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Radiation and Thyroid Cancer

Technical Considerations for the Use of Stable Iodine after a Nuclear Reactor Accident in Australia

prepared by

Dr Stephen B Solomon
Health Physics Section
ARPANSA, Melbourne

ARPANSA
Lower Plenty Road
YALLAMBIE VIC 3085
Phone 61 3 9433 2211
Fax: 61 3 9432 1835
Email: info@arpansa.gov.au
Web: www.arpansa.gov.au

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Executive Summary

Thyroid cancer is an uncommon form of cancer in children, with an incidence rate of about 1 to 2 case per million per year in Australia for children under the age of 12 years. The risk for adolescents is ~6 cases per million per year and for adults ~45 cases per million per year, It is one of the most curable of cancers, with survival rates in Australia after treatment of ~95% after 5 years. The thyroid cancer incidence rate for females is up to 3 times higher than that for males.

Exposure to radiation can increase the risk of thyroid cancer. Studies on individuals exposed to external radiation or to internal exposure, from ingestion or inhalation of radioactive iodine, provide values for the radiation induced thyroid cancer risk. These risks are specified as:

- the excess relative risk (ERR), which is the ratio of the risk per unit exposure relative to the background or spontaneous thyroid cancer rate at a particular age, or
- the excess absolute risk (EAR), which is the risk per unit exposure at a particular age.

The additive risk model (absolute risk) is the appropriate risk measure for use in estimating the additional thyroid cancers from exposure to radiation.

The Life Span Study (LSS) of Hiroshima bomb survivors provides detailed estimates of age dependence of thyroid cancer for external radiation exposure. These results are summarised in the 2000 Report of the United Nations Committee on the Effects of Atomic Radiation (UNSCEAR 2000). For the LSS group, the relative risk decreases smoothly with age, and the values of relative risk are ten times higher for infants than for adolescents. This is because the spontaneous rate is ten times lower for infants than for adolescent. The absolute risk is relatively constant for the 0 to 18 year age group, with a value of ~0.4 cases per million per year per mGy, compared to the adult value of 0.01 cases per million per year per mGy.

The Chernobyl accident dispersed large quantities of radioactive iodine over Belarus, Russia and Ukraine, resulting in a significant thyroid dose to individuals, mainly through ingestion of contaminated milk and food. From studies in Belarus and Russia the most recent estimate for the absolute risk for child thyroid cancer is 0.23 cases per million per year per mGy, for children less than10 years old and 0.1 case per million per year per mGy for adolescent less than 18 years. No statistically significant increase in thyroid cancers has been found from adult exposure. The dose response was linear from thyroid dose of less than 100 mGy to more than 2 Gy. The present estimates of absolute risk for internal exposure are about half that from the LSS studies, but the Chernobyl studies have only been followed for 15 years, and the rate may continue to rise.

For planning purposes, models of reactor accidents, typically a loss-of-coolant accident (LOCA) are used to estimate the radiation doses for different age groups, as a function time and distance from the release. These models can be used to estimate the additional thyroid cancers from the radiation exposure, using the calculated thyroid dose estimates and the reported values of radiation risk from the epidemiological studies (excess absolute risk).

Australia has no nuclear power reactors but there are accident models for the HIFAR Research Reactor at Lucas Heights and for the Nuclear Powered Warships (NPW) that visit Australian ports. The ANSTO HIFAR *Reference Accident* model provides the most realistic estimates of radiation doses for a HIFAR accident. This model predicts that the child thyroid dose in the closest populations would be less than 13 mGy. Based on the higher LSS risk factors, the additional thyroid cancer risk to these children is about 5 cases per million per year, compared with the age adjusted spontaneous thyroid cancer risk of 40 cases per million per year. For the population around the ANSTO site, the maximum number of additional thyroid cancer cases in any 30 degree wind sector is about 3 cases (less than 0.3 fatalities) over a 50 year period, compared with 150 spontaneous thyroid cancer cases.

Similarly, the *2000 Reference Accident* model is used for planning emergency arrangements for NPW visits to an Australian port. For an accident during a visit by an NIMITZ class aircraft carrier, the maximum child thyroid dose for the closest population is estimated to be about 50 mGy for Hobart and about 30 mGy for Perth, corresponding to an additional risk of 20 cases per million and 12 cases per million, respectively, per year. For the populations in the downwind sector, this corresponds to 1.7 additional thyroid cancer cases for Hobart (compared with approximately 12 spontaneous cases) and 2.7 for Perth (compared with approximately 72 spontaneous cases). None of the three scenarios pose a significant health risk. The estimates of the consequences for the three accident scenarios are summarised in the attached Summary Table.

Iodine prophylaxis can be used to reduce the thyroid cancer risk for children after a reactor accident that releases radioactive iodine. Taking iodine tablets after an accident involving a release of radioactive iodine saturates the blood with non-radioactive stable iodine, reducing the fraction of radioactive iodine taken up by the thyroid and the resultant cancer risk. Australian guidance on when to issue iodine tablets follows international recommendations, balancing the risks of a protective measure against the averted (prevented) radiation risks.

There is currently no international consensus on the intervention level for child iodine prophylaxis (see APPENDIX VII). In a guidance document published in 1999, the WHO suggests that iodine prophylaxis for children be considered at a 10 mGy child thyroid dose (WHO 1999). The child thyroid cancer risk for 10 mGy is one tenth that for the present intervention level of 100 mGy, but the analysis in this study shows that the health benefit does not scale proportionally.

For Australian radiation emergency scenarios, involving the release of radioactive iodine from a loss of coolant accident analysed in this study, the application of protective measures at 10 mGy intervention level could result in a reduction of a maximum of 1.4 radiation-induced thyroid cancer cases (0.14 fatalities) from the expected 3 cases expected over the next 50 years. For the same scenarios, the implementation of child iodine prophyllaxis at 30 mGy intervention level could result in a reduction of a maximum of 1 radiation-induced thyroid cancer case (0.1 fatality) from the estimated 3 cases expected over the subsequent 50 years. The application of protective measures at the 50 mGy or 100 mGy intervention level would make no change to the number of estimated cases, since the projected child thyroid doses are below the intervention levels. There is a small health benefit in using a lower value than 100 mGy for the Intervention Level for child iodine prophylaxis, but there is minimal benefit in using 10 mGy over 30 mGy.

Summary Table

	HIFAR ANSTO Reference Accident (2002)	NPW (NIMITZ) Reference Accident Hobart (2000)	NPW (NIMITZ) Reference Accident Perth (2000)
Child Thyroid Dose to Population in closest distance band	13 mGy	51 mGy	28 mGy
Spontaneous Thyroid Cancer Risk closest population 50y	2.0×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
Additional Child Thyroid Cancer Risk closest population 50y	0.3×10^{-3}	1.1×10^{-3}	0.6×10^{-3}
Maximum Additional Thyroid Cancer Cases per Sector over 50y	3	1.7	2.7
Maximum Additional Thyroid Cancer Deaths per Sector over 50y	~0.3	0.2	0.3
Spontaneous Thyroid Cancers Cases in Sector over 50y period	150	5.7	48
Spontaneous Thyroid Cancers Deaths in Sector over 50y period	15	0.6	5
Reduction in Thyroid Cancer Cases over 50y			
Averted Dose 100 mGy	0	0	0
50 mGy	0	0 – 0.1	0
30 mGy	0	0 – 1	0
10 mGy	0.2	0 - 1.4	0.3
UPZ (Zone 2) Boundary Radius (km)			
Projected Dose 100 mGy	-	2.0	2.0
50 mGy	0.9	2.9	2.9
30 mGy	1.2	3.9	3.9
10 mGy	2.8	6.3	6.3
Population within UPZ All sectors, all ages			
Projected Dose 100 mGy	0	0	0
50 mGy	0	13000	0
30 mGy	0	35000	0
10 mGy	8000	70000	2700

1.0 INTRODUCTION

In November 2002, a consultation draft of the *Recommendations on Interventions in Emergency Situations Involving Radiation* was made available for public comment. A number of the comments on the draft Recommendations expressed concern about the level of the child thyroid radiation dose recommended as the intervention level for issuing stable iodine after a reactor accident. The Radiation Health Committee requested a more detailed technical assessment of the issues associated with the provision of stable iodine as a protective measure for nuclear emergencies.

The aims of this report are:

- to provide information on the current knowledge of radiation induced thyroid cancer,
- to clarify some of the technical issues with radiation risk assessments and
- to investigate some of the implications for emergency planning.

This report is not intended as an exhaustive review of current knowledge on radiation induced thyroid cancer. The Report of the United Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2000) provides an extensive review of the studies on radiation induced thyroid cancer up to the year 1999.

The UNSCEAR report has be used as the basis for the present study, supplemented by the results of more recent published data on the Chernobyl accident, to provide estimates of the thyroid cancers risk in children from exposure to radioiodine. These risk factors have been combined with the accident model for the HIFAR research reactor at Lucas Heights, NSW, and for nuclear powered NIMITZ class aircraft carriers visiting Australia ports, to estimate the potential for reducing the thyroid cancer risk for children exposed to radioactive iodine following a reactor accident in Australia.

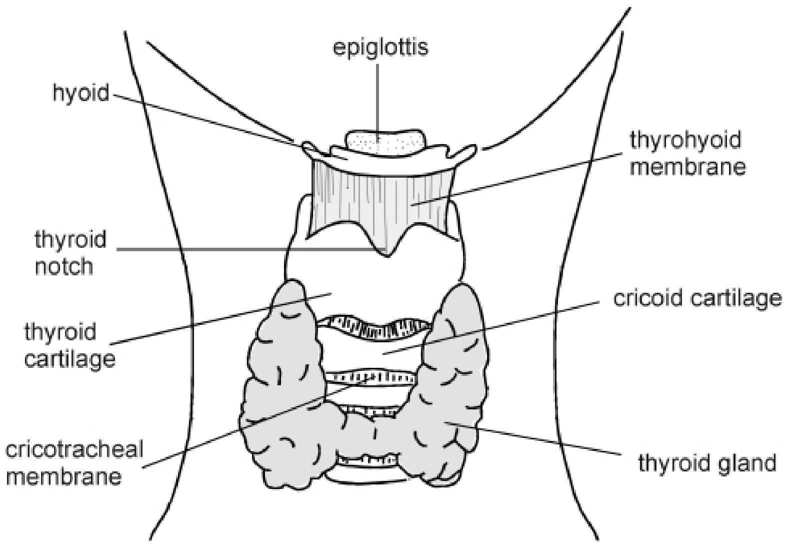
For this report, thyroid radiation doses have been specified in units of Grays (Gy) or milliGrays (mGy), rather than the more correct equivalent dose in units of Sieverts (Sv). This has been done to minimise the confusion between equivalent dose and effective dose, which is also specified in units of Sievert. The definitions of these radiation units are discussed in more detail in APPENDIX I.

2.0 THYROID CANCER

2.1 Thyroid Gland

The thyroid gland is a butterfly shaped structure that lies on the windpipe below the Adam's Apple, as illustrated in Figure 1. The thyroid lobes can be imagined as wings that wrap themselves around the windpipe while the body lies in front of the windpipe and is called the thyroid isthmus. The thyroid is usually larger in women than men. The total weight of the thyroid is approximately 20-25 grams but is smaller in parts of the world where supplies of iodine are abundant (www.endocrinesurgeon.co.uk/thyroid).

Figure 1 The Thyroid Gland and Larynx



The thyroid gland is an important endocrine gland (part of the chemical messaging system within the body) that makes three different hormones. Two of the hormones are iodinated (have iodine attached to them) and are called iodothyronines. The three hormones are:

- Triiodothyronine (T3)
- Tetraiodothyronine (T4) also called thyroxine
- Calcitonin (CT) helps regulate the body’s calcium.

Thyroxine (T4) is made by the cells which line the follicles of the thyroid gland. Thyroxine regulates the body’s metabolic rate. If too much is produced, weight loss, palpitations, anxiety, sleeplessness, bulging eyes, tremulous hands and weakness result. Too little can produce dry hair and skin, hair loss, lethargy, intolerance of cold and slow thinking. Thyroxine hormone has iodine as part of its structure, and the thyroid gland takes up most of the iodine we absorb in our diet (Burton 2001).

Thyroxine production, and hence iodine uptake, by the thyroid gland is controlled by thyroid stimulating hormone (TSH), which is a hormone produced by the pituitary gland, a part of the brain. When TSH rises, more thyroxine is produced and this feeds back on the brain so TSH production falls. Most papillary and follicular thyroid cancers take up iodine under the influence of TSH, and some of them also produce thyroxine.

2.2 Thyroid Cancer

Thyroid cancer is one of the less common forms of cancer. Like other forms of cancer, there is more than one type of thyroid cancer. Papillary and follicular thyroid cancer make up more than 90% of all new cases, with C-cell thyroid cancers accounting for most of the rest. The degree of malignancy varies widely with histological type, ranging from the rapidly fatal anaplastic type to the relatively benign papillary type (Cancer in Australia 2000).

Table 1 shows the range of thyroid cancer incidence rates around the world (UNSCEAR 2000). The male age adjusted rates for thyroid cancer are in the range 0.7 to 6 per 100000 men per year. The equivalent range for females is 1.6 to 25 per 100000 women per year. Iodine intake, diet and other factors can affect risk factors. Follicular cancer rarely occurs in Iceland where, due to high dietary intake of fish, there is high iodide intake. In contrast, in areas of low iodide intake (mountainous region such as the Alps, Andes and Himalayas) follicular cancer has a high incidence.

Table 1 Thyroid Cancer Incidence Rates per 100000 per year (*UNSCEAR 2000).*

Sex	High Range		Low Range	
	Population	**Rate**	**Population**	**Rate**
Males	Iceland	6.1	United Kingdom, Wessex	0.7
	United States, Hawaii	5.1	Estonia	0.7
	United States, Los Angeles	4.0	Denmark	0.8
Females	United States, Hawaii	25.5	India, Madras	1.6
	United States, Los Angeles	11.2	United Kingdom, Yorkshire	1.7
	Italy, Ferrara	11.1	Netherlands, Eindhoven	1.9

In 1997 there were 860 new cases (incidence) and 71 deaths from thyroid cancer in Australia, making it the 16th most common incident cancer (Cancer in Australia 2000). The age-standardised rates for Australia, by State, are summarised in Table 2. These are based on the standardised age distribution in APPENDIX II. The Australian age-adjusted annual incidence rates were 2.5 per 100000 for males, 6.4 per 100000 for females and 4.5 per 100000 total, placing Australia at the lower end of the global ranges.

Table 2 Age-Standardised rates per 100,000 per year for thyroid cancer in Australia by State and gender for period 1993–1997 (*Cancer in Australia 2000)***

State	Incidence			Mortality	
	Males	**Females**	**Persons**		**Persons**
NSW	2.6	7.3	5.0		0.3
Vic	1.8	5.0	3.5		0.4
Qld	2.3	6.8	4.5		0.3
WA	2.3	5.9	4.1		0.5
SA	2.2	5.8	4.0		0.3
Tas	2.1	7.1	4.7		0.5
ACT	1.7	5.0	3.4		0.6
NT	1.8	7.7	4.6		2.0
Australia	2.5	6.4	4.5		0.4

The incidence of thyroid cancer is dependent on many factors, particularly age. Table 3 shows the incidence of thyroid cancer by sex and age in Victoria, based on data for the 10-year period 1988 – 1997, (Anti-Cancer Council, 1999), for NSW for the year 2001 (NSW Cancer Registry 2001), and for Australia for the year 1997 (Cancer in Australia, 2000). The Victorian incidence rates are about two-thirds the Australian average, while NSW rates are about 10% higher. The data shows that thyroid cancer is a very uncommon cancer in children, with ~ 1 case per million children per year or about 1/40 the adult rate. Thyroid cancer incidence is relatively high in adults before age 40 years, increases comparatively slowly with age, and is about three times higher in women than men. Thyroid cancer is one of the two most common cancers in females aged 20-24 and 40-44.

Thyroid cancer is the most curable cancer in Australia, after non-melanoma skin cancer. Survival after treatment for thyroid cancer was 95% at 5 years in New South Wales for the period 1980 to 1995, (250,000 new cases and 324 deaths in 1995) (Cancer in Australia, 2000).

Table 3 Incidence of Thyroid Cancer per year in Victoria 1988–1997 *(Anti-Cancer Counci, 1999),* **NSW 2001** *(NSW Cancer Registry 2001)* **and Australia 1997** *(Cancer in Australi, 2000)* **by age group.**

Age Group	% of total cases by age	Age Specific annual rate per 100,000 in each age group						
		Male		Female		Person		
		VIC	Aust	VIC	Aust	VIC	NSW	Aust
0 -4	0.1	0.12	0.0	0.00	0.0	0.06		(0.08)
5 – 9	0.2	0.13	0.0	0.07	0.0	0.10	0.25	(0.14)
10 – 14	0.4	0.13	0.3	0.20	0.2	0.16	0.45	0.2
15 – 19	1.4	0.35	0.5	0.79	1.4	0.56	1.6	0.9
20 – 24	5.1	0.9	0.9	3.0	3.1	2.0	4.3	2.0
25 – 29	8.1	1.3	1.9	4.9	8.0	3.1	5.8	5.0
30 – 34	10.0	1.7	3.7	6.0	9.2	3.9	9.2	6.5
35 – 39	10.9	1.9	2.6	6.9	9.4	4.4	9.6	6.0
40 – 44	9.9	2.0	5.2	6.5	9.1	4.3	9.2	7.2
45 – 49	10.1	2.3	3.1	7.8	15.3	5.0	11	9.1
50 – 54	9.1	2.8	2.7	8.5	11.2	5.6	15	6.9
55 - 59	6.4	3.2	5.3	5.8	8.8	4.5	7.3	7.0
60 – 64	6.2	3.6	5.3	5.6	8.3	4.6	15.1	6.8
65 – 69	6.0	4.5	5.3	5.2	10.2	4.8	8.9	7.8
70 – 74	5.8	4.7	4.3	6.6	8.2	5.8	10.6	6.4
75 – 79	5.2	5.3	3.7	8.5	10.6	7.2	12.8	7.6
80 – 84	3.5	3.8	6.5	9.5	8.4	7.4	10.3	7.7
Over 85	1.7	5.2	4.7	4.8	8.0	4.9	7.7	7.0

3.0 RADIATION INDUCED THYROID CANCER

Ionising radiation is a well-documented cause of human cancer (UNSCEAR 2000). The effects of radiation on the human body is dependent on the type of radiation, the type of tissue, the conditions of the exposure and other factors. Tissue within the human body can be categorised in three types:

- Permanent tissue, with all tissue growth finished at birth or soon afterwards (neurons for example),
- Stable tissue, with tissue growth completed before maturity, but capacity for growth on demand, and
- Labile tissue, where the cells continually replicate (colon cells for example).

The thyroid is stable tissue and completes most of its growth during childhood and adolescence. From a weight at birth of about 1.5 g, at maturity the thyroid gland it weighs around 20 gm. Radiation induced cancer is associated with cell division. The lack of cell division within the adult thyroid means that radiation exposure of an adult thyroid will not produce a significant cancer risk. In contrast, the rapid growth of the gland during childhood makes the child thyroid more susceptible to radiation induced cancer (Williams 1999).

Epidemiological studies of thyroid cancer incidence and radiation exposure provide estimates of the risk. These studies are for either external radiation exposure or for internal exposure, from ingestion or inhalation of radioactive iodine. Most of the published results up to the year 1999 have been summarised in UNSCEAR (2000), including recent studies of:

- pooled cohort studies of external exposure
- Chernobyl exposure studies and
- continued follow-up studies of children

3.1 Epidemiological Studies

In order to interpret the results of these epidemiological studies it is necessary to understand the risk models used to transport cancer risks estimated for one population (Japanese bomb survivors for example) to other populations, including Australians. Two risk models are commonly used, either

- the multiplicative risk model uses the excess relative risk (ERR), which is the ratio of the risk per unit exposure relative to the background or spontaneous thyroid cancer rate at a particular age, or
- the additive risk model uses the excess absolute risk (EAR), which is the risk per unit exposure at a particular age.

3.2 Excess Relative Risk Model

Relative risk models express the total risk as the product of the age-specific background risk and a dose rate dependant factor. The ERR is the ratio of the excess risk to the spontaneous risk, at a particular age.

Radiation Risk (age) = Background Risk (age) * [1 + ***ERR*** (age) * Radiation Dose]

Where

Radiation Risk (age) = Cases / [Person. * Years]

3.3 Excess Absolute Risk Model

The second method is the absolute risk model, where the risk is expressed as a product of a single age dependant risk factor and the radiation dose.

Radiation Risk (age) = ***EAR*** (age) * Radiation Dose

Where

Radiation Risk (age) = Risk (age) – Background Risk (age)

The EAR and the ERR are related though:

EAR(age) = ***ERR*** (age) * Background Risk (age)

3.4 External Exposure Studies

Radiation exposure of the thyroid can occur through external exposure (radiation source external to the body) or through internal exposure from uptake of radioactivity into the body and the thyroid gland. The data for external radiation exposure has been extensively reviewed and this in turn has been summarised in UNSCEAR 2000. The ERR and EAR values derived from theses studies are summarised in Table 4 and Table 5.

Table 4. ERR and EAR from cohort studies of children *(UNSCEAR 2000)*

Study	Observed cases	Expected cases	Mean thyroid dose (Gy)	Person years	Average excess relative risk at 1 Gy	Average excess absolute risk (10^4 PYGy)
Life Span Study Age at exposure 0 - 19 years	59	22.2	0.26	375600	6.3 (5.1-10.1)	3.8 (2.7-5.4)
Israeli tinea capitis	43	10.7	0.1	274180	34 (23-47)	13 (9.0 - 18)
New York tinea capitis	2	1.4	0.1	79500	7.7(<0_60)	1.3 (<0-10.3)
Rochester thymic irradiation	37	2.7	1.4	82204	9.5 (6.9-12.7)	3.0 (2.2-4.0)
Childhood cancer	23	0.4	12.5	50609	4.5 (3.1-6.4)	0.4 (0.2-0.5)
Stockholm skin haemangioma	17	7.5	0.26	406355	4.9 (1.3-10.2)	0.9 (0.21.9)
Gothenburg skin haemangioma	15	8	0.12	370517	7.5 (0.4-18.1)	1.6 (0.09-3.9)

Table 5. ERR and EAR from screening studies of children ***(UNSCEAR 2000)***

Study	Observed cases	Expected cases	Mean thyroid dose (Gy)	Person years	Average excess relative risk at 1 Gy	Average excess absolute risk (10^4 PYGy)
Lymphoid hyperplasia screening	13	5.4	0.24	34700	5.9 (1.8-11.8)	9.1 (2.7-18.3)
Thymus adenitis screening	16	1.1	2.9	44310	4.5 (2.7-7.0)	1.2 (0.7-1.8)
Michael Reese, tonsils	309	110.4	0.6	88 101	3.0 (2.6-3.5)	37.6 (32-43)
Tonsils/thymus/acne screening	11	0.2	4.5	6 800	12.0 (6.6-20)	3.5 (2.0-5.9)

Recent results of pooled cohort studies are also summarised in the UNSCEAR Report. The pooled analysis covered 7 studies, involving 120,000 people and more than 700 thyroid cancers (Ron 1995). The pooled analysis used data from five studies of children: the Life Span Study (Thompson 1994), the Israeli tinea capitis study (Ron 1989), the Rochester thymic irradiation study (Shore 1993), the Lymphoid hyperplasia screening study (Pottern 1990, Shore 1992) and the Michael Reese tonsil study (Schneider 1993). There were a total of 436 observed thyroid cases in the pooled study. The average ERR at I Gy was 7.7 with 95% confidence interval of 2.1 to 28.7. The average EAR was 4.4 per 10000 person year Gy, with a 95% confidence interval of 1.9 to 10.1.

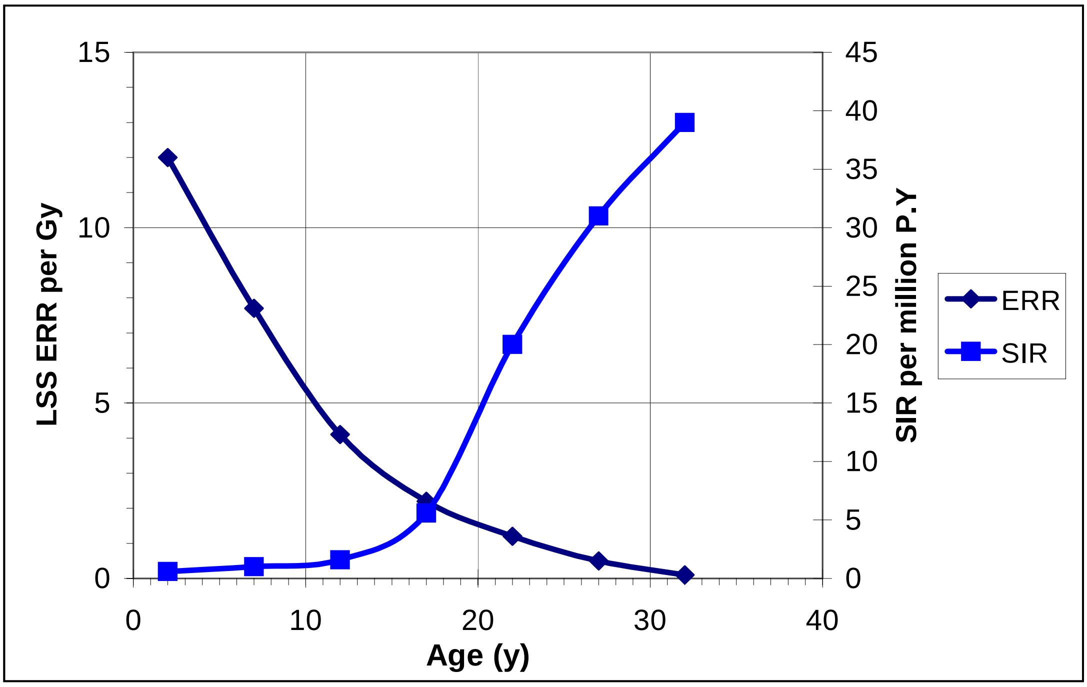
The follow up of health effects amongst the Japanese atomic bomb survivors, the Life Span Study (LSS), provides the most extensive data on thyroid cancer from external exposure to radiation. The LSS provides information on thyroid cancer induction as a function of time, sex and age. The LSS is based on cancer incidence data for the period from 1958 for nearly 80,000 Hiroshima and Nagasaki atomic bomb survivors. The published LSS data for thyroid cancer to 1990 (Thompson 1994, Nagataki 1999, UNSCEAR 2000), shows that the induction of thyroid cancer to has a strong linear-dose response. The excess risk as a function of age and gender from this study is summarised in Table 6.

Table 6. EER and EAR from Life Span Study ***(UNSCEAR 2000)***

Study	Observed cases	Expected cases	Mean dose (Gy)	Person years	Average excess relative risk at 1 Gy	Average excess absolute risk (10^4 P.Y.Gy)
Sex						
Male	22	14.9	0.27	307167	1.80	0.87
Female	110	79.4	0.26	510388	1.49	2.32
Age at exposure						
0-9 years	24	7.6	0.21	185507	10.25	4.21
10-19 years	35	14.6	0.31	190087	4.50	3.46
20-29 years	18	17.5	0.28	132738	0.10	0.13
>30 years	55	54.5	0.25	309224	0.04	0.06
All	132	94.3	0.26	817600	1.5	1.8

The ERR data from the Life Span Study is shown in Figure 3, compared with the spontaneous incidence rate as a function of age, in this case based on data for a ten year period for the State of Victoria (chosen because of the good statistics). For the LSS group, the ERR decreases smoothly from a value of more than 10 per Gy for infants to close to zero for young adults. In contrast, the spontaneous incidence rate increases by more than a factor of ten for the same age interval, rising from near zero for infants to greater than 2 per 100000 for young adults.

Figure 3. Excess relative risk (ERR) for thyroid cancer from Life Span Study and thyroid cancer spontaneous incidence rate (SIR) for Victoria.



While the relative risk factors for children change markedly with age, in contrast the absolute risk factors EAR values are relatively constant for the 0 to 18-year group. The values for the absolute risk for particular age groups are listed in Table 6 (UNSCEAR 2000). For the 0 to 9 year age group the EAR is ~ 4.2 per 10000 person years Gy, while for the 10 to 19 year age group the EAR is not significantly different, with a value of ~ 3.5 per 10000 person years Gy.

For thyroid cancer in children, the distinction between ERR and EAR is very important, since the spontaneous thyroid cancer rate is very low and increases with increasing age. Since the absolute risk for radiation induced thyroid cancer is relatively constant for children, the increase of the spontaneous rate with the increasing age implies that the relative risk must decrease (since $EAR = ERR * Spontaneous\ Rate$). The increased relative risk for a 5 year old over that for a 10 year old does not imply that the radiation induced thyroid cancer risk is higher, rather it reflects the underlying age dependency of the spontaneous rates.

In interpreting the epidemiological study results it is important to identify which risk transport model is being used. The relative risk model is commonly used because data on age dependent spontaneous rates is difficult to obtain. For estimating the additional cancers from radiation exposure, the absolute risk (EAR) is the appropriate risk factor, not the relative risk.

3.5 Internal Exposure Studies

Prior to the Chernobyl accident there was very little data on thyroid cancer radiation risk for internal exposure. Radioiodine is used for diagnostic procedures and hyperthyroidism, but studies on exposed groups of children did not have sufficient statistical power to demonstrate any risk (Holm 1999).

In April 1986, the reactor accident at Chernobyl released nearly 1800 PBq (1800 x 10^{15} Bq) of ^{131}I into the environment (UNSCEAR 2000), contaminating large portions of Belarus, Russia and Ukraine. About 40% of the ^{131}I was released on the first day, April 26. The radioactive fallout contaminated ~3000 km^2 to levels exceeding 1.5 MBq m^{-2}, with more than 100,000 km^2 contaminated to levels greater than 37 kBq m^{-2}. The principal exposure pathway for exposure to ^{131}I was not through inhalation, but from ingestion of contaminated milk and foodstuff from the affected areas. It is estimated that the inhalation pathway contributed between 2% to 10% of the thyroid dose (Kenigsberg 2002).

Since the Chernobyl accident there has been a significant increase in the incidence of thyroid cancer in children in the affected regions. Immediately following the accident there was an increase in the child thyroid cancer, part due to improved screening and detection, amounting to a factor of 2 to 3, depending on region. However, by the end of 1999, there a total of 2905 cancer cases had been recorded in Belarus and the Ukraine, from a population of 16 million children (Jacob 2002), far exceeding the expected spontaneous incidence.

Large-scale epidemiological studies have been established to determine the radiation risk for thyroid cancer in the exposed population. The results of most of these studies up to the year 1999 are summarised in UNSCEAR 2000. Cohort studies have proved difficult due to the large uncertainties in assessing individual doses and the long observation times required to obtain enough thyroid cancer cases. After the Chernobyl accident, less than 10% of exposed individuals were monitored for ^{131}I in the thyroid gland. Thyroid doses estimates for the remaining population have been estimated from radioecological models, based on the place of residence (Kenigsberg 2002, Jacob 2002).

An aggregate study published in 1999 provides some data on the age dependency of the EAR for thyroid cancer risk (Jacob 1999). This aggregate study involved the averaging of 100’s of thyroid cancer cases across the contaminated areas in Belarus and Russia. The study used both direct measurements of radiation in the thyroid gland where available, supplemented by a radioecological model of radioiodine uptake to estimate thyroid doses on the basis of the place of residence at the time of the accident. The number of thyroid cancer cases recorded in the cancer registries after 1986 were analysed by region to estimate the EAR by dose range and age. The results for children under the age of 18 years are summarised in Table 7. The risk factors per unit exposure are relatively constant for thyroid doses of less than 100 mGy to doses greater than 2000 mGy. Like the external radiation studies, studies of adults exposed after Chernobyl have not shown any statistically significant increase in thyroid cancer (Ivanov 2003).

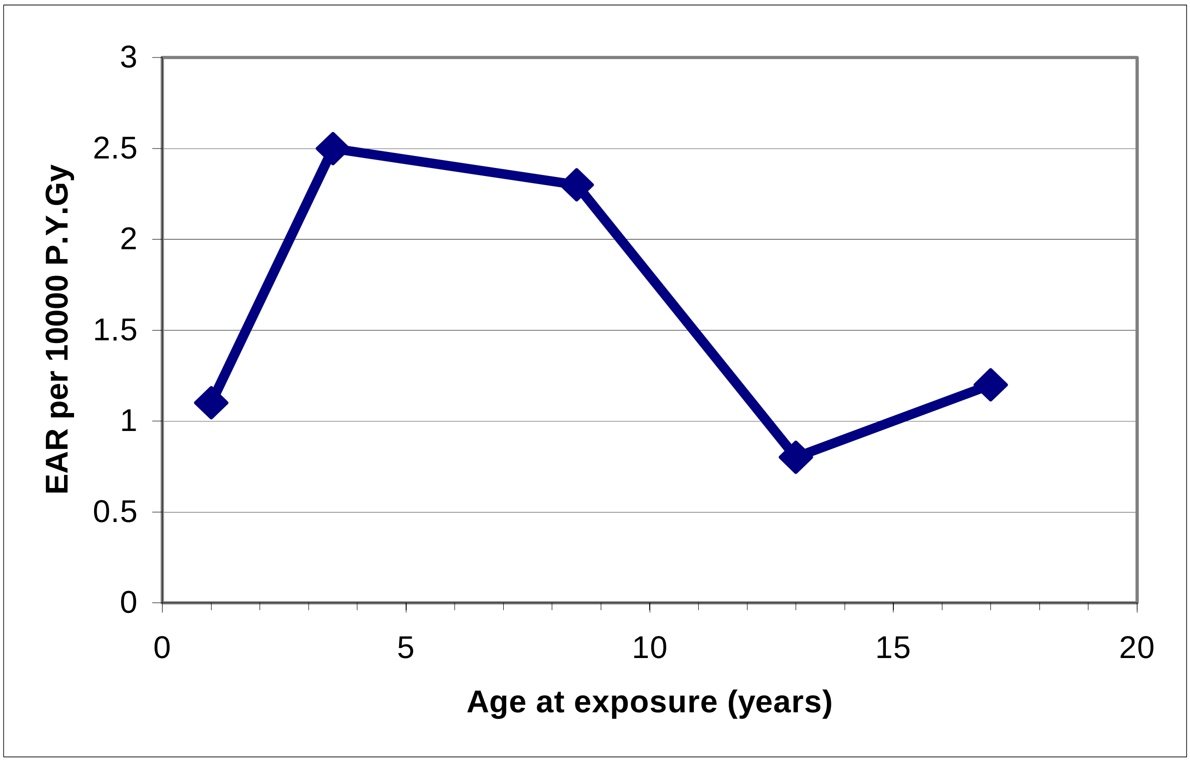
The age dependence of the estimates of absolute risk for thyroid cancer in children is shown in Figure 5, based on the aggregate study of child thyroid cancers in Belarus and Russia (Jacob 1999). The analysis in this study used more age groups than for the LSS external exposure studies, and would seem to show some variation in EAR with age. The present estimate of EAR for children less than 10 years of age of 2.3 per 10000 P.y.Gy is about half of the 4.5 per 10000 P.Y.Gy from the external radiation studies, but double the value for infants and for adolescents. Given the large statistical and measurement uncertainties inherent in the epidemiological studies, some caution in needed in interpreting this variation with age.

For the Chernobyl exposures, the radiation induced thyroid cancers will be manifest over 10's of years. The annual rate is currently ~160 to 200 cases per year, and while there are some indications that the incidence rates are leveling off, the rates may be still increasing (Kenigsberg 2002). The study groups will need to be followed for 40 to 50 years to fully assess the total risk.

Table 7 Excess Absolute risk for thyroid cancers children 0 – 18, for data 1991 – 1995 for 3 cities and 2729 settlements in Belarus and Russia (*Jacob 1999*).

Thyroid Dose (mGy)	Person.Years	EAR (x 10^4 P.Y.Gy)	95% Confidence Interval
0 – 100	1 756 000	2.6	0.5 – 6.7
100 – 500	1 398 000	1.9	0.8 – 4.1
500 – 1000	386 000	2.0	0.9 - 4.2
1000 – 2000	158 000	2.3	1.1 – 4.9
>2000	56 000	2.4	1.1 – 5.1

Figure 5. Excess Absolute Risk (EAR) for thyroid cancer in children in Belarus and Russia after the Chernobyl accident *(Jacob,1999)*.



4.0 RADIATION EMERGENCY PLANNING

No human activity is totally free of risk: the issue for radiation protection is deciding on an acceptable level of risk for particular activities. The perception of risk, particularly radiation risk, is strongly influenced by the degree of control that an individual has in avoiding a risk. For radiation risks, Australian and international recommendations seek to take the ALARA approach: as-low-as-reasonably-achievable, social and economic factors taken into account. The later qualification is important in setting levels for interventions or protective measures. It is also not a zero radiation risk approach, but all efforts should be made to achieve a maximum net benefit (more good than harm)

Nuclear safety practice is Australia uses a defense n depth approach, and significant reactor accidents are considered to be a very low probability events, typically < 1 event per million years. While the physical damage may be catastrophic, the combined risk (probability of occurrence x probability of health effect) is very small. The radiation protection response required to the public health effects of a nuclear reactor accident are termed interventions. The Australian approach to interventions, detailed in the *Recommendations on Interventions in Emergency Situations Involving Radiation, (ARPANSA 2004)* follows the international guidance provided by the international Atomic Energy Agency (IAEA 1994, IAEA 1996, IAEA 2002) and the International Commission on Radiological Protection (ICRP 1991, 1CRP 1993). The principles for implementation of protective measures are summarised in APPENDIX III. The decision to implement a particular intervention or protective measure should take account of

- all the potential risks, both from the radiation and the protective measure,
- the social and economic factors associated with the measure (holding and distributing sufficient tablets, degree of social disruption, etc), and
- the practical issues (distributing large numbers of tablets in a short time frame, notifying residents of the need to shelter or evacuate.

4.1 Reference Accident

Australia has no nuclear power reactors, but there is a research reactor (HIFAR) at Lucas Heights and there are visits to Australian ports by nuclear powered warships (NPW). 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 or for a visiting nuclear powered vessel in an Australian port.

For a reactor accident involving a release of radioactive material the main pathways for exposure to members of the public shown schematically in Figure 7. These include:

(a) Direct external radiation from the radioactive cloud or plume
(b) Direct external exposure from radioactivity deposited on the ground
(c) Internal exposure from inhalation of particles or volatile radionuclides
(d) Internal exposure from ingestion of contaminated material.

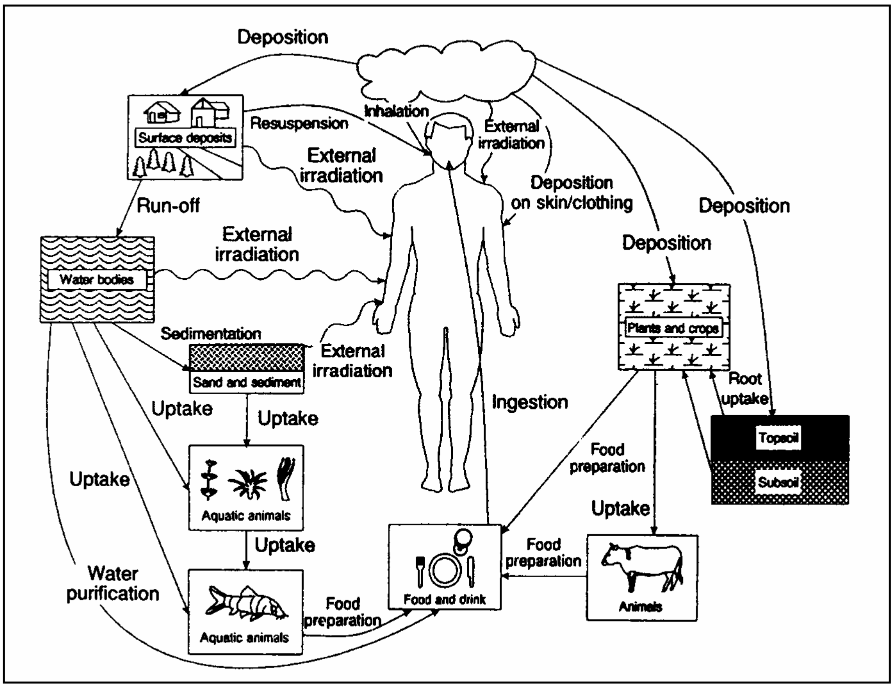
The *Reference Accident* is computer model devised for estimating the nature and extent of the radioactive contamination for a severe accident scenario involving a loss of coolant accident in a nuclear reactor and the subsequent release of radioactive material to the environment. The *Reference Accident* is defined as a failure of the primary coolant circuit of the reactor, resulting in a loss of coolant and melt down of the fuel in the reactor core and the release of volatile and gaseous fission products to the reactor containment. These would then be available to leak to the atmosphere and be dispersed according to the prevailing weather. The dispersion of released fission products in the atmosphere following the accident can be estimated using a conservative meteorological model. Each nuclear reactor scenario will have different core inventories and operating conditions, but each accident could result in the release of a cloud of volatile radionuclides and noble gases.

The *Reference Accident* methodology has been applied to a each possible reactor accident scenarios in Australia. These include:

- *Reference Accident* for HIFAR Research Reactor, Lucas Heights
- *Reference Accident* for Replacement Research Reactor
- *Reference Accident* for nuclear powered submarines
- *Reference Accident* for nuclear powered aircraft carriers

The initial exposure pathway of concern for exposure to members of the public is through the inhalation of the radioactivity in this cloud, principally ^{131}I, with the subsequent radiation dose to the thyroid. Resuspension of surface contamination and the subsequent inhalation would be very small. As the radioactive cloud moves forward, radioactivity is deposited onto the ground under the cloud, leading to contamination of soil, buildings, plants and water. After the passage of the radioactive cloud, the two principal pathways for exposure are through the external irradiation from contamination on the ground and from ingestion of radioactivity in foodstuff.

Figure 7. Human Exposure Pathways *(from IAEA Safety Series 109, (1994))*



4.2 Emergency Planning Zones

The approach to the implementation of protective measures following a radiation emergency is described in APPENDIX III. The three general principals to be used are that:

1) serious deterministic effects should be avoided
2) the protective measure should do more good than harm, and
3) the protective measure should provide maximum net benefit

In the planning for radiological emergencies at a fixed site (a reactor facility or an nuclear powered warship berth or anchorage), three emergency planning zones are defined. These zones, the *Precautionary Action Zone* (PAZ), the *Urgent Protective Action Zone* (UPZ) and the *Long Term Protective Action Zone* (LPAZ), are described in more detail in APPENDIX IV. In the PAZ (or Zone 1) the protective measures are automatic on confirmation of an emergency. The implementation of protective measures within the UPZ (Zone 2) should be based on environmental measurements and estimates of the radiation dose that can be averted by carrying out the protective measure. The level of averted dose should be pre-planned and chosen on the basis of principals (2) and (3) above.

The Generic Intervention Levels in the *Recommendations on Interventions in Emergency Situations Involving Radiation (ARPANSA 2004)* are based on international guidance and are intended to provide optimal risk levels for different types of protective measures. The administration of stable iodine (iodine prophylaxis) is a protective measure that can be used in the event of a nuclear reactor accident involving the release of radioactive iodine. Stable iodine is a relatively low risk protective measure. The associated risks are discussed in more detail in Appendix V. In the case of intervention levels for child iodine prophylaxis, there are differences between the values of averted dose recommended by the WHO (WHO 1999) and by the International Atomic Energy Agency (IAEA 1994). The WHO, IAEA and international approaches are discussed in APPENDIX VII.

4.3 Child Thyroid Cancer Risk for HIFAR Accident

In 2000, the Australian Nuclear Science and Technology Organisation (ANSTO) used a design-based accident to re-assess planning zones around the ANSTO the HIFAR Research Reactor at the Lucas Heights site (ANSTO 2002). This model is a loss-of-coolant accident involving a release of radioactive material to the environment and it is considered that this model provides the best estimates of radiation doses for an accident HIFAR Research Reactor. The predicted doses to exposed individuals as a function of distance are shown in Figure 9.

The child thyroid dose from inhalation of the airborne radioiodine for the HIFAR accident model, as function of distance, are summarised in Figure 10 and Table 8. In the model, the inhalation doses is calculated assuming a 12 hour exposure from the beginning of the release. In practice the ^{131}I concentration in the plume changes with time and with distance and the radiation dose from inhalation takes time to accumulate. Much of the ^{131}I is released within the first few hours, but the radiation exposure to the thyroid occurs over a longer period as the body adsorbs the ^{131}I and it builds up in the thyroid. This build-up is discussed in more detail in Appendix VI. For the purposes of the present analysis, the projected dose at 12 hours was taken as the maximum dose avertable by administration of stable iodine.

Figure 9 Total radiation dose to an adult and a child as a function of distance for the ANSTO HIFAR Design-based Reference Accident *(ANSTO 2000)*.

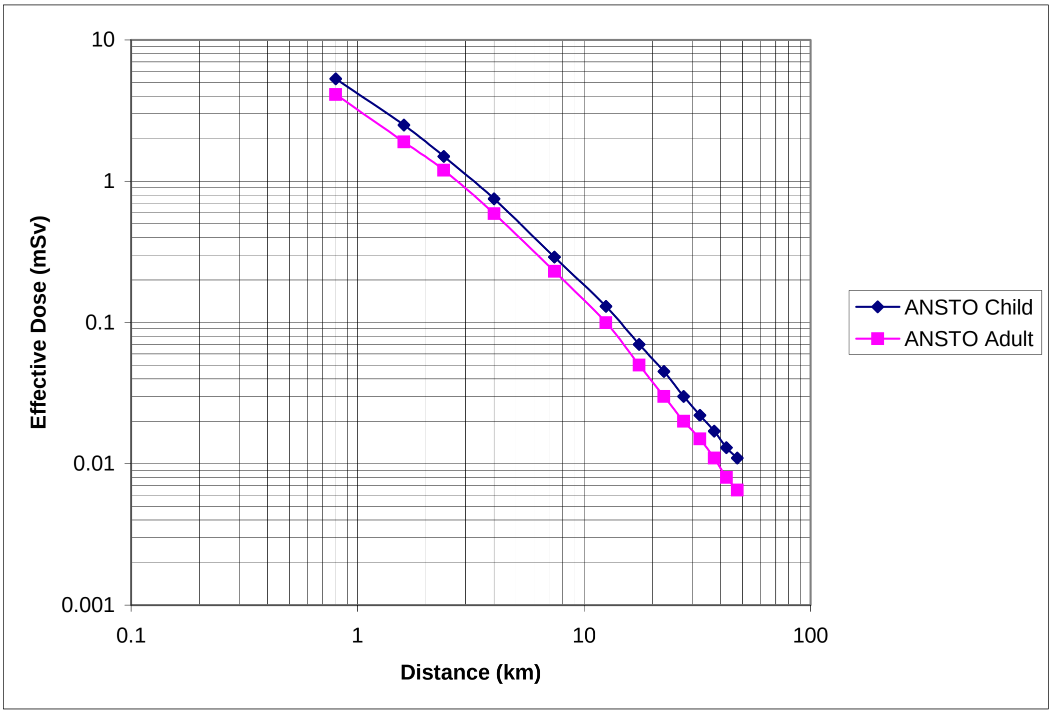


Figure 10. Child thyroid dose as a function of distance for the ANSTO HIFAR Reference Accidents *(ANSTO 2000*).

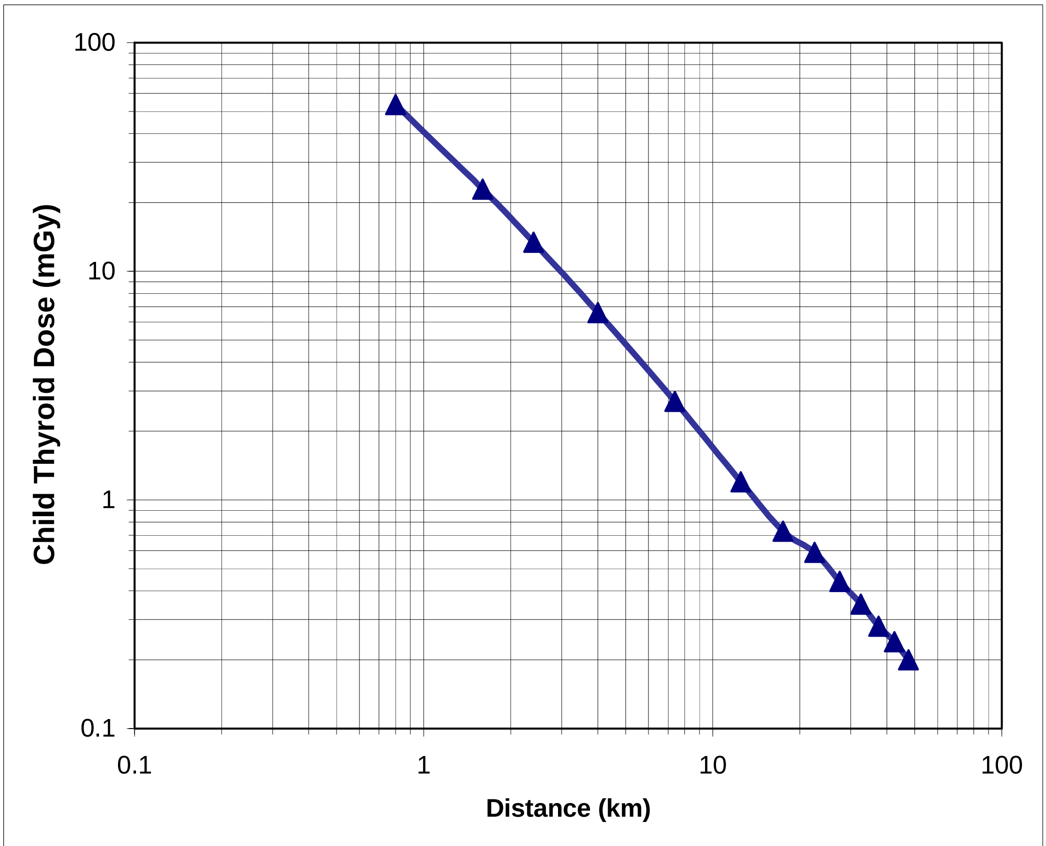


Table 8 Child thyroid dose as a function of distance band for the ANSTO HIFAR Reference Accidents *(ANSTO 2002)* .

Distance (km)	Mean (km)	Child Thyroid Dose (mGy) ANSTO (2000)
0 - 1.6	1.6	22
1.6 - 3.2	2.4	13
3.2 - 4.8	4	6.3
4.8 - 10	7.4	2.6
10 - 15	12.5	1.2
15 - 20	17.5	0.7
20 - 25	22.5	0.6
25 - 30	27.5	0.4
30 - 35	32.5	0.3

Thyroid doses as a function of age and distance from the models were combined with the thyroid cancer risk factors to estimate the number of additional thyroid cancers by distance and sector around the HIFAR site. The total number of projected thyroid cancers arising from an accident at the HIFAR reactor was estimated from:

- the age dependant thyroid cancer spontaneous incidence rate (Table 3),
- the age dependant excess absolute risk for the Life Span Study (Table 6),
- the estimates of child thyroid dose as a function of distance from the HIFAR accident model (Table 8), and
- the projected population by distance and sector, centered on the HIFAR reactor, for the year 2006 (ANSTO 2002). This data is summarised in Table 9.

The number of radiation induced thyroid cancers was calculated from the product of the number of children and adults in each distance band, the average thyroid dose for the distance band and the EAR for thyroid cancer for 50 years after the exposure. Table 10 summarises the estimates of spontaneous thyroid cancers for a 50-year follow-up period and the estimated additional thyroid cancers for each of the 22.5 degree sectors centered on the HIFAR research reactor. Sectors 2 to 6 contain the closest populations to the HIFAR site. The ANSTO HIFAR *Design-based Accident* model predicts 0 to 3.2 additional cases per sector, against a spontaneous incidence of 0.8 to 154 cases per sector over a 50-year period.

The child thyroid doses for the HIFAR accident models, shown in Table 8, define the distance at which an unprotected individual would receive a particular projected radiation dose over an extended exposure period. If a protective measure such as iodine prophylaxis is implemented rapidly, then these projected doses represent the maximum avertable dose and provide a measure of the extent of the protective action zone, in this case the UPZ. The extent of the UPZ boundaries for projected thyroid doses of 100 mGy, 50 mGy, 30 mGy or 10 mGy are summarised in Table 11, together with the estimates of the spontaneous thyroid cancer risk, the additional thyroid cancer risk and the number of potentially exposed members of the public. The reduction in the number of estimated cases of radiation induced thyroid cancer as a function of the projected thyroid dose for implementation of stable iodine administration, is shown in Table 12, assuming the protective measure is fully effective.

Table 9. Population 2006 by distance band and sector, centered on HIFAR Research Reactor (ANSTO 2002).

Distance	Mean	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
(km)	(km)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	
0 - 1.6	**1.6**		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
1.6 - 3.2	**2.4**	0	0	0	0	2978	2582	1360	1005	0	17	0	0	0	0	0	0	**7942**
3.2 - 4.8	**4**	0	1869	5988	3612	6064	3750	2446	2055	0	0	0	0	0	0	0	0	**25784**
4.8 - 10	**7.4**	4511	14091	25307	32688	18989	0	1548	934	469	0	0	0	476	1162	4687	359	**105221**
10 - 15	**12.5**	26219	66671	78980	42320	50804	571	43	0	2548	0	351	6921	31176	31690	24707	43963	**406964**
15 - 20	**17.5**	78,259	119582	149227	36511	19400	2301	0	307	5660	0	0	35071	30275	11047	35553	116569	**639762**
20 - 25	**22.5**	112425	121506	171608	18929	897	0	0	0	594	0	1960	954	22259	2768	7740	89460	**551100**
25 - 30	**27.5**	144073	112101	251471	126793	0	0	0	0	6960	1923	0	1785	12337	2439	3085	10669	**673636**
30 - 35	**32.5**	126346	138490	206010	26421	0	0	0	0	8221	9935	1238	1379	931	1472	6707	98585	**625735**
35 - 40	**37.5**	86759	108479	72625	0	0	0	0	0	12413	20854	509	4426	2377	6406	19540	121462	**455850**
40 - 45	**42.5**	14335	58159	77336	1285	0	0	0	0	9429	34362	1924	7381	2045	0	68594	23190	**298040**
45 - 50	**47.5**	9128	14902	30440	0	0	0	0	0	9046	30745	2569	1990	0	0	22919	19013	**140752**
	Total	602055	755850	1068992	288559	99132	9204	5397	4301	55340	97836	8551	59907	101876	56984	193532	523270	**3930786**

Table 10. Spontaneous and radiation induced thyroid cancer incidence in exposed children for 50 years follow-up, by sector and age group, based on Australian age-dependent incidence rate 1993 -1997 and 2006 extrapolated Sydney population.

Spontaneous and Induced Thyroid Cancer Incidence over 50 year s by Sector																	
Age Group	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**Total**
	N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	**S**	**SSW**	**SW**	**WSW**	**W**	**WNW**	**NW**	**NNW**	
0 - 4	17.5	22.0	31.1	8.4	2.9	0.3	0.2	0.1	1.6	2.9	0.2	1.7	3.0	1.7	5.6	15.2	114.5
5 - 9	20.2	25.4	35.9	9.7	3.3	0.3	0.2	0.1	1.9	3.3	0.3	2.0	3.4	1.9	6.5	17.6	131.9
10 - 14	22.9	28.7	40.7	11.0	3.8	0.4	0.2	0.2	2.1	3.7	0.3	2.3	3.9	2.2	7.4	19.9	149.5
15 - 19	26.2	32.8	46.4	12.5	4.3	0.4	0.2	0.2	2.4	4.3	0.4	2.6	4.4	2.5	8.4	22.7	170.8
Total Spontaneous																	
Total Induced	0	2.2	3.2	1.3	1.0	0.3	0.2										

Table 11. Urgent Protective Action Zone boundaries and affected population for the ANSTO HIFAR accident model, as a function of the projected child thyroid dose.

Projected Thyroid Dose (mGy)	Spontaneous Thyroid Cancer Risk (50y)	Additional Child Thyroid Cancer Risk (50y)	HIFAR Research Reactor UPZ Distance (km)	Number of members of public living within UPZ
100	0.002	0.002	0.5	0
50	0.002	0.001	0.8	0
30	0.002	0.0007	1.4	0
10	0.002	0.0002	3.0	8000

Table 12. Estimated cases of radiation induced thyroid cancer as a function of the projected dose for stable iodine administration, for children aged 0 – 19 at time of exposure, and 50 years follow-up period after ANSTO HIFAR Reference Accident,

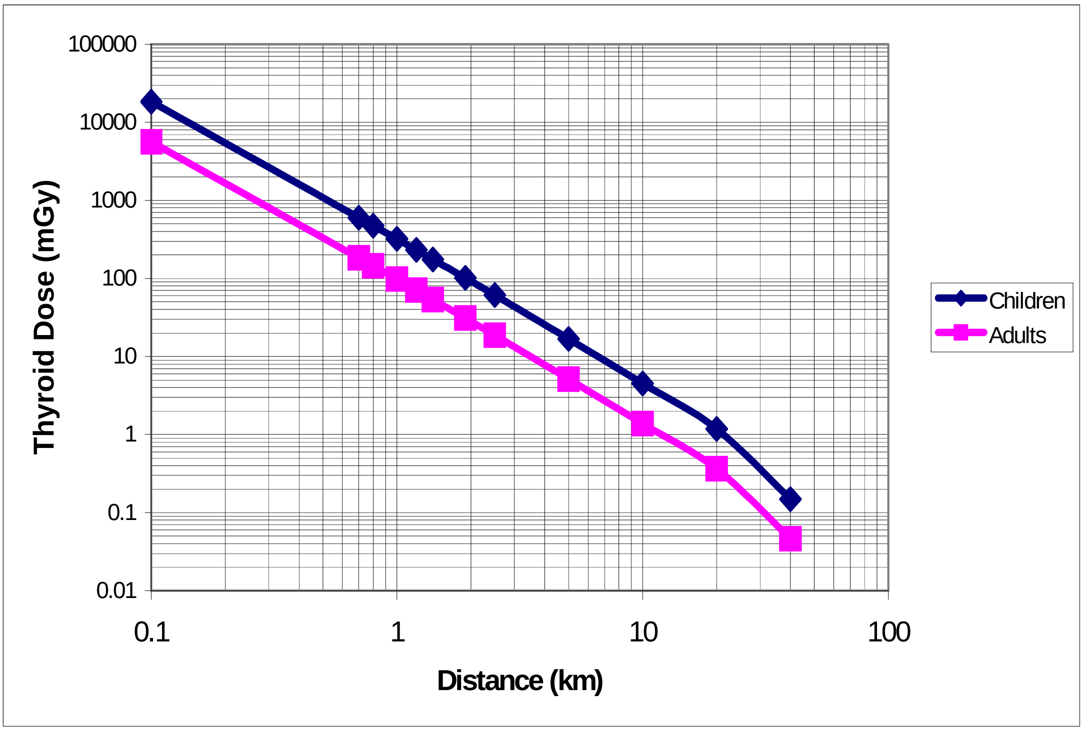
Projected Thyroid Dose (mGy)	Child Thyroid Cancer Cases (50y)					
	2	**3**	**4**	**5**	**6**	**7**
	NNE	**NE**	**ENE**	**E**	**ESE**	**SE**
No action	2.2	3.2	1.3	1.0	0.3	0.2
100	2.2	3.2	1.3	1.0	0.3	0.2
50	2.2	3.2	1.3	1.0	0.3	0.2
30	2.2	3.2	1.3	1.0	0.3	0.2
10	2.2	3.2	1.3	0.8	0.1	0.1
Spontaneous Thyroid cancers	109	154	42	14	1.3	0.8

4.4 NPW Reference Accident for NIMITZ Class Nuclear Powered Warship

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) (OPSMAN1 2003). The reference accident model for assessing the suitability of ports for visits by nuclear powered warships, called the *2000 Reference Accident* was revised in December 2000 by ARPANSA (ARPANSA 2000). There are nominated anchorages in Australia for visits by both submarines and by aircraft carriers. The NIMITZ class aircraft carriers are powered by two nuclear reactors each having a power level well in excess of 100 Megawatts thermal. The approved anchorages for these vessels are located at Gage Roads, Fremantle, Western Australia and Hobart, Tasmania.

The *2000 Reference 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. The radiation doses to individuals and to the total population exposed can then be calculated. Figure 13 shows the calculated thyroid doses for adults and children as a function of distance from the accident.

Figure 13. Adult and Child Thyroid doses from 2000 Reference Accident for NIMITZ Class Aircraft Carrier *(APRANSA 2000).*



4.5 Child Thyroid Cancer Risk for NPW Reference Accident for Hobart

The nominated anchorage for a nuclear powered aircraft carrier lies in the River Derwent at the entrance to Ralphs Bay, Hobart at the position 42 ° 57.2'S, 147 ° 24.08'E. No land lies within 1.3 kilometres of the anchorage. The population around this anchorage as a function of 30 degree sectors are shown in Table 13, based on Australian Census data for 1996. The area within approximately 3.5 kilometres is mainly water but takes in parts of the Droughty Point and Gellibrand Point peninsulas, and about 100 people reside inside this distance. The most densely populated sector, Sector 11, is to the north-west of the anchorage and encompasses the city of Hobart. The Central Business District (CBD) of Hobart lies in Sector 11 some 10 km from the anchorage. The population figures in Table 13 do not account for the transient working and shopping population that would occupy the CBD for some of the day.

Thyroid doses, by sector and distance, for an accident involving a NIMITZ Class NPW at an anchorage in Hobart, were determined from the *2000 Reference Accident* model. Thyroid doses as a function of age and distance from the models were combined with the thyroid cancer risk factors to estimate the number of additional thyroid cancers by distance and sector around the NPW anchorage. The total number of projected thyroid cancers arising from an NPW accident at the anchorage was estimated from:

- the age dependant thyroid cancer spontaneous incidence rate (Table 3),
- the age dependant excess absolute risk for the Life Span Study (Table 6),
- the estimates of child thyroid dose as a function of distance from *2000 Reference Accident* model (Figure 13), and
- the projected population by distance and sector, centered on the based on the 1996 Census, (Table 13)

Table 13. Population by sector and distance band centered on NIMITZ class anchorage for Port of Hobart (CDATA 1996).

Distance Band (km)	Population by Sector (Hobart)												
	All	**1 N**	**2**	**3**	**4 E**	**5**	**6**	**7 S**	**8**	**9**	**10 W**	**11**	**12**
1	**68**	46	0	0	0	0	0	0	0	0	22	0	0
2.75	**14520**	3777	2341	1711	701	60	7	21	2055	877	0	225	2745
4.25	**24151**	2858	530	1517	1830	404	8	788	1981	4190	5531	614	3900
6.25	**34190**	453	235	1697	314	28	3	1806	469	3092	13102	5641	7350
8.75	**26430**	132	550	1318	1631	216	98	473	819	1054	4723	13012	2404
12.5	**43661**	228	356	1140	798	844	454	9514	4946	516	2472	20842	1551
17.5	**26950**	1046	3820	1179	1	422	425	1163	1841	348	669	11956	4080
30	**34788**	1073	1035	3898	365	922	63	3150	4075	3898	6075	5626	4608
Total	**204761**	**9613**	**8867**	**12460**	**5640**	**2896**	**1058**	**16915**	**16186**	**13975**	**32594**	**57916**	**26638**

The spontaneous thyroid cancer incidence over 50 years by sector and age group, based on Australian age-dependent incidence rate 1993 -1997 and 1996 Hobart population centered on NIMITZ anchorage is shown in Table 14. For the 2000 Reference Accident scenario, the number of radiation induced thyroid cancers for 50 years after the exposure are summarised in the first row of Table 15, assuming no protective measures were implemented. For Hobart, the model predicts 0 to 1.7 additional cases, compared with 0.2 to 12.3 spontaneous cases, over 50 years.

As for the HIFAR Reference accident model, the child thyroid doses for the NIMITZ Class Reference accident model, define the distance at which an unprotected individuals would receive a particular projected radiation dose over an extended exposure period following an accident. If a protective measure such as iodine prophylaxis is implemented rapidly, then these projected doses represent an upper limit on the avertable dose and provide a measure of the extent of the protective action zone, in this case the UPZ. This in turn provides an estimate of the number of potentially exposed members of public within the UPZ.

Table 14. Spontaneous thyroid cancer incidence over 50 years by sector and age group, based on Australian age-dependent incidence rate 1993-1997 and 1996 Hobart population centered on NIMITZ anchorage.

Age Group	Spontaneous Thyroid Cancers by Sector (Hobart)												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Total**
	N			**E**			**S**			**W**			
0 - 4	0.4	0.4	0.6	0.3	0.1	0.0	0.8	0.7	0.6	1.4	2.6	1.2	9.1
5 - 9	0.5	0.4	0.6	0.3	0.1	0.1	0.8	0.8	0.7	1.6	2.9	1.3	10.2
10 - 14	0.5	0.5	0.7	0.3	0.2	0.1	0.9	0.9	0.8	1.8	3.2	1.5	11.4
15 - 19	0.6	0.6	0.8	0.4	0.2	0.1	1.1	1.0	0.9	2.0	3.6	1.7	12.9
Children	**2.0**	**1.9**	**2.7**	**1.2**	**0.6**	**0.2**	**3.6**	**3.4**	**3.0**	**6.9**	**12.3**	**5.7**	**43.6**
All	**21.6**	**20.0**	**28.0**	**12.7**	**6.5**	**2.4**	**38.1**	**36.4**	**31.4**	**73.3**	**130.3**	**59.9**	**460.7**

The extent of the UPZ boundaries for the Hobart Nimitz anchorage for projected thyroid doses of 100 mGy, 50 mGy, 30 mGy or 10 mGy are summarised in Table 16, together with the estimates of the spontaneous thyroid cancer risk, the additional thyroid cancer risk and the number of potentially exposed members of the public. The reduction in the number of estimated cases of radiation induced thyroid cancer as a function of the projected thyroid dose for implementation of stable iodine administration, is shown in rows two to five of Table 15, assuming the protective measure is fully effective.

Table 15. Effect of implementation of stable iodine prophylaxis at different levels of projected thyroid dose on the number of additional thyroid cancers over 50 years for the *2000* ***Reference Accident*** **for Hobart NIMITZ Class anchorage, as a function of sector.**

Projected Thyroid Dose (mGy)	**Additional Thyroid Cancers by Sector (Hobart)**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	N			**E**			**S**			**W**		
No Action	1.4	0.7	0.8	0.5	0.1	0.0	0.4	0.9	0.9	1.6	1.2	1.7
100 mGy	1.3	0.7	0.8	0.5	0.1	0.1	0.4	0.9	0.9	1.5	1.2	1.7
50 mGy	0.4	0.1	0.3	0.3	0.1	0.0	0.4	0.4	0.7	1.5	1.2	1.0
30 mGy	0.4	0.1	0.3	0.3	0.1	0.0	0.4	0.4	0.7	1.5	1.2	1.0
10 mGy	0.0	0.1	0.1	0.1	0.0	0.0	0.2	0.1	0.1	0.2	0.8	0.1
Spontaneous < 19 y	**2.0**	**1.9**	**2.7**	**1.2**	**0.6**	**0.2**	**3.6**	**3.4**	**3.0**	**6.9**	**12.3**	**5.7**
Spontaneous All	**21.6**	**20.0**	**28.0**	**12.7**	**6.5**	**2.4**	**38.1**	**36.4**	**31.4**	**73.3**	**130.3**	**59.9**

Table 16. Boundary radius and population within the Urgent Protective Action Zone as a function of the projected child thyroid dose, based on the *2000* ***Reference Accident*** **for Hobart NIMITZ Class anchorage**

Projected Thyroid Dose (mGy)	**Spontaneous Thyroid Cancer Risk (50y)**	**Additional Child Thyroid Cancer Risk (50y)**	**NIMITZ Class Reactor UPZ Distance (km)**	**Number of members of public living within UPZ**
100	0.002	0.002	1.9	0
50	0.002	0.001	2.9	13000
30	0.002	0.0007	3.9	35000
10	0.002	0.0002	6.3	70000

4.6 Child Thyroid Cancer Risk for NPW Reference Accident for Perth

The nominated anchorage for NIMITZ class aircraft carriers is at Gage Roads North at the position 32 º 02.0'S, 115 º 42.0'E. Population details, based on the 1996 Census, are given in the Table 17. No land lies within 3.2 kilometres of the anchorage. The area within approximately 4.5 kilometres is mainly port and industrial use. The closest populated sector, Sector 3 and 4, is to the east of the anchorage and encompasses the city of Fremantle. The Central Business District (CBD) of Freemantle lies in Sector 4 some 5 km from the anchorage. The population figures above do not account for the transient working and shopping population that would occupy the CBD for some of the day.

Thyroid doses as a function of age and distance from the models were combined with the thyroid cancer risk factors to estimate the number of additional thyroid cancers by distance and sector around the NPW anchorage. Thyroid doses, by sector and distance, for an accident involving a NIMITZ Class NPW at an anchorage at Gage Roads, were determined from the *2000 Reference Accident* model.

The total number of projected thyroid cancers arising from an NPW accident at the anchorage was estimated from:

- the age dependant thyroid cancer spontaneous incidence rate (Table 3),
- the age dependant excess absolute risk for the Life Span Study (Table 6),
- the estimates of child thyroid dose as a function of distance from *2000 Reference Accident* model (Figure 13), and
- the projected population by distance and sector, centered on the based on the 1996 Census, (Table 17.)

Thyroid doses, by sector and distance, for an accident involving a NIMITZ Class NPW at an anchorage in Perth, were determined from the *2000 Reference Accident* model. The additional thyroid cancer cases from this exposure are summarised in the first row of Table 18. For Perth, the model predicts 0 to 2.7 additional cases, compared with up to 72 spontaneous cases, over 50 years.

The extent of the UPZ boundaries for the Gage Roads NIMITZ anchorage for projected thyroid doses of 100 mGy, 50 mGy, 30 mGy or 10 mGy are summarised in Table 19, together with the estimates of the spontaneous thyroid cancer risk, the additional thyroid cancer risk and the number of potentially exposed members of the public. The reduction in the number of estimated cases of radiation induced thyroid cancer as a function of the projected thyroid dose for implementation of stable iodine administration, is shown in rows two to five of Table 18, assuming the protective measure is fully effective.

Table 17. Population by Sector and Distance Band centered on NIMITZ class anchorage for Gage Roads (Perth) (CDATA 1996).

Distance Band (km)	Population by Sector (Perth)												
	1	2	3	4	5	6	7	8	9	10	11	12	All
	N			E			S			W			
1.25	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3.75	0	0	530	2065	70	0	0	0	0	0	0	0	**2665**
7.5	24	20441	22391	28574	12914	0	7	0	0	0	0	0	**84351**
12.5	5487	36940	24476	42812	22558	530	35	0	0	17	0	0	**132855**
17.5	40110	64491	63351	38646	5688	676	103	0	0	308	0	0	**213373**
25	152625	186335	86792	81285	4832	48360	81	0	0	82	0	0	**560392**
35	60314	30350	49246	33576	6182	22830	0	0	0	0	0	138	**202636**
Total	**258560**	**338557**	**246786**	**226958**	**52244**	**72396**	**226**	**0**	**0**	**407**	**0**	**138**	**1196272**

Figure 18. Spontaneous thyroid cancer incidence over 50 years by sector and age group, based on Australian age-dependent incidence rate 1993 -1997 and the 1996 Fremantle population centered on NIMITZ anchorage.

Age Group	Spontaneous Thyroid Cancers by Sector (Perth)												
	1	2	3	4	5	6	7	8	9	10	11	12	Total
	N			E			S			W			
0 - 4	11.5	15.0	11.0	10.1	2.3	3.2	0.0	0.0	0.0	0.0	0.0	0.0	53.1
5 - 9	12.9	16.9	12.3	11.3	2.6	3.6	0.0	0.0	0.0	0.0	0.0	0.0	59.8
10 - 14	14.4	18.8	13.7	12.6	2.9	4.0	0.0	0.0	0.0	0.0	0.0	0.0	66.5
15 - 19	16.2	21.3	15.5	14.2	3.3	4.5	0.0	0.0	0.0	0.0	0.0	0.0	75.1
Children	**55.0**	**72.0**	**52.5**	**48.3**	**11.1**	**15.4**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**	**254.4**
All	**582**	**762**	**555**	**510**	**117**	**1639**	**0.5**	**0.0**	**0.0**	**0.9**	**0.0**	**0.3**	**2691.6**

Table 19. Effect of implementation of stable iodine prophylaxis at different projected thyroid dose on the number of additional thyroid cancers over 50 years for *2000* ***Reference*** *Accident* **for Gage Roads NIMITZ Class anchorage, as a function of sector.**

Projected Thyroid Dose (mGy)	Spontaneous and Additional Thyroid Cancer Cases by Sector (Perth)											
	1	2	3	4	5	6	7	8	9	10	11	12
	N			E			S			W		
No Action	1.09	2.60	2.21	2.70	0.91	0.24	0.00	0.00	0.00	0.00	0.00	0.00
100 mGy	1.09	2.60	2.21	2.70	0.91	0.24	0.00	0.00	0.00	0.00	0.00	0.00
50 mGy	1.09	2.60	2.21	2.70	0.91	0.24	0.00	0.00	0.00	0.00	0.00	0.00
30 mGy	1.09	2.60	2.21	2.70	0.91	0.24	0.00	0.00	0.00	0.00	0.00	0.00
10 mGy	1.09	2.60	2.14	2.41	0.90	0.24	0.00	0.00	0.00	0.00	0.00	0.00
Spontaneous < 19 y	**55.0**	**72.0**	**52.5**	**48.3**	**11.1**	**15.4**	**0.0**	**0.0**	**0.0**	**0.1**	**0.0**	**0.0**
Spontaneous All	**582**	**762**	**555**	**510**	**117**	**1639**	**0.5**	**0.0**	**0.0**	**0.9**	**0.0**	**0.3**

Table 20. Boundary radius and population within the Urgent Protective Action Zone as a function of the projected child thyroid dose, based on the *2000* ***Reference Accident*** **for Gage Roads (Perth) NIMITZ Class anchorage.**

Projected Thyroid Dose (mGy)	Spontaneous Thyroid Cancer Risk (50y)	Additional Child Thyroid Cancer Risk (50y)	NIMITZ Class Reactor UPZ Distance (km)	Number of members of public living within UPZ
100	0.002	0.002	1.9	0
50	0.002	0.001	2.9	0
30	0.002	0.0007	3.9	0
10	0.002	0.0002	6.3	2700

DISCUSSION

Iodine prophylaxis can be used to reduce the thyroid cancer risk for children after a reactor accident that releases radioactive iodine. Taking iodine tablets after an accident involving a release of radioactive iodine saturates the blood with non-radioactive iodine, reducing the fraction of radioactive iodine taken up by the thyroid and the resultant cancer risk. Australian guidance on when to issue iodine tablets follows international recommendations, balancing the risks of a protective measure against the averted (prevented) radiation risks.

For radiation induced thyroid cancer the absolute risk is constant between the ages of 0 and 18 years and has a value of about 0.4 cases/million/year/mGy and drops to close to zero for adults. For exposed children, implementing iodine prophylaxis at at the current Generic Intervention Level of 100 mGy retains an additional risk of up to 40 cases (4 fatalities) per million persons per year. For the range of Australian radiation emergency scenarios in the previous section involving the release of radioactive iodine, it is estimated that child exposure to this radioiodine could result in a maximum of 3 cases (0.3 fatalities), expected over the subsequent 50 years.

There is currently no international consensus on the intervention level for child iodine prophylaxis (see APPENDIX VII). In a guidance document published in 1999, the WHO suggests that iodine prophylaxis for children be considered at a 10 mGy child thyroid dose (WHO 1999). The child thyroid cancer risk for 10 mGy is one tenth that for 100 mGy, but the health benefit does not scale proportionally. For the range of Australian radiation emergency scenarios involving the release of radioactive iodine from a loss of coolant accident, the application of protective measures at 10 mGy intervention level could result in a reduction of a maximum of 1.4 cases from the expected 3 cases expected over the next 50 years. The application of protective measures at the 50 mGy or 100 mGy intervention level would not reduce this estimate of cases (the projected child thyroid doses are below the intervention levels), while the implementation of child iodine prophyllaxis at 30 mGy intervention level could result in a reduction of a maximum of 1 case from these estimated 3 cases expected over the subsequent 50 years. There is a small health benefit in using a lower value than 100 mGy for the Intervention Level for child iodine prophylaxis, but there is minimal benefit in using 10 mGy over 30 mGy.

For stable iodine prophylaxis to be effective against inhaled radioiodine, it must be administered within a few hours of the inhalation. Clearly, there is a trade-off between the number of people to whom stable iodine tablets are issued and the promptness with which they can be administered: enlarging the planning zone will not inevitably increase the overall level of protection achieved. The framework established for responding to an emergency must allow flexibility to tailor the response to the specific circumstances of the accident, and so to ensure that those most at risk are given priority in protection.

The estimates of reduced thyroid cancer risk in the previous section assume that iodine prophylaxis is 100% efficient in reducing the thyroid cancer risk, and that 100% of the predicted thyroid dose can be averted. In practice, it will take some time to initiate a protective measure, so not all the radiation dose can be avoided. Using this assumption provides an upper bound on estimates of any benefits. It was assumed that stable iodine could be distributed to all individuals within the defined distance and that the thyroid dose would be reduced to zero for this group.

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APPENDIX I RADIATION DOSE UNITS

The basic radiation protection principles that underlie the approach to implementing protective measures during a radiation emergency are usually directed at reducing stochastic effects.

"The probability of a cancer resulting from radiation usually increases with increments of dose, probably with no threshold, and in a way that is roughly proportional to dose, at least for doses well below the thresholds for deterministic effects. The severity of the cancer is not affected by the dose. This kind of effect is called 'stochastic', meaning 'of a random or statistical nature'. If the damage occurs in a cell whose function is to transmit genetic information to later generations, any resulting effects are expressed in the progeny of the exposed person. This type of stochastic effect is called 'hereditary'. The system of radiation protection described in these Recommendations is designed to keep the probability that stochastic effects will occur from exceeding a level that is regarded as unacceptable."

A full discussion of the concepts of radiation protection, adsorbed dose and effective dose can be found in Radiation Protection Series Publication No. 1. *(Republished March 2002, available at www.arpansa.gov.au/rps_pubs.htm)*

A number of different quantities are used to specify the radiation dose to an individual, in particular adsorbed dose, equivalent dose and effective dose. The Generic Intervention Levels (GIL) for Iodine Prophylaxis are specified in units of radiation dose to the thyroid (***absorbed dose***), in units of milligray (mGy). The GILs for sheltering, evacuation and relocation are specified in terms of ***effective dose***, in units of millisievert (mSv).

Adsorbed Dose

The fundamental dosimetric quantity in radiation protection is the **absorbed** dose, D. This is the energy absorbed per unit mass and its unit is joule per kilogram, which is given the special name **gray** (Gy). This is a large unit and for normal radiation protection levels of radiation a series of prefixes are used:

- nanogray (nGy) is one thousand millionth of a gray (1/ 1,000,000,000).
- microgray (μGy) is one millionth of a gray (1/ 1,000,000).
- milligray (mGy) is one thousand of a gray (1/ 1,000).

Equivalent Dose

Equivalent dose is an additional quantity that is used for radiation protection purposes, and it takes account of the type of radiation, but not the tissue type. The probability of stochastic effects is found to depend not only on the absorbed dose, but also on the type and energy of the radiation. This is taken into account by weighting the absorbed dose by a factor related to the type of radiation. The weighting factor is called the **radiation weighting factor**, w_R, and the weighted dose is called the **equivalent dose.** (Previously, this weighting factor was called the quality factor, Q, and the weighted dose was called the dose equivalent.)

The unit for equivalent dose is joule per kilogram with the special name **sievert** (Sv). Values of radiation weighting factors are given in Table I - 1.

Table I - 1 Recommended radiation weighting factors 1
(RPS 1 from ICRP Publication 60)

Type and energy range		Radiation weighting factor, w_R
Photons, all energies		1
Electrons and muons, all energies		1
Neutrons ,	energy <10 keV	5
	10 keV to 100 keV	10
	> 100 keV to 2 MeV	20
	> 2 MeV to 20 MeV	10
	> 20 MeV	5
Protons, other than recoil protons, energy >2 MeV		5
Alpha particles, fission fragments, heavy nuclei		20

All values relate to the radiation incident on the body or, for internal sources, emitted from the source.

Table 2 Recommended tissue weighting factors [1]
(from RHS1 and ICRP Publication 60)

Tissue or organ	Tissue weighting factor, w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder	0.05 [2,3]

1 The values have been developed by the ICRP from a reference population of equal numbers of both sexes and a wide range of ages. In the definition of effective dose they apply to workers, to the whole population, and to either sex.

2 For purposes of calculation, the remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. The list includes organs which are likely to be selectively irradiated. Some organs in the list are known to be susceptible to cancer induction. If other tissues and organs subsequently become identified as having a significant risk of induced cancer they will then be included either with a specific wT or in this additional list constituting the remainder. The latter may also include other tissues or organs selectively irradiated

Like the gray, the sievert is a large unit and for normal radiation protection levels of radiation a series of prefixes are used:

- nanoSievert (nSv) is one thousand millionth of a sievert (1/ 1,000,000,000).
- microSievert (μSv) is one millionth of a sievert (1/ 1,000,000).
- milliSievert (mSv) is one thousand of a sievert (1/ 1,000).

Effective Dose

Effective dose is a measure of the risk detriment (usually a radiation induced cancer). The relationship between the probability of stochastic effects and equivalent dose is found also to depend on the organ or tissue irradiated.

Effective dose, therefore takes into account the radiological sensitivities of different tissues. If the whole body were uniformly irradiated, the fractional contribution of each organ or tissue, T, to the total **detriment** resulting from the exposure to radiation is represented by a **tissue weighting facto**r, w_T. The effective dose, E, is the sum of the weighted equivalent doses in all tissues and organs:

The unit for effective dose is joule per kilogram with the special name sievert (Sv). Values of tissue weighting factors are given in Table 2. Like equivalent dose, its is specified in units of milliSievert.

Units for Thyroid Dose

The use of the same unit for equivalent dose and effective dose is a potential source of confusion, since some documents use thyroid dose ***(equivalent dose***) in mSv and whole body dose (***effective dose***) also in mSv. But they are different quantities. In the case of the radiation exposure to the thyroid from intakes of I-131:

- the ***tissue weighting factor*** for the thyroid is 0.05 (5%), and
- the ***radiation weighting factor*** is one, since the radiation from I-131 is gamma rays and beta rays.

This is a factor of 20 difference. Applying these factors to the thyroid GILs:

An ***absorbed dose*** of 10 mGy to the thyroid corresponds to an ***effective dose*** of 0.5 mSv.
30 mGy thyroid dose corresponds to 1.5 mSv ***effective dose*** and
100 mGy thyroid dose corresponds to 5 mSv ***effective dose***.

The 100 mGy (5 mSv) GIL has a similar risk detriment to the 10 mSv GIL for sheltering, which is why they are usually considered in parallel (if radioactive iodine is present).

Reference

Radiation Protection Series Publication No. 1. (Republished March 2002)
Recommendations for limiting exposure to ionizing radiation (1995)
(Guidance note [NOHSC:3022(1995)]), and
National standard for limiting occupational exposure to ionizing radiation
[NOHSC:1013(1995)]

APPENDIX I I AGE DISTRIBUTION OF STANDARD POPULATIONS

Australian resident population 1997

Age	Males	Females	Total
0–4	663326	628962	1292288
5–9	674264	640884	1315148
10–14	671797	640312	1312109
15–19	663680	630243	1293923
20–24	697074	674613	1371687
25–29	727726	724812	1452538
30–34	710389	714205	1424594
35–39	737306	740902	1478208
40–44	688428	692235	1380663
45–49	649590	640059	1289649
50–54	557455	536230	1093685
55–59	432830	419785	852615
60–64	360382	362859	723241
65–69	336529	351722	688251
70–74	281090	328316	609406
75–79	189861	255728	445589
80–84	108495	178966	287461
85+	63988	149112	213100
Total	**9214210**	**9309945**	**18524155**

Source: Australian Bureau of Statistics 1997b.

Australian Standard Population* and World Standard Population**

Age	Australian Standard Population (1991)		World Standard Population	
	Persons	**% of total**	Persons	**% of total**
0–4	1271703	7.4	12000	12.0
5–9	1272208	7.4	10000	10.0
10–14	1241619	7.2	9000	9.0
15–19	1364074	7.9	9000	9.0
20–24	1396764	8.1	8000	8.0
25–29	1399663	8.1	8000	8.0
30–34	1425735	8.2	6000	6.0
35–39	1328387	7.7	6000	6.0
40–44	1294271	7.5	6000	6.0
45–49	1029145	6.0	6000	6.0
50–54	846934	4.9	5000	5.0
55–59	725950	4.2	4000	4.0
60–64	736868	4.3	4000	4.0
65–69	671390	3.9	3000	3.0
70–74	510755	3.0	2000	2.0
75–79	384495	2.2	1000	1.0
80–84	229828	1.3	500	0.5
85+	154247	0.9	500	0.5
Total	**17284036**	**100.0**	**100000**	**100.0**

* Australian Bureau of Statistics 1993.

** Doll & Smith 1982.

APPENDIX III IMPLEMENTATION OF PROTECTIVE MEASURES

The decision on the use of a particular intervention should be based on three general principles:

$ Serious deterministic health effects should be avoided.

$ The intervention should be justified (that is do more good than harm)

$ The intervention should be optimised (that is provide maximum net benefit)

Radiation emergency protective actions include:

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

- Sheltering. Sheltering involves keeping members of the population indoors, in suitable buildings, to reduce radiation exposure from airborne radioactive material and from the 'ground shine'. Sheltering is not recommended for a period exceeding 48 hours. This period may be significantly less depending upon climatic conditions.
- Evacuation. Evacuation is the urgent removal of the population from the affected area. It is generally the most effective protective action against major airborne releases of radioactive material. Evacuation and accommodation in emergency facilities is not recommended for a period exceeding 7 days.
- Administration of stable iodine tablets. Inhaled radioactive iodine tends to concentrate in the thyroid gland and can cause early or latent effects such as thyroid cancer. Ingesting stable, non radioactive iodine, before or immediately after exposure to a release of radioactive iodine saturates the thyroid gland and prevents the absorption of radioactive iodine in the body.

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

Protective actions should be carried out on the basis of intervention levels and action levels. The procedures for the determination of appropriate values of intervention and/or action level are based on the balancing the risks associated with the implementing the countermeasure, against the risks reduction associated with the averted radiation dose. For planning purposes, the optimisation process is carried out for representative populations exposed to conditions expected following a range of radiation accident scenarios, to give a set of generic optimised levels. The derived *generic intervention levels* (GIL) apply to urgent and longer-term protective actions for the public and *generic action levels* (GAL) apply to controls on food.

The decision to use a particular protective measure should be based on an estimate of the averted dose to be averted by carryout the protective action, relative to the appropriate Generic Intervention Level or Generic Action Levels.

APPENDIX IV STABLE IODINE

The effectiveness of stable iodine as a specific blocker of thyroid radioiodine uptake is well established, as are the doses necessary for blocking uptake. As such, it is reasonable to conclude that stable iodine will likewise be effective in reducing the risk of thyroid cancer in individuals or populations at risk for inhalation or ingestion of radioiodines.

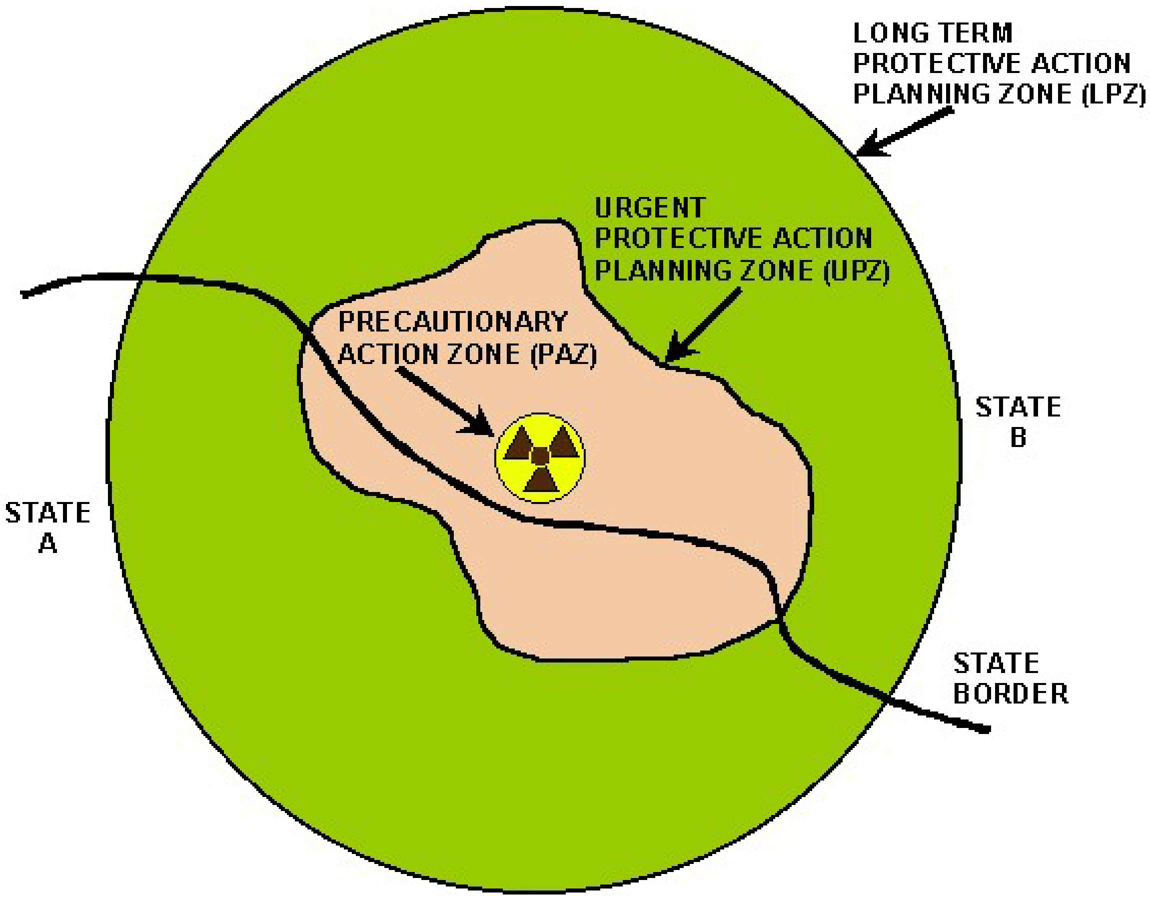
In its *Guidance on Iodine Prophylaxis*, the World Health Organisation advised that; (WHO 1999).

> *Short-term administration of stable iodine at thyroid blocking doses involves an extremely low risk of any side effects (less than 1 in 10^6) and, in general, less risk in children than adults. The risks of thyroidal side effects from stable iodine administration are likely to be higher in iodine deficient regions. These risks include sialadenitis (an inflammation of the salivary gland), gastrointestinal disturbances, allergic reactions and minor rashes. In addition, persons with known iodine sensitivity should avoid stable iodine. There is also an increased risk in connection with thyroid disorders, such as auto-immune thyroiditis, Graves' disease and nodular goitre. Such disorders are common in the adult population and in the elderly but relatively rare in children.*
>
> *Following the Chernobyl accident, widespread administration of stable iodine (in the form of potassium iodide) took place in Poland, but no serious side effects were seen. Approximately 10.5 million children under age 16 and 7 million adults received at least one dose of stable iodine. Of note, among newborns receiving single doses of 15 mg of potassium iodide, 0.37 percent (12 of 3214) showed transient increases in TSH (thyroid stimulating hormone) and decreases in FT4 (free thyroxine). The side effects among adults and children were generally mild and not clinically significant. Side effects included gastrointestinal distress, which was reported more frequently in children (up to 2 percent, felt to be due to bad taste of supersaturated potassium iodide solution) and rash (~1 percent in children and adults). Two allergic reactions were observed in adults with known iodine sensitivity (Nauman & Wolff 1993).*
>
> *There is no question that the benefits of potassium iodide treatment to reduce the risk of thyroid cancer outweigh the risks of such treatment in neonates. Nevertheless, in light of the potential consequences of even transient hypothyroidism on intellectual development, it is recommended that neonates (within the first month of life) treated with stable iodine be monitored for this effect and that thyroid hormone therapy be instituted in cases in which hypothyroidism develops.*
>
> *Pregnant women should be given stable iodine for their own protection and for that of the fetus, as iodine (whether stable or radioactive) readily crosses the placenta. However, because of the risk of blocking fetal thyroid function with excess stable iodine, repeat dosing with stable iodine of pregnant women should be avoided. Lactating females should be administered stable iodine for their own protection, as for other young adults, and potentially to reduce the radioiodine content of the breast milk, but not as a means to deliver stable iodine to infants, who should get their stable iodine directly.*

APPENDIX V EMERGENCY PLANNING ZONES

In the planning for radiological emergencies at a facility, three emergency planning zones are defined. These are the Precautionary Action Zone, the Urgent Protective Action Planning Zone and the Long Term Protective Action Planning Zone., as illustrated in Figure III-1.

FIG. III- 1. Concept of emergency planning zones.



(a) Precautionary Action Zone (PAZ) or Zone 1

The PAZ is a predesignated area around a facility where urgent protective actions have been preplanned and will be implemented immediately upon declaration of a general emergency. The goal is to substantially reduce the risk of deterministic health effects by taking protective action *before* a release.

The size of the precautionary action zone is based on a best estimate of the consequences in the case of a worst accident. Protective actions should be implemented for the whole zone whenever the conditions for a severe accident develop.

The PAZ is the area where preparations should be made to quickly alert the public and workers (e.g., siren systems) and instruct them on the urgent protective action to take. Protective actions such as substantial sheltering, evacuation and distribution of thyroid blocking agents should be recommended immediately when severe conditions are detected in the facility without waiting for monitoring.

(b) Urgent Protective Action Planning Zone (UPZ) or Zone 2

The UPZ is a predesignated area around a facility where preparations are made to promptly implement urgent protective measures based on environmental monitoring.

The choice of the size of the protective action planning zones represents a judgement on the extent of detailed planning which must be performed in order to ensure effective response. In a particular emergency, protective actions might well be restricted to a small part of the planning zones. On the other hand, for the worst possible accidents, protective actions might need to be taken beyond the planning zones.

The UPZ is the area where preparations are made to promptly perform environmental monitoring and implement urgent protective measures based on the results. Plans and capabilities should be developed to implement sheltering or evacuation and distribute thyroid blocking agents (if appropriate). They should also reflect the fact that evacuation could be required up to the boundary of the zone (e.g. reception centres for evacuees should be sited outside this zone).

(c) Long Term Protective Action Planning Zone (LPZ) or Zone 3

The LPZ is a predesignated area around a facility furthest from the facility and including the urgent protective action planning zone.

It is the area where preparations for effective implementation of protective actions to reduce the risk of deterministic and stochastic health effects from long term exposure to deposition and ingestion of locally grown food should be developed in advance. More time will be available to take effective action within this zone. In general, protective actions such as relocation, food restrictions and agricultural countermeasures will be based on environmental monitoring and food sampling.

In the initial planning, these zones should be roughly circular areas around the facility or accident. However, during an actual incident only part of the zone may be affected, such as the downwind quadrant where airborne radioactivity have been generated. The size of the zones can be determined by an analysis of the potential consequences. The boundaries of the zones should be defined by local landmarks (e.g., roads or rivers) to allow easy identification during a response. It is important to note that the zones do not stop at State or Territory borders.

APPENDIX VI THYROID DOSES FROM RADIOIODINE

Prepared by
Peter Burns, Director,
Environmental and Radiation Health Branch, ARPANSA

It is well known that harmful effects of radioactive iodine uptake to the thyroid can be ameliorated by the intake of stable iodine, however the reasons for this and the limitations on its usefulness are often not well understood. Whether ingested, inhaled or injected iodine is transported very quickly (within minutes) to the blood. Once in the blood between 5 and 25% of the intake will go to the thyroid with a half time of uptake of about 6 to 8 hours (ICRP 53). The half time of discharge from the thyroid is considerably longer than this and is approximately 80 days for adults, 65 days for 15 year olds, 50 days for 10 year olds, 40 days for 5 year olds and 30 days for 1 year olds (ICRP 53). Consequently once in the thyroid iodine is not easily displaced or flushed by an intake of more iodine. Because of the delay of several hours in the transport of iodine from the blood to the thyroid, diluting the radioiodine in the blood with stable iodine before it is taken into the thyroid will restrict the uptake of the radioactive component. To be effective this must be done within a few hours of intake. The radiological dose from ^{131}I is ultimately dependent on how much activity reaches the thyroid and is delivered over a period of a few weeks, limited by the physical half life of ^{131}I (8 days) rather than the biological half of iodine in the thyroid.

For a planned event such as an emergency where a worker is to be sent into a contaminated area, an intake of iodine will saturate the thyroid restricting uptake and reducing dose. For individuals who have already been exposed to iodine as a result of an accident an intake of stable iodine can also have a beneficial effect. The mass of radioactive iodine inhaled is extremely small and is easily diluted by a dose of stable iodine. However the amount of stable iodine that must be administered needs to be substantially greater than the daily uptake of iodine otherwise all the iodine in the blood, including the radioactive component, would be taken into the thyroid. For this strategy to be effective in averting dose the stable iodine must administered within a few hours of an intake as after 12 hours most of the radioactive iodine will have already been taken into the thyroid.

The adult thyroid contains about 8000µg of iodine and the average daily uptake by the thyroid is 70 µg (NRPB R140). In England the average daily intake of iodine is 225 µg and approximately 95 µg of this comes from milk. For a 10 year old child the daily intake is 184 µg and for 1 year olds 151 µg (NRPB R140). The uptake of iodine by the thyroid remains fairly constant and consequently the fractional uptake falls as dietary levels increase up to a few hundred µg per day (NRPB R140). Because the thyroid can take up hundreds of microgram per day a prophylactic dose can be up to 100,000µgm (100mgm) to effectively reduce further intake to the thyroid. Iodine deficiency can be a problem in some regions where there are low natural levels of iodine in the soil. In this situation a thyroid could take up more iodine per day than otherwise possible. Iodine deficiency is a problem in some areas of Australia and as part of a public health program iodised table salt is available which contains between 25 and 40 µg/g of iodine.

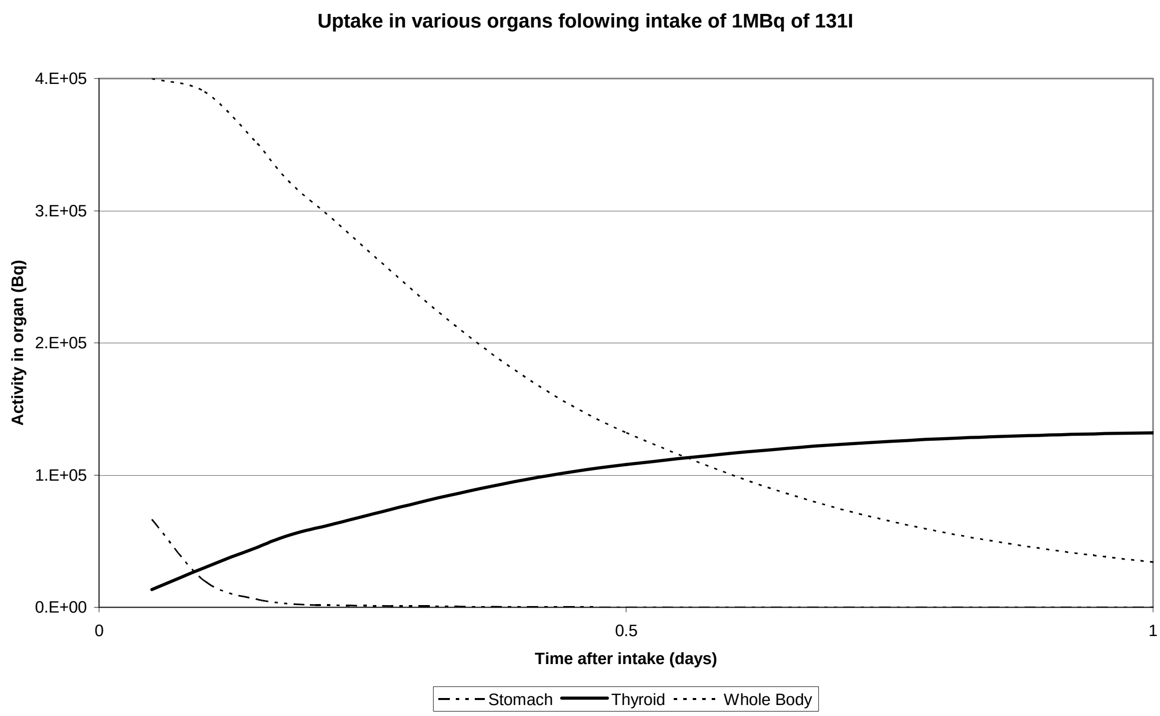
Iodine Uptake

The committed effective dose from an acute intake of iodine is easy to calculate using well-established dose conversion factors (ICRP 71). In a real reactor emergency situation, however, a release is more likely to be a sustained release over a period of hours or days as material vents from the containment vessel. As maximum doses are usually associated with very low wind speeds there will also be a delay between the start of an emergency and radioactive material reaching critical groups several kilometres downwind of the reactor. In what follows no allowance has been made for this delay.

Instantaneous release

The rate of uptake by various organs of the body can be estimated using the LUDEP computer program (NRPB LUDEP 2.0). Figure 1 shows the activity in various organs following an acute intake of 1MBq of ^{131}I by inhalation. There is almost no retention in the lungs and the stomach only retains radioactive material for a few hours. The only organ retaining significant material after one day is the thyroid as the iodine in the blood falls quickly due to either uptake by the thyroid or excretion through the kidneys.

Figure 1. The activity in various organs following an acute intake of 1MBq of ^{131}I by inhalation.



The dose to an organ is dependent on the cumulative number of disintegrations in the organ. Figure 2 shows the cumulative number of disintegrations with time for various organs and the organ doses at a given time after inhalation is shown in Figure 3. Figure 4 shows the activity in the thyroid at a given time during the first 50 hours and demonstrates that the maximum activity in the thyroid peaks after 25 to 30 hours as the rate of radioactive decay of ^{131}I becomes greater than the rate of uptake from the blood. From these Figures it can be seen that capping the activity in the thyroid at an early stage will cause a decrease in the total dose to the thyroid.

Figure 2. The cumulative number of disintegrations in various organs following an acute intake of 1MBq of ^{131}I by inhalation.

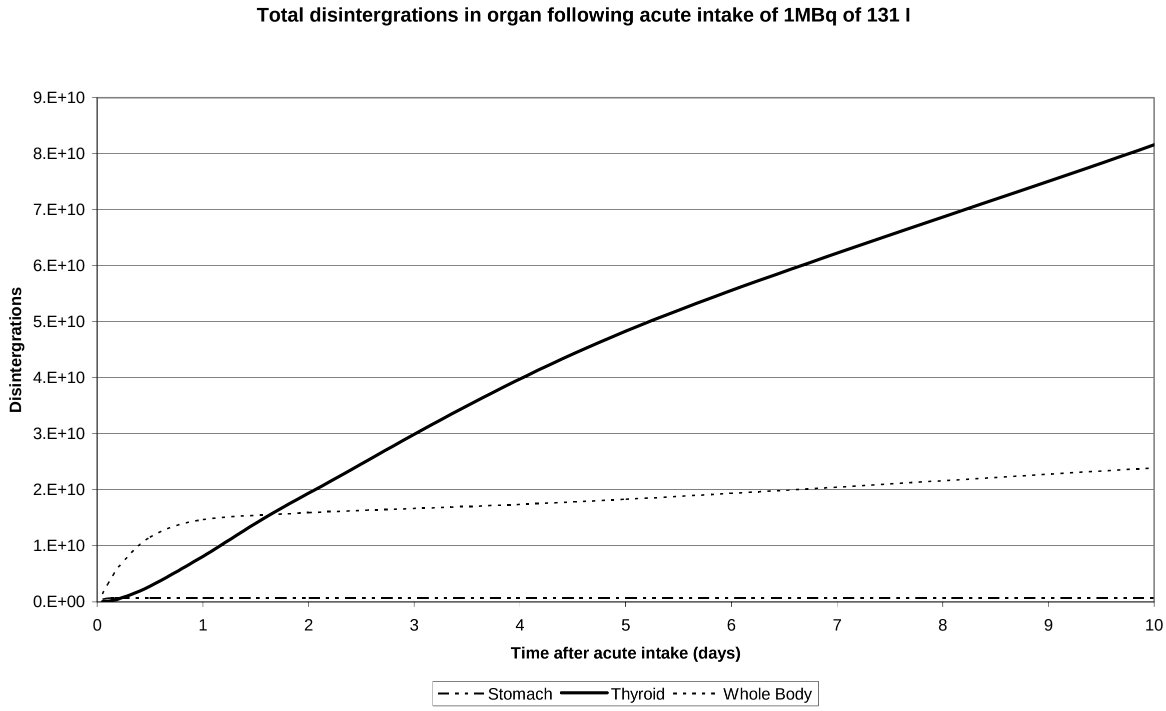


Figure 3. Doses to various organs with time following an acute intake of 1MBq of ^{131}I by inhalation

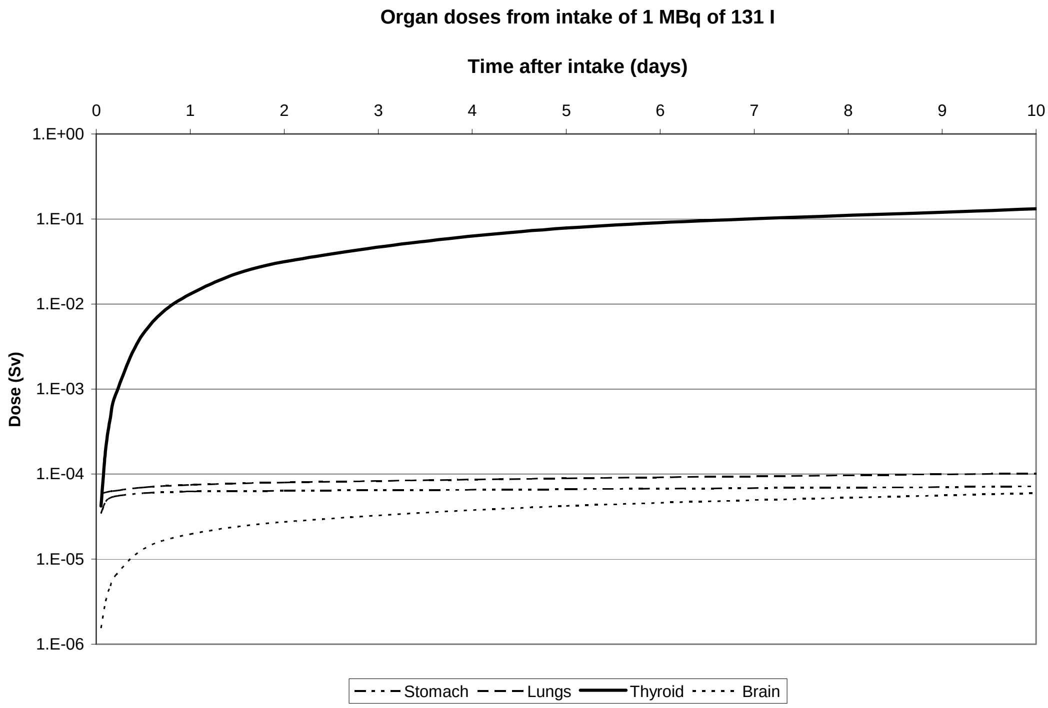
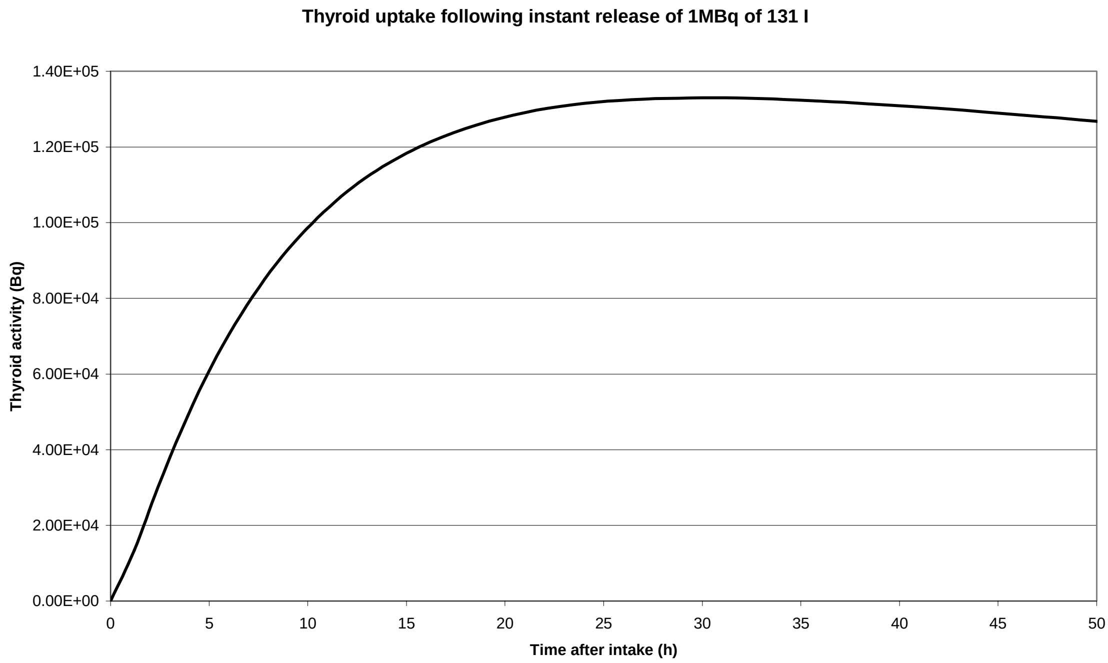


Figure 4. The activity in the thyroid for the first 50 hours following an acute intake of 1MBq of ^{131}I by inhalation.



In an emergency situation where the release of iodine is for a short duration (ie less than half an hour) stable iodine must be administered within a period of a few hours to have a beneficial effect, that is to avert 80 - 90% of the potential dose (Table 1). In emergency planning a decision and distribute the iodine must be made within this time period to be fully effective, but even 3 – 4 hours after the event doses could be reduced by a factor of two or three which would be beneficial.

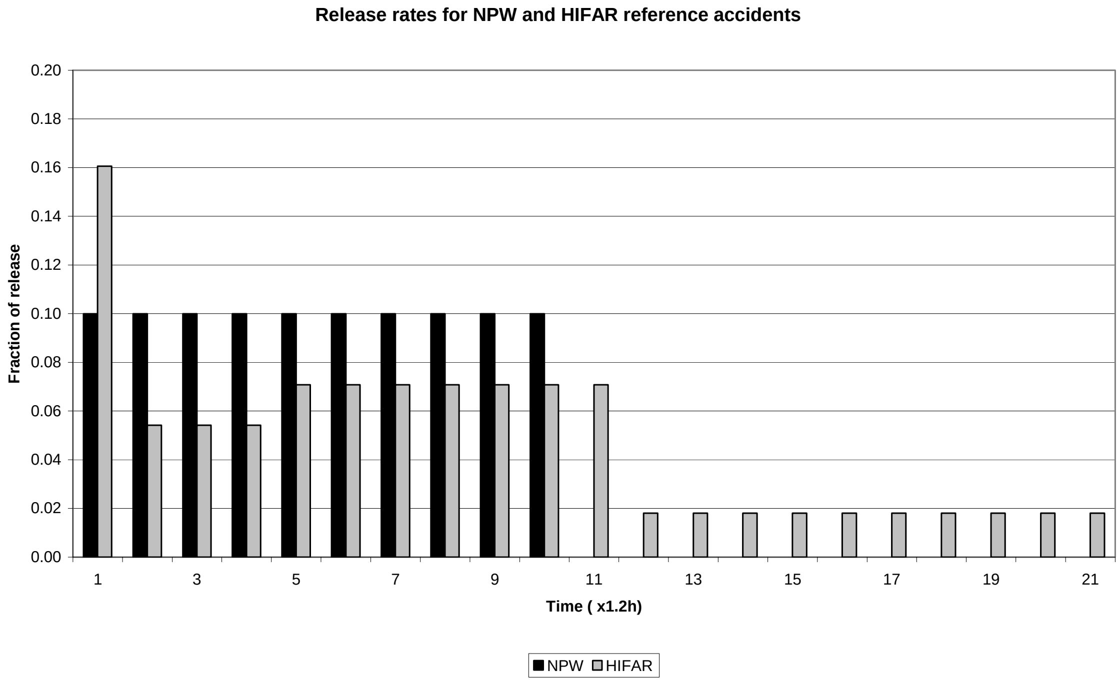
Table 1 Time of administration of iodine (hours) and % dose averted.

Dose averted	Instant	NPW	HIFAR
90%	1	4.5	4.5
80%	2	6.5	7
70%	3	8.5	9.5
50%	5	11.5	13.5

Accidental Releases

In an accidental release situation such as those expected in a Nuclear Powered Warship accident or a release from the research reactor at ANSTO, the release of fission products will take place over a period of hours. There have been many models of reference accidents for these situations and two of these have been taken to illustrate the likely rate of uptake of iodine to an exposed individual. The Nuclear Powered Warship accident postulates a uniform release over 12 hours whilst the HIFAR model is based on variable release rates over 24 hours. An initial release in the first hour is followed by a fall in release rate as pressure builds up in the containment vessel. For the next eight hours the release is steady followed by a fall again as the pressure in the containment vessel drops. The profile of the release rates can be seen in Figure 5.

Figure 5. The profile of the release rates following 1, a NPW reference accident and 2, a HIFAR reference accident



The rate of thyroid uptake for an individual exposed from such releases can be estimated and Figure 6 compares the activity in the thyroid for the first 50 hours following an event for an instantaneous release, a NPW reference accident and a HIFAR reference accident. It has been assumed that the intake was the same (1MBq) but that the activity was released over a 24hour period with the profiles shown in Figure 5. While the maximum activity in the thyroid is much the same for each release the time profile of uptake is significantly different in the first 12 hours as shown in Figure 7. In Figure 7 the activity limits in the thyroid to avert 90%, 80% and 70% of the dose are shown and the time at which iodine prophylaxis should be administered to achieve these figures can be estimated from the curves. These times are summarised in Table 1.

Thyroid dose compared to whole body dose

For HIFAR 2000reference accident the child thyroid dose at 2.4km is 13.4mSv and the effective whole body dose is 1.52mSv, a ratio of approximately ten. That is for an individual exposed to a radioactive cloud of mixed fission products as the result of a reactor accident the effective whole body dose will be approximately one tenth of the thyroid dose. Much of this dose is from immersion in the radioactive cloud as it passes over an area and would be received by the thyroid as well. This has two implications for adoption of countermeasures following an accident. Firstly it is only possible to avert 90% of the thyroid dose even if iodine were administered as soon as the accident happened and secondly that individuals are receiving radiation exposure which is potentially more significant than exposure of the thyroid.

Figure 6. The activity in the thyroid for the first 50 hours following: 1. Instantaneous release 2. NPW reference accident 3. HIFAR reference accident

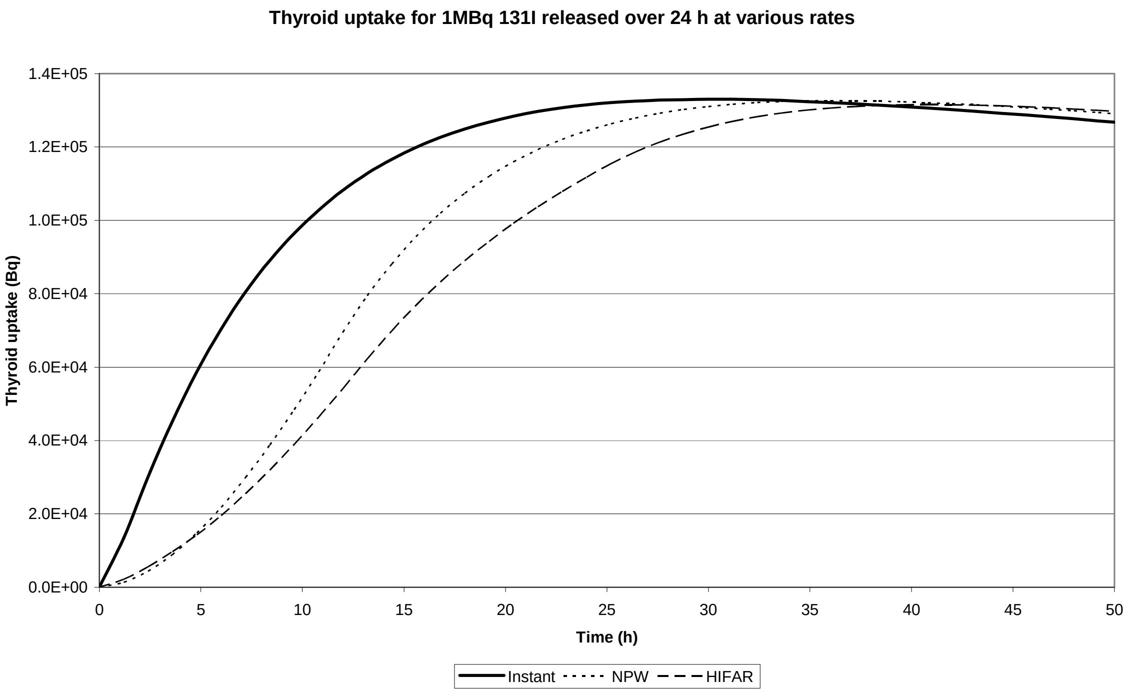
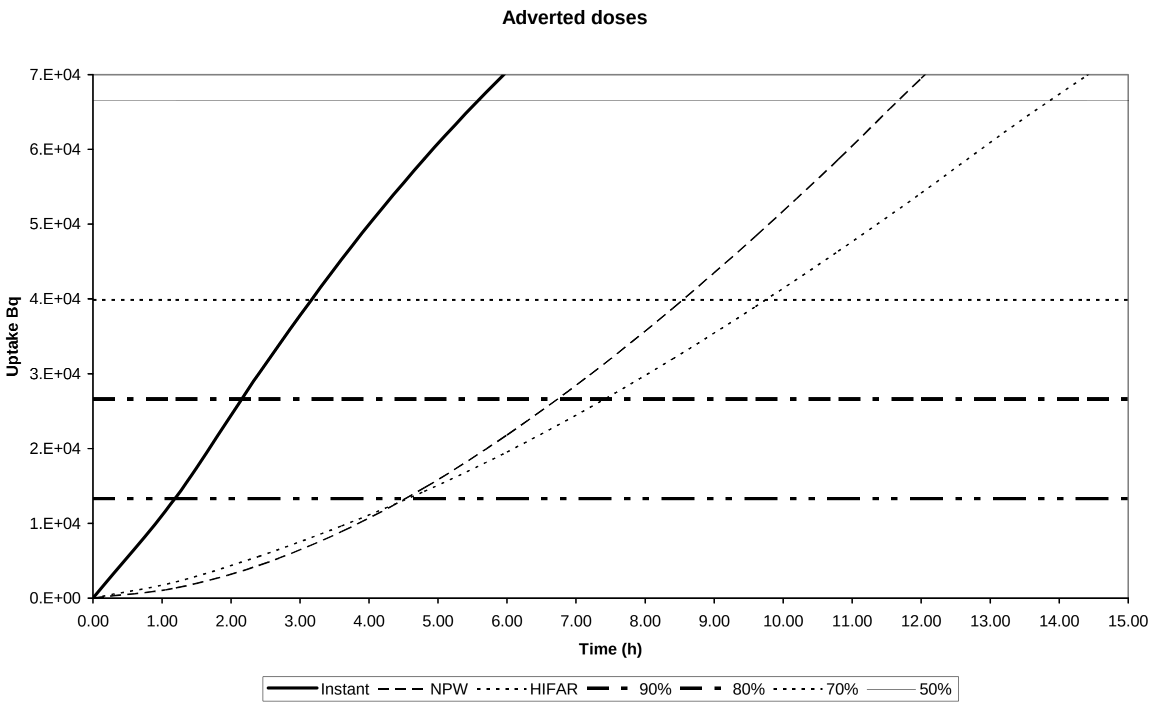


Figure 7. Time of administration to achieve averted doses of 90%, 80%, 70% and 50%.



Whole body exposure could cause cancers in other organs that are potentially fatal whereas thyroid cancer is rarely fatal and this can be illustrated using the figure for EAR from the Chernobyl data in UNSCEAR 2000. From this data the number of childhood thyroid cancers expected for10000 children who receive a thyroid dose of 100mSV is approximately 0.3. Fatalities for thyroid cancer are conservatively estimated by ICRP (ICRP 60) to be one tenth of the incidence although the Chernobyl data shows a much lower figure than this. Using a figure of one-tenth the estimated fatalities would be less than 0.03 per year.

The use or iodine prophylaxis in a typical accident situation up to 8 hours after the start of the event could reduce the thyroid dose by 70% and reduce fatalities to 0.01 per year. Over a 50year period the number of fatalities in the exposed group would be less than 0.5. However, if the group were also exposed to a whole body dose of 10mSv the lifetime risk of fatal cancer is 1 in 2,000, or 5 fatalities per 10,000. Consequently there may be more benefit in adopting intervention measures such as sheltering and evacuation rather that in administering iodine.

Conclusions

The above data can be useful in assisting emergency planners implement appropriate and timely counter measurers following a reactor accident. There is sufficient time for the administration of iodine prophylaxis to be effective in averting significant doses to the thyroid. The data shows that it would be better to target those who would receive doses of the order of 100mSv in the first few hours. Whilst those expected to received doses of the order of 30 mSv could still expect a significant reduction in dose up to 7 to 8 hours after the start of the event. Even 12 hours after the event there would still be a 50% reduction in thyroid dose. Iodine prophylaxis should however not be seen as the only counter measure that should be adopted. A reduction in thyroid dose as well as a reduction in whole body dose, which would be more beneficial in terms reducing the number of fatal cancers, could be achieved by sheltering or by evacuation.

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APPENDIX VII INTERNATIONAL APPROACH TO IODINE PROPHYLAXIS

The Australian approach to interventions, detailed in the draft *Recommendations on Interventions in Emergency Situations Involving Radiation, (ARPANSA 2000)* follows the international guidance provided by the international Atomic Energy Agency (BSS115, SS109, GS-R-2) and the International Commission on Radiological Protection (ICRP63). This guidance advises the use of Generic Intervention Levels to assist in the decision making process and for stable iodine, a single GIL of 100 mGy is suggested.

The WHO in a guidance document published in 1999 *Guidelines for Iodine Prophylaxis following Nuclear Accidents* (WHO 1999). On the basis of the minimal health from taking stable iodine, this document advised that:

> *Intervention levels for emergency response are for national authorities to decide, but the latest information suggests that stable iodine prophylaxis for children up to the age of 18 years be considered at 10 mGy, that is 1/10th of the generic intervention level expressed in the International basic safety standards for protection against ionizing radiation and for the safety of radiation sources.*
>
> *For adults over 40, the scientific evidence suggests that stable iodine prophylaxis not be recommended unless doses to the thyroid from inhalation are expected to exceed levels that would threaten thyroid function. This is because the risk of radiation induced thyroid carcinoma in this group is very low while, on the other hand, the risk of side effects increases with age.*

The most recent international guidance on iodine prophylaxis as a protective measure is contaned in the International Atomic Energy Agency (IAEA*) Safety Standards Series No. Gs-R-2, Preparedness And Response For A Nuclear Or Radiological Emergency Safety Requirements.* This was *p*ublished by the International Atomic Energy Agency, VIENNA, November 2002. Jit was jointly sponsored by the Food and Agriculture Organization of the United Nations, International Atomic Energy Agency, International Labour Organization, OECD Nuclear Energy Agency, Pan American Health Organization, United Nations Office for the Co-Ordination Of Humanitarian Affairs and World Health Organization The relavant guidance on stable iodine is contained in the ADDENDUM TO ANNEX III of the GS-R-2. It states that:

> ***ADDENDUM to ANNEX III Gs-R-2***
>
> *III–8. A joint IAEA/WHO Technical Committee Meeting (TCM)*[4] *reviewed the guidelines issued in the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (Basic Safety Standards, BSS115) for intervention in emergency situations involving exposure to radioactive iodine, including the action level of dose to the thyroid for acute exposure 5 , the intervention level for iodine prophylaxis, long term iodine prophylaxis to reduce the uptake of radioiodine from contaminated food*[6]*, and planning, distribution zones and distribution strategies for iodine prophylaxis*[7]*.*
>
> *III–9. With regard to the intervention level for iodine prophylaxis (the administration of stable iodine to reduce the uptake of radioiodine) in the event of a nuclear*

emergency, the TCM advised the IAEA and the WHO secretariats to consider amendments to the Basic Safety Standards [8] that reflect the following consensus:

—The administration of stable iodine to the public is an effective early measure for the protection of the thyroid to prevent deterministic effects and to minimize stochastic effects for persons of any age. However, it is primarily intended for the protection of children and the embryo or foetus.

—The current generic optimized intervention level for iodine prophylaxis of 100 mGy provides an operational basis for prompt decision making and efficient application in the event of a nuclear or radiological emergency. However, as there are strong indications of an age dependence of the risk of induction of thyroid cancer by radioiodine, the administration of stable iodine at significantly lower levels of dose to the thyroid may be recommended in order to take into account the higher sensitivity to radioiodine of children and the embryo or foetus.

—This advice is proffered to serve as a basis for planning, which needs to be optimized to take into account practical, operational, social and economic considerations; other protective actions to reduce the intake of radioiodine, such as sheltering and control of food supplies, also need to be considered.

III–10. This advice to the IAEA and WHO secretariats, which is presented for information in this Addendum to Annex III, will only become a requirement if established as such in an IAEA safety standard and agreed to by the co-sponsoring organizations of the Basic Safety Standards (IAEA BSS 115). Nevertheless, relevant operating and response organizations with responsibilities for the formulation of emergency plans may wish to take it into consideration, in particular the need to give priority to the protection of children, newborn babies and the embryo or foetus.

Footnotes to ADDENDUM

4 This addendum is based on the advice of a joint IAEA/WHO Technical Committee Meeting to assess and review the international safety standards for intervention in emergency exposure situations involving radioactive iodine, held on 17–19 September 2001 at the IAEA in Vienna.

5 With regard to the action level of dose for acute thyroid exposure (see Table IV-I of the BSS115, the TCM advised the IAEA and WHO secretariats to re-examine the action level with a view to lowering it.

6 With regard to long term iodine prophylaxis as a possible protective action against the ingestion of food contaminated with radioiodine, the TCM advised the IAEA and WHO secretariats to consider amending the BSS to reflect the following: (a) that iodine prophylaxis is intended primarily as a protective action against inhalation and that it is therefore primarily a short term measure (up to a few days); (b) that iodine prophylaxis should only be used to reduce the uptake of ingested radioiodine if it is impossible to provide supplies of uncontaminated food, especially for children and particularly in relation to milk; and that, even if this is the case, iodine *prophylaxis is intended for relatively short periods of time, since supplies of uncontaminated food should be provided as soon as possible.*

7 *With regard to planning, distribution zones and distribution strategies, the TCM advised the IAEA and WHO secretariats to consider amending the BSS to emphasize the need for considering the early administration of stable iodine in a nuclear emergency in conjunction with other possible protective actions, such as evacuation. This would imply the possible need for the predistribution of stable iodine in certain areas and rapid distribution strategies for other areas.*

8 In revising the Basic Safety Standards 115 and related Safety Guides the IAEA and co-sponsoring organizations will need to take account of all the recommendations made by the joint IAEA/WHO Technical Committee Meeting to the IAEA and the WHO secretariats.

In 1999 the Nuclear Energy Agency distributed a questionnaire on the use of stable iodine as a short term countermeasures. Eleven countries answered the questionnaire, namely Australia, Canada, Czech Republic, Finland, Germany, Hungary, Ireland, Japan, Luxemburg, United Kingdom, and Switzerland. The results on the Intervention Level used for children are summarised in Table VII-1. In June 2003, at a meeting of National Competent Authorities for Radiation Emergencies at the IAEA, Vienna, a of participating Member States were survey to determine additional values of intervention levels. As of October 2003, there is no international consensus on an appropriate value, an intervention levels in the range 10 mGy to 100 mGy are used.

Table VII-1. Intervention levels criteria used to initiate the use of stable iodine

Country	Intervention level (NEA questionnaire)	Intervention level (NCA survey, June 2003)
Australia	100 mGy	30 mGy for children 100 mGy for adults
Austria		10 mGy for children 100 mGy for adults < 40y 500 mGy for adults > 40y
Brazil		100 mGy
Canada	100 mSv[1]	50 mSv
Czech Republic	5 – 50 mSv 50 – 500 mSv	
Finland	10 mGy (for children under 18) 100 mGy (for adults)	Unchanged. Stable iodine pre-distributed to all Finnish homes.
France		100 mSv
Germany	50 mSv (for children up to 12 and pregnant women) 250 mSv (for adults up to age of 45)	Unchanged
Hungary	100 mGy	
Ireland	100 mSv	
Luxemburg	30 – 250 mSv	
Norway		10 mGy (Children)
Portugal		100 mGy
Switzerland	30 – 300 mSv	
US		50 mSv (Children)
United Kingdom	30 – 300 mSv	

[1] Health Canada's Federal Recommendation. The province of Quebec has other intervention levels: ≥ 50 mSv (0 – 20 years), ≥ 100 mSv (20 – 40 years)