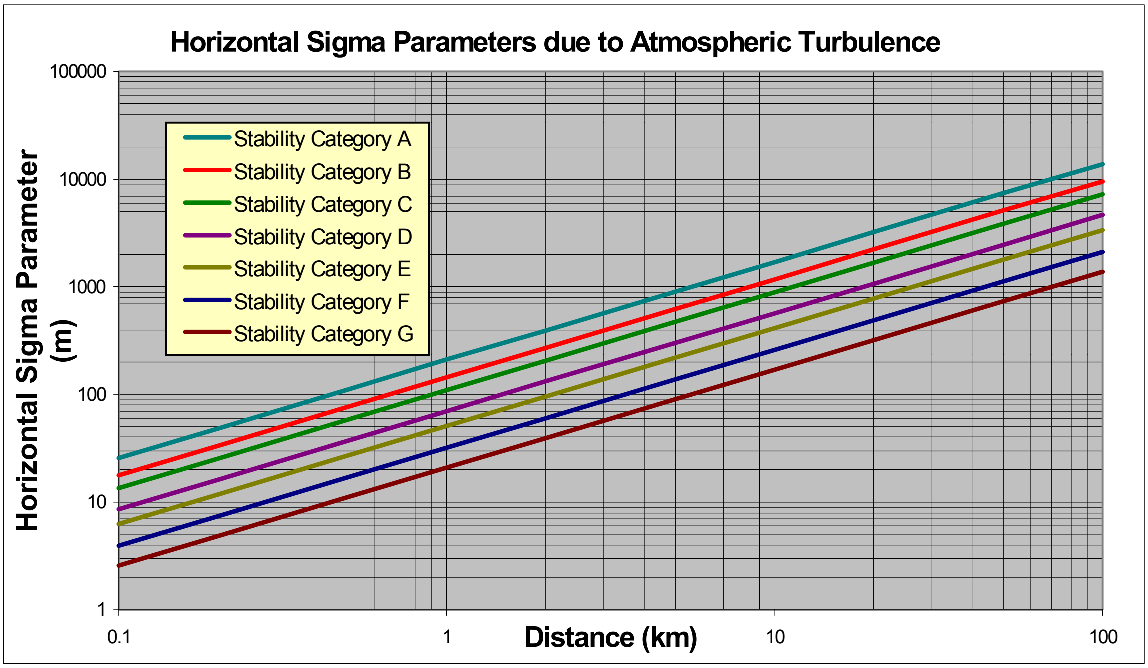
Figure 4.1 Vertical Sigma Parameters due to Atmospheric Turbulence



4.1.3 Horizontal Sigma Parameters

The horizontal sigma parameter specifies the size of the plume in the horizontal direction. The size of the plume in the horizontal direction depends on the level of atmospheric turbulence and the variability in the wind direction. These two processes are treated separately in determining the values of the horizontal sigma parameter. Figure 4-2 shows the effect of atmospheric turbulence on the horizontal sigma factor.

Figure 4-2 Horizontal Sigma Parameters due to Atmospheric Turbulence



4.1.4 Factors that influence the Sigma Parameters

The value of the sigma parameters in the Gaussian plume model depends on:

(i) the level of atmospheric turbulence;

(ii) the amount of variability in the wind direction; and

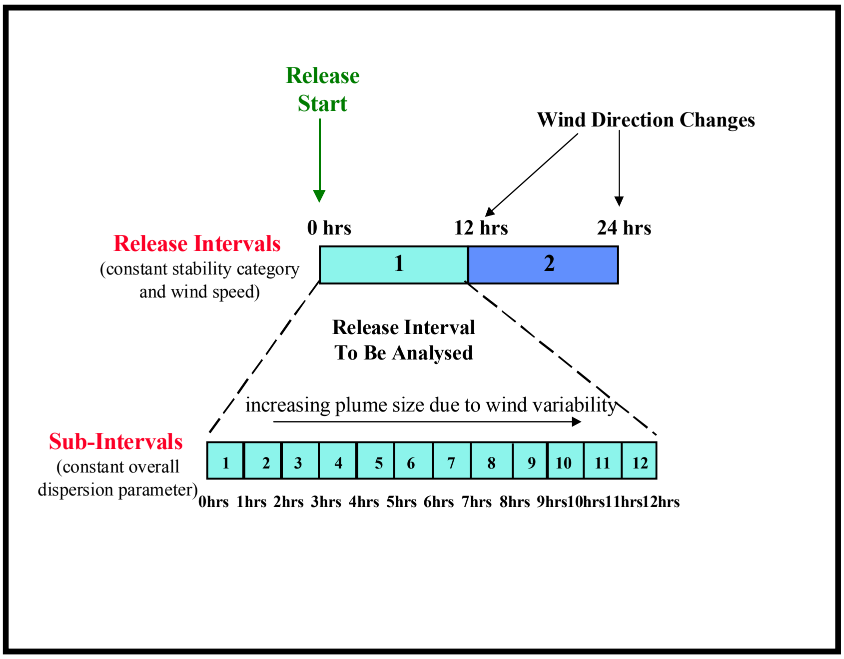
(iii) the terrain roughness.

Variability in wind direction and terrain roughness act in addition to normal atmospheric turbulence to aid the dispersion of material in the atmosphere [48,50]. Variation in wind direction increases the size of the plume in the horizontal direction (increases the horizontal sigma parameter), while terrain roughness increases the amount of turbulence in the vertical direction (increases the vertical sigma parameter). These processes are allowed for by applying modifying factors to the sigma parameters.

The ACCIDENT code [20] allows for wind direction variability over an extended release, and allows for the effects of terrain roughness. The ACCIDENT code includes wind variability using a model developed by the UK National Radiological Protection Board (NRPB) and factors associated with Pasquill wind categories [47]. The use of wind variability is included because it is observed to occur in real plumes that are over extended release intervals.

For releases of less than 30 minutes, the ACCIDENT code uses a standard Gaussian horizontal sigma parameter, which is the same as a release of a few minutes. For prolonged releases of greater than 30 minutes duration, it takes into account fluctuations in wind direction and wind turbulence effects.

Figure 4-3 Modelling of Extended Releases



The longer the release of material the greater the dispersion due to wind variability and turbulence and the modelling of the extended releases is shown in Figure 4-3. For the Reference Accident, the radioactivity is assumed to be released at ground level release and concentrations are calculated for a ground level receptor in the downwind direction on the centreline of the plume travel.

Full details of the atmospheric dispersion model used in ACCIDENT may be found in the ACCIDENT Descriptive Manual [20]. Other specific parameters involved in the calculation of air concentrations of fission products for the new model are:

1. Meteorological parameters, consisting of:
    (i) atmospheric stability category; and
    (ii) wind speed.
2. Terrain roughness.

4.1.5 Meteorological Conditions Assumed in 2000 Reference Accident

Meteorological conditions existing at the time of the Reference Accident determine the extent of dispersion and the extent of the dilution of radioactive material released to the atmosphere. The two parameters specifying the meteorological conditions, are the atmospheric stability category, and the wind speed.

In general, stability categories A through D occur during daylight hours when insolation heats the land surface resulting in turbulence due to natural convection. Stability category A is associated with very turbulent conditions while category D is associated with calmer conditions. On the other hand, stability categories D through F generally occur at night when the land is cool resulting in little atmospheric turbulence and the formation of stable inversion layers. Stability category F is associated with low wind speeds and strong inversion conditions, while category D is associated with higher wind speeds.

Analysis of meteorological data for various Australian coastal sites [65] shows that stable meteorological conditions generally occur only at night and are unlikely to last for longer than 12 hours. The analysis also shows that the stable conditions are followed by more dispersive conditions accompanied by a change in wind direction. Analysis of wind data from specific ports confirms the validity of this when using the 1975 Reference Accident [4,5, 6,7,8,9,10]. The maximum vessel removal time specified in the conditions of entry for NPW visits to Australia is 24 hours [1], so consideration of meteorological conditions beyond this time scale is not necessary.

The meteorological conditions assumed for the 1975 Reference Accident provide a conservative assessment of accident consequences, yet they occur sufficiently frequently in Australian coastal locations to warrant consideration in port assessments. Therefore, the meteorological conditions assumed for the 1975 Reference Accident, as described above, are used in the 2000 Reference Accident

The 2000 Reference Accident assumes that inversion meteorological conditions, characterised by stability category F and a conservative wind speed of 1 ms^{-1}, exist for 12 hours following the occurrence of the accident. Following this initial 12 hour period, conditions are assumed to become more dispersive and the wind direction is assumed to change, resulting in a different population being affected by the plume. For this second 12 hours stability category D and a wind, speed of 3 ms^{-1} is assumed.

The wind is assumed to blow in a different direction during the second 12 hour period following the Reference Accident compared to the initial 12 hour period, exposing two separate populations to the radioactive plume. The doses received due to the radioactive plume during the second 12 hour period are negligible compared to those received during the first 12 hour period. This is due to the significantly lower atmospheric radioactivity concentrations during the second 12 hour period, which are a result of the more dispersive meteorological conditions and the significantly lower release rate of radioactivity from the vessel.

Wet deposition, due to rainfall is a sporadic event that would remove more particulate from a cloud than the dry deposition processes. However, rainfall is not expected during stability category F and is not considered (wet deposition would normally be associated with more dispersive conditions than are assumed for the Reference Accident).

In calculating both individual and collective inhalation and cloudshine doses, only the initial 12 hour period of stable meteorological conditions is considered. In calculating groundshine doses, however, a period of 24 hours is considered since groundshine doses continue to accrue following passage of the radioactive plume.

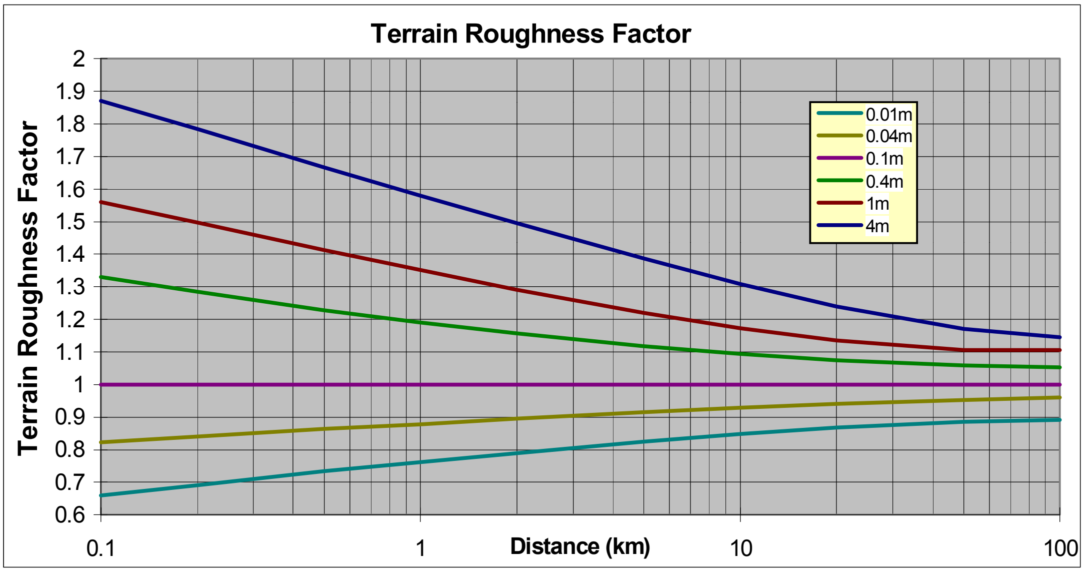
4.1.6 Terrain Roughness

Terrain roughness affects the dispersion of radioactive material in the atmosphere by enhancing atmospheric turbulence. Currently, terrain roughness is not considered in calculating the consequences of the Reference Accident, however, for the new Reference Accident, the dispersion is modified to account for terrain roughness as described in the ACCIDENT code [20]. Allowance is made by applying a correction factor in the Gaussian plume model related to roughness length, which is a measure of the mean variation in the ground surface. The following terrain roughness options are available in ACCIDENT [20]:

Terrain Type	**Roughness Length**
1. Short Grass	0.01m
2. Pasture	0.04m
3. Root Crops	0.1m
4. Mixed Agricultural Area	0.4m
5. Dense Suburbs, Woodland	1.0m
6. City Centres	4.0m

A conservative roughness length of 0.1 m is assumed in calculating the consequences of the Reference Accident. This value allows for the fact that many NPW berths are within ports surrounded by various buildings and structures, and the fact that waves affect the water surface surrounding NPW anchorages. Figure 4-4 shows the variation in Terrain Roughness factor with distance for the various roughness options.

Figure 4-4 Terrain Roughness Factor



4.2 GROUND DEPOSITION

Ground deposition refers to the settling out of non-gaseous material from the plume onto the ground, vegetation and structures as the plume travels downwind. Currently, ground deposition is not considered in calculating the consequences of the 1975 Reference Accident. For the 2000 Reference Accident, dry deposition of material is determined from the calculated air concentrations, using a parameter termed the ground deposition velocity [20]. Wet deposition is not considered in the ACCIDENT code. This is considered acceptable since wet deposition would normally be associated with more dispersive conditions than are assumed for the 2000 Reference Accident, resulting in little, if any, increase in calculated consequences.

The accident specific parameters involved in the calculation of ground concentrations of fission products are:

(i) Ground deposition velocities; and

(ii) Physical removal half-life of deposited material.

4.2.1 Ground Deposition Velocities

The ground deposition velocity specifies the rate with which airborne material in the radioactive plume deposits onto the ground and other surfaces as it travels downwind. From information available [11,44,45,51,50,52], the ground deposition velocities used for assessing the consequences of the Reference Accident are shown in Table 4.2-1.

Table 4.2-1 Ground Deposition Velocities for the Reference Accident

Radionuclides	Ground Deposition Velocity (ms^{-1})
Inorganic iodine	0.01
Organic iodine	0
Noble Gases	0
All other radionuclides	0.003

4.2.2 Physical Removal Half-Life

The physical removal of ground deposited radioactivity by natural processes such as wind and rain is modelled in ACCIDENT by defining a physical removal half-life and applying this to the ground deposited activity in addition to the radioactive half-life [20]. However, since this report is only concerned with the early phase consequences of the Reference Accident (ie. the first 24 hours), removal of deposited material by physical removal processes is not included and an infinitely long half-life is assumed.

4.2.3 Mathematical Uncertainty

This 2000 Reference Accident uses a number of assumptions from the ACCIDENT code. This can lead to an uncertainty in the results provided. With any calculation of this type uncertainties can exist in factors such as:

(i) estimate of the source term;
(ii) atmospheric dispersion;
(iii) individual breathing rate;
(iv) risk for intake factor;
(v) containment leak
(vi) performance;
(vii) deposition half-life within the containment;
(viii) core release fractions;
(ix) averaging of exposure data; and

(x) shielding available to individuals.

The ACCIDENT model is suitable for planning an emergency response provided the uncertainties discussed above are taken into account by the use of conservative assumptions.

Since real-time data is available, the ACCIDENT model should not be used in actual emergencies for the estimation of airborne radionuclide concentrations, or for risk assessments of individuals that have been exposed. However, the real time data can be checked against the model estimates, and the results used to adjust the model parameters to refine the model estimates.

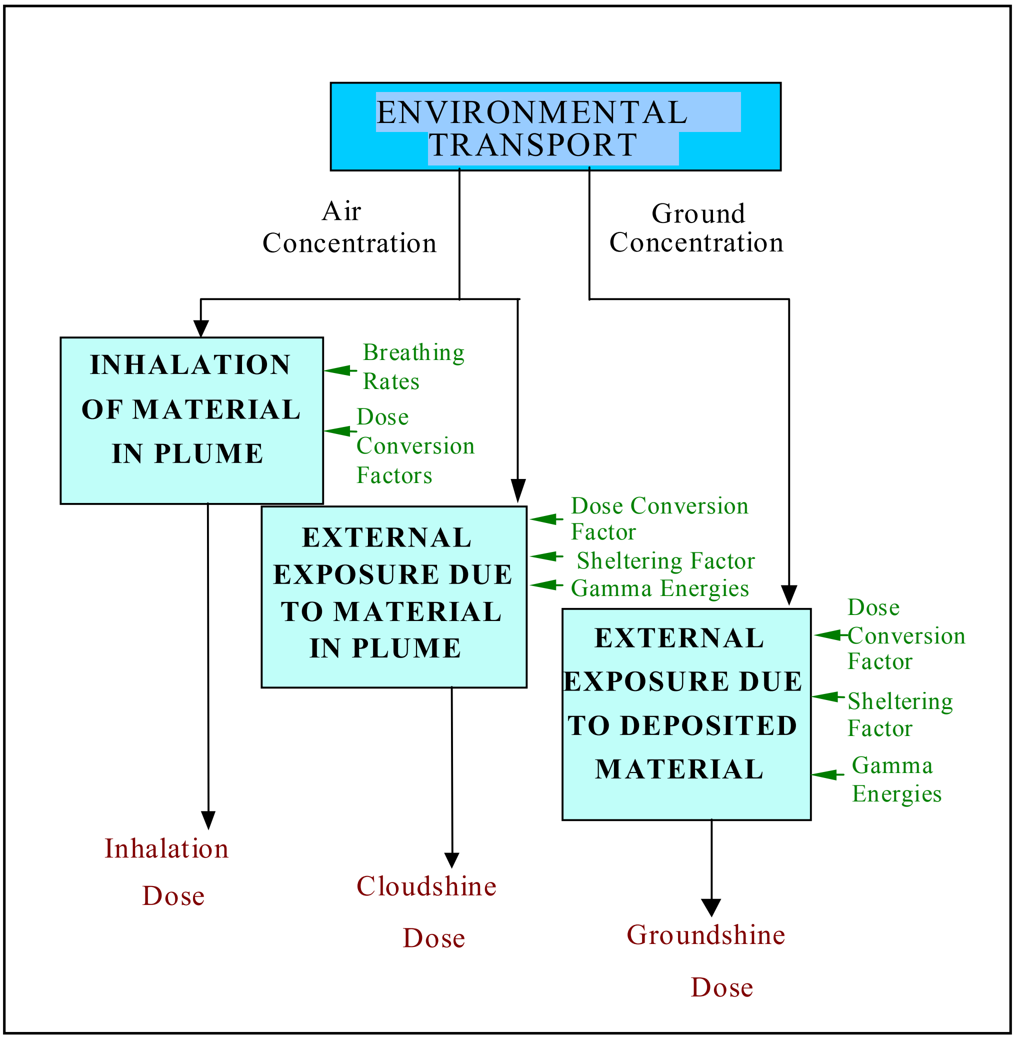
5. RADIATION DOSE

Radiation dose modelling is concerned with the calculation of radiation doses, which may be received by the surrounding population from exposure to the environmental concentrations of radioactivity. Since the doses are based on calculation there will be some uncertainty, and this is discussed in more detail in Appendix A-4.

The most important dose pathways considered in assessing the consequences of the Reference Accident are shown in Figure 5-1 and include:

- Cloudshine, or direct external exposure from material in the plume;
- Inhalation, or internal exposure from inhalation of material in the plume; and
- Groundshine or direct external exposure from material deposited on the ground.

Figure 5.1 2000 Reference Accident Environmental Transport Model



The radiological acceptability criteria for port assessments include limits on dose received by individuals within the exposed population, and the sum of the doses to all individuals within the exposed population. In order to assess a port against the radiological acceptability criteria, both individual and collective doses must be calculated. A port is suitable for visits by NPWs where:

- countermeasures can be implemented in a timely manner to maximise the averted doses to individuals; and
- the collective dose criterion is satisfied

5.1 INDIVIDUAL DOSE

The models and parameters used for the calculation of individual doses resulting from the 2000 Reference Accident due to each major dose pathway are briefly described below.

5.1.1 Cloudshine Dose

Cloudshine is the pathway by which radiation doses are received externally by direct irradiation from radioactive material in the plume. A correction factor, termed a sheltering factor, is included in the cloudshine dose model to allow for dose reduction due to the sheltering effect of residential and other structures. The ACCIDENT code neglects plume depletion with distance, due to ground deposition of material, resulting in conservative estimates of air concentration. The accident specific parameters involved in the calculation of cloudshine doses are:

- Cloudshine Dose Conversion Factor; and
- Cloudshine Sheltering Factor.

5.1.1.1 Cloudshine Dose Conversion Factor

In assessing the consequences of the 2000 Reference Accident cloudshine doses are calculated using a semi-infinite cloud model which gives conservative dose results at all downwind distances for ground level releases [20]. The dose conversion factor for the semi-infinite cloud model used in the ACCIDENT code for calculating the consequences of the 2000 Reference Accident is 5×10^{-14} Sv Bq^{-1} MeV^{-1} s^{-1} m^{3} [44,45].

5.1.1.2 Cloudshine Sheltering Factor

In assessing the consequences of the 2000 Reference Accident, it is assumed that an individual remains outdoors for 12 hours following the accident so that there is no attenuation due to sheltering, and therefore the cloudshine sheltering factor of 1 is assumed.

5.1.2 Inhalation Dose

The pathway by which radiation doses are received internally is through inhalation of material in the plume. In calculating individual inhalation doses following the 2000 Reference Accident, the individual is assumed to remain outdoors and hence exposed to the radioactive plume for 12 hours following the accident.

The method used to assess inhalation doses from the 1975 Reference Accident model considers only the single organ thyroid inhalation dose. This is because the thyroid is likely to be the critical organ for inhalation dose following a nuclear reactor accident. The consequences of the fission product release are dominated by radioactive iodine isotopes, which concentrate in the thyroid gland after entering the body. Thyroid inhalation dose is calculated for two groups according to age, namely children and adults.

Two types of inhalation dose should be considered in calculating the consequences of the 2000 Reference Accident. These are the single organ thyroid inhalation dose, and the effective inhalation dose. The parameters involved in the calculation of these inhalation doses are:

1. Breathing rates, consisting of:
    (i) child breathing rate; and
    (ii) adult breathing rate.
2. Inhalation dose conversion factors for:
    (i) effective dose; and
    (ii) thyroid dose.

5.1.2.1 Breathing Rates

The breathing rate determines the quantity of radioactive material inhaled from the radioactive plume. The child and adult breathing rates used for assessing the consequences of the 2000 Reference Accident are 1.7×10^{-4} m^3s^{-1} and 2.7×10^{-4} m^3s^{-1} respectively [53].

5.1.2.2 Inhalation Dose Conversion Factors

Inhalation dose conversion factors are nuclide specific factors, in units of $SvBq^{-1}$, which are used to determine the committed radiation dose (Sv) received per unit activity (Bq) of that nuclide inhaled. Two sets of dose conversion factors are required, one set for effective inhalation dose, and one set for single organ thyroid inhalation dose.

The dose conversion factors used in the ACCIDENT code for effective inhalation dose are taken from the IAEA Basic Safety Standards [54], while those used to calculate thyroid inhalation dose are taken from ICRP 71 [55] where possible, or otherwise from NRPB-GS7 [56]. These values are used in assessing the consequences of the 2000 Reference Accident.

5.1.3 Groundshine Dose

Groundshine is the pathway by which radiation doses are received externally by direct radiation from radioactive material deposited onto the ground or other surfaces such as vegetation or structures. The method for calculating the consequences of the 1975 Reference Accident does not consider the groundshine pathway. For the 2000 Reference Accident, groundshine doses are calculated using the ACCIDENT code [20].

The accident specific parameters involved in the calculation of groundshine doses are:

(i) Groundshine Dose Conversion Factor;

(ii) Groundshine Sheltering Factor.

5.1.3.1 Groundshine Dose Conversion Factor

Groundshine doses are calculated assuming exposure to an infinite uniformly contaminated plane using a dose conversion factor of 9×10^{-16} Sv Bq^{-1} MeV^{-1} s^{-1} m^{2} [44].

5.1.3.2 Groundshine Sheltering Factor

In calculating 24 hour groundshine doses, it is assumed that an individual spends 50% of the time indoors and 50% of the time outdoors during the first 24 hours following the accident. A sheltering factor of 1 is assumed for outdoor exposure, while a sheltering factor of 0.2, appropriate for residential structures, is assumed for indoor exposure [27,53,57]. Therefore, the overall sheltering factor assumed for groundshine is 0.6 (ie. [0.5x1]+[0.5x0.2]).

5.2 RECOMMENDED INDIVIDUAL DOSE CRITERIA FOR INTERVENTION

The suitability of Australian ports for visits by NPWs has previously been assessed by the NSB, using radiological criteria developed in the mid 1970s [14,59]. Compliance with the radiological criteria was assessed by the calculation of radiation doses to the whole body from airborne radioactive materials, and to the child thyroid from inhalation of radioactive iodine released following the 1975 Reference Accident.

5.2.1 Generic Intervention Levels

In its November 1998 meeting, the Radiation Health Committee approved the use of the Generic Intervention Levels, as described by the IAEA Safety Series 109 [62], for future emergency planning. This decision is likely to be reflected in the revision of the NH&MRC recommendations on intervention in radiation emergencies. The IAEA Safety Series 109 recommends that the implementation of a particular countermeasure be based on an optimisation process, to maximise the potential benefit.

For emergency planning, this optimisation decision is based on estimates of the dose averted through carrying out the countermeasure. For the derivation of planning zones, the estimate of avertable dose is based on the projected effective dose or organ dose from the 2000 Reference Accident.

Countermeasures considered were:

(i) Sheltering, where the maximum avertable doses arising from the 2000 Reference Accident exceed 10mSv;

(ii) The administration of stable iodine, where the maximum avertable thyroid doses arising from the 2000 Reference Accident exceed 100mGy for any age group; and

(iii) Evacuation, where the maximum avertable doses arising from the 2000 Reference Accident exceeds 50mSv.

This information is summarised in Table 5-1.

Table 5-1 Individual Dose Criteria for Intervention [62]

Criteria	Maximum Avertable Dose (mSv)	Maximum Avertable Thyroid Dose
Sheltering	10	-
Evacuation	50	-
Stable I Administration	-	100 mGy

The NHMRC's current intervention levels [53] consider the dose to the thyroid. For the NPW Reference Accident, iodine is a dominant factor in the release. Thus, in determining the zone distances, a lower level of intervention of 500mGy has been retained in the assessment of the zone distances described in this report.

5.3 COLLECTIVE DOSE

Collective dose provides a measure of the societal consequences in terms of the number of health effects, which may appear over the ensuing lifetime of the surrounding population. In the Safety Assessment Principles [58] for controlled facilities, and in the ARPANSA criteria for siting of controlled facilities [2], guidance is given on criteria for the consequences of a reference accident. Principle 119 of the Safety Assessment Principles covers both individual and collective effective dose requirements namely:

The consequences of the Reference Accident are determined for meteorological conditions which result in the maximum consequences of the accident, but which occur no less than 10% of the time. For these consequences, it is determined that:

(a) *emergency intervention would be feasible at any location around the site, at the intervention levels recommended by national and international bodies and adopted by ARPANSA;*

(b) *the maximum collective effective dose would be less than 200 person-Sv; and*

(c) *the long term use of any land surrounding the site would not be disrupted due to radioactive contamination.*

In calculating collective effective doses, no allowance is made for the imposition of short-term emergency interventions. A calculation cut-off is set so those individual doses representing very low levels of risk are not included in the collective dose. This cut-off value may be determined by the population distribution of the area around the site, topographical or geographical features, or based on a level of dose that is considered to represent an acceptable level of risk in the circumstances. The population considered when determining the collective effective dose must represent the worst case in terms of location.

The current port assessments [4,5,6,7,8,9,10] calculate the doses using the 1975 Reference Accident radiological criteria [59]. The whole body dose and the thyroid dose are estimated, and the port acceptability criterion is stated in terms of additional cancer fatalities that might occur over the ensuing lifetimes of persons exposed. The criterion in these port assessments is that the collective dose estimated would result in no more than 10 additional fatalities. The 200 person-Sv effective collective dose criterion used by ARPANSA is equivalent to this original criterion.

For the ports covered by the 1975 Reference Accident the collective dose is calculated on a port specific basis for 12 different wind directions blowing into 30 degree sectors. It is essentially calculated multiplying the sector average individual dose received in the surrounding population by the total population in the sector. In order to determine the maximum consequences the wind direction giving the highest collective dose is used to assess port acceptability. The 2000 Reference Accident will retain this approach in estimating the consequences of the population. The acceptability of a port will depend on satisfying the ARPANSA collective dose requirement of 200 person-Sv.

The accident specific parameters involved in the calculation of collective doses are:

(i) Population data;

(ii) Child population fraction;

(iii) Collective dose cut-off assumption;

(iv) Sheltering parameters, consisting of:

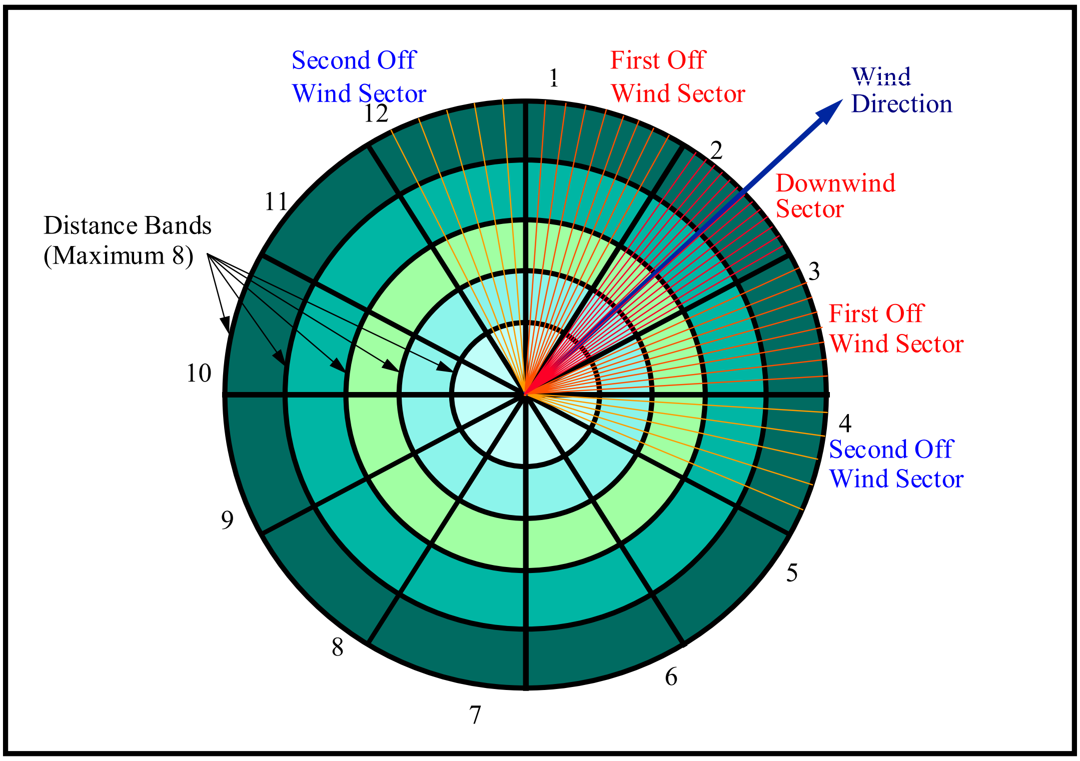
    (a) Proportion of population indoors;

    (b) Sheltering factor;

5.3.1 Population Data

To calculate collective doses, population data is specified on a polar grid around the port consisting of twelve 30-degree sectors and up to 8 distance bands (see Figure 5-2).

Figure 5-2 Wind Variability Dose Effect on Adjacent Sectors



Population data for Australian ports is obtained using the MapInfo and CDATA software packages [60,61]. The MapInfo package contains geographical data for the whole of Australia and interfaces with CDATA, a CDROM package containing census data for the whole of Australia. The CDATA package is updated, as new census data becomes available (every 5 years). A customised MapInfo application is used to obtain the population data for each element of the polar grid described above.

Transient populations such as workers or shoppers occupying the central business district (CBD) of cities and towns are also considered in calculating collective doses. The inclusion of wind variability leads to an increase in the population exposed, due to the plume spread over a greater number of sectors. This means there is some contribution to population dose from the sectors adjacent to the downwind sector

5.3.2 Child Population Fraction

Since individual inhalation dose depends on age group, the distribution of age in the exposed population is required to determine the average dose for each grid element. This age distribution is specified as a child population fraction, that is, the fraction of the exposed population that are children. The child population fraction assumed for assessing collective doses in the 1975 Reference Accident is 0.2 for all Australian ports. This value is consistent with currently available census data and will be used for calculating collective doses in future port specific assessments based on the 2000 Reference Accident.

5.3.3 Collective Dose Cut-Off Distance

Collective dose cut-off is determined either by the limits on population, topographical or geological features, or alternatively it can be based on a level of dose, which is considered an acceptable level of risk in the circumstances of an accident [58]. The general problem with calculating collective doses is the disproportionate weighting of small doses affecting a large population at large distances.

For NPW visits to Australian ports collective doses are calculated out to a certain distance termed the cut-off distance (the outer distance of the outermost distance band). The cut-off distance is determined on a port specific basis, such that the additional contribution to total collective dose from distances beyond the cut-off distance is negligible. A truncation distance of dose summation to a maximum distance of 40km is used in the existing assessment reports [4,5,6,7,8,9,10]. This port specific approach will continue to be used to determine cut-off distances.

The cut-off distance used for each port will be justified in individual port assessment reports. In any case, the cut-off distance for a port would not exceed 40km since this is the distance to which the plume approximately travels during the first 12 hours, based on the 1m/s wind speed used in the 2000 Reference Accident. The additional collective dose received by the population beyond this distance is negligible, due to a change of wind direction and more dispersive atmospheric conditions.

5.3.4 Sheltering

It is likely that a significant proportion of the population would be indoors at any given time following the Reference Accident. In calculating collective doses, a sheltering factor is applied to the calculated collective cloudshine and groundshine doses. The sheltering factor allows for the proportion of the population assumed to be indoors, and the effect of shielding provided by buildings and other structures.

A technical safety assessment performed for NPWs in a Canadian port [18] assumed that 85% of the population is indoors in calculating collective doses. It is considered that an assumption of 50% of the population indoors is more appropriate for calculating collective doses for Australian ports due to the warmer climate. From available information [27,53,57], the sheltering factor assumed for residential structures for both cloudshine and groundshine dose is 0.2. Therefore, the overall dose reduction factor for cloudshine and groundshine doses, due to shielding provided by buildings and other structures, is assumed to be 0.6 ([0.5x1]+[0.5x0.2]).

6. RADIOLOGICAL CONSEQUENCES OF THE REFERENCE ACCIDENT

6.1 SUBMARINES AND SMALLER SURFACE VESSELS

6.1.1 Fission Product Release to Atmosphere

In the 1975 Reference Accident model, the atmospheric release is defined in terms of an iodine-131 release and a total gamma release. For submarines and smaller surface vessels, the values calculated using the 1975 Reference Accident model and the 2000 Reference Accident are shown in Table 6-1 below.

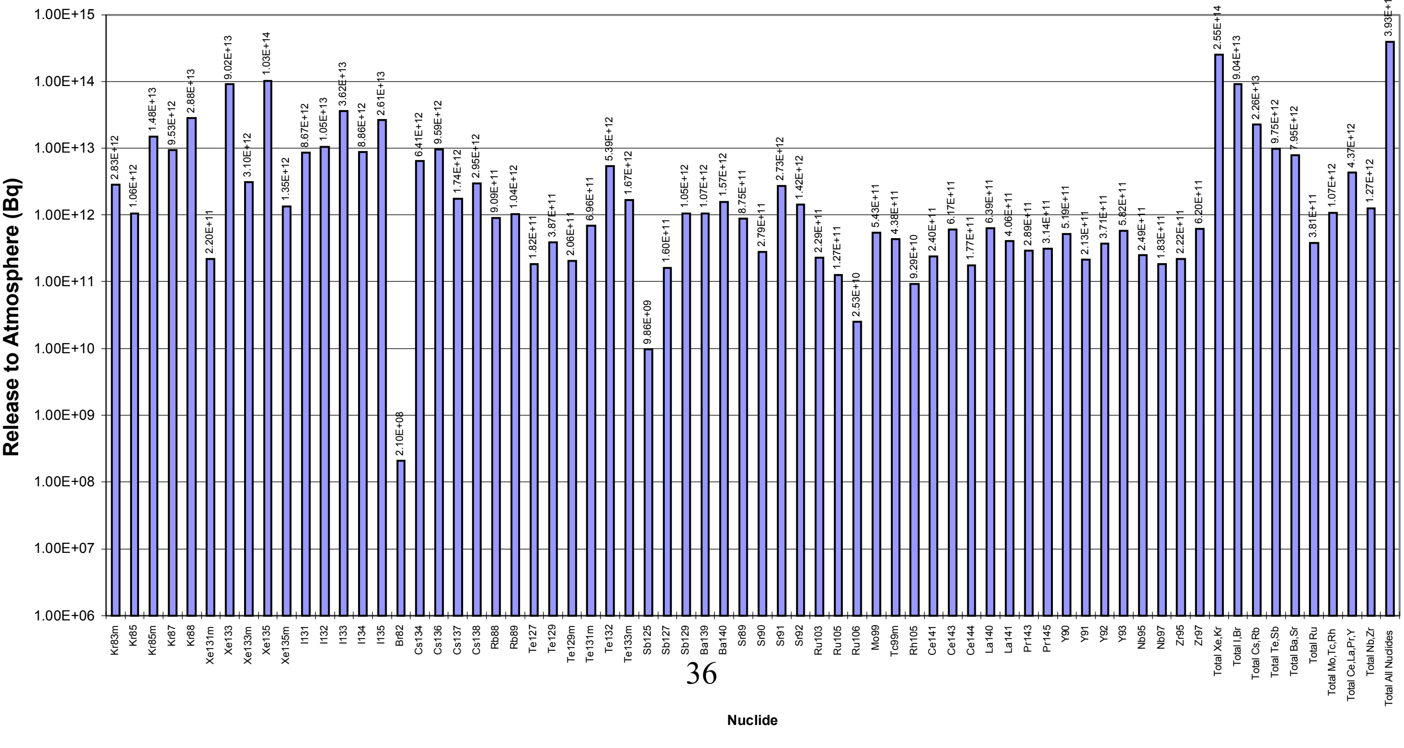
Table 6-1 Source Release from a Submarines and Smaller Vessels Reference Accident

	Reference Accident		
Radioisotope	*1975*	*2000* *1st 12 hours*	*2000* *2nd 12 hours*
Iodine-131 released (TBq)	66.7	8.7	1.89
Total Gamma Release (TBq.MeV)	630	232.5	32.1

The use of ACCIDENT in the 2000 Reference Accident permits a much more detailed examination of the fission product release as shown in Figure 6.1-1.

Figure 6.1-1

Submarines & Smaller Surface Vessels
Total Release to Atmosphere Versus Nuclide

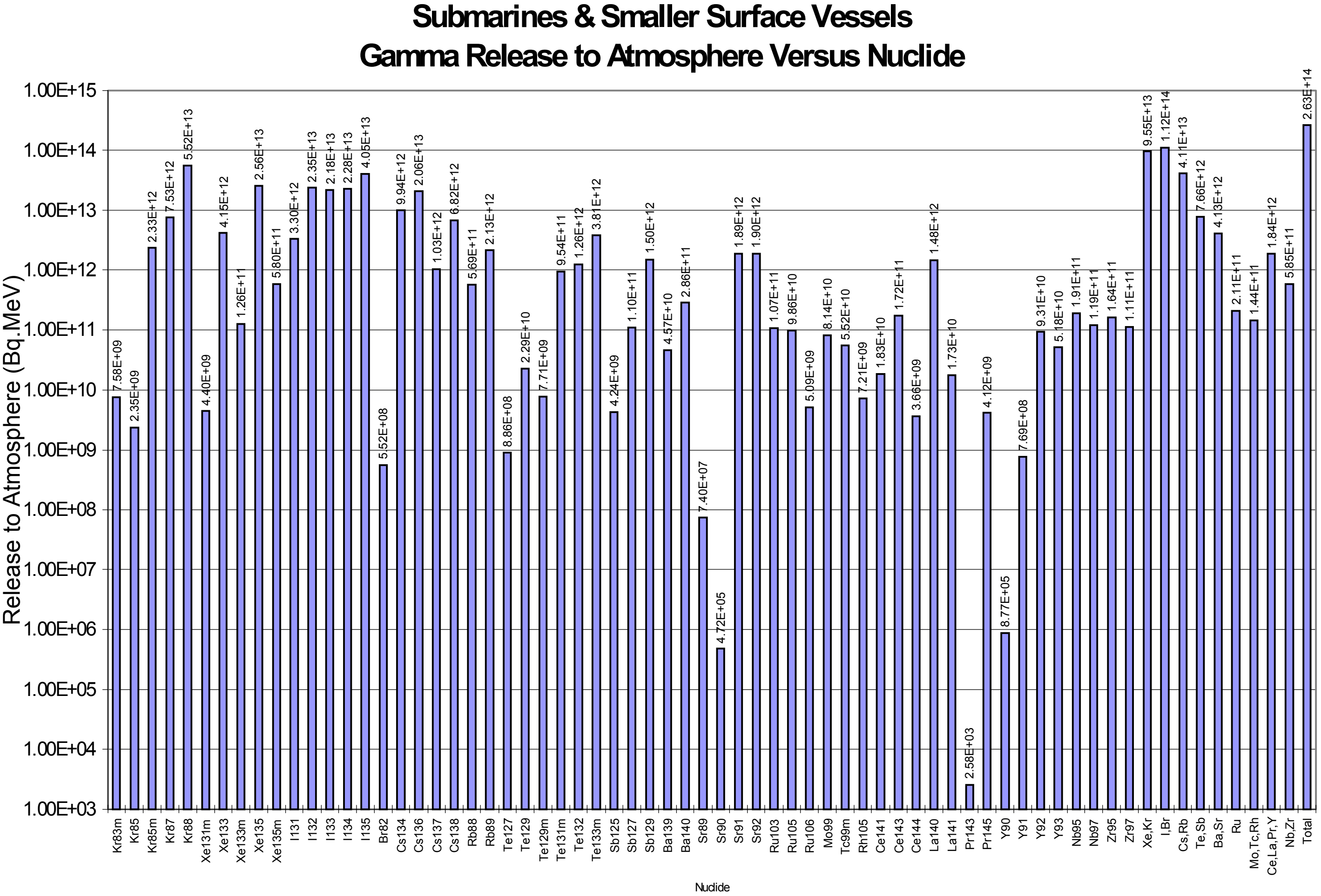


The major reasons for the reduction in iodine-131 release are the decreased containment leak rate, which takes into account the presence of a secondary containment (see Section 3.3.1), and the revised fission product containment deposition model (see Section 3.3.2). However, the effect of these changes is somewhat counteracted by the assumption of operation at maximum power immediately prior to the accident, which acts to increase the iodine release (see Section 3.1.3).

The total gamma release is also reduced due to the lower containment leak rate; however, the reduction is not as significant as for iodine-131 due to the additional radionuclides, such as iodine -133 considered in the source term for the 2000 Reference Accident model.

The calculated total release and gamma release of fission products to the atmosphere following a Reference Accident on board a submarine or smaller surface vessel is shown for the various nuclides in Figure 6.1-1 and Figure 6.1-2 respectively.

Figure 6.1-2

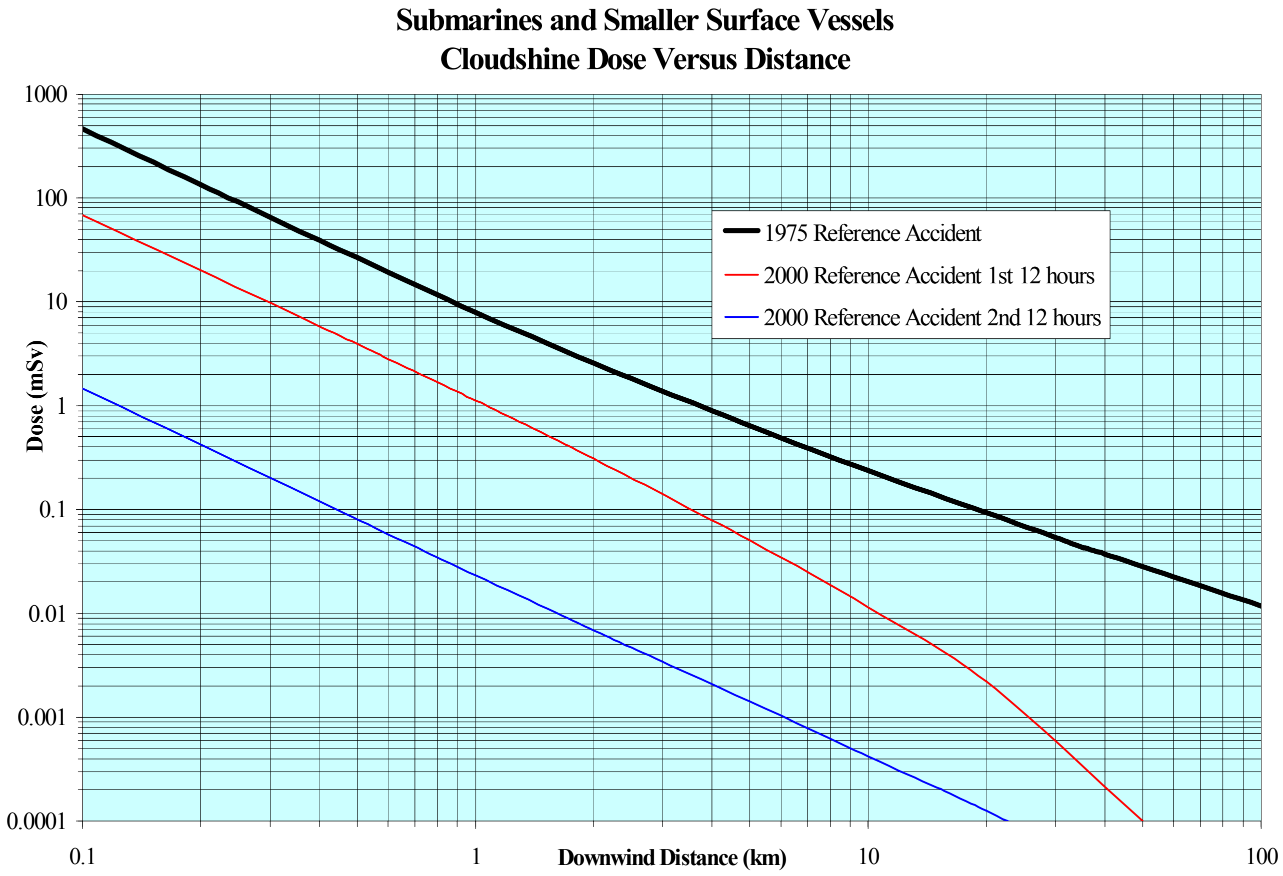


6.1.2 Cloudshine Dose

Cloudshine dose is accrued over the first 12 hours following the accident during the passage of the radioactive plume. The rate of accrual decreasing during this time, due to the decreasing source release rate (see Section 6.1.1) and increasing atmospheric dispersion (due to wind variability [20] and time). After 12 hours, cloudshine doses cease to accrue to the downwind population since the plume breaks up due to, a wind direction change, the onset of more dispersive conditions (see Section 4.1.1), and a different population is exposed. Even if there is no wind change, the additional dose under the more dispersive conditions is a small fraction of that calculated for the first 12 hours. The major radionuclide contributors to cloudshine dose are the noble gas and iodine isotopes.

Figure 6.1-3 shows, for a 24-hour vessel removal time, the projected centre line individual cloudshine dose calculated for the Reference Accident, as a function of downwind distance.

Figure 6.1-3



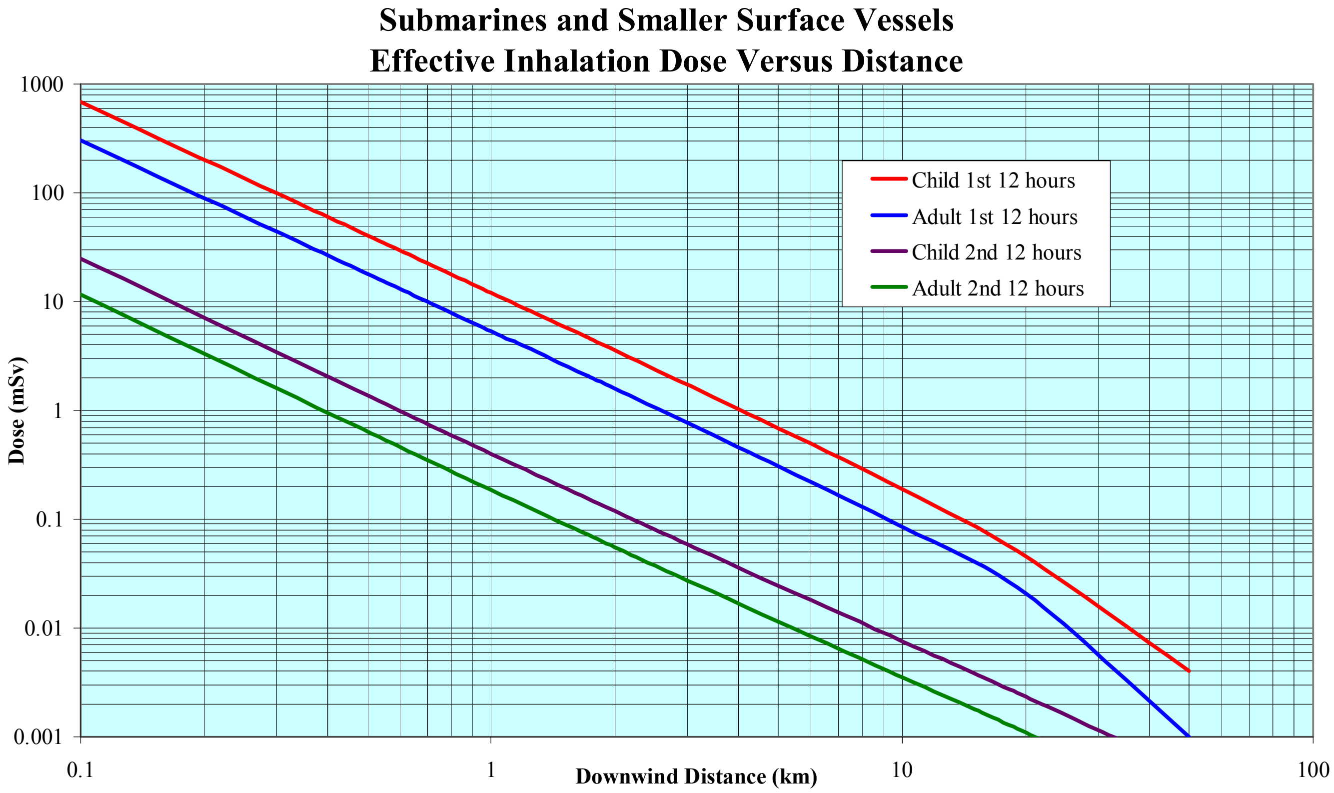
The cloudshine doses are reduced by a factor of about 8 at both 600m and 1.4km. Less significant reductions are observed for shorter vessel removal times. This is due to the differences between the 1975 Reference Accident and 2000 Reference Accident models in relation to modelling the availability of the fission products in the containment and radiation dose accrual.

6.1.3 Effective Inhalation Dose

The major radionuclide contributors to effective inhalation dose are iodine isotopes. Effective inhalation dose is accrued over the first 12 hours during the passage of the radioactive plume. The rate of accrual to the downwind population reducing during this time due to the decreasing source release rate (see Section 6.1.1), and increasing atmospheric dispersion (due to wind variability [20] and time). After 12 hours, inhalation doses cease accruing to the downwind population, since the plume breaks up due to, a wind direction change, the onset of more dispersive conditions (see Section 4.1.1), and exposure of a different population.

Figure 6.1-4 shows for a 24-hour vessel removal time, the projected centre line individual effective dose from inhalation, calculated in the first 12 hours for the 2000 Reference Accident, for both a child and adult, as a function of downwind distance.

Figure 6.1-4



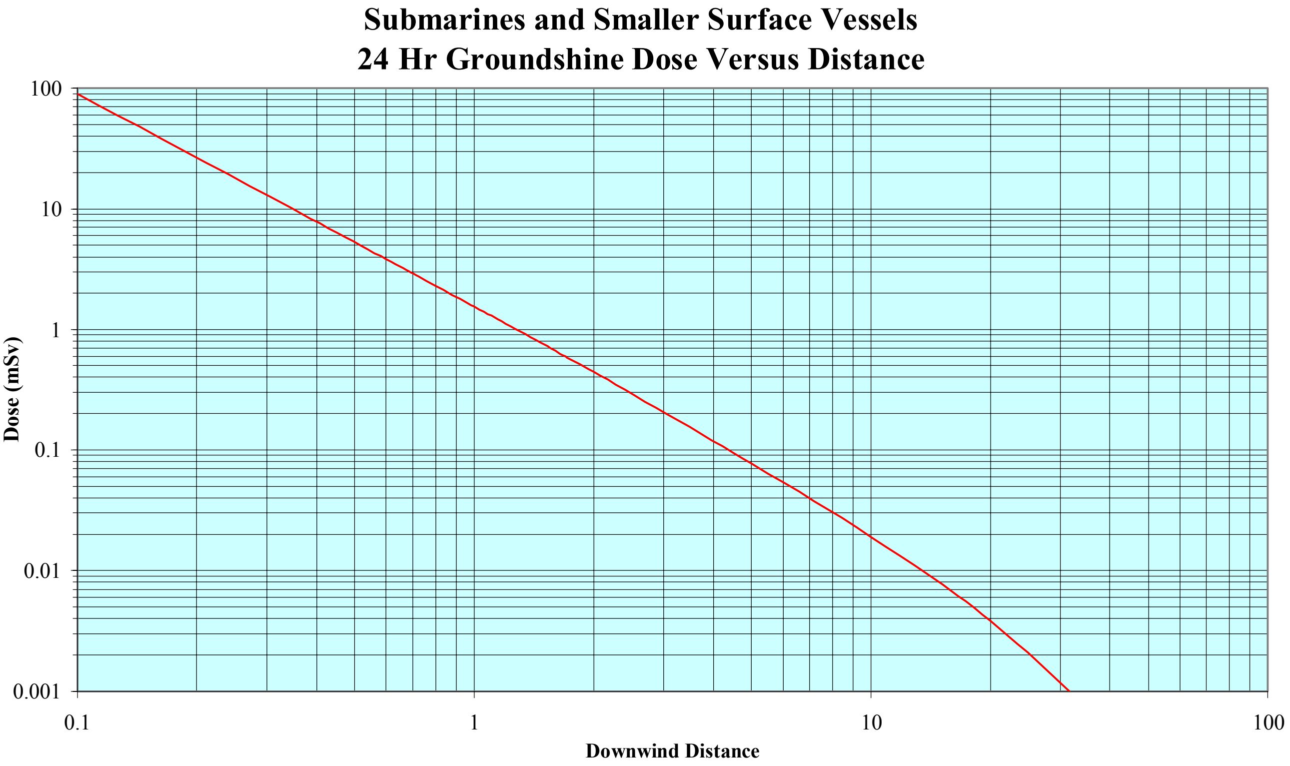
6.1.4 Groundshine Dose

Port assessments are concerned with planning for the early phase of the emergency response, when action must be taken rapidly to control radiation doses from a NPW accident. Only the short-term consequences of the 2000 Reference Accident, taken as the first 24 hours following the accident, are considered in this report.

Groundshine dose continues to accrue following the passage of the radioactive plume due to the continued presence of ground deposited radioactive material. The rate of accrual of groundshine dose initially increases as the deposited activity builds up, but then decreases due to decay of the deposited material. Groundshine will continue after the NPW has departed, and recovery measures will need to be evaluated on the basis of radiation measurements in the areas affected.

Figure 6.1-5 shows, for a 24 hour vessel removal time, the projected centre line individual groundshine dose calculated for the 2000 Reference Accident, as a function of downwind distance at 24 hours following the accident.

Figure 6.1-5



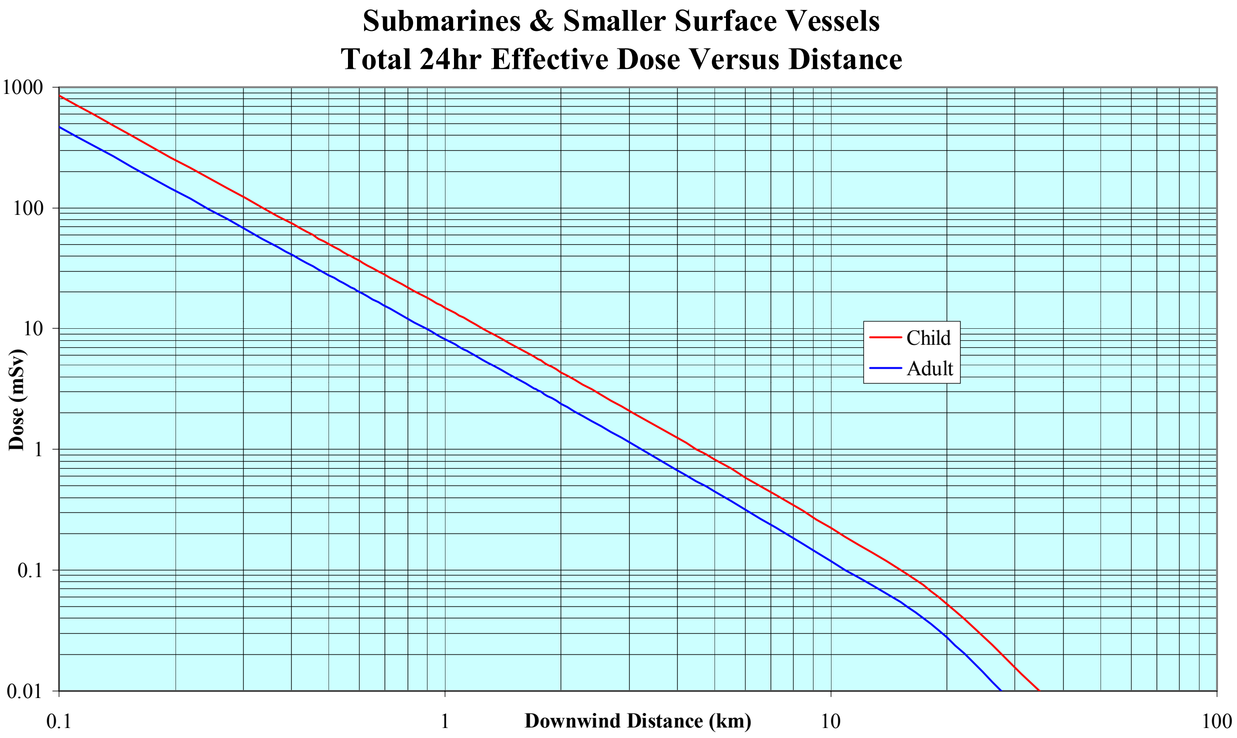
6.1.5 Total Effective Dose

Total projected effective dose refers to the sum of the effective doses received from cloudshine, inhalation and groundshine. The bulk of the total effective dose to the downwind population is accrued during the first 12 hours from the inhalation and cloudshine pathways. However, due to the ground shine pathway, the dose continues to accrue following the passage of the radioactive plume.

The major radionuclide contributors to the total 24-hour child effective dose during the first 12 hours are iodine isotopes, in particular iodine-133 and iodine-131. During the second 12 hours, a different population group is exposed.

Figure 6.1-6 shows the projected total effective dose calculated for a Reference Accident for both a child and adult as a function of downwind distance at 24 hours following the accident.

Figure 6.1-6



Figures 6.1-7 and 6.1-8 show, the projected child total effective dose calculated for the 2000 Reference Accident, as a function of time after the accident at distances of 600 m and 1.4km.

Figure 6.1-7
Submarines & Smaller Surface Vessels
Child Total Effective Dose at 600m versus Time

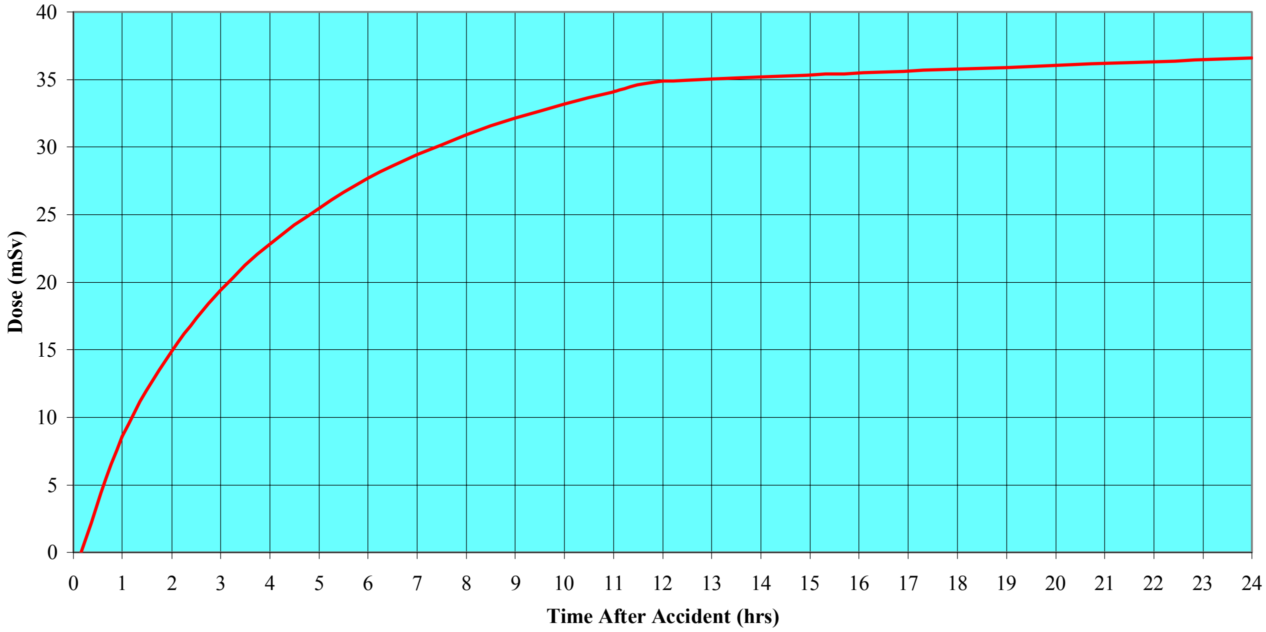


Figure 6.1-8
Submarines & Smaller Surface Vessels
Child Total Effective Dose at 1.4km versus Time

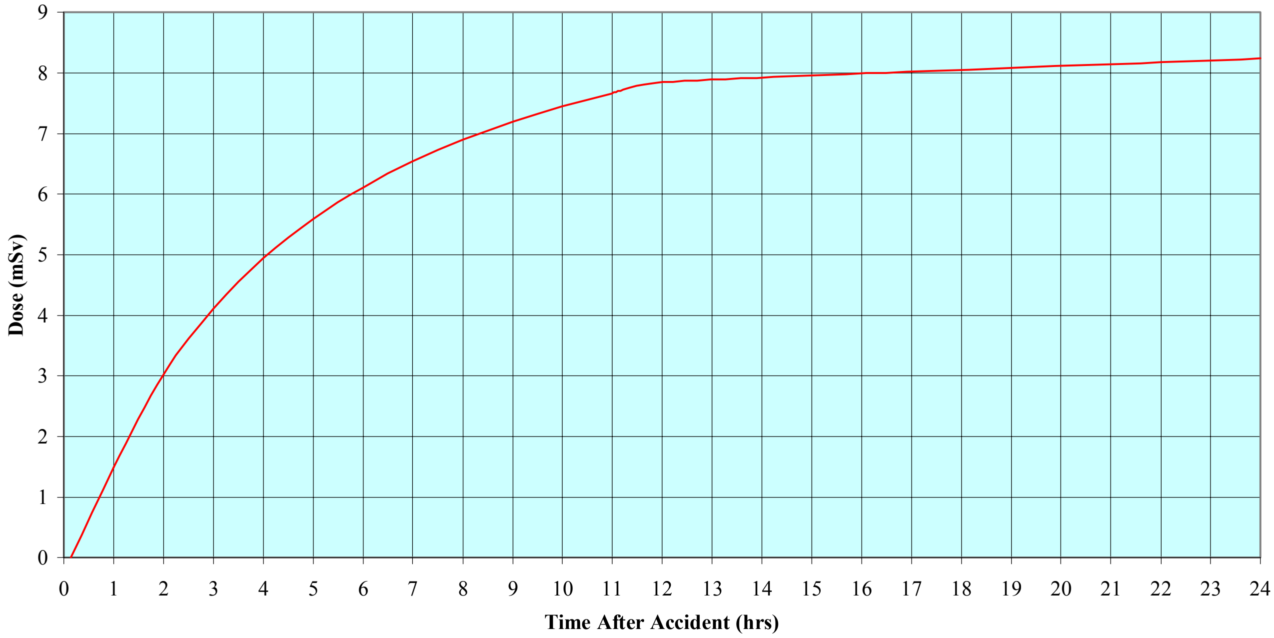


Figure 6.1-9 shows, the projected child total effective dose calculated for the 2000 Reference Accident, as a function of radionuclide at 24 hour, at distance of 1.4km.

Figure 6.1-9

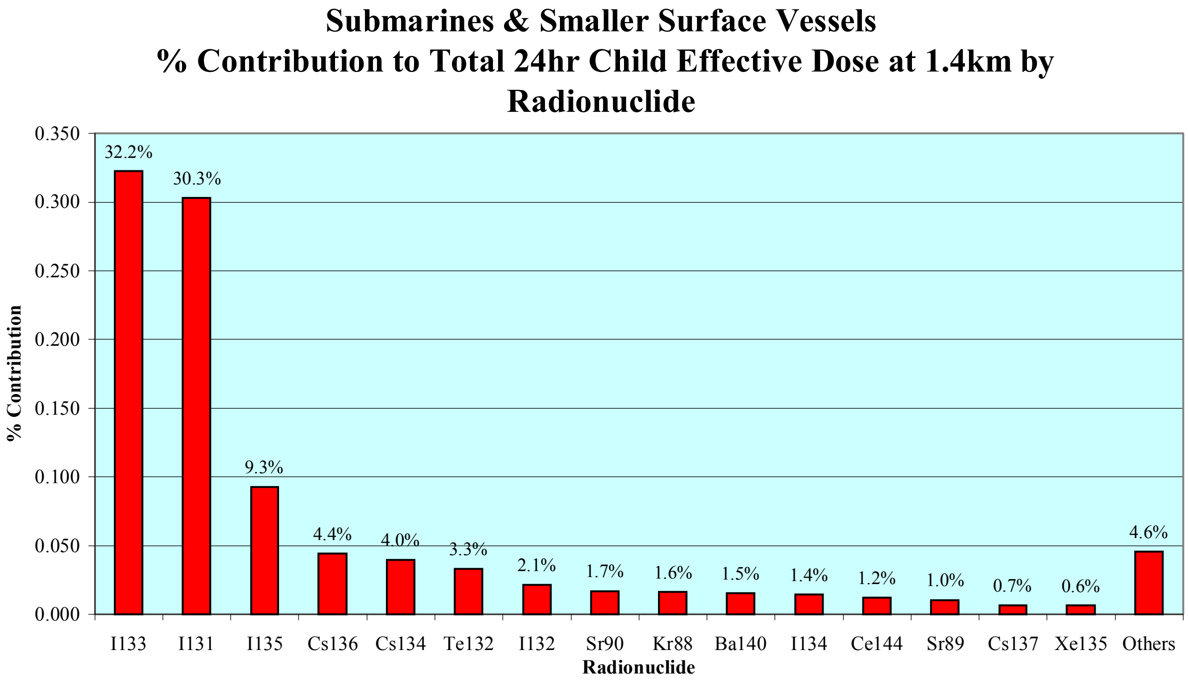
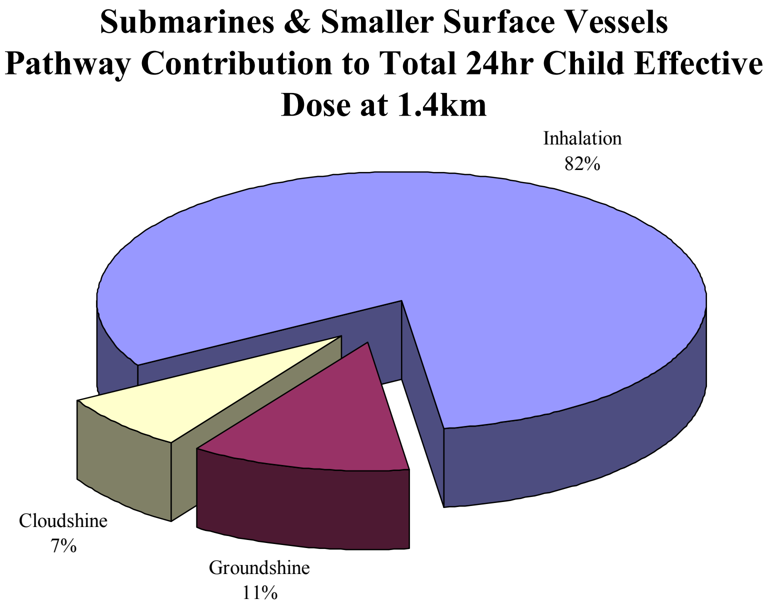


Figure 6.1-10 shows the contribution to the total 24 hour child effective dose by each dose pathway considered, for a downwind distance of 1.4km. It is seen that the inhalation pathway dominates the total effective dose, followed by groundshine and cloudshine.

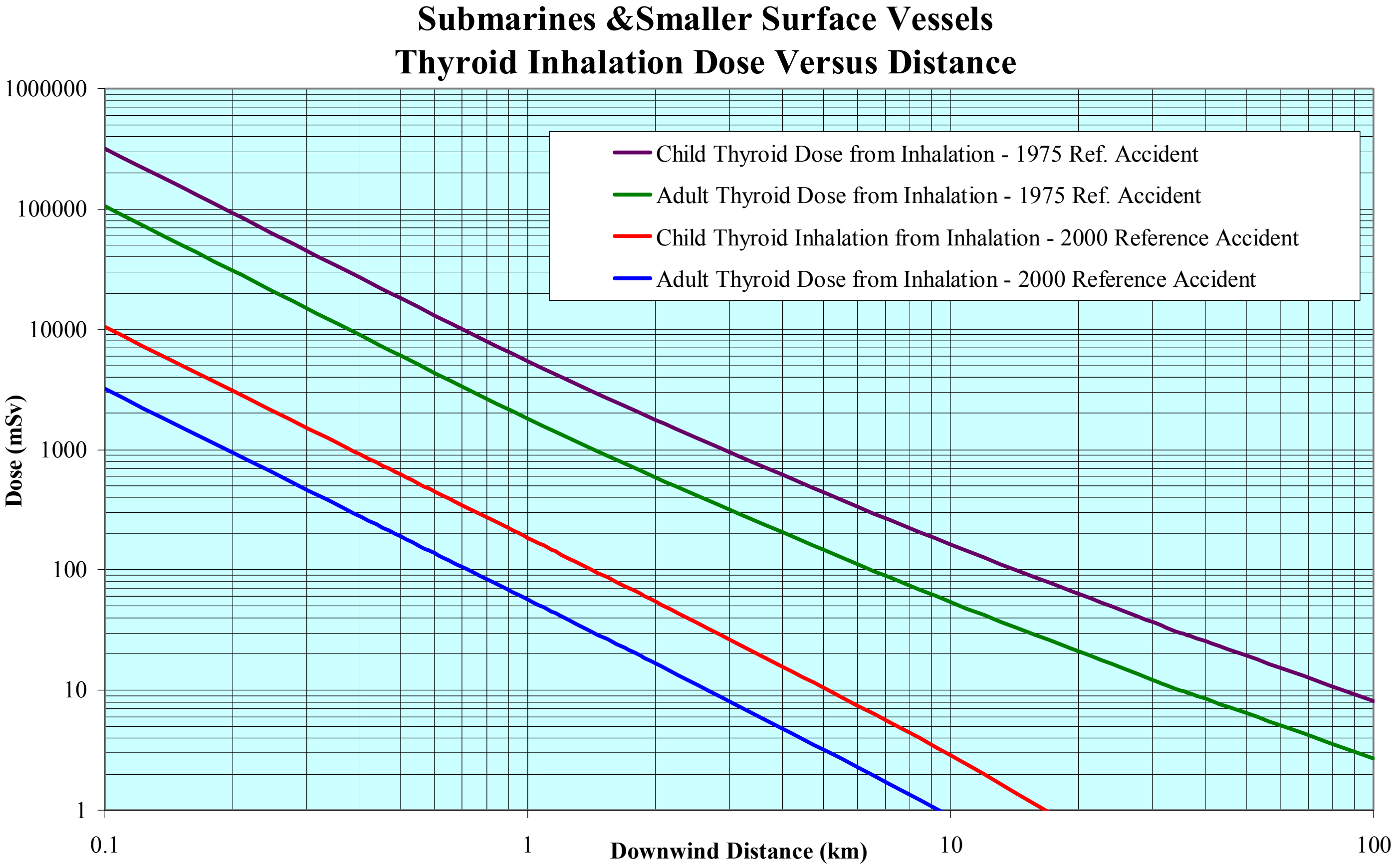
Figure 6.1-10



6.1.6 Thyroid Inhalation Dose

The projected centreline individual single organ thyroid dose from inhalation calculated for the 2000 Reference Accident is shown for both a child and adult as a function of downwind distance in Figure 6.1-11,

Figure 6.1-11



The thyroid inhalation dose calculated using the 2000 Reference Accident model is compared to that calculated using the 1975 Reference Accident model in Figure 6.1-11 (24 hour vessel removal time). The child thyroid doses are reduced by a factor of about 30, at both 600m and 1.4km distances. Calculations for shorter NPW removal times show less significant reductions. This is due to the differences between the 1975 and 2000 Reference Accident models in relation to modelling the time variation of fission product release and radiation dose accrual (see Section 7.2.1).

The projected centreline individual single organ thyroid dose from inhalation calculated for the 2000 Reference Accident is shown for a child as a function of time after the accident in Figures 6.1-12 and 6.1-13 at a distances of 600m and 1.4km respectively.

Figure 6.1-12

Submarines & Smaller Surface Vessels
Child Thyroid Inhalation Dose at 600m versus Time

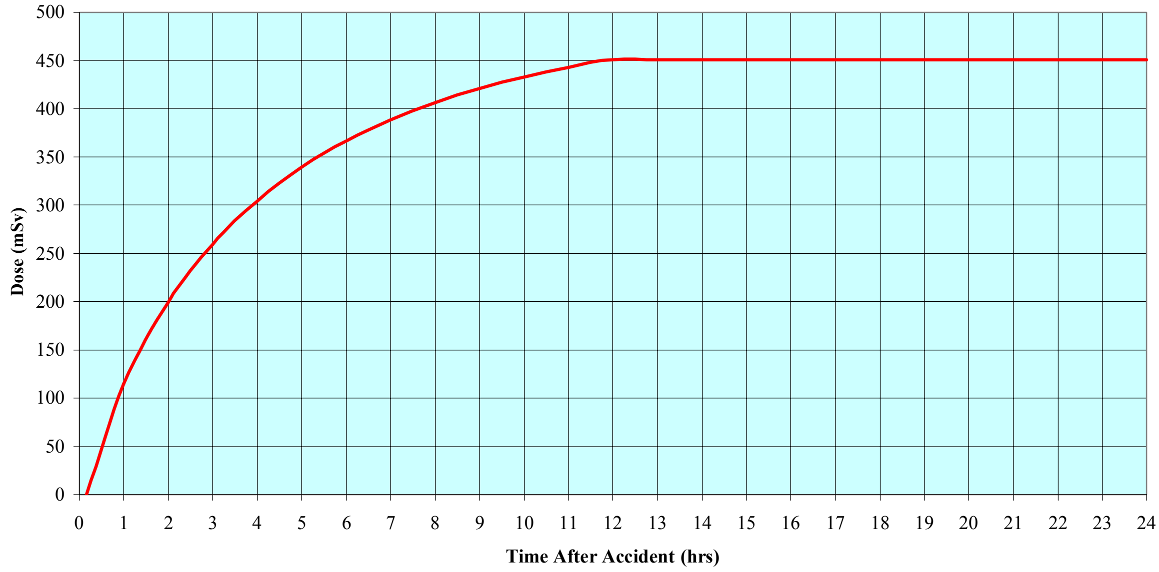
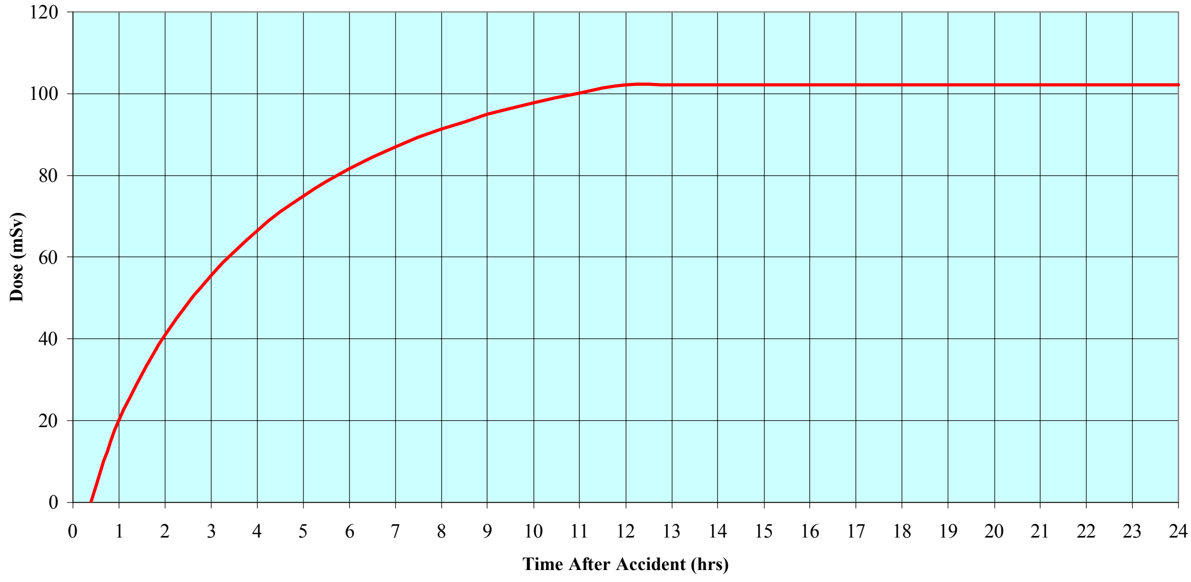


Figure 6.1-13

Submarines & Smaller Surface Vessels
Child Thyroid Inhalation Dose at 1.4km versus Time



The major radionuclide contributors to child thyroid inhalation dose are iodine isotopes, in particular iodine-131 and iodine-133. Thyroid inhalation dose is accrued over the first 12 hours following the accident during the passage of the radioactive plume with the rate of accrual decreasing during this time due to the decreasing source release rate (see Section 6.1.1) and increasing atmospheric dispersion (due to wind variability and time [20]). After 12 hours, inhalation doses to the downwind population cease accruing, since the plume breaks up due to a wind direction change, the onset of more dispersive conditions (see Section 4.1.1) and the exposure of a different population.

6.2 NIMITZ CLASS AIRCRAFT CARRIERS

6.2.1 Fission Product Release to Atmosphere

In the 1975 Reference Accident model, the atmospheric release is defined in terms of an iodine-131 release and a total gamma release. For NIMITZ class vessels, the values calculated using the 1975 Reference Accident model and the 2000 Reference Accident are shown in Table 6-2 below.

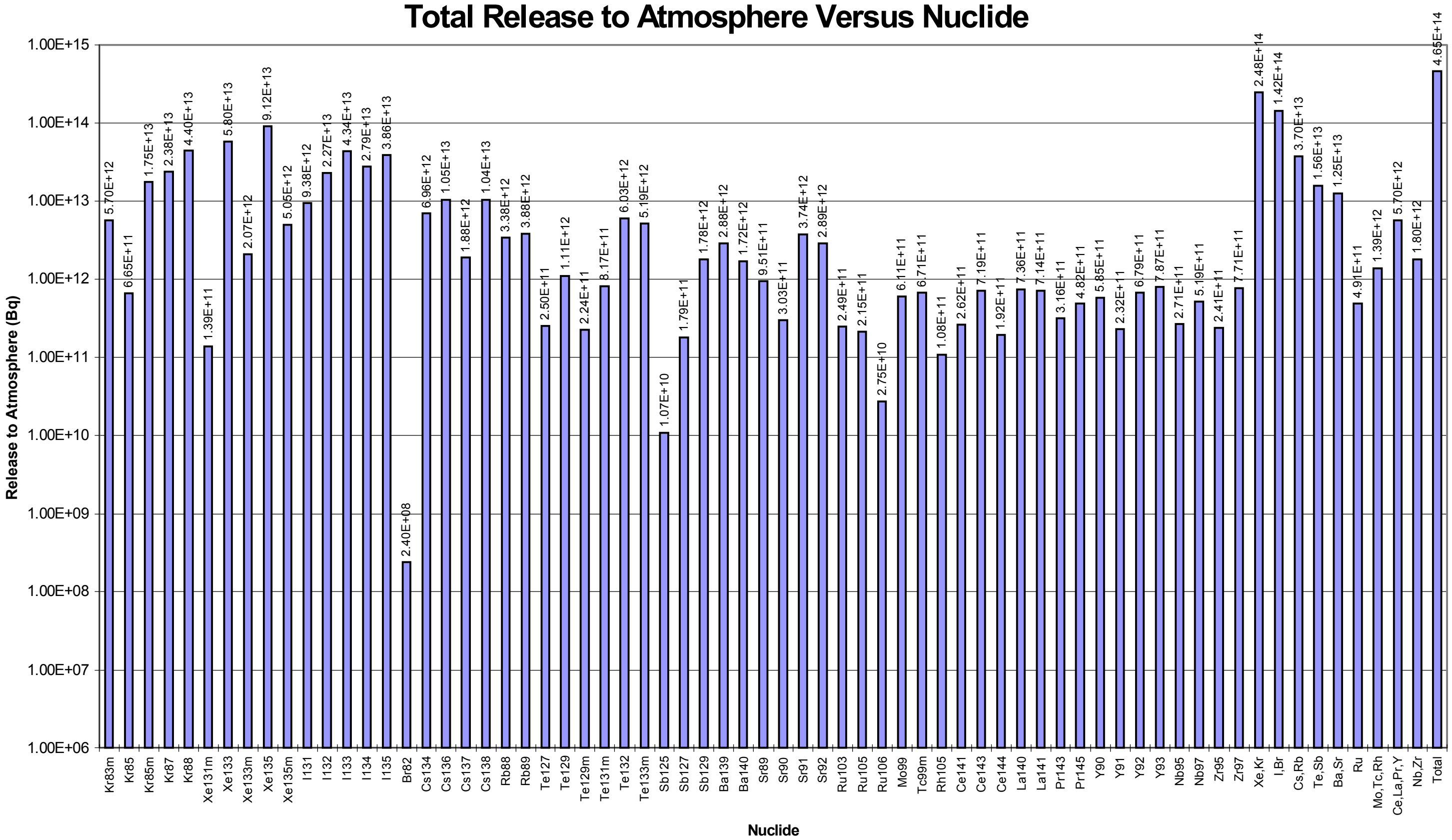
Table 6-2 Source Release from a NIMITZ Class Vessels Reference Accident

	Reference Accident	
Radioisotope	***1975***	***2000***
Iodine-131 Activity Release (TBq)	133	9.4
Total Gamma Release (TBq.MeV)	2300	409

The use of ACCIDENT in the 2000 Reference Accident permits a much more detailed examination of the fission product release as shown in Figure 6.2-1.
The major reasons for the reduction in iodine-131 release are the decreased containment leak rate, which takes into account the presence of a secondary containment (see Section 3.3.1), and the revised fission product containment deposition model (see Section 3.3.2).

Figure 6.2-1

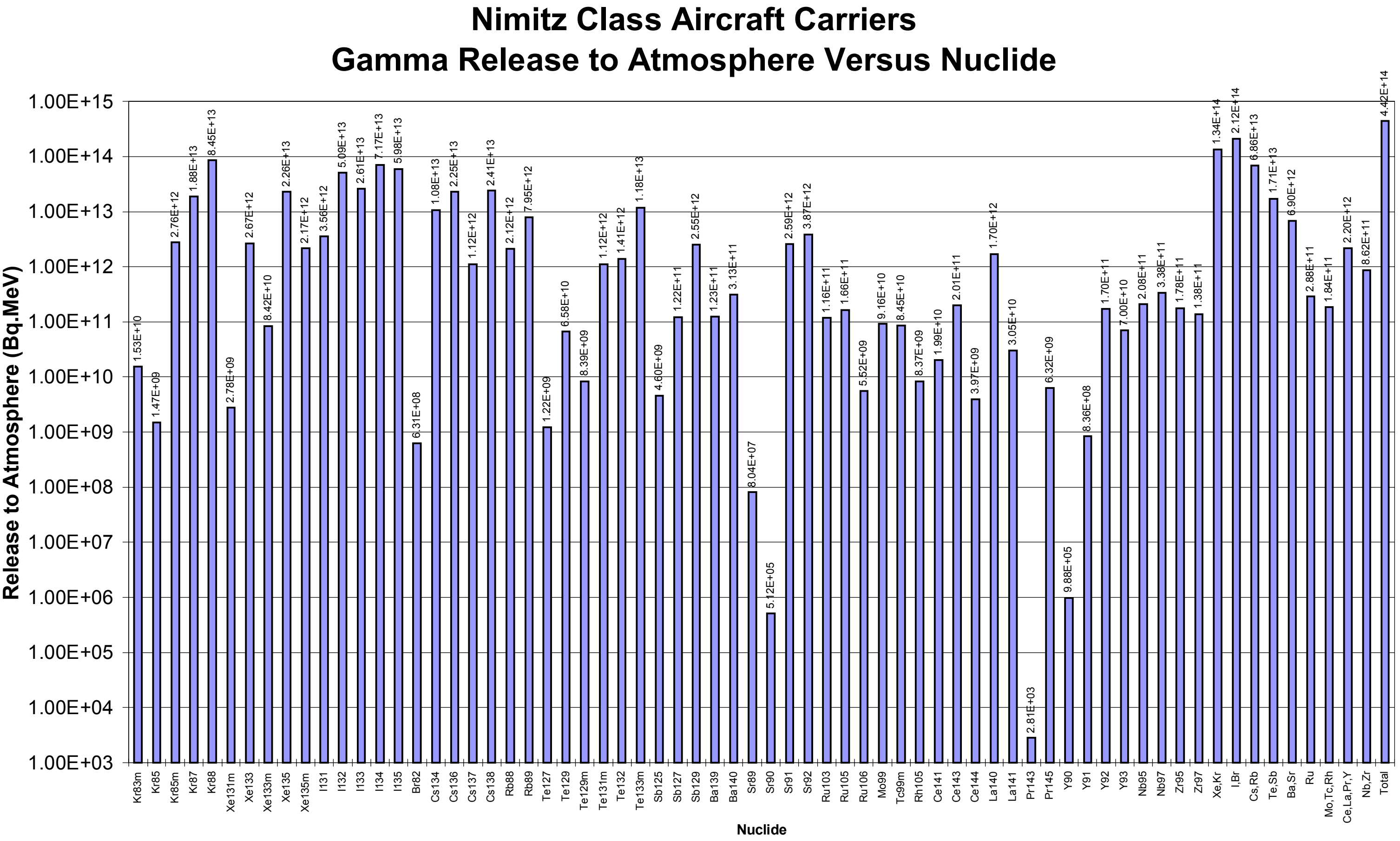
Nimitz Class Aircraft Carriers
Total Release to Atmosphere Versus Nuclide



The total gamma release is also reduced due to the lower containment leak rate; however, the reduction is not as significant as for iodine-131 due to the additional radionuclides, such as iodine -133 considered in the source term for the 2000 Reference Accident model.

The calculated total release and gamma release of fission products to the atmosphere following the 2000 Reference Accident is shown for various nuclides in Figure 6.2-1 and Figure 6.2-2 respectively.

Figure 6.2-2



6.2.2. Cloudshine Dose

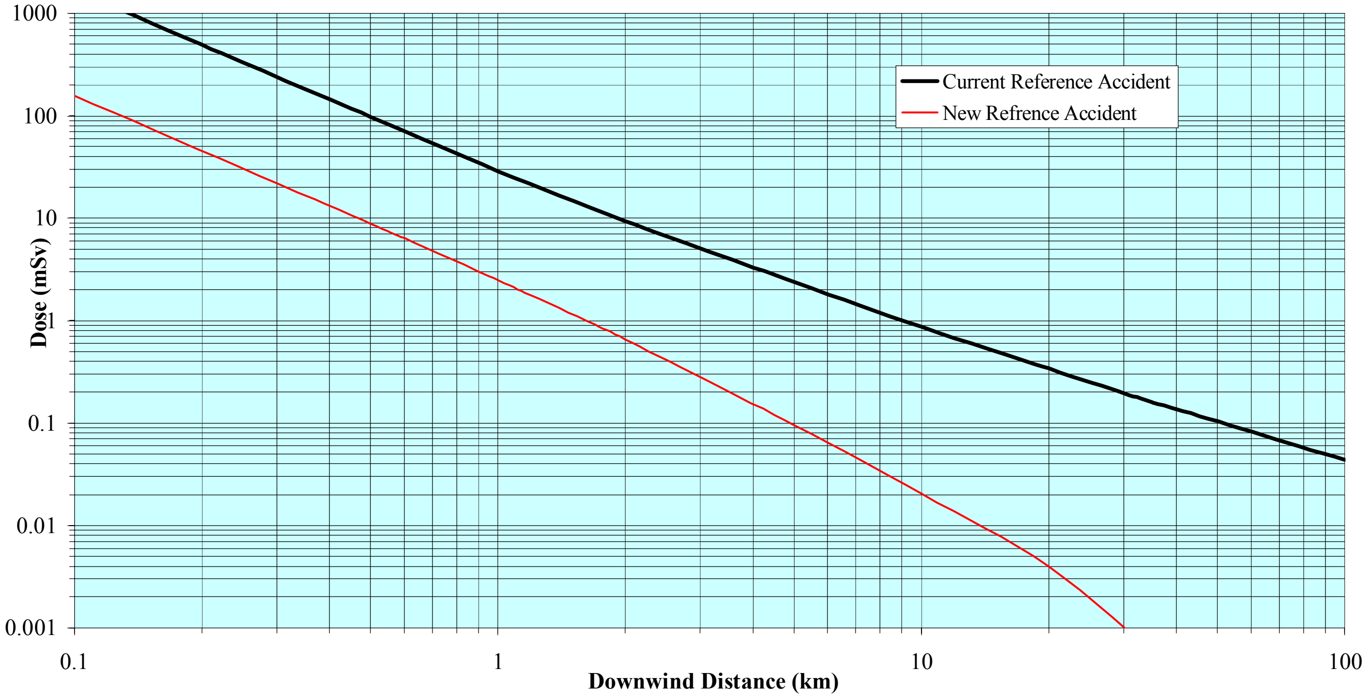
Cloudshine dose is accrued during the passage of the radioactive plume, ie. during the first 2 hours following the arrival of the plume at each downwind distance. After this time, cloudshine doses cease accruing since the NPW is assumed to be removed from the port 2 hours after the occurrence of the accident using its independent reactor [6,9]. The major radionuclide contributors to cloudshine dose are noble gas and iodine isotopes.

The projected centreline individual cloudshine dose calculated for a Reference Accident on board a NIMITZ class aircraft carrier is shown as a function of downwind distance in Figure 6.2-3. The cloudshine dose calculated using the new Reference Accident model is compared to that calculated using the 1975 Reference Accident model in Figure 6.2-3. This figure shows a reduction in cloudshine dose by a factor of about 14 at both 800 m and 1.9 km.

Figure 6.2-3

NIMITZ Class Aircraft Carriers

Cloudshine Dose Versus Distance

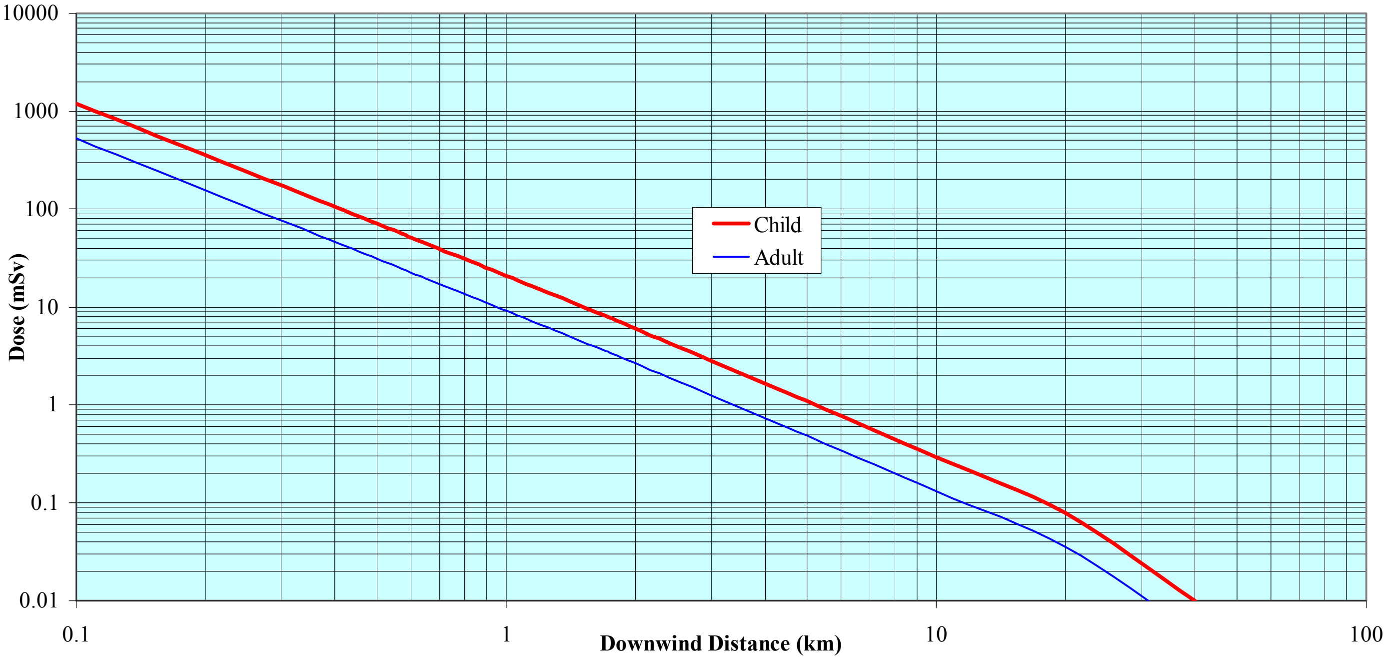


6.2.3 Effective Inhalation Dose

Effective inhalation dose is accrued during the passage of the radioactive plume, ie. during the first 2 hours following the arrival of the plume at each downwind distance. After this time, inhalation doses cease accruing since the NPW is assumed to be removed from the port 2 hours after the occurrence of the accident. The major radionuclide contributors to effective inhalation dose are iodine isotopes.

The projected centreline individual effective dose from inhalation calculated for a Reference Accident on board a NIMITZ class aircraft carrier is shown for both a child and adult as a function of downwind distance in Figure 6.2-4.

Figure 6.2-4
NIMITZ Class Aircraft Carriers
Effective Inhalation Dose Versus Distance



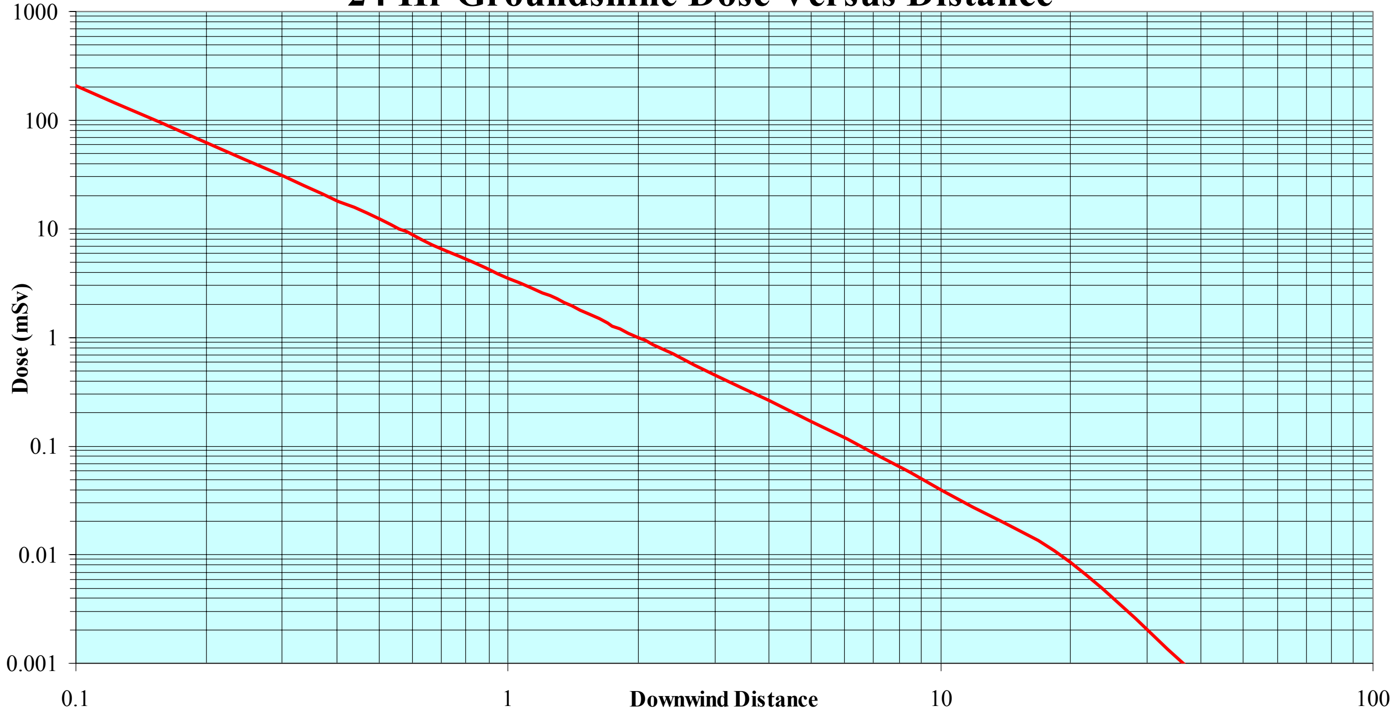
6.2.4 Groundshine Dose

Groundshine dose continues to accrue following the passage of the radioactive plume due to the continued presence of ground deposited radioactive material. The rate of accrual of groundshine dose initially increases as the deposited activity builds up, but then decreases due to decay of the deposited material. Groundshine will continue after the NPW has departed, and recovery measures will need to be evaluated on the basis of radiation measurements in the areas affected.

Port assessments are concerned with planning for the early phase emergency response, when action must be taken rapidly to control radiation doses from a NPW accident. Only the short-term consequences of the Reference Accident, taken as the first 24 hours following the accident, are considered in this report.

The projected centreline individual groundshine dose calculated for a Reference Accident on board a NIMITZ class aircraft carrier is shown as a function of downwind distance at 24 hours following the accident in Figure 6.2-5.

Figure 6.2-5
NIMITZ Class Aircraft Carriers
24 Hr Groundshine Dose Versus Distance

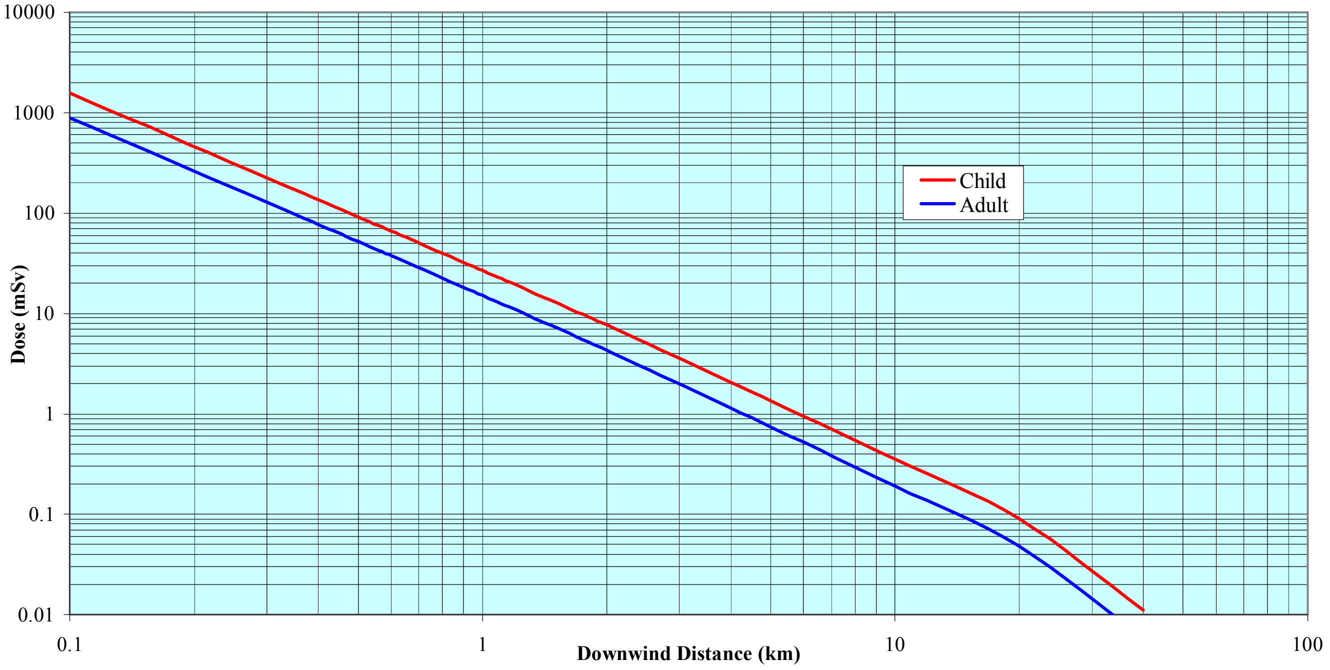


6.2.5 Total Effective Dose

Total effective dose refers to the sum of the effective doses received from cloudshine, inhalation and groundshine. The bulk of the total effective dose is accrued during the passage of the radioactive plume (ie. during the first 2 hours following plume arrival at each distance) due to the inhalation and cloudshine pathways, however, the dose continues to accrue following plume passage due to the groundshine pathway. The major radionuclide contributors to the total 24-hour child effective inhalation dose are iodine isotopes, in particular iodine-133 and iodine-131.

Figure 6.2-6 shows the projected total effective dose calculated for the 2000 Reference Accident for both a child and adult as a function of downwind distance at 2 hours following the accident.

Figure 6.2-6
NIMITZ Class Aircraft Carriers
Total 24hr Effective Dose Versus Distance



Figures 6.2-7 and 6.2-8 show, the projected child total effective dose calculated for the 2000 Reference Accident, as a function of time after the accident at distances of 800 m and 1.9km.

Figure 6.2-7

NIMITZ Class Aircraft Carriers
Child Total Effective Dose at 800m versus Time

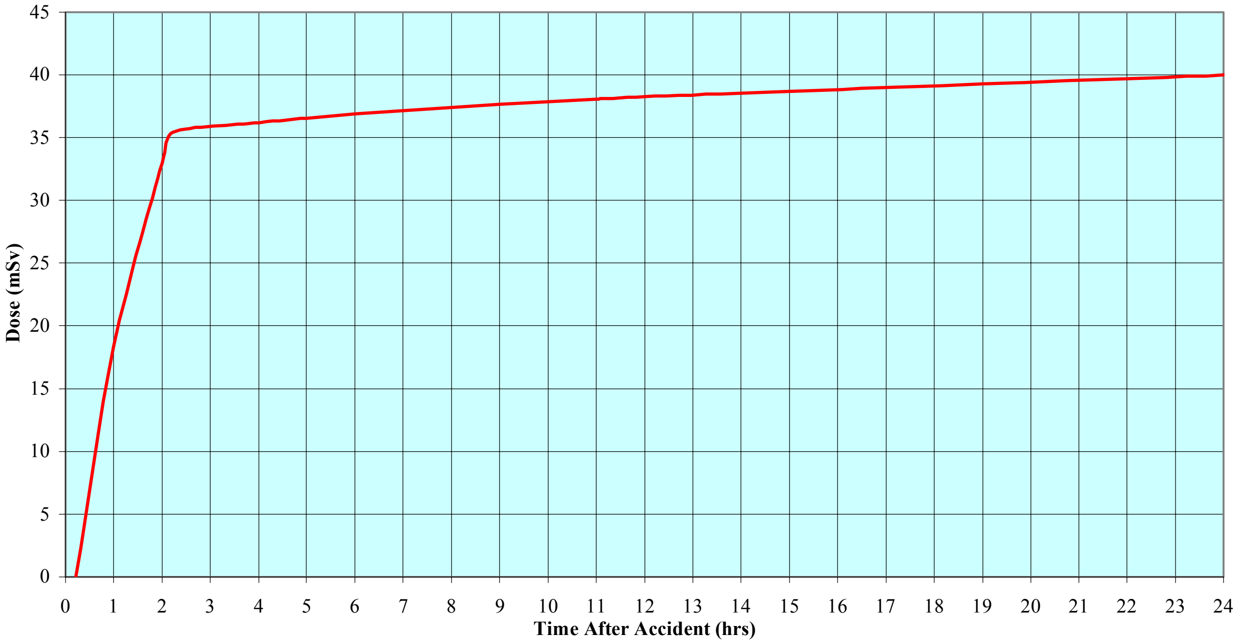


Figure 6.2.8

NIMITZ Class Aircraft Carriers
Child Total Effective Dose at 1.9km versus Time

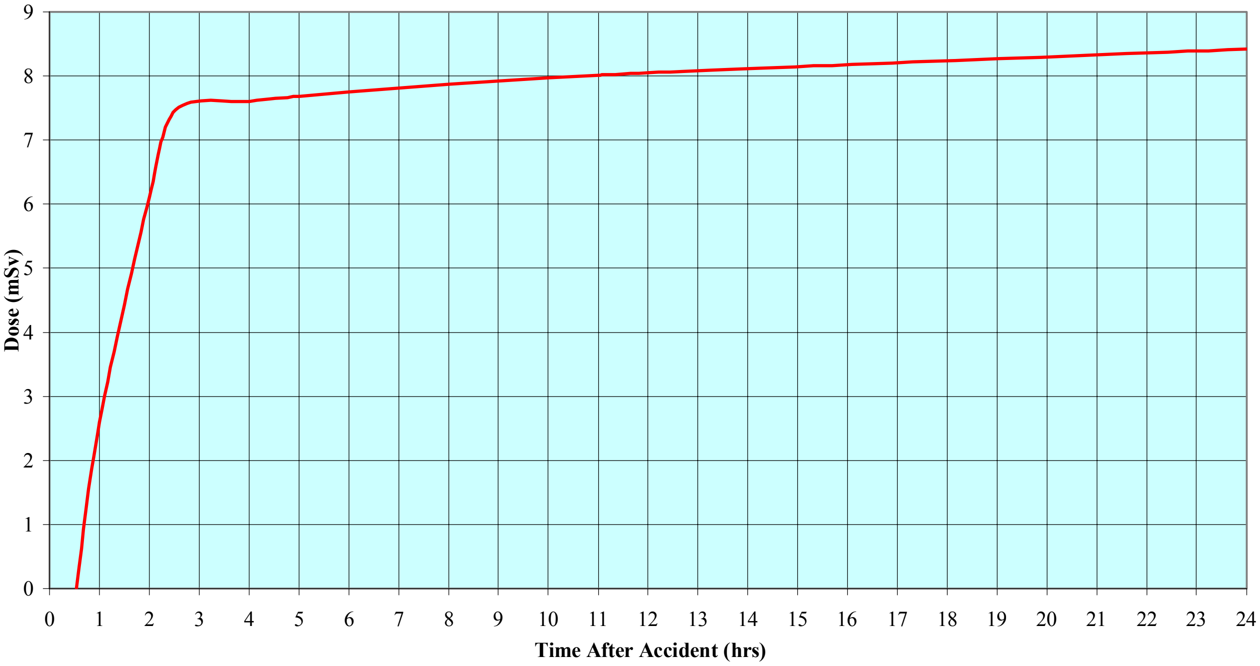


Figure 6.2-9 shows, the projected child total effective dose calculated for the 2000 Reference Accident, as a function of radionuclide at 24 hour, at distance of 1.9km.

Figure 6.2-9

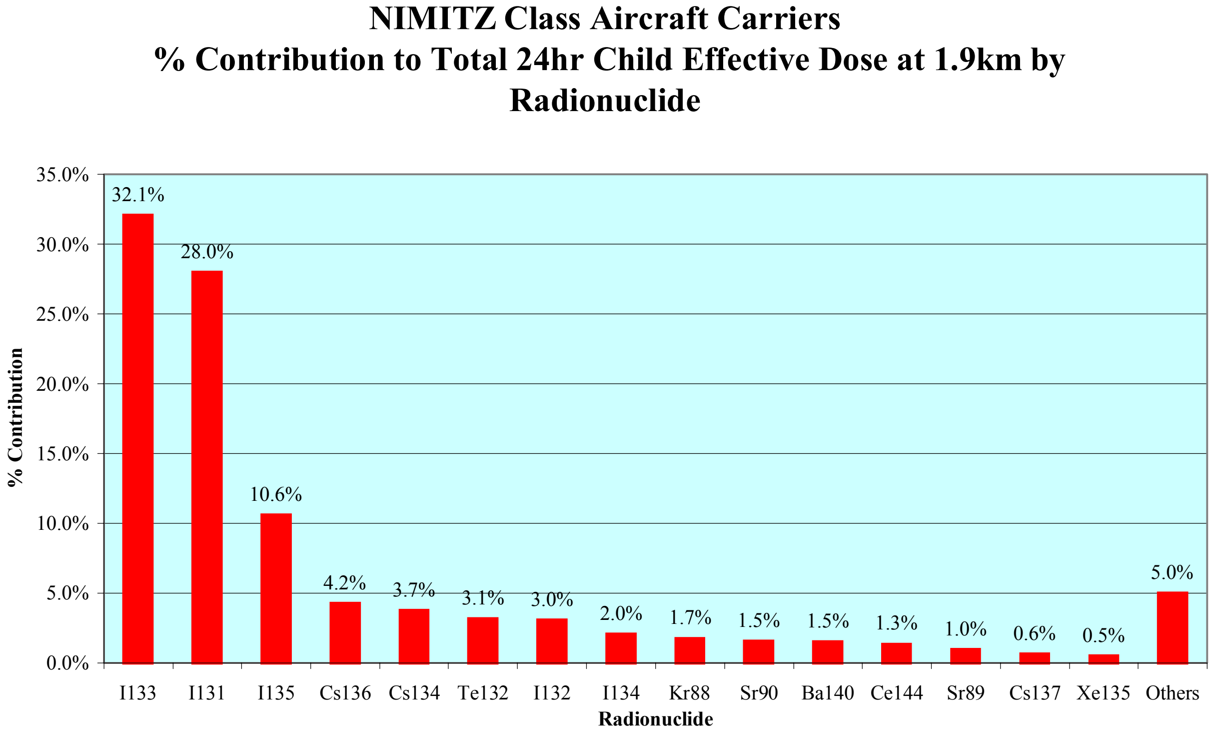
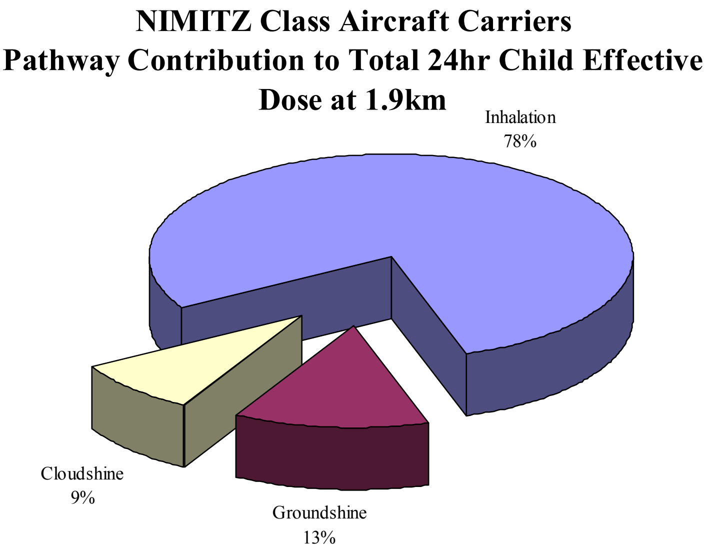


Figure 6.2-10 shows the contribution to the total 24 hour child effective dose by each dose pathway considered, for a downwind distances of 1.9km. It is seen that the inhalation pathway dominates the total effective dose, followed by groundshine and cloudshine.

Figure 6.2-10



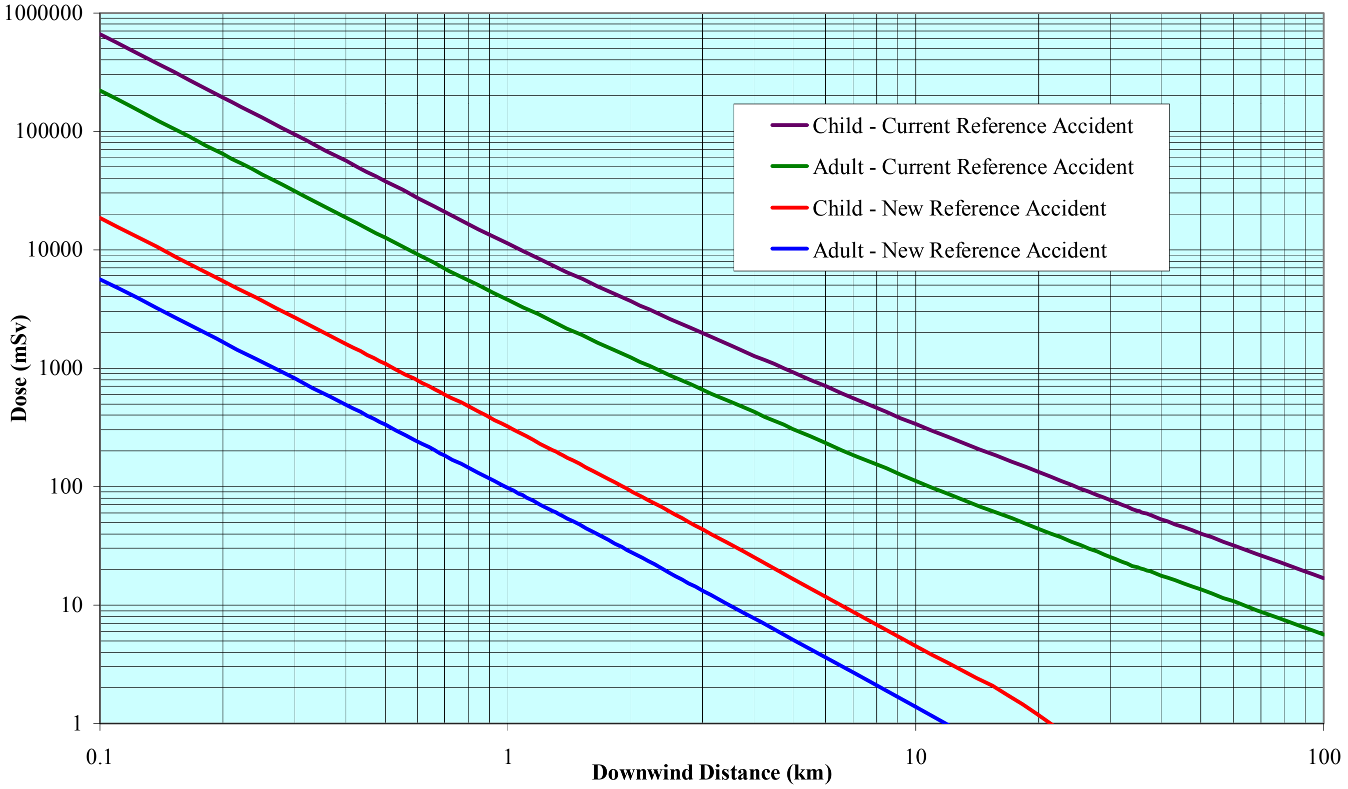
6.2.6 Thyroid Inhalation Dose

Thyroid inhalation dose is accrued during the passage of the radioactive plume, that is, during the first 2 hours following the arrival of the plume at each downwind distance. After this time, inhalation doses cease accruing since the NPW is assumed to be removed from the port 2 hours after the occurrence of the accident. The major radionuclide contributors to thyroid inhalation dose are iodine isotopes, in particular iodine-131 and iodine-133.

The thyroid inhalation dose calculated using the 2000 Reference Accident model is compared to that calculated using the 1975 Reference Accident model in Figure 6.2-11. This figure shows a reduction in thyroid inhalation dose by a factor of about 30 to 35 at 1 km and by a factor of about 40 at 1.9 km.

Figure 6.2-11

NIMITZ Class Aircraft Carriers
Thyroid Inhalation Dose Versus Distance



The projected centreline individual single organ thyroid dose from inhalation calculated for the 2000 Reference Accident is shown for a child, as a function of time after the accident, in Figures 6.2-12 and 6.1-13 at distances of 800m and 1.9km respectively.

Figure 6.2-12

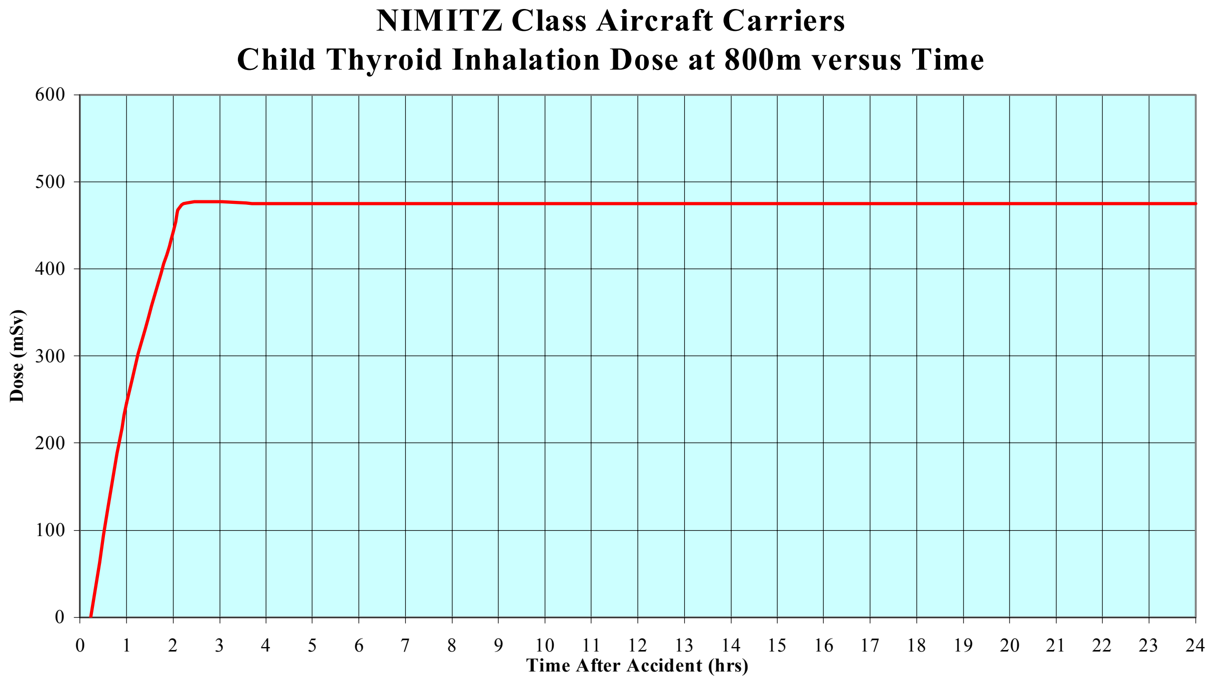
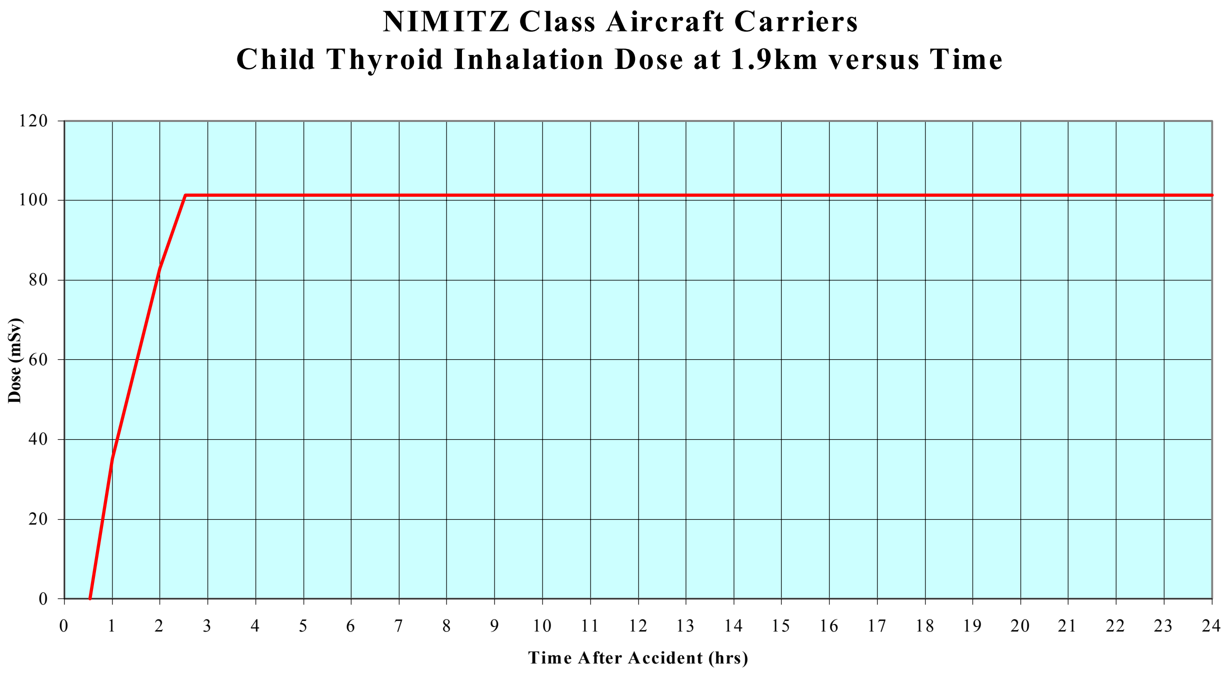


Figure 6.2-13



7. EMERGENCY PLANNING ZONES

Emergency Planning Zones (EPZs) are designated around NPW berths and anchorages for planning purposes. EPZs assist in the identification of areas where hazards might arise and allow planning to ensure that appropriate countermeasures can be taken promptly and effectively to protect individuals in accordance with the recommendations of the National Health and Medical Research Council [53,58,59,63]. The zones are based on the projected doses, but countermeasures or intervention can maximise the averted dose to individuals. The intervention levels for counter measures are summarised below in Table 7-1.

Table 7-1 Individual Dose Criteria for Intervention [62]

Criteria	Maximum Avertable Dose (mSv)	Maximum Avertable Thyroid Dose
Sheltering	10 mSv	-
Evacuation	50 mSv	
Stable I Administration	-	100 mGy

The NHMRC's current intervention levels (53) consider the dose to the thyroid. The lower level of intervention is 500mGy and this will still be considered in the assessment of the suitability of a port using the 2000 Reference Accident.

The extent of the EPZs is determined based on the projected consequences of the 2000 Reference Accident, an accident that has been selected so that its consequences are unlikely to be exceeded in any actual accident. Therefore, the EPZs are considered to represent an upper bound to the extent to which detailed emergency planning for the implementation of countermeasures is considered necessary for NPW visits,

The EPZs do not represent the maximum extent to which countermeasures may be required since NPW accidents more severe than the Reference Accident are possible. Emergency arrangements should be sufficiently flexible and extendible to cope with such accidents.

Three EPZs are defined, denoted as Zone 1, 2 and 3, which are described below.

7.1 ZONE 1

Zone 1 is a region close to the NPW within which the surrounding population may be exposed to two distinct radiation hazards following an accident, namely direct gamma shine from the vessel and airborne radioactive material.

Following the Reference Accident, the large quantity of fission products contained within the reactor compartment act as an intense gamma source causing a significant but localised direct radiation hazard. It has been shown that shielding provided by the vessel hull, as well as distance in air would reduce the direct gamma shine from the vessel to negligible levels beyond about 200m [22]. At distances beyond about 200m, radiation doses from the airborne plume of radioactive are likely to dominate.

The extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be justified on the basis of the 2000 Reference Accident. This is estimated from the distance at which the projected dose exceeds the Generic Intervention Level for implementation of evacuation as a countermeasure (See Table 7.1). Beyond Zone 1, automatic evacuation would not be justified on the basis of the Reference Accident.

Authorities should be able to exercise full control over all persons within Zone 1. In order to limit the radiation exposure of individuals and maximise averted doses, evacuation of Zone 1 should be initiated immediately following notification of an accident. Since doses may accrue very rapidly within about 200 m of the NPW due to direct gamma shine (as discussed above), evacuation of this region should be completed within minutes following notification of an accident. The remainder of Zone 1 should be evacuated within about 1 hour following notification of an accident.

7.1.1 Submarines and Smaller Surface Vessels

For a 24 hour vessel removal time the calculated effective and thyroid doses on the plume centreline following the Reference Accident are shown as a function of distance in Figures 6.1-6 and 6.1-11.

With the new intervention levels (see Table 7.1) the extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be justified on the basis of the 2000 Reference Accident. This is estimated from the distance at which the projected dose exceeds the Generic Intervention Level for implementation of automatic evacuation as a countermeasure. Beyond Zone 1, automatic evacuation would not be justified on the basis of the 2000 Reference Accident.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.1-6), the individual dose criterion of 50 mSv effective dose for evacuation is exceeded out to a distance of 500 m in 12 hours (see Table 7.1).

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.1-11), the individual thyroid dose criterion of 500 mGy [53] to a child is exceeded out to a distance of 600m in 12 hours.

Therefore, for submarines and smaller surface vessels, Zone 1 is defined as a circle of radius 600m centred on the NPW. A child on the plume centreline at 600 m for 1 hour, following the 2000 Reference Accident would receive a total effective dose of about 9 mSv (Figure 6.1-7).

7.1.2 NIMITZ Class Aircraft Carriers

For NIMITZ class aircraft carriers, Zone 1 is currently defined as a keyhole shaped region consisting of a circle of radius 600m centred on the NPW and a region in the downwind 60 degree sector out to a distance of 1.2 km [1]. As for submarines and smaller surface vessels, this distance is determined as that at which the individual dose criterion of 1500 mSv to the child thyroid would be exceeded in about 1 hour following the 1975 Reference Accident [1].

With the new intervention levels (see Table 7.1) the extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be justified on the basis of the 2000 Reference Accident. This is estimated from the distance at which the projected dose exceeds the Generic Intervention Level for implementation of automatic evacuation as a countermeasure. Beyond Zone 1, automatic evacuation would not be justified on the basis of the 2000 Reference Accident.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.2-6), the individual dose criterion of 50 mSv (see Table 7.1) effective dose for evacuation is exceeded out to a distance of 700 m in 2 hours.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.2-11), the individual thyroid dose criterion of 500 mGy [53] to a child is exceeded out to a distance of 800m in 2 hours.

Therefore, for NIMITZ class aircraft carriers, Zone 1 is defined as a circle of radius 800m centred on the NPW. This simplifies the Zone from the keyhole shape currently used.

A child on the plume centreline at 800m for 1 hour following a Reference Accident on board a NIMITZ class aircraft carrier would receive a total effective dose of about 19 mSv [See Figure 6.2-7].

7.2 ZONE 2

Zone 2 represents an area within which the surrounding population may be subject to risk due to airborne radioactive material released from the NPW following an accident, and in which countermeasures might be taken to protect individuals during the initial phase of the accident. The major exposure pathways within this zone are:

- inhalation of material from the radioactive plume;
- direct gamma radiation from material in the radioactive plume (cloudshine); and
- direct gamma radiation from material deposited on the ground (groundshine).

The extent of Zone 2 is defined as the maximum distance to which countermeasures of sheltering and/or stable iodine distribution could be required following the Reference Accident, that is, the distance to which the most restrictive individual dose criterion for these countermeasures is exceeded. The individual dose criterion for sheltering has been specified as 10 mSv effective dose while that for distribution of stable iodine has been specified as 100 mGy thyroid dose (see Table 7-1).

The most restrictive of the distances for the countermeasures of sheltering and stable iodine distribution determines the extent of the Zone 2 boundary. The maximum extent of sheltering following the Reference Accident is determined from the calculated effective dose, while the maximum extent of stable iodine distribution is determined from the calculated thyroid dose.

A feasible emergency plan should be established for the implementation of countermeasures within Zone 2. Since doses accrue at a faster rate closer to the NPW, countermeasures should be implemented progressively in a graded fashion within Zone 2 starting from the Zone 1 boundary. Normally, countermeasures would be restricted to a 30 degree down wind sector within Zone 2.

Outside this sector and beyond Zone 2 generally, no evacuation, sheltering or distribution of stable iodine would be required following the Reference Accident.

7.2.1 Submarines and Smaller Surface Vessels

For a 24 hour vessel removal time the calculated effective and thyroid doses on the plume centreline following the Reference Accident are shown as a function of distance in Figures 6.1-6 and 6.1-11.

With the new intervention levels (see Table 7.1) the extent of Zone 2 is defined as the maximum distance to which countermeasures would be justified on the basis of the 2000 Reference Accident. Beyond Zone 2, such countermeasures would not be justified on the basis of the 2000 Reference Accident.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.1-6), the individual dose criterion of 10mSv effective dose for sheltering is exceeded out to a distance of 1.2km in 12 hours.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.1-11), the individual dose criterion of 100mGy for consideration of stable iodine administration is exceeded out to a distance of 1.4km in 12 hours.

Therefore, for submarines and smaller surface vessels, the extent of Zone 2 should be defined as 1.4 km (the larger distance) for a 24 hour vessel removal time.

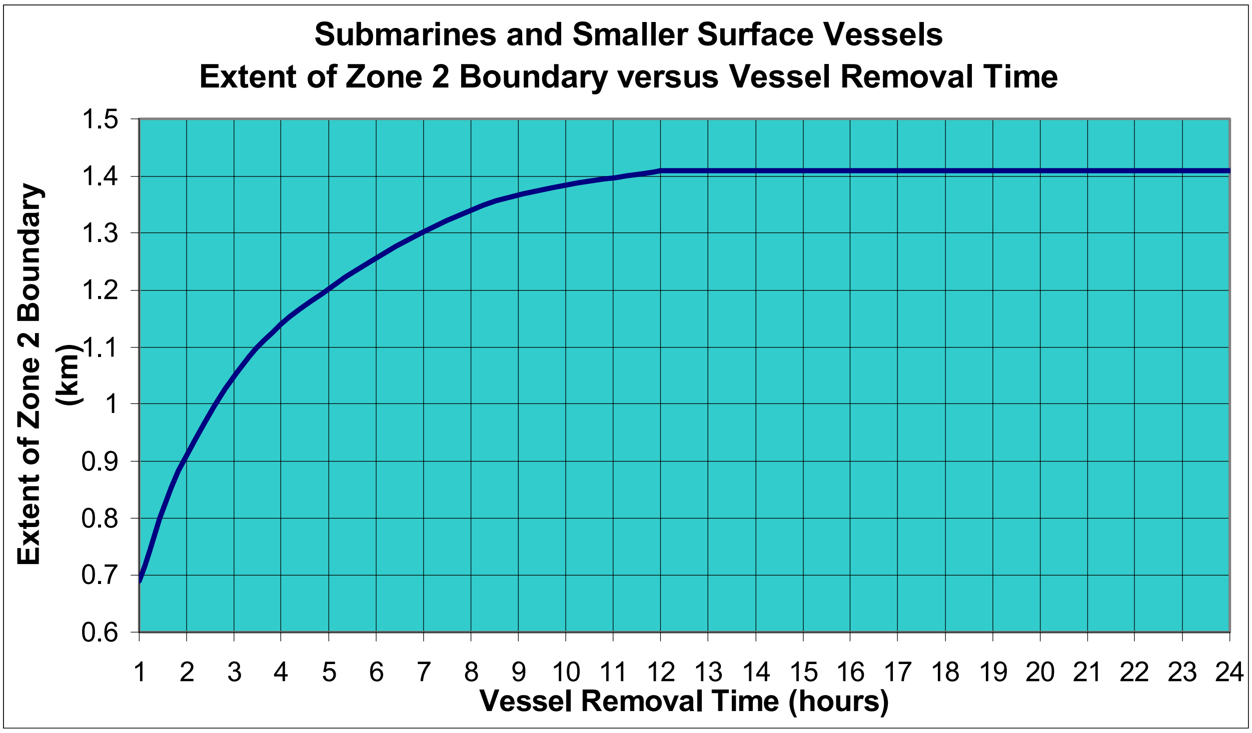
This is compared to the extent of Zone 2, determined using the 1975 Reference Accident model and individual dose criteria, of 2.2 km for a 24 hour vessel removal time [1]. The 1975 Reference Accident used a dose limit of 250mSv whole body dose, and a child thyroid dose of 1500 mSv.

The reduction in projected radiation doses calculated using the 2000 Reference Accident model leads to a significant reduction in Zone 2 boundary, despite the far more restrictive individual dose criteria now being applied [62].

The extent of the Zone 2 boundary for submarines and smaller surface vessels is shown as a function of vessel removal time in Figure 7-1, based on the 2000 Reference Accident and individual dose criteria. From Figure 7-1, it is seen that the extent of Zone 2 for a 4 hour vessel removal time is approximately 1.15km which is rounded up to 1.2km, and is identical to that calculated using the 1975 Reference Accident model.

The Zone 2 boundary has not been reduced for the 4-hour vessel removal time. The 1975 Reference Accident model assumes that the release of fission products to the atmosphere and the accrual of radiation doses occur at a uniform rate following the accident. In the 2000 Reference Accident model, the bulk of the release and radiation dose occur at the beginning of the release. This is due to the gradual radioactive decay and deposition of fission products inside the containment, and the increasing atmospheric dispersion due to the effects of wind variability with time.

Figure 7-1

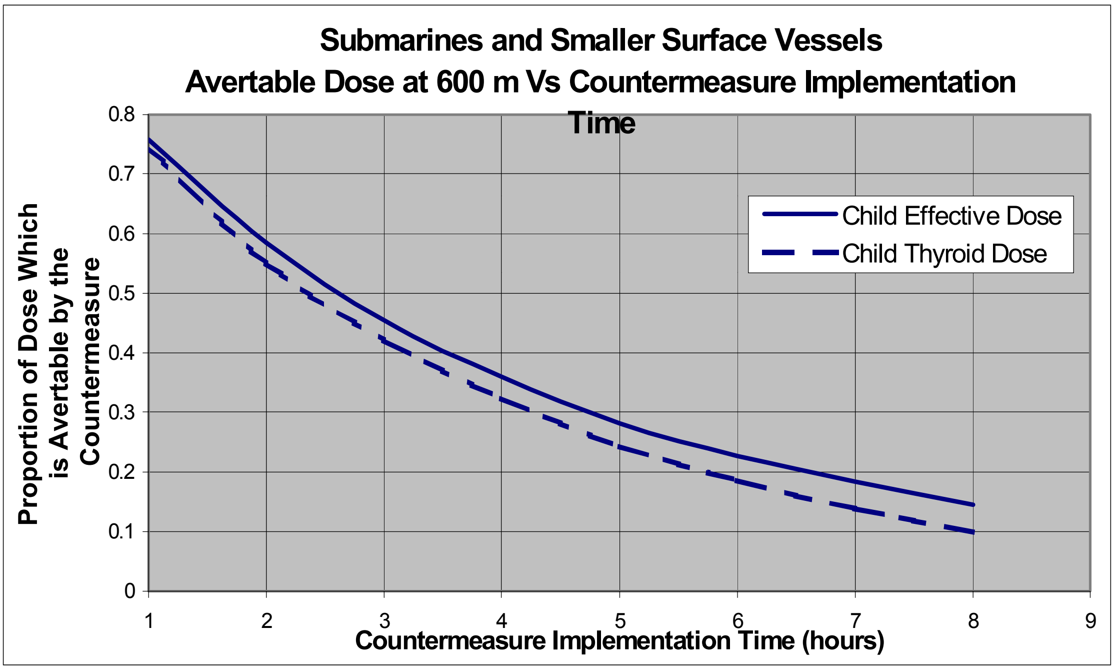


In addition to the extent of Zone 2, the timescale for the implementation of countermeasures within Zone 2 requires consideration. Figures 6.1-7 and 6.1-12 show the rate with which child effective doses and child thyroid doses accrue on the Zone 1 boundary following the 2000 Reference Accident for submarines and smaller surface vessels. Based on these figures, the maximum dose, which can potentially be averted by implementation of countermeasures at 600 m, is shown in Figure 7-2 as a function of countermeasure implementation time.

From Figure 7-2, it is seen that the dose, which could be averted by implementing countermeasures, increases with decreasing implementation time. Therefore, countermeasures should be implemented as soon as possible following an accident in order to minimise doses to the public. As is currently the case, countermeasures should be implemented progressively within Zone 2 starting from the Zone 1 boundary, since doses accrue at a faster rate closer to the NPW.

Radiation measurements are essential to determine the actual magnitude of the release and for making decisions on the need to increase or decrease the extent of countermeasures to suit the specific accident.

Figure 7-2



7.2.2 NIMITZ Class Aircraft Carriers

The total 24 hour effective and thyroid doses calculated following the 2000 Reference Accident for NIMITZ class aircraft carriers are shown as a function of distance in Figures 6.2-6 and 6.2-11 for a 2 hour vessel removal time.

With the new intervention levels (see Table 7.1) the extent of Zone 2 is defined as the maximum distance to which countermeasures would be justified on the basis of the 2000 Reference Accident. Beyond Zone 2, such countermeasures would not be justified on the basis of the 2000 Reference Accident.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.2-6), the individual dose criterion of 10mSv (see Table 7.1) effective dose for sheltering is exceeded out to a distance of 1.6km in 2 hours.

Based on the projected consequences of the 2000 Reference Accident (see Figure 6.2-11), the individual dose criterion of 100mGy (see Table 7.1) for consideration of stable iodine administration is exceeded out to a distance of 1.9m in 2 hours.

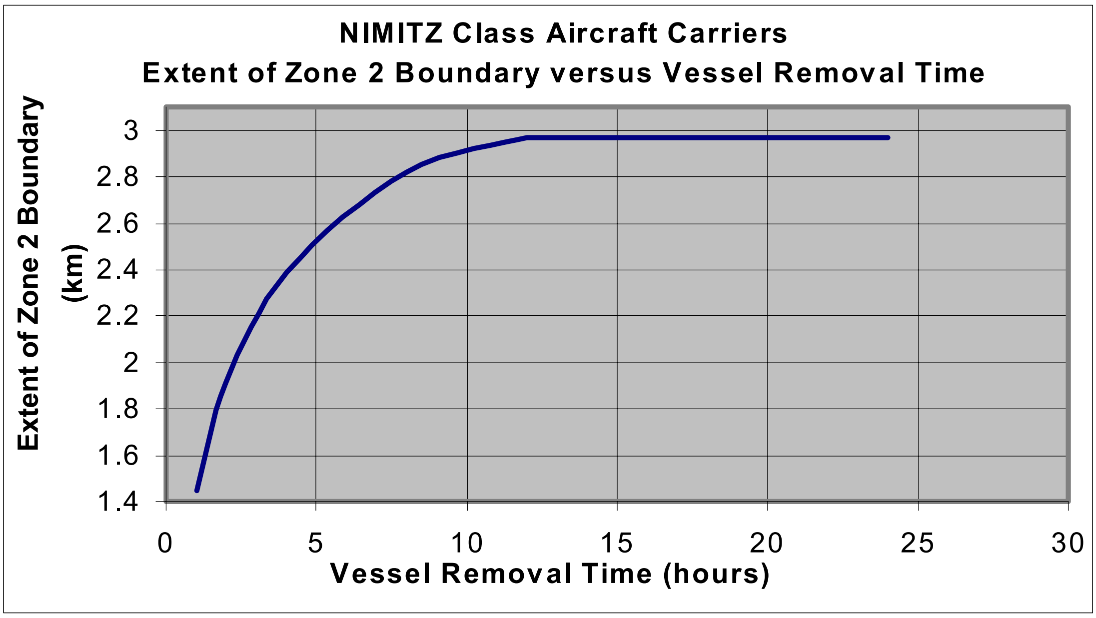
Therefore, for NIMITZ vessels, the extent of Zone 2 should be defined as 1.9 km (the larger distance) for a 2 hour vessel removal time.

The extent of Zone 2 determined using the 1975 Reference Accident model and individual dose criteria is 3.6 km for a 2-hour vessel removal time [1]. The individual dose criterion used a dose limit of 250mSv whole body dose and a child thyroid dose of 1500mSv with evacuation as the only countermeasure.

The significant reduction in radiation doses calculated using the 2000 Reference Accident model leads to a significant reduction in Zone 2 boundary, despite the far more restrictive individual dose criteria now being applied [58,62].

The extent of the Zone 2 boundary for NIMITZ class air craft carriers is shown as a function of vessel removal time in Figure 7-3, based on the new Reference Accident and individual dose criteria.

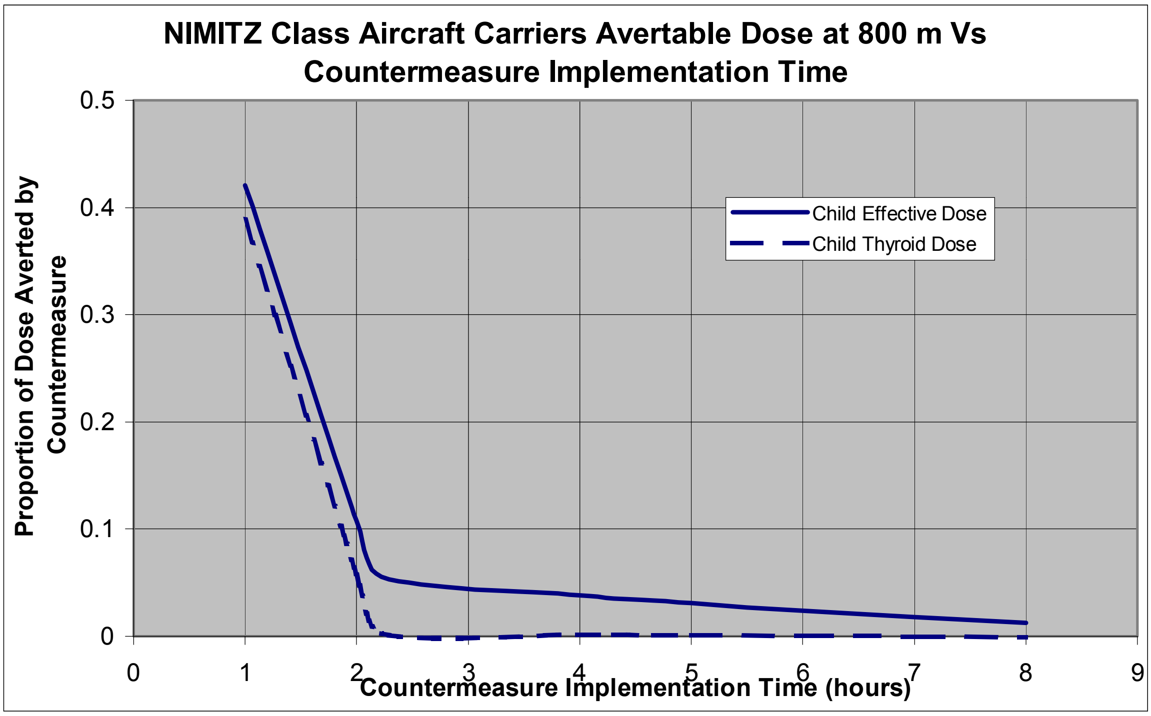
Figure 7-3



Figures 6.2-7 and 6.2-12 show that doses accrue very rapidly following a Reference Accident on board a NIMITZ class aircraft carrier, ceasing to accrue once the vessel is removed from the port and the plume has passed. Based on these figures, the maximum proportion of the dose at 800 m, which can potentially be averted by implementation of countermeasures following the Reference Accident, is shown in Figure 7-4 as a function of countermeasure implementation time. It is seen that a significant proportion of dose would be averted only if countermeasures are implemented within 2 hours following the accident occurring, with the averted dose increasing rapidly with decreasing implementation time within 2 hours.

Radiation measurements are essential to determine the actual magnitude of the release and for making decisions on the need to increase or decrease the extent of countermeasures to suit the specific accident. In practice, anchorages at sea would be used for NIMITZ class aircraft carriers, and most likely, there would be no land, but only sea for the full extent of the Zone 2 radius of 1.9 km.

Figure 7-4



7.3 ZONE 3

Zone 3 represents an area within which the surrounding population may be subject to hazards associated with long term exposure to ground deposited radioactive material (groundshine) and ingestion of contaminated water, foodstuffs, milk and agricultural produce. Due to the slow rate of accrual of groundshine and ingestion doses, immediate action is not required to protect the population from these hazards. Decisions to implement protective actions, such as relocation and food restrictions, would be made based on the results of extensive radiation and contamination monitoring. The extent of Zone 3 would be determined on an accident specific basis based on the results of monitoring and comparison with Operational Interventional Levels [53]. As discussed in Section 2, the purpose of NPW port assessments is to plan for the early phase emergency response when action must be taken rapidly to control radiation doses. Longer-term consequences and the intermediate and late phases of emergency response associated with Zone 3 are therefore not considered in this report.

8. SUMMARY AND CONCLUSIONS

The model currently used to calculate the consequences of the 1975 Reference Accident is a simplified, but conservative model developed during the 1970s. A significant advancement since the development of this model is the availability of improved calculation models and techniques through the use of computer codes.

The code used for assessing the consequences of the 2000 Reference Accident for port assessments is the ACCIDENT code. ACCIDENT is a generic nuclear reactor accident consequence assessment code developed by the Nuclear Safety Bureau [20], which has been validated against the internationally used accident consequence code PCCOSYMA.

In calculating the consequences of the 2000 Reference Accident, two classes of NPW have been considered, namely submarines and smaller surface vessels, and NIMITZ class aircraft carriers.

As a condition of entry to Australian ports, submarines and smaller surface vessels are subject to a vessel removal time of 24 hours following an accident. NIMITZ class aircraft carriers, which have a higher reactor power, are subject to a vessel removal time of 2 hours following an accident [1].

The major changes to the models, parameters and assumptions used to calculate the consequences of the Reference Accident for both submarines and smaller surface vessels and NIMITZ class aircraft carriers are:

(i) revised estimates of reactor power and core operating history (see Section 3.1);

(ii) revised fission product core release fractions (see Section 3.2);

(iii) a revised estimate of containment leak rate, allowing for the presence of a secondary containment (see Section 3.3.1);

(iv) inclusion of an improved fission product containment deposition model (see Section 3.3.2);

(v) a revised atmospheric dispersion model, incorporating updated wind variability and terrain roughness effects (see Section 4.1);

(vi) inclusion of a model for ground deposition of fission products (see Section 4.2);

(vii) updated dose conversion factors for cloudshine and inhalation (see Section 5.1.1/5.1.2);

(viii) inclusion of a model for effective inhalation dose (see Section 5.1.2);

(ix) inclusion of a model for groundshine dose (see Section 5.1.3); and

(x) revised criteria for countermeasures following an accident (see Section 7).

The above changes have a significant impact on the calculated consequences of NPW Reference Accident. While some of the changes act to increase the calculated consequences and some act to reduce them, the overall effect is a significant reduction in both the calculated release of fission products and radiation doses following the 2000 Reference Accident.

The reduction in the magnitude of the calculated release of fission products to the atmosphere is due primarily to the revised estimate of the containment leak rate, which takes into account the presence of a secondary containment (see Section 3.3.1). This leads to a significant reduction in calculated radiation doses. Other changes, which act to reduce calculated radiation doses are the updated atmospheric dispersion model, and reduced radiation dose conversion factors in the case of thyroid inhalation dose.

The major impact of the 2000 Reference Accident model on NPW visits is the effect on the extent of Emergency Planning Zones (EPZs). For NPW visits to Australia, three EPZs are defined around NPW berths and anchorages for planning purposes. They help in the identification of areas where hazards might arise, and ensure that appropriate and timely protective actions can be taken to control radiation doses in the event of an accident. The projected consequences of the 2000 Reference Accident are used to establish the extent of two of these zones, namely Zone 1 and Zone 2 described in section 7.

ZONE 1

Zone 1 is a region close to the NPW within which the surrounding population may be exposed to direct gamma shine from the vessel as well as airborne radioactive material following an accident. The extent of Zone 1 is defined as the maximum distance to which immediate evacuation would be required following the Reference Accident, that is, the distance at which the avertable dose for an individual exceeds the Generic Intervention Level for evacuation (as defined in IAEA Safety Series 109, Intervention Criteria in a Nuclear or Radiation Emergency [62]).

For submarines and smaller surface vessels, the 2000 Reference Accident estimates Zone 1 as a circle of radius 600m centred on the NPW. This is the same as estimated using the 1975 Reference Accident.

For NIMITZ-class aircraft carriers, the 2000 Reference Accident estimates Zone 1 as a circle of radius 800m centred on the NPW. This is an increase from the 600m radius estimated using the 1975 Reference Accident.

ZONE 2

Zone 2 represents an area within which the projected doses do not justify evacuation, but where, subject to actual field measurements of radioactivity, the maximum avertable doses that are estimated may justify sheltering as a countermeasure. A viable emergency plan for the implementation of sheltering and distribution of stable iodine, or evacuation within this zone is established in each port special plan.

For submarines and smaller surface vessels, with a vessel removal time of 24 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.4km. This is a reduction from the 2.2km estimated by the 1975 Reference Accident.

For submarines and smaller surface vessels, with a vessel removal time of 4 hours, the 2000 Reference Accident estimates Zone 2 as any 30 degree downwind sector within a circle of radius 1.2km. This is the same as the Zone 2 radius estimated by the 1975 Reference Accident.

For NIMITZ class aircraft carriers, with a vessel removal time of 2 hours, the 2000 Reference Accident estimates Zone 2 as a 30 degree downwind sector within a circle of radius 1.9km. This is a reduction from the 3.5km radius estimated by the 1975 Reference Accident.

ZONE 3

Zone 3 represents an area within which the surrounding population may be subject to hazards associated with long term exposure to ground deposited radioactive material (groundshine) and ingestion of contaminated water, foodstuffs, milk and agricultural produce. Due to the slow rate of accrual of groundshine and ingestion doses, immediate action is not required to protect the population from these hazards. Decisions to implement protective actions, such as relocation and food restrictions, would be made based on the results of extensive radiation and contamination monitoring.

COLLECTIVE DOSE

Collective dose provides a measure of the societal consequences of the 2000 Reference Accident in terms of the number of health effects, which may appear over the ensuing lifetime of the surrounding population. It is essentially calculated by multiplying the sector average individual dose received in the various distance bands by the population in the downwind sector. The collective dose is calculated, on a port specific basis for 12 different wind directions, with the direction giving the highest collective dose used to assess port acceptability. Since collective doses are port specific they will be calculated in the individual port assessments, and are not presented in this report.

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GLOSSARY

absorbed dose - The energy transferred from radiation to unit mass of the exposed matter.

accident - Any unintended event, including operator error, equipment failure or other mishap, the consequences or potential consequences of which are not negligible from the point of view of protection or safety. For public information purposes, an accident is an event classified as level 4 or above on the International Nuclear Event Scale (INES), that is, an event that involves a release of radioactive material offsite likely to cause public exposure of the order of prescribed limits, or requiring countermeasures to be taken, or causes significant damage to the facility, or results in exposure of workers onsite to such a degree that there is a high probability of early death.

ACCIDENT Code – A generic nuclear reactor accident consequence assessment code developed by the Nuclear Safety Bureau. It is the computer code used for assessing the consequences of the Reference Accident.

action level - In general, the value of a specified measurable quantity above which a specified action will be taken. Most commonly used to mean a level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations.

activity - The rate at which atomic disintegration occur in a radioactive material.

activity concentration - The activity of a radionuclide per unit mass (or per unit volume) of a material.

ANSTO - Australian Nuclear Science and Technology Organisation; a body corporate established by the Australian Nuclear Science and Technology Organisation Act 1987.

ARPANSA *– Australian Radiation Protection and Nuclear Safety Agency.*

atmospheric dispersion - the dispersion of the radioactivity released from a source and is used to determine the airborne radioactivity concentrations in the atmosphere.

barrier - A physical barrier for the confinement of nuclear material. Examples are the nuclear fuel matrix; the nuclear fuel cladding; the boundary of the controlled facility's coolant system; the containment system. Site personnel, the public and the environment are protected primarily by means of these barriers. The defence in depth concept includes protecting and maintaining the integrity of barriers against internal and external initiating events.

Becquerel (Bq) – Unit of amount of radioactivity 1Bq= 1 disintegration per second.

buffer zone - An offsite public access control zone which is referenced in the emergency plan. This is an area around the site where generally, there may be no public residences and that may be evacuated and where public access may be restricted in an emergency response situation.

calculation - Any use of theoretical methods whether by using computer modelling programs, look-up tables, or other means.

cloudshine - Ionizing radiation emanating from the radioactive plume as it passes overhead.

consequence - The adverse effect of an event on site personnel, the public and the environment.

conservative - The use of models, data, assumptions and practices which would be expected to lead to a result that bounds the best estimate on the safe side to a high degree of confidence.

containment leak rate – The rate at which a containment about a nuclear reactor will leak under accident conditions. This can vary considerably over the period of the accident.

containment – primary – The compartment surrounding the reactor plant made up of the pressure hull of the vessel and internal bulkheads designed to withstand the build-up of pressure after a severe reactor accident.

containment – secondary – The compartment within the vessel hull on either side of the primary containment which can prevent internal leakage from primary containment to the atmosphere. Ultimate secondary containment comprises the entire immensely strong pressure hull of the submarine/vessel.

containment system - A structure and associated subsystems that form a barrier around the controlled facility's core and coolant systems. The containment system can be sealed to withstand a high internal pressure in order to contain nuclear material that might otherwise be released to the environment.

contamination - The presence of radioactive substances or materials on surfaces, or within solids, liquids or gases (including the human body), where they are undesirable or could be harmful.

core – The region of the reactor containing fuel within which the fission reaction is occurring.

core damage - Loss of a controlled facility's core structural integrity (for example, in the case of a nuclear reactor, partial nuclear fuel melting accompanied by partial loss of the effectiveness of the nuclear fuel cladding barrier, following the failure of heat removal or a reactivity excursion).

core inventory - the quantity of each radioactive fission product inside the reactor core prior to the accident and depends on the reactor operating power and its operating history.

countermeasure - An intervention aimed at alleviating the radiological consequences of an accident. These may be protective actions or remedial actions.

critical – A reactor is critical when the fission chain reaction is in a self-sustaining state.

deterministic - When applied to an analysis or an assessment, this indicates that single numerical values are assumed for all key parameters, giving a single result.

deterministic analysis - An analysis that uses deterministic assumptions and procedures without explicit consideration of probabilities. Deterministic analysis is advocated in design-basis analyses, in line with international practice. For a beyond-design-basis accident, the confidence level of the deterministic evaluation of consequences must be high enough not to underestimate the risk, and at the same time, the confidence level in the deterministic consequences evaluation could be reduced for such highly improbable accidents.

dispersion - The resulting effect of processes such as transport, diffusion, and mixing of wastes or effluents (for example, liquid and gaseous releases) in water or air - ultimately resulting in dilution.

dose -A measure of the radiation received or 'absorbed' by a target.

dose, avertable - The dose to be saved by a protective action; that is, the difference between the dose to be expected with the protective action and that to be expected without it.

dose, collective - The total dose (normally effective dose) to a defined population, calculated as the product of the number of exposed individuals and their average dose.

dose, collective effective - A measure of the total radiation exposure group of people which is obtained by summing their individual effective doses.

dose, effective dose - The weighted sum of all the equivalent doses in all the tissues and organs of the body. The weighting ensures that the detriment is equal whether or not the whole body is irradiated uniformly.

dose, equivalent - A measure of the dose to a tissue or organ designed to reflect the amount of harm caused, calculated as the product of the average absorbed dose in the tissue or organ and the appropriate radiation-weighting factor.

dose limit - The value of the effective dose to individuals from controlled radiation practices that shall not be exceeded.

dose rate - A measure of the rate at which energy is transferred from radiation to a target.

emergency countermeasures – Measures consisting of shelter, evacuation or the administration of stable iodine, which may be implemented to protect the public in the emergency phase of the accident.

emergency core cooling system - For nuclear reactors, a system designed to prevent nuclear fuel damage by maintaining forced cooling to the nuclear fuel.

emergency plan - A plan that applies to a controlled facility site and covers all activities planned to be carried out by all agencies, authorities and organisations involved in the event of an emergency situation leading to, or likely to lead to, a significant release of nuclear material. It includes the coordinated emergency plans of the operating organisation and the public authorities.

emergency planning zones - Offsite public access control zones, which are referenced in the emergency plan. They may consist of, or be a combination of, exclusion zones where there are no public residences, areas that may be evacuated, and areas where public access may be restricted in an emergency response situation.

engineered safety features - Any engineered components, systems or structures that are safety-related.

equivalent dose - A quantity that expresses all radiation doses on a common biological scale. It is the product obtained by multiplying the absorbed dose in tissue by a radiation-weighting factor to account for the different potential for injury of different types of radiation.

evacuation - The removal of persons from locations where projected doses are high, as an immediate protective action in an emergency intervention situation.

event, initiating - The first event in a sequence. Initiating events are typically categorised by the area in which they occur. In the case of nuclear reactors, examples are: loss of electrical power supply; insertion of reactivity; loss of coolant; an equipment failure; internal events; external events; and human error.

exclusion zone - Refer to ‘emergency planning zones’.

exposure - The act or condition of being subject to irradiation.

exposure, natural -Exposure from natural sources.

exposure pathways - The routes by which radioactive material can reach or irradiate humans.

exclusion zone - A special control area for personnel, established in the immediate vicinity of the NPW

fail-safe - If an item important to safety should fail, it passes into a safe state without a requirement to initiate any actions.

fissile material - Nuclides capable of undergoing nuclear fission as a result of interaction with neutrons. This includes nuclides such as U233, U235, Pu239 and Pu241 which are able to support a fission chain reaction with neutrons of all energies, but predominantly with slow neutrons, and includes nuclides such as Np237 and Pu238 which are able to support a fission chain reaction predominantly with fast neutrons. By this definition, natural uranium, enriched uranium and depleted uranium are regarded as containing fissile material but are not regarded as being wholly fissile material.

fission product release fraction - The fraction of each fission product radionuclide that is released from the fuel of a nuclear reactor to a specified space (for example, to the containment building or the environment).

fuel (metallic) – nuclear reactor fuel which has uranium bound to a metal, usually an alloy to stabilise it from phase expansion at low temperature which would otherwise lead to mechanical instability.

fuel (nuclear) - Fissile material, sometimes in combination with other nuclear materials such as moderator and fertile material, in the form of uranium or plutonium metal, alloy or chemical compound. Examples include unirradiated and irradiated nuclear fuel elements and natural uranium.

fuel (oxide) – nuclear reactor fuel which is generally almost pure uranium oxide (UO_2) bound less densely than metallic fuels which allows for flow of fission product yield through the fuel matrix.

fuel element - The smallest structurally discrete part of a controlled facility which has fuel as its principal constituent.

gamma radiation - High energy electro-magnetic radiation of considerable penetrating power emitted by most radioactive substances.

gamma shine – The gamma radiation which would emanate directly from a submarine following a reactor accident.

Gaussian plume – A plume or release whose cross-section approximates the normal or binomial distribution as a function of distance from the release point.

half-life - The time taken for the activity of a radionuclide to halve as a result of radioactive decay.

IAEA - International Atomic Energy Agency. Headquarters located in Vienna, Austria.

ICRP - International Commission on Radiological Protection.

international best practice - practice that predominantly conforms to guidelines and standards issued by international radiation protection and nuclear safety organisations (such as the IAEA, ICRP) and that is regularly subjected to peer or other critical review at an international level or forum.

intervention - A remedial action referenced in the emergency plan which may include the evacuation of an emergency planning zone and sheltering inside buildings, and which is intended to reduce or avert radiation exposure or the likelihood of radiation exposure in an emergency response situation.

intervention level - The level of avertable dose at or above which a specific protective action or remedial action is taken in an emergency exposure or chronic exposure situation.

ionizing radiation - Radiation capable of producing ion pairs in biological material(s). In the context of the ARPANS Act, this means electromagnetic or particulate radiation capable of producing ions directly or indirectly, but does not include electromagnetic radiation of a wavelength greater than 100 nanometres.

limit, acceptable - Limit acceptable to the regulatory body.

LOCA – loss of coolant accident

long-term - Refers to periods which exceed the time during which active institutional control can be expected to last.

Los Angeles class – class of United States submarine which has a 6000 ton standard displacement and is powered by a reactor which has 10 years between refuelling.

meltdown – in a severe accident the melting of fuel elements within the core.

migration - The movement of materials (for example, radionuclides) through various media (for example, barrier materials or solids) usually by being carried or transported by fluid flow.

monitoring, environmental - Monitoring in which the parameters measured relate to characterising an environment allowing the possible exposure in that environment to be estimated.

NHMRC - National Health and Medical Research Council of Australia. The ARPANS Regulations require, as conditions of licence, that licence holders ensure that all conducts at facilities are in accordance with the NHMRC publications 'Recommendations for Limiting Exposure to Ionizing Radiation' and 'National Standards for Limiting Occupational Exposure to Ionizing Radiation'.

NIMITZ – type of aircraft carrier which has two reactors, which are assumed to generate a maximum reactor operating power of about 600 MW(t) and an average reactor operating power of 150 MW(t).

noble gases - In the context of nuclear reactor-based source terms, the elements krypton and xenon. They are chemically inactive.

NPW – Nuclear Powered Warship, a sea- going military vessel which is primarily powered by one or more nuclear reactors. This includes non-surface travelling vessels such as submarines.

NSB (Nuclear Safety Bureau) – commonwealth government body which regulated ANSTO's nuclear reactor prior to the formation of ARPANSA. Has now largely become the ARPANSA Regulatory Branch

nuclear material - Fissile material, fertile material, moderator material, fission products, radioactive isotopes, radioactive waste and other nuclear fuel cycle materials including nuclear fuel which are used for (or are wholly or partly attributable to) nuclear fission and other processes wherein a substance is subjected to bombardment by neutrons or ionizing radiation.

nuclear reactor - A neutron fission device, together with all structures, systems and components necessary for safety, that is intended to sustain a controlled fission chain reaction at power levels significantly above those of a critical assembly for purposes such as the irradiation of materials and the production of isotopes. The term nuclear power plant is reserved for nuclear reactors that are used for the production of power in the form of heat or electricity.

operating lifetime - The period during which a controlled facility is used for its intended purpose.

OPSMAN 1 – Prescribes the conditions, procedures and responsibilities for the conduct of visits to Australia by United States and Royal Navy nuclear powered warships (NPWs).

organic iodine – airborne iodine which does not readily plate out onto a surface and is easily resuspended.

Pasquill stability category – method of classifying different atmospheric wind conditions ranges from category A (very turbulent) to F (stable inversion conditions).

performance failure - Occurs when a system important to safety functions when required (ie. no components fail), but it functions in a way that does not provide the intended protection. A performance failure can arise, for example, from incorrect analyses or inadequate functional independence between a safety system and a process control system, and can be manifest under accident conditions as the wrong type of operation, or as an operation having insufficient capacity or inadequate time response. The term 'integrity' includes the impact of performance failures.

plume - The trail of airborne contamination from a radiation accident.

potassium iodate tablets – Tablets containing the stable (ie. non-radioactive iodine) which would minimise the uptake of radioactive iodine into the thyroid gland.

primary circuit – The completely sealed pipework containing the primary coolant system connecting the reactor pressure vessel to the steam generator.

probabilistic safety analysis (PSA) - A method of safety analysis which takes into account the probabilities and frequencies of occurrence of events and event sequences by assuming a probability distribution for the numerical values of some or all key parameters, and which is used to evaluate the likelihood on an accident and its consequences. It allows a systematic examination of the full spectrum of postulated events and provides a relative estimate of the overall risk. The term is sometimes used interchangeably with probabilistic risk analysis (PRA).

public - Those persons who occupy areas beyond the site. In a radiation protection context, the public are those who do not receive occupational exposure.

public exposure - All radiation exposure which is neither occupational exposure nor medical.

radiation (ionising) – alpha, beta gamma and neutron radiation capable of displacing electrons from atoms and therefore producing ions.

radiation protection - The protection of persons and the environment against the harmful effects of ionizing radiation, while still allowing necessary activities from which radiation exposure might result.

radiation source - Anything that may cause exposure to ionizing radiation or non-ionizing radiation.

radiation weighting factor - A number by which the absorbed dose in a tissue or organ is multiplied to reflect the relative biological effectiveness of the radiation in inducing stochastic effects at low doses, the result being the equivalent dose.

radioactive material - Any natural or artificial material whether in solid or liquid form, or in the form of a gas or vapour, which exhibits radioactivity.

radioactivity - Spontaneous disintegration of certain nuclides, generally resulting in the formation of new nuclides, in which one or more types of radiation such as alpha particles, beta particles and gamma rays are emitted, and energy is liberated.

radionuclide - A nucleus (of an atom) that exhibits radioactivity.

reactivity - A parameter giving the deviation from criticality of an arrangement of fissile material such that positive values correspond to supercriticality, negative values to subcriticality, and zero value to criticality.

reactivity excursion - A transient in neutron flux level produced by an uncontrolled fission chain reaction, characterised by a release of thermal energy and radiation (n,γ).

reference accident - A hypothetical beyond-design-basis accident based on a conservative, deterministic model, which is used for assessing: siting, accident management, and emergency planning. It depends on the type of controlled facility and in general terms, assumes degraded performance of one or more safety systems that leads to a release of radioactive material and an increased leak rate of radioactive material from a confinement or containment system, together with assumptions about prevailing meteorological conditions.

refuelling cycle – refers to the time between replacement of fuel rods within the core.

release fraction – specifies the fraction of the core inventory of each fission product radionuclide which is released from the core into the containment.

remedial action - Action taken when a specified action level is exceeded, to reduce radiation doses that might otherwise be received, in an intervention situation involving chronic exposure.

research reactor - A nuclear reactor that is used mainly for the generation and utilisation of neutron flux and ionizing radiations for research purposes.

risk - The likelihood, expressed as a frequency or a probability, of a specified undesired event occurring within a specified period or in specified circumstances. The specification of the event includes both the magnitude and the character of the consequences.

risk, individual - The frequency at which an individual may be expected to sustain a given level of harm from the realisation of specified hazards.

risk, societal - The relationship between the frequency and the number of people suffering from a specified level of harm in a given population from the realisation of specified hazards.

sector – 30 degree segment of the region around a NPW accident site. Associated with the downwind direction following an accident. Used in the calculation of the port assessment for NPW visits.

sector averaging – the average radiation dose within a sector.

sheltering - A protective action whereby members of the public are advised to stay indoors with windows and doors closed, intended to reduce their exposure in an emergency exposure situation.

sigma parameters- coefficients associated with the mathematical calculation of the Gaussian plume model specifically refers to the standard deviation of the Gaussian distribution across the plume.

significant consequence - A serious human injury, or significant damage to the environment, or a situation where a safety limit is exceeded. For the purposes of this document, the consequences of industrial workplace hazards that are not nuclear by nature are excluded.

source, natural - A naturally occurring source of radiation, such as the sun and stars (sources of cosmic radiation) and rocks and soil.

source term - An expression used to denote information about the actual or potential release of radioactive material from a given source, most commonly in the case of an accident. This may include information about the radionuclides present, and the composition, quantity, rate and mode of release of the material.

survey - A systematic investigation and measurement of radiation and/or contamination levels.

validation - The process of demonstrating that an item designed or manufactured, or a process, method, measurement, experiment, data or computer program, complies with its intended purpose and its specifications. Whilst the process of validation necessarily includes some elements of verification, the two processes are otherwise independent of each other.

Visiting Ships Panel (Nuclear) (VSP(N)) – A Commonwealth Government interdepartmental standing committee to control arrangements for visits to Australia by Nuclear Powered warships (NPWs). Its responsibilities are to advise the Minister of Defence on proposals for NPW visits, develop and maintain procedures related to NPW visits; and oversee the implementation of specific arrangements, especially safety requirements, for visits by NPWs.

VPD – volume per day, usually refers to a percentage of the volume of containment atmosphere released in one day.

List of Appendices

APPENDIX A-1 SOURCE TERM PARAMETERS

Parameter	1975 Reference Accident	2000 Reference Accident
Core Inventory		
Reactor Power (General Fission Product Inventory):		
Submarines and Smaller Surface Vessels	40 MW(t)	40 MW(t)
NIMITZ Class Aircraft Carriers	500 MW(t)	150 MW(t)
Reactor Power (Iodine Fission Product Inventory):		
Submarines and Smaller Surface Vessels	40 MW(t)	160 MW(t)
NIMITZ Class Aircraft Carriers	500 MW(t)	600MW(t)
Operating Time (average power)	several years	15 years
Operating Time (full power)	-	4 days
Reactor Shutdown Time	0	0
Release to Reactor Containment		
Core Release Fractions:		
Xe,Kr	100%	100%
I,Br	50%	50%
Cs,Rb	15%	30%
Te,Sb	-	15%
Ba,Sr	0.1%	5%
Ru	10%	2%
Mo,Tc,Rh	1%	1%
Ce,La,Pr,Y	1%	1%
Nb,Zr	1%	1%
Release to Atmosphere		
Containment Leak Rate	1.5 %VPD	0.1 %VPD
Containment Deposition Velocities:		
Xe,Kr	0	0
I,Br	50% plated out	3×10^{-5} m/s
Cs,Rb	0	3×10^{-5} m/s
Te,Sb	0	3×10^{-5} m/s
Ba,Sr	0	3×10^{-5} m/s
Ru	0	3×10^{-5} m/s
Mo,Tc,Rh	0	3×10^{-5} m/s
Ce,La,Pr,Y	0	3×10^{-5} m/s
Nb,Zr	0	3×10^{-5} m/s
Containment Surface Area to Volume Ratio:	-	1.2

APPENDIX A-2 ENVIRONMENTAL TRANSPORT PARAMETERS

Parameter	**1975 Reference Accident**	**2000 Reference Accident**	
Atmospheric Dispersion		**1st 12 hours**	**2nd 12 hours**
Stability Category	F	F	D
Wind Speed	1 m/s	1 m/s	3 m/s
Mixing Depth	-	200 m	800 m
Terrain Roughness	-	0.1 m	0.1m
Duration of meteorological conditions	12 hours	12 hours	12 hours
Ground Deposition			
Ground Deposition Velocities:			
I,Br	-	1×10^{-2}	
Cs,Rb	-	3×10^{-3}	
Te,Sb	-	3×10^{-3}	
Ba,Sr	-	3×10^{-3}	
Ru	-	3×10^{-3}	
Mo,Tc,Rh	-	3×10^{-3}	
Ce,La,Pr,Y	-	3×10^{-3}	
Nb,Zr	-	3×10^{-3}	

APPENDIX A-3 GAUSSIAN MODEL USED IN THE REFERENCE ACCIDENT

The basic formulation of the Gaussian Plume Model used to calculate air concentrations of radioactivity is shown below.

$$\frac{c(x)}{Q} = \begin{cases} \dfrac{1}{2\pi u\,\sigma_y(x)\sigma_z(x)}\exp(-\dfrac{y^2}{2\sigma_y^2})[\exp(-\dfrac{(z\pm h)^2}{2\sigma_z^2})+\exp(-\dfrac{(2A\pm z\pm h)^2}{2\sigma_z^2})] \ldots\ldots\ldots \sigma_z \le A \\ \dfrac{1}{\sqrt{2\pi}u\,\sigma_y(x)A}\exp(-\dfrac{y^2}{2\sigma_y^2}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \sigma_z > A \end{cases}$$

where:

$c(x)$	Air concentration of radioactivity at distance x $(Bq\ m^{-3})$
Q	Source release rate of radioactivity $(Bq\ s^{-1})$
u	Wind speed $(m\ s^{-1})$
$\sigma_y(x)$	Horizontal sigma parameter at distance x (m)
$\sigma_z(x)$	Vertical sigma parameter at distance x (m)
x	Downwind distance of receptor (m)
y	Horizontal distance of receptor from plume centreline (m)
z	Height of receptor above ground (m)
h	Height of release point (m)
A	Atmospheric mixing depth (m)

Overall Dispersion Parameter

$$D^{i,j}(x) = \begin{cases} \dfrac{1}{\pi\,u_i\sigma_y^{i,j}(x)\sigma_z^i(x)}[1+2\exp(-\dfrac{2A_i^2}{\sigma_z^i(x)^2})] \ldots\ldots\ldots\ldots\ldots \sigma_z^i(x) \le A_i \\ \dfrac{1}{\sqrt{2\pi}\,u_i\sigma_y^{i,j}(x)A_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \sigma_z^i(x) > A_i \end{cases}$$

where:

$D^{i,j}(x)$= Overall dispersion parameter at distance x during sub-interval j of release interval i sm^{-3})

$\sigma_y^{i,j}(x)$ = Horizontal sigma parameter at distance x during sub-interval j of release interval i (m)

$\sigma_z^i(x)$ = Vertical sigma parameter (corrected for terrain roughness) during release interval i (m)

A_I = Atmospheric mixing depth during release interval i (m)

Horizontal Sigma Parameter for a Short Release Duration

$$\sigma_{yt}^i(x) = a_y^i x^{b_y^i}$$

where:

$\sigma_{yt}{}^{i}(x)$=Horizontal sigma parameter due to atmospheric turbulence during release interval i (m)

x = Downwind distance (m)

$a_y{}^i$, $b_y{}^I$ = Constants dependent on atmospheric stability category during release interval i

Horizontal Sigma Parameter for a 30 Minute Release

$$\sigma_y 30^i(x) = \sqrt{\sigma^i_{yt}(x)^2 + \sigma^i_{yw}(x)^2}$$

where:

$\sigma^i_{y30}(x)$=Horizontal sigma parameter for a 30 minute release duration during release interval i (m)

$\sigma^i_{yt}(x)$ = Component of the 30 minute horizontal sigma parameter due to atmospheric turbulence during release interval i (m)

$\sigma^i_{yw}(x)$= Component of the 30 minute horizontal sigma parameter due to wind direction fluctuation during release interval i (m)

x = Downwind distance (m)

$$\sigma^i_{yw}(x) = 0.065x\sqrt{\frac{3.5}{u_i}}$$

Component of Horizontal Sigma Parameter Due to Wind Fluctuation

where:

$\sigma^i_{yw}(x)$ = Component of the 30 minute horizontal sigma parameter due to wind direction fluctuation during release interval i (m)

x = Downwind distance (m)

u_I = Wind speed during release interval i (ms^{-1})

$$\sigma^{i,j}_y(x) = f^{i,j}_w \sigma_y 30^i(x)$$

Horizontal Sigma Parameter for an Extended Release

where:

$\sigma_y{}^{i,j}(x)$= Horizontal sigma parameter at distance x during sub-interval j of release interval i (m)

$f_w{}^{i,j}$ = Wind variability factor for sub-interval j of release interval I

$\sigma^i_{y30}(x)$= Horizontal sigma parameter for a 30 minute release duration during release interval i (m)

Wind Variability Factor

$$f_w^{i,j} = a_w^i t_j^{b_w^i}$$

where:

$f_w^{i,j}$ = Wind variability factor for sub-interval *j* of release interval *I*
a_w^i, b_w^I = Constants dependent on atmospheric stability category for release interval *I*
t_j = Time of end of sub-interval *j (s)*

APPENDIX A-4 MATHEMATICAL UNCERTAINTY IN THE REFERENCE ACCIDENT

For a typical component of the total potential exposure (eg. inhalation of ^{131}I) the risk to an individual member of the exposed population is calculated using a formula of the type

$$R(T) = \int_T S(t).D(x,y,t).B(t).K.dt \qquad \text{where,}$$

R(T) is the risk for the exposure pathway being considered,
T is the exposure time,
S(t) is the source term (Bq s^{-1}),
D(x,y,t) is the atmospheric dispersion factor,
K is the risk per unit intake (K includes the effects of movement of the radionuclides within the body, etc.), and
B(t) is the breathing rate (m^3 s^{-1}),

This can be written in the approximate form

$$\overline{R} = \overline{S}.\overline{D}(x,y).\overline{B}.K.\overline{T}$$

Provided there are no correlations between the different parameters in this expression, the variance in the risk can be written as

$$\sigma_{risk}^2 = \left(\frac{\partial R}{\partial \overline{S}}\right)^2 \sigma_{\overline{S}}^2 + \left(\frac{\partial R}{\partial \overline{D}}\right)^2 \sigma_{\overline{D}}^2 + \left(\frac{\partial R}{\partial \overline{B}}\right)^2 \sigma_{\overline{B}}^2 + \left(\frac{\partial R}{\partial \overline{K}}\right)^2 \sigma_{\overline{K}}^2 + \left(\frac{\partial R}{\partial \overline{T}}\right)^2 \sigma_{\overline{T}}^2$$

or

$$\left(\frac{\sigma_R}{R}\right)^2 = \left(\frac{\sigma_{\overline{S}}}{\overline{S}}\right)^2 + \left(\frac{\sigma_{\overline{D}}}{\overline{D}}\right)^2 + \left(\frac{\sigma_{\overline{B}}}{\overline{B}}\right)^2 + \left(\frac{\sigma_{\overline{K}}}{\overline{K}}\right)^2 + \left(\frac{\sigma_{\overline{T}}}{\overline{T}}\right)^2$$

The relative uncertainty in the source term could be large, easily as great as a factor of 2, and possibly much larger, particularly in the early stage of an accidental release of radionuclides, where little or no quantitative data are available. The relative uncertainty in the atmospheric dispersion is approximately a factor of 2-4 [64].

The relative uncertainty in the breathing rate could be as high as a factor of 2 if the exposed individual is in a heavy exercise regime (eg. running), or if the exercise regime is changing during the period of exposure. The relative uncertainty in the risk per unit intake factor is at least 20%. If a value is assumed for the average exposure time, then the last term is zero, but if one is averaging over the entire exposed population then the relative uncertainty in the exposure time could also (easily) be as high as a factor of two.

This calculation also takes no account of shielding, which could vary from one individual to another, introducing further uncertainty. This suggests that the relative uncertainty in the risk R is likely to be in the range 3-5 and possibly much higher in some situations.

The same analysis can be applied to other pathways, by using the appropriate error propagation formula.

The uncertainties suggest that the ACCIDENT model should not be used for immediate post accident risk assessment to exposed individuals or estimation of airborne radionuclide concentrations since this should be based on actual measurements. When real-time data is available it can be checked against the model estimates, and the results used to adjust the model parameters and refine the model estimates.

The model is quite suitable for planning an emergency response, provided the uncertainties discussed above are taken into account (eg. in setting automatic evacuation or sheltering zones).

APPENDIX A-5 RADIATION DOSE PARAMETERS

Parameter	**1975 Reference Accident**	**2000 Reference Accident**
Inhalation Dose		
Child Breathing Rate	-	1.7×10^{-4} m^3/s
Adult Breathing Rate	-	2.7×10^{-4} m^3/s
Inhalation Dose Conversion Factors	-	BSS/ICRP71/NRPB-GS7
Cloudshine Dose		
Cloudshine Dose Conversion Factor	6.8×10^{-14} Sv m^3 Bq^{-1} MeV^{-1} s^{-1}	5×10^{-14} Sv m^3 Bq^{-1} MeV^{-1} s^{-1}
Cloudshine Sheltering Factor	1	1
Groundshine Dose		
Groundshine Dose Conversion Factor	-	9×10^{-16} Sv m^2 Bq^{-1} MeV^{-1} s^{-1}
Groundshine Sheltering Factor	-	0.6
Collective Dose		
Child Population Fraction	0.2	0.2
Sheltering Factor (cloudshine and groundshine)	-	0.6
Cancer Risk Factors:		
Cloudshine	0.05 Sv^{-1}	0.05 Sv^{-1}
Groundshine	-	0.05 Sv^{-1}
Inhalation (Thyroid Component)	0.0002 Sv^{-1}	0.0002 Sv^{-1}
Inhalation (Other Organ Component)	-	0.05 Sv^{-1}

APPENDIX B

INTERCOMPARISON OF THE REFERENCE ACCIDENT

1 INTRODUCTION

The ACCIDENT code [20] is used to provide the basis for the calculation of the consequences of the 2000 Reference Accident and is used to assess the suitability of Australian ports for visits by NPWs. The purpose of this appendix is to revisit the original verification of the ACCIDENT code by comparing the consequences of the 2000 Reference Accident calculated by ACCIDENT with those calculated by the European code PCCOSYMA [27].

2 METHOD

The consequences of the 2000 Reference Accident calculated by ACCIDENT are the result of two Reference Accident scenarios. These scenarios are denoted 'Submarines and Smaller Surface Vessels', for which a 12 hr exposure associated with a 24hr vessel removal time is assumed, and 'NIMITZ Class Aircraft Carriers', for which a 2 hr exposure associated with a 2 hr vessel removal time is assumed. The consequence results calculated by ACCIDENT and PCCOSYMA for each of these scenarios are compared. The version of PCCOSYMA used for the comparison is Version 2.01.

The atmospheric source terms for the two 2000 Reference Accident scenarios are given in Figure 6.1-1 (submarines and smaller surface vessels) and Figure 6.2-1 (NIMITZ class aircraft carriers). The atmospheric release of each radionuclide was entered directly into PC-COSYMA as core inventories and given release fractions of 1.

For the first 12 hours, meteorological conditions were specified as a single stability category (category F) with a conservative wind speed of 1 m/s and atmospheric mixing depth of 200 m. The terrain was specified as smooth. Ground deposition velocities were specified as 0.003 m/s for aerosols and 0.01 m/s for elemental iodine. Sheltering factors for normal activity were specified as 1 for inhalation and cloudshine and as 0.6 for groundshine. All these parameters are consistent with the input data used in the ACCIDENT code for the 2000 Reference Accident.

3 RESULTS

Five dose results are compared between ACCIDENT and PCCOSYMA. These are:

- Cloudshine Dose
- Adult Effective Inhalation Dose
- 24 hour Groundshine Dose
- Adult 24 hour Total Effective Dose
- Adult Thyroid Inhalation Dose

Only adult doses are compared since PCCOSYMA only calculates adult doses. The Adult Total Effective Dose is the sum of cloudshine, inhalation dose results, and the 24 hr groundshine doses. The dose was calculated by dividing the calculated total effective dose, or thyroid dose, in accordance with the calculated pathway contribution fractions. Each of the above dose results are compared at two plume centreline distances, namely 1 km and 5 km. The results are shown in Table 1 for submarines and smaller surface vessels and in Table 2 for NIMITZ class aircraft carriers.

Table1
Comparison between ACCIDENT and PCCOSYMA for Submarines and Smaller Vessels

	1 KM		**5 KM**	
	ACCIDENT	**PCCOSYMA**	**ACCIDENT**	**PCCOSYMA**
Cloudshine Dose	1.1 mSv	0.5 mSv	0.1 mSv	0.1 mSv
Adult Effective Inhalation Dose	5.4 mSv	6.3 mSv	0.3 mSv	0.5 mSv
24 hour Groundshine Dose	1.7 mSv	1.7 mSv	0.1 mSv	0.1 mSv
Adult Total Effective Dose	8.2 mSv	8.5 mSv	0.5 mSv	0.7 mSv
Adult Thyroid Inhalation Dose	130 mSv	63.6 mSv (101.8 mSv)*	7.5 mSv	4.1 mSv (6.6 mSv)*

* The numbers in brackets allow for the differences in the thyroid dose conversion factor.

Table 2
Comparison between ACCIDENT and PCCOSYMA for NIMITZ Class Aircraft Carriers

	1 KM		**5 KM**	
	ACCIDENT	**PCCOSYMA**	**ACCIDENT**	**PCCOSYMA**
Cloudshine Dose	2.5 mSv	1.2 mSv	0.1 mSv	0.1 mSv
Adult Effective Inhalation Dose	9.1 mSv	7.4mSv	0.5 mSv	0.5 mSv
24 hour Groundshine Dose	3.6 mSv	2.2 mSv	0.2 mSv	0.1 mSv
Adult Total Effective Dose	15.2 mSv	10.8 mSv	0.8 mSv	0.7 mSv
Adult Thyroid Inhalation Dose	97.7 mSv	72.8 mSv (116.5 mSv)*	5.1 mSv	4.7 mSv (7.5 mSv)*

* The numbers in brackets allow for the differences in the thyroid dose conversion factor.

This thyroid dose conversion factor is calculated as shown below.

4 THYROID INHALATION DOSE CONVERSION FACTOR CORRECTION

ACCIDENT uses thyroid inhalation dose conversion factors from NRPB-GS7 [56] whereas it is expected that PCCOSYMA uses the effective dose conversion factors from the BSS [54] divided by the tissue-weighting factor for the thyroid. In order to compare the ACCIDENT and PCCOSYMA models, the PCCOSYMA thyroid doses have been corrected to allow for differences in thyroid inhalation dose conversion factor.

ACCIDENT calculates each individual nuclide contributions to thyroid dose. These contributions have been used to determine a correction factor for thyroid inhalation dose conversion factor (DCF).

	% Contribution	**Thyroid DCF ACCIDENT**	**Thyroid DCF PCCOSYMA**	**Correction Factor**
I-131	51%	2.7e-7	1.5e-7	1.8
I-133	36%	4.4e-8	3.0e-8	1.5
Te-132	7%	4.2e-8	4.0e-8	1.1
I-135	5%	7.6e-9	6.4e-9	1.2
Total Correction Factor:				**1.6**

Therefore, a correction factor of 1.6 has been applied to the PCCOSYMA thyroid doses to remove the differences in thyroid inhalation dose conversion factors.

5 DISCUSSION

The tables above show that doses calculated by ACCIDENT are generally consistent with those calculated by PCCOSYMA. The difference in cloudshine doses is considered to be due to the differences in cloudshine dose models (semi-infinite cloud versus finite cloud), as discussed in (i) and (ii) below. The semi-infinite cloud model used by ACCIDENT provides conservative estimates of cloudshine doses and is considered acceptable for NPW accident consequence assessments. The differences in doses for the NIMITZ scenario are due to the shorter release duration, as discussed in (iii) below. The ACCIDENT model is more conservative than PCCOSYMA for shorter release duration and is considered to provide a more realistic atmospheric dispersion model for extended releases.

The following observations and explanations are made regarding the comparison of ACCIDENT and PCCOSYMA dose results:

(i) *Differences between ACCIDENT and PCCOSYMA are more significant for cloudshine doses than other doses.*

ACCIDENT uses a semi-infinite cloud model whereas PCCOSYMA uses a finite cloud model. The semi-infinite cloud model overestimates cloudshine doses, particularly at shorter distances, hence the higher doses calculated by ACCIDENT. The semi-infinite cloud model overestimates doses by a factor of about 2 for at 1 km and a factor of about 1.3 at 5 km for a ground level release.

(ii) *ACCIDENT doses are relatively higher than PCCOSYMA at 1 km compared to 5 km.*

PCCOSYMA models atmospheric dispersion as a plume of fixed dimension irrespective of the duration of the release. Therefore, the calculated doses depend only on the amount of activity released and not the release duration. ACCIDENT, on the other hand, models atmospheric dispersion as a plume that increases in size during the release because of increasing wind direction variability and time. Due to the longer plume travel time to 5 km, the plume would have increased in size by more upon reaching 5 km compared to 1 km. Therefore, doses calculated by ACCIDENT are relatively higher than PCCOSYMA at 1 km compared to 5 km.

The semi-infinite cloud model used by ACCIDENT overestimates cloudshine doses at shorter distances, hence the higher dose at 1 km compared to 5 km as explained in (i) above.

(iii) *ACCIDENT doses are relatively higher for NIMITZ compared to submarines*

PCCOSYMA models atmospheric dispersion as a plume of fixed dimension irrespective of the duration of the release. Therefore, the calculated doses depend only on the amount of activity released and not the release duration. ACCIDENT, on the other hand, models atmospheric dispersion as a plume that increases in size during the release because of increasing wind variability and time. Therefore, doses calculated by ACCIDENT are relatively lower for a 12-hour release compared to a 2-hour release.

6 CONCLUSION

The doses calculated by ACCIDENT are generally within 30% of those calculated by PCCOSYMA, with the exception of cloudshine doses and some of the doses for the NIMITZ scenario. Where differences exist between ACCIDENT and PCCOSYMA, ACCIDENT generally provides results that are more conservative. The reasons for the differences between ACCIDENT and PCCOSYMA have been identified and explained. Based on the results of the comparison, ACCIDENT is considered appropriate for assessing the consequences of the 2000 Reference Accident for the purposes of port assessment. This intercomparison exercise demonstrates that the ACCIDENT code results are valid and conservative to a high degree of confidence.