NCRP REPORT No. 55

PROTECTION OF THE THYROID GLAND IN THE EVENT OF RELEASES OF RADIOIODINE

Recommendations of the
NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS

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Preface

Over the past two decades the NCRP has carried out several studies and issued two reports on problems associated with a possible nuclear attack on this country. In each of these reports, any questions centering primarily about a nuclear reactor accident were avoided. The Council noted, however, the increasing interest in the potential of protective actions for alleviating some of the effects of the release of radioactive materials that might ensue in the event of a reactor accident. Protective actions relating to the release of radioactive iodine had received considerable attention. One of the proposals frequently mentioned calls for the administration of natural iodine in a form which would quickly enter the blood system and be taken up by the thyroid gland, thus blocking the admission of radioactive iodine. This report deals with the overall question of the uptake of radioactive iodine by the thyroid gland and the radiobiological effects resulting from the uptake, and with considerations that would have to be instituted to establish an effective prophylactic program. The report is intended to be informative in nature and does not attempt to suggest that iodine prophylaxis is the method of choice in any particular situation. Further, the report does not attempt to deal with the economics of this method of protecting people, especially in comparison with any other methods that might be considered. Actual applications of a prophylactic procedure would have to depend upon careful analysis by appropriate authorities of all the factors that may be involved.

The present report was prepared by the Council's Ad Hoc Committee on Thyroid Blocking. Serving on the Committee during the preparation of this report were:

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The Council wishes to express its appreciation to the members and consultants for the time and effort devoted to the preparation of this report.

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Contents

1. Introduction

With the rapid development of nuclear power reactors, and especially in view of a deepening energy crisis, concern has been voiced that serious accidents may result in hazards from these sources. These apprehensions on the part of the public appear with increasing recognition of the prospect of about 1,000 reactors operating in the United States by the year 2000. The significance of these concerns is complicated by the record of the very successful operation of a large number of reactors over the past 15 years.

In November 1975, the U.S. Nuclear Regulatory Commission issued a report entitled, *Reactor Safety Study* (USNRC, 1975), in which many phases of such accidents, including estimates of their possible frequencies, have been explored by use of a complex model. Nuclear power reactors considered were of the Light Water moderated type (LWR), the Pressurized Water type (PWR), or the Boiling Water type (BWR). Possible health effects are detailed in Appendix VI of the document, *Calculations of Reactor Accident Consequences*. Another treatise on accident consequences may be found in an earlier document (USAEC, 1973).

Of the several possibilities, however remote, that could affect the public, the one causing greatest concern is the sudden release of large quantities of radionuclides to the environment. An important constituent in such a release would be a number of isotopes of radioiodine which could affect large numbers of people soon after the incident.

The systems now utilized to protect the public from radioiodine and other radionuclides include:

(1) elaborate mechanical features intended to maintain nuclear fuel integrity;
(2) containment structures;
(3) chemical sprays or charcoal adsorption systems to hold iodine within the containment structure.

These devices are the engineered safeguards and are successive defenses against dissemination of radioiodine to the environment, and, of themselves, are considered to be sufficient for public protection.

This report considers the feasibility of utilizing thyroid blocking agents, as an additional option, for protection of the public in case of

off-site releases. The National Council on Radiation Protection and Measurements does not take any position concerning the question of utilizing thyroid blocking agents in any given situation. Rather, the purpose of this report is to define the efficacy of such agents and the contraindications for their use, and, hence, the potential for use of thyroid blocking agents. In view of concern about the possibility of large releases of radioiodine from nuclear reactors, the use of evacuation to mitigate the consequences of such a release is also discussed in this report.

On-site personnel and other support personnel can be adequately cared for with the emergency plans for the reactor site although this aspect will be discussed briefly.

For children and adults, the recommended daily dose is 130 mg of potassium iodide—equivalent to 100 mg of iodide—taken by mouth. Infants may be given half this dose although the adult dose is safe (see Section 4.4).

2. Biological Effects of ^{131}I

If the release of a large amount of iodine-131[1] to the atmosphere from a power reactor were to take place (USNRC, 1975), some members of the public could inhale or ingest amounts that could produce acute, continuing, or late thyroid effects. The acute effects include thyroiditis induced about two weeks after exposure and hypothyroidism (myxedema) arising within 3–6 months. Continuing and late effects encompass hypothyroidism arising after several years, adenomatous and fibrous nodules, and thyroid cancer. Several excellent reviews of the effects of ionizing radiation of the thyroid of human beings have appeared recently. Since the effects considered here may result from exposure varying between low and high absorbed doses delivered at relatively high absorbed dose rates, the risk estimates presented in several recent reports may be especially applicable (USNRC, 1975; USAEC, 1973; NAS-NRC, 1972; UNSCEAR, 1972; Hutchison, 1972), particularly those given in USNRC (1975) which presents the most recent data in greater detail than will be given here.

Certain simplifying assumptions are utilized here. These data have been adjusted, wherever possible, for spontaneous occurrence of thyroid lesions observed in unirradiated cohorts where environments or existing diseases are similar to the irradiated cohorts. Alternatively, adjustments have been made for spontaneous prevalence of thyroid disease. For the case of neoplasms, a linear, no-threshold risk model has been used. For hypothyroidism, a linear model with a threshold has been postulated, since a large number of cells would probably have to be altered to result in hypothyroidism because of the large reserve capacity of the thyroid gland.

2.1 Human Experience

There have been three well-documented studies of exposures of populations to radioiodine from fallout. The first and most serious

[1] ^{131}I is identified as the isotope of principal concern to the neighboring population (see Section 3).

exposure occurred in the Marshall Islands in March 1954, when some Marshallese natives and American servicemen were exposed to fallout from a thermonuclear weapon test (Conard, 1974; Conard *et al.*, 1975). This population was exposed to whole-body gamma radiation and to inhalation and ingestion of radioiodines. To date, the 86 inhabitants of Rongelap and Ailingnae exposed to the highest absorbed doses (estimated external gamma dose 69–175 rad and about 1100 rad to the thyroid from radioiodines) have developed 4 malignant lesions, 30 benign lesions, and two cases of clinical hypothyroidism. Of the 37 Marshallese natives who have developed thyroid neoplasms (Conard *et al.*, 1975), 22 were less than 15 years of age at the time of exposure.

A group of 1378 children in Utah was exposed to varying levels of radioiodines by ingestion of milk and other food products after atmospheric weapons testing during the 1950's (Conard *et al.*, 1975; Rallison *et al.*, 1974). The mean absorbed dose was estimated as 46 rad with a maximum of 120 rad. This group was compared to 3801 non-exposed children from similar environments. There were no significant differences between irradiated and non-irradiated subjects in the prevalence of thyroid nodules, benign or malignant.

The nuclear reactor accident at Windscale, United Kingdom, in October 1957, resulted in the release of about 20,000 curies of ^{131}I with a potential hazard to workers and the general public (Loutit *et al.*, 1960). The average thyroid absorbed dose to 96 workers in the plant was 0.4 rad. The average absorbed dose to adult thyroids in the general population exposed was 0.3–1.8 rad and that to the thyroid glands of children was 0.8–12.2 rad. In this incident the source of the population hazard was the ^{131}I in milk, and this route was restricted by confiscation of contaminated milk. No late effects were anticipated (Loutit *et al.*, 1960), and none have been sought or reported.

2.2 Dose-Response Relationships for ^{131}I

2.2.1 *Thyroiditis*

Thyroiditis of a mild but occasionally severe degree is sometimes seen in euthyroid patients receiving large (20–100 mCi) doses of ^{131}I for thyroid ablation during treatment of severe cardiac disease or thyroid cancer (deGroot and Stanbury, 1975). Usually the thyroid gland had not had prior surgery in the cardiac patients. There appears to be a threshold for radiation thyroiditis in euthyroid individuals at about 20,000 rad. At slightly above this absorbed dose level, approximately 5 percent of patients will develop symptoms. An addi-

tional 5 percent of exposed individuals are estimated to develop thyroiditis for each 10,000-rad increment above 20,000 rad. In a reactor accident, the occurrence of radiation-induced thyroiditis would seem to be most unlikely except at extremely high concentrations of ^{131}I which might be encountered near the reactor site. Thyroid storm, an acute, intense exacerbation of the symptoms and signs of thryroid toxicity, is far less likely to appear than thyroiditis but may occur under some circumstances.

2.2.2 *Hypothyroidism*

Of the acute and continuing effects, hypothyroidism following ^{131}I exposure is by far the most common. Most data used for analysis come from those patients treated for hyperthyroidism, but experience with these individuals may not be directly transferable to the euthyroid population. Although the uptake of ^{131}I is greater in the hyperthyroid patients, the turnover of ^{131}I is more rapid (Doniach, 1971). Since these factors of increased uptake and rapid turnover tend to offset each other, it is possible to utilize the experience with hyperthyroidism to approximate that of the euthyroid individual.

Total ablation of the thyroid within the first year after administration of ^{131}I has been shown to require at least 27,000 rad (Segal *et al.*, 1958; Goolden and Davey, 1963) and is always associated with hypothyroidism.

Hypothyroidism without total thyroid ablation can also occur within one year of exposure to lower doses from ^{131}I. In the Cooperative Thyrotoxicosis Follow-Up Study (Becker *et al.*, 1971), clinical hypothyroidism was noted to occur in many cases within the first year after therapy. Data for this study were collected from 6000 patients treated solely with a single dose of ^{131}I. These data have been used to estimate the absorbed dose to the thyroid by multiplying the thyroidal concentration of ^{131}I, at one day after exposure, by 91 rad/μCi g^{-1}. This calculation assumes a 6-day effective half-life, which may slightly overestimate the absorbed dose in patients with thyrotoxicosis but is reasonably close to the effective half-life in euthyroid individuals. Figure 1 shows the results in terms of the cumulative probability of hypothyroidism at different absorbed-dose levels (expressed as the corresponding concentration of ^{131}I per estimated gram of thyroid) over a 15 year follow-up period. The dose-response relationship for the development of hypothyroidism 1 and 5 years after treatment, based on the results of Figure 1, is shown in Table 1.

There are few data on the effects of thyroid absorbed doses from ^{131}I of less than 2500 rad. Preliminary results of a follow-up survey of

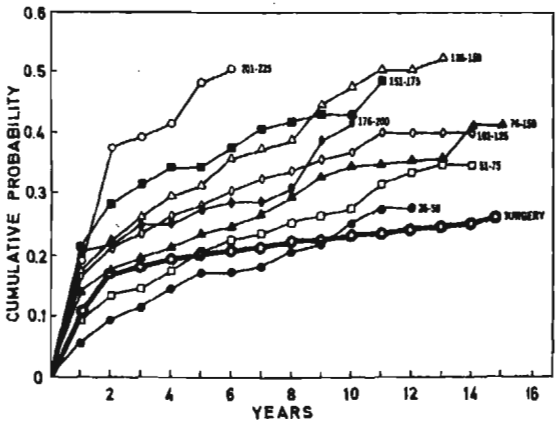

Fig. 1. Probability of becoming hypothyroid with a single treatment of ^{131}I. The numbers on the curves show the thyroidal concentration of ^{131}I in microcuries per estimated gram of thyroid tissue. From Becker *et al.* (1971).

TABLE 1—*Probability of hypothyroidism in adults after exposure to* ^{131}I[a]

Estimated thyroidal concentration of ^{131}I	Estimated dose to thyroid	Estimated probability of hypothyroidism within	
		1 year	5 years
μCi/g	rad		
26–50	3,400	0.06	0.13
51–75	5,750	0.09	0.17
76–100	8,000	0.14	0.20
101–125	10,000	0.16	0.24
126–150	12,600	0.17	0.28
151–175	14,900	0.20	0.31
176–200	17,150	0.20	0.24
201–225	19,400	0.19	0.45

[a] From USNRC (1975).

individuals regarded as having normal thyroids after diagnostic ^{131}I tests at ages of less than 16 years (Hamilton and Tompkins, 1975) suggest that 8 of 443 (1.8 percent) subsequently became hypothyroid. Two additional patients were excluded because they had a goiter before ^{131}I was administered. One of these was hypothyroid after an absorbed dose of less than 10 rad while the other was not after an absorbed dose of 200 to 300 rad. The mean elapsed time after exposure to ^{131}I was 14 years and the mean age at follow-up was 25 years. A summary of these preliminary data is presented in Table 2.

The data presented in Table 2 indicate that no cases of hypothyroidism attributable to radiation occurred in the 146 patients with a mean

dose of 18 rad given at least 14 years prior to accumulation of the data shown in Table 2. One study found only two cases of overt hypothyroidism in 1378 children exposed to ^{131}I fallout (Rallison *et al.*, 1974), as compared with no cases in 3801 non-irradiated controls (Rallison, 1975). The average follow-up time was 16 years, and the mean dose to the thyroid was considered to be 46 rad (Rallison *et al.*, 1974). Analysis of these data shows that the difference in the incidence of hypothyroidism between the irradiated and non-irradiated groups is not statistically significant ($p = 0.15$).

For hypothyroidism, a linear model with a threshold has been postulated since a large number of cells would probably have to be altered to result in hypothyroidism because of the large reserve capacity of the thyroid gland. It would seem reasonable, in making a realistic estimate of the consequences of exposure to ^{131}I, to consider that the threshold for the induction of hypothyroidism is 20 rad. Analysis of the 5-year data (Becker *et al.*, 1971) suggests a linear relationship (Figure 2) between the absorbed dose to the thyroid gland from ^{131}I and the probability of hypothyroidism above a lower

TABLE 2—*Relationship between low-dose exposure to ^{131}I in children and subsequent hypothyroidism*[a,b]

Number of subjects	Thyroid absorbed dose range	Estimated mean thyroid absorbed dose	Number hypothyroid	Incidence of hypothyroidism
	rad	rad		percent/yr
146	10 to 30	18	0	0
146	31 to 80	52	3	0.15
151	81 to 1900	233	5	0.23

[a] Preliminary results (Hamilton and Tompkins, 1975).
[b] Table from USNRC (1975).

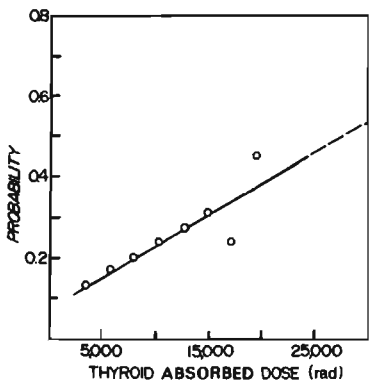

Fig. 2. Probability of hypothyroidism induction by ^{131}I absorbed doses greater than 2500 rad. Data from the Cooperative Thyrotoxicosis Follow-Up Study (Becker *et al.*, 1971) at 5 years after exposure. See Table 1.

limit of approximately 2500 rad—the lowest absorbed dose for which data are available in the study by Becker *et al.*; a linear extrapolation based on the data in Fig. 2 suggests that an absorbed dose of approximately 60,000 rad would render all individuals hypothyroid by 5 years after the exposure. On the basis of the data derived from the Cooperative Thyrotoxicosis Follow-up Study, the absolute risk to the individual of hypothyroidism after treatment of Graves' disease (diffuse hyperthyroidism) with ^{131}I for absorbed doses greater than 2500 rad is 4.6×10^{-6} rad^{-1} y^{-1} (Dobyns *et al.*, 1974).

2.2.2.1 *Hypothyroidism from Exposure to a Mixture of Radioiodines.* Chapman and Evans (1946) published data on 22 patients treated for thyrotoxicosis with a mixture of radioiodines (approximately 90 percent ^{130}I and 10 percent ^{131}I). The mean administration was 55.6 mCi of ^{130}I, with an estimated additional amount of 5.6 mCi of ^{131}I. Converting these values to absorbed dose yields a mean total absorbed dose of 20,300 rad, consisting of 12,400 rad due to ^{130}I and 7900 rad due to ^{131}I. The mean age of patients at the time of therapy was 41.6 years, and the mean follow-up time was 20 months. Four of the patients had become hypothyroid during that period.

Based on these 22 cases, the absolute individual risk of developing hypothyroidism is approximately 5×10^{-6} rad^{-1} y^{-1} for absorbed doses greater than 2500 rad. This value is not significantly different from the value of 4.6×10^{-6} rad^{-1} y^{-1} from ^{131}I alone. The similarity between risk estimates suggests that, for induction of hypothyroidism, the short-lived ^{130}I (physical half-life 0.51 days) is no different than ^{131}I (physical half-life 8.05 days).

2.2.2.2 *Relation of External Irradiation to Clinical Hypothyroidism.* Exposure of the thyroid gland to external radiation appears to be associated with the induction of clinical hypothyroidism at absorbed dose levels above 1000 rad and external radiation has not been reported to induce hypothyroidism at absorbed dose levels below 100 rad (USNRC, 1975). Too little data are available to permit an estimate of risk because of the small number of cases and short follow-up times. Nonetheless, from the data presented above, the estimate of absolute individual risk for the induction of hypothyroidism by external irradiation, assuming a linear model, is 10×10^{-6} rad^{-1} y^{-1} for absorbed doses greater than 2500 rad. Although this is approximately twice the risk estimated for ^{131}I, the numbers are too small and the assumptions in the estimate too great to establish this ratio with certainty. On a purely radiobiological basis, the more uniform distribution within the thyroid of the absorbed dose from external irradiation might well increase the efficiency of inducing

clinical hypothyroidism, but further data are needed to establish or refute this point.

2.2.2.3 *Effects of Radioiodine on the Fetus.* Radioiodine passes readily across the placenta. The human fetal thyroid is capable of taking up iodine beginning at about the 10th–13th week of gestation (Shepard, 1971; Hamburgh *et al.*, 1971). Between 14 and 22 weeks, the percent uptake ranges from 55 to 75 percent (Cole, 1972). In sheep, during the last trimester, there is a state of relative fetal thyroidal hyperactivity as compared to the mother and it is reasonable to assume that a similar state of fetal hyperactivity exists in the human fetus (Fisher, 1975). Thus, the absorbed dose to the fetal thyroid increases sharply as the fetus approaches term (Dyer and Brill, 1972).

The only well-documented effect of radioiodine in the human fetus is that of hypothyroidism. The children in these reported instances manifested well-recognized symptoms and signs of cretinism. The mothers had been treated with total doses of ^{131}I ranging from 12.2 to 225 mCi (Russell *et al.*, 1957; Hamill *et al.*, 1961; Fisher *et al.*, 1963; Green *et al.*, 1971). Conard *et al.* (1975) found that one case, exposed in utero in the second trimester, developed thyroid adenomas. The latent period in this case was 19 years.

2.2.3 *Thyroid Neoplasms, Nodules and Cancer*

In evaluating thyroid neoplasms, risk estimates have been developed for thyroid cancer and for total thyroid nodules. The reason for discussing total nodularity rather than benign lesions is that diagnostic procedures and therapy, either surgical or medical, are directed to nodules. Only after the procedures are performed is it known whether the nodules are benign or malignant.

From the data on the Marshall Islanders (USNRC, 1975) and on children with thyrotoxicosis given high-dose (>2500 rad) ^{131}I therapy, it appears that children are twice as susceptible as adults to the induction of benign thyroid neoplasms. Since the thyroid gland increases in size with age, the juvenile gland will receive a larger average absorbed dose per millicurie intake than will the adult (Figure 3). Children and adults appear to be equally susceptible to the induction of cancer from ^{131}I, mixed radioiodines, or external irradiation (Table 3).

At absorbed doses greater than 50,000 rad to the thyroid, ^{131}I appears to cause thyroid ablation with no subsequent risk of neoplasm in either age group.

The details of the data base for risk estimates for the induction of

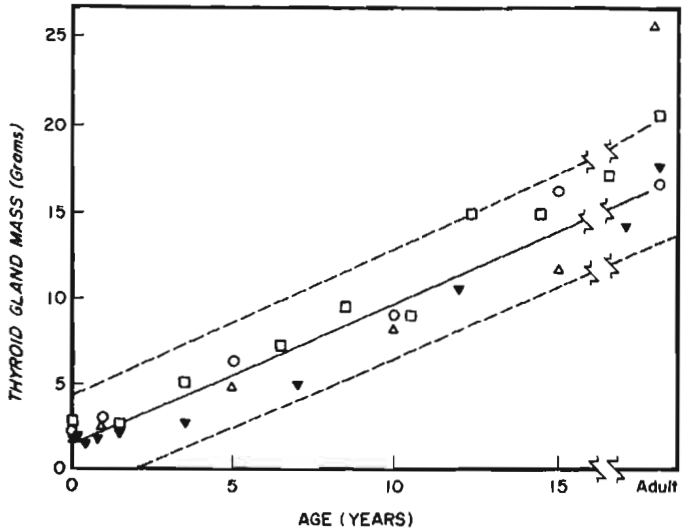

Fig. 3. Weight of thyroid gland in relation to age of child and adult. □ – Kereiakes *et al.* (1968); ▼ – Mochizuki *et al.* (1963); △ – Spector (1957); ○ – Wellman and Anger (1971). The solid line is the mean, while the dotted lines represent the 95-percent confidence limits.

TABLE 3 – *Absolute individual risk of thyroid abnormalities after exposure to ionizing radiation* [a]

Type of abnormality and population surveyed	Mean absorbed dose or dose range for which data were available	Absolute individual risk	Statistical risk range[b]
	rad	10^{-4} rad^{-1}y^{-1}	10^{-4} rad^{-1}y^{-1}
	Internal Irradiation (^{131}I)		
Thyroid Nodularity:			
Children	9000	0.23	0 to 0.52
Adults	8755	0.18	0.13 to 0.23
Thyroid Cancer:			
Children	9000	0.06	0 to 0.158
Adults	8755	0.06	0.044 to 0.075
Hypothyroidism:			
"Low dose" – Children	10 to 1900	4.9[c]	3.9 to 22.9
"High dose" – Adults[d]	2500 to 20,000	4.6[c]	2.8 to 7.8[e]
	External Irradiation		
Thyroid Nodularity in Children	0 to 1500	12.4	4 to 47.4[e]
Thyroid Cancer in Children	0 to 1500	4.3	1.6 to 17.3[e]
Hypothyroidism in Adults	1640	10.2	0 to 24.8

[a] From USNRC (1975).

[b] Unless otherwise indicated the range of risk was determined by assuming that the number of cases, n, out of the population at risk represents the true mean of a Poisson distribution. The range is then estimated by using $\pm 2\sqrt{n}$ as the 95 percent confidence level.

[c] Threshold of 20 rad.

[d] See Figure 2.

[e] In these cases, the risk was determined from the slope of the linear regression line. The range was estimated from the extreme data points, which provide the lowest and highest slopes.

TABLE 4—*Comparison of risk estimates for thyroid cancer in children and adults*

Source	Population	Type of exposure and radiation	Mean tissue dose or dose range	Absolute individual risk
			rad	10^{-6} rad^{-1}y^{-1}
NAS-NRC (1972)	Children	Thymic x ray, general population	229	2.5
		Thymic x ray, high-risk group	329	9.3[a]
	Children	Japanese atom bomb survivors, gamma and neutron	143	2.6
UNSCEAR (1972)	Male adults and children	Japanese atom bomb survivors, gamma and neutron	25 to 200	1 to 2
	Female adults and children	Japanese atom bomb survivors, gamma and neutron	25 to 200	2 to 4
	Male and female infants	X ray to neck	50 to 600	2.5
USNRC (1975)	Adults and children	External irradiation	0 to 1500	4.3
	Adults and children	External irradiation	1500 to 2500	2.2

[a] Modified recently by Hempelmann *et al.* (1975) to a value of 4.0.

thyroid nodules by external irradiation are presented in Appendix H of Appendix VI of the *Reactor Safety Study* (USNRC, 1975). For ^{131}I the estimated absolute individual risks for children are 0.064 and 0.23 $\times 10^{-6}$ rad^{-1} y^{-1} for cancer and for total nodules, respectively, whereas the estimated absolute individual risks for children from external irradiation are 4.3 and 12.4 $\times 10^{-6}$ rad^{-1} y^{-1} for cancer and for total nodules, respectively. Thus the ratios of ^{131}I risks to external-irradiation risks are 1/67 for cancer and 1/53 for total nodules. These factors are smaller than the 1/10 to 1/20 derived from animal data by other workers (Klassovskii, 1971).

After external radiation above 2500 rad, there is no evidence of the induction of neoplasms, benign or malignant. At absorbed doses lower than 1500 rad, a linear no-threshold model suggests an absolute individual risk in children of 4.3 and 12.4 $\times 10^{-6}$ rad^{-1} y^{-1} for thyroid cancer and for total nodules, respectively. Assuming that adults are only half as sensitive as children to the induction of benign thyroid nodules by external irradiation, the individual risk for adults would be 4.4 and 8.4 $\times 10^{-6}$ rad^{-1} y^{-1} for cancer and for total nodules,

respectively. (Benign = total nodules minus cancer = 12.4 − 4.3 = 8.1. 8.1 ÷ 2 ≃ 4. Total = benign + cancer = 4 + 4.4 = 8.4 for adults.)

At absorbed doses of 1500 to 2500 rad there appears to be a gradual decrease in incidence, the average absolute individual risk in this region being assumed to be approximately half of that in the region below 1500 rad.

2.2.4 *Summary of Radiation Effects*

The several radiation effects on the thyroid in terms of the absolute risks of both ^{131}I and external x irradiation are summarized in Tables 3 and 4 which combine the most recently available data.

3. Nature of the Hazard

3.1 Properties of the Iodine Isotopes

The radioisotopes of iodine are among the most abundant of the fission products. All told, 27 isotopes of iodine are known to exist naturally or to have been produced artificially, but only the naturally-occurring ^{127}I is stable. Of the 26 radioisotopes, 12 are produced in fission, and these have half-lives ranging from 1.5 seconds (^{140}I) to 16 million years (^{129}I).

Some properties of the fission-produced isotopes of iodine are listed in Table 5. It is seen that some of the isotopes are produced directly, and have direct fission yields that range up to 2.9 percent (Holland, 1963). However, many of the isotopes are not formed directly, but occur as a result of successive disintegrations of fission product chains (Table 6) beginning with the radionuclides of indium, tin, antimony, or tellurium. The radioiodine isotopes, in turn, decay to stable isotopes of xenon, cesium, or barium.

3.2 Reactors

3.2.1 *Radioiodine from Nuclear Reactors*

When a nuclear reactor is operating, the radioisotopes of iodine accumulate until the rate of decay of any given species is equal to the rate at which the species is being produced. ^{129}I with its 16-million year half-life accumulates so slowly that it does not reach equilibrium and could not present a hazard to individuals exposed to sudden massive release from a reactor. While ^{129}I may be important for long-term environmental considerations, this topic is not appropriate for this report.

Since the iodine isotopes, other than ^{129}I, all have half-lives of 8.05 days or less, the inventory of these nuclides reaches equilibrium in a few weeks. The saturation inventory of the principal iodine isotopes in a reactor core is given in Table 7. Of the isotopes other than ^{129}I,

TABLE 5—*Iodine isotopes*[a]

Mass number	Half-life	Direct fission yield	Yield from fission product chains
		percent	percent
127	stable	0.0	0.1
129	1.6×10^7 y	0.0	0.8
131	8.05 d	0.0	2.9
132	2.3 h	0.2	4.4
133	20.8 h	0.6	6.6
134	52.5 min	2.2	7.8
135	6.7 h	2.9	5.5
136	86 s	2.9	3.9
137	22 s	2.2	2.7
138	5.9 s	1.3	1.5
139	2.7 s	0.8	0.8
140	1.5 s	0.3	0.3

[a] Reference: from Holland (1963).

only those with mass numbers from 131 through 135 are significant sources of potential exposure (Cuddihy, 1964), since the longest half-life of the remaining nuclides is that of ^{136}I, 86 seconds (see Table 5).

3.2.2 *Nature of Reactor Accident*

Power reactors of contemporary design can operate under normal conditions such that the dose equivalent to the general population from radioiodine can be maintained well below the dose limits recommended by the National Council on Radiation Protection and Measurements (NCRP, 1971). However, in the event of certain types of postulated reactor accidents, it is conceivable that large amounts of radioiodine could be released to the environment. Although there has been worldwide experience with about 700 reactors of various kinds, over a period of about 30 years, there has been only one reactor accident in which significant amounts of radioiodine were released. This was the accident to the air-cooled and uncontained Windscale reactor in the United Kingdom in October 1957, when an estimated 20,000 Ci of ^{131}I were discharged to the atmosphere (see Section 2.1). Sufficient pasture contamination occurred to require the confiscation of milk for several days in a 200-square-mile area downwind of the reactor (Loutit *et al.*, 1960; Eisenbud, 1973). The milk produced in a much smaller area remained contaminated above the confiscation level chosen by the British for more than a month. As a result of this confiscation and other precautionary procedures, the mean absorbed dose to the thyroid glands of children downwind of the Windscale reactor was estimated to be 16 rad, and the mean adult absorbed dose was estimated to be 4.0 rad.

TABLE 6—*Fission-product radioiodine chains*[a]

Mass number	Atomic number (element)							
	$_{49}$In	$_{50}$Sn	$_{51}$Sb	$_{52}$Te	$_{53}$I	$_{54}$Xe	$_{55}$Cs	$_{56}$Ba
129	1.5 s 11	→ 6.2 min 34	→ 4.2 h 29	64% → 70 m 36% → 32 d 6	→ 1.6×10^7 y 0	→ Stable 0		
131	1 s 18	→ 3 s 97	→ 23 m 131	95% → 25 m 5% → 30 h 46	→ 8.05 d 78% → 1	12% → Stable 88% → 12 d 0		
132	(?) 5	→ 2.5 s 88	→ 2 m 206	→ 78 h 122	→ 2.3 h 17	→ Stable 0		
133		2 s 66	→ 4.5 m 266	28% → 2 m 72% → 63 m 261	→ 20.8 h 64	98% → 5.3 d 2% → 2.3 d	→ Stable 0	
134		(?) 11	→ 10 s 170	→ 44 m 378	→ 52.5 m 217	→ Stable 28		
135			6 s 44	→ 10 s 225	→ 6.7 h 285	70% → 9 h 30% → 15 m 93	→ 2×10^6 y 3×10^{-10} s 0	→ Stable 0

[a] Reference: from Holland (1963).

Note: The numbers under the half-life values are the fission yield in atoms per 10,000 fissions.

TABLE 7—*Saturation inventory of iodine isotopes in a reactor core*[a,b]

Isotope	Activity
	(Ci/MW$_t$) × 10^4
131	2.5
132	3.8
133	5.6
134	6.6
135	5.1

[a] For the calculation of saturation activities see Appendix A.

[b] The values for the saturation inventory shown in this table are essentially the same as those calculated for the "Reactor Safety Study," WASH-1400 (USNRC, 1975), which appeared during the preparation of the final draft of the present report. The calculation of the values in the table involves ^{235}U thermal fission yields at constant power for three years with removal of radionuclides only by radioactive decay. The calculation of the values for the WASH-1400 report involves the ORIGEN code which is more realistic (including neutron absorption, three-region core, loss by neutron capture, Pu buildup, etc.). Since the maximum difference between the two results is <12 percent for these iodine nuclides, the values in this table are retained because these have been used to obtain the results on absorbed dose which appear in Appendix B. The results in Appendix B have been prepared especially for this report since no documentable reference is available in the literature.

[c] MW$_t$ is megawatts thermal.

The kind of reactor accident in which there is a possibility of release of massive amounts of radioiodine is the "loss-of-coolant" accident. In an accident it is assumed that there would be a sudden rupture of the primary coolant system with consequent overheating of the core, and failure of the fuel cladding (Eisenbud, 1973). The probability of such an accident occurring is very small. Elaborately engineered safeguards are provided to prevent such an accident and to lessen its consequences in the event it should occur. Safeguards include: (1) various methods for condensing the radioiodine-bearing steam that would be released to the reactor building; (2) enclosing the reactor in a sealed containment structure; (3) recirculating the contained atmosphere through absorbents and filters that remove radioiodines; and (4) operation of sprays containing chemicals capable

of absorbing the radioiodines and reducing their concentration in the atmosphere of the containment building.

3.2.3 *Consequences of Release of Radioiodine from the Containment Building*

There are ways of estimating potential absorbed doses to the thyroid gland from a given reactor accident under a given set of reactor, meteorological, and topographic conditions. This report uses the model employed by the Accident Analysis Branch of the Nuclear Regulatory Commission (see Appendix B). The main differences in the absorbed dose estimates result from differing assumptions relative to releases that take place in the reactor and the containment building, the effects on these releases of the engineered safeguards, and the meteorological conditions. Depending on the assumptions chosen, the dose estimates can vary widely. Illustrations of two such calculations are given in Appendix B for the "conservative" model in which the releases of radioiodine from the fuel are large and the engineered safeguards are not fully operable, and for a "realistic" model in which all events and processes take place as designated and engineered. The radioiodines are the most significant of the nuclides that must be considered for acute exposure. Significant absorbed doses to the thyroid glands of the public may result if the engineered safeguards do not function properly and/or proper countermeasures are not applied.

The thyroid absorbed dose to the public from a loss-of-coolant accident can vary from near zero to several hundred or a few thousand rad, depending on a large number of factors, including distance from the reactor site. As noted in Table 10, Appendix B, a major portion of the thyroid absorbed dose from the radioiodines (~50 percent or more) occurs in about one day.

For the hypothetical accident in which the major release would be to the atmosphere, the principal route of exposure would be by inhalation. Higher absorbed doses could result from contamination of milk (via the air-pasture-cow-milk pathway for those areas with dairies), but mitigation could be achieved by diversion of milk to uses other than fresh consumption or, in extreme cases, by confiscation (see Appendix C).

The Federal Radiation Council recommended (FRC, 1964) that countermeasures to reduce the absorbed dose from fallout of ^{131}I should be taken when the average projected thyroid absorbed dose to the general population exceeds 10 rad (or 30 rad to the individual).

The population at risk would then be located downwind from the reactor site out to a distance of 10 to 20 miles *based on the "conservative" model* (Table 10, Appendix B). If there were unusual environmental conditions, such as a temperature inversion, the threat of exposures of this magnitude could be maintained (altered only by the 8-day half-life) for many days. Conversely, if a strong wind should prevail, the duration of an exposure would be short. Obviously, the above variables introduce much uncertainty into any projection of the size of the population at risk. Still another variable is the site in question. Irregularities of terrain can influence the distribution of airborne radioactivity. As the number of reactors increases, the degree of isolation of the available building sites will decrease; and population growth will not necessarily leave a reactor site as far from cities as at construction time. For current emergency planning, the population of concern for a single accident is assumed to be of the order of hundreds of thousands to a few millions.

3.3 Transportation and Reprocessing of Spent Fuel

When the spent fuel is removed from the reactor, it would be normally stored at the reactor site for several months or more before being transported to a fuel reprocessing plant, where the fuel would then be stored for an additional period of time. When transported by truck, about 0.5 metric tons of spent fuel would constitute a single shipment. Rail shipments could contain as much as 3.2 metric tons. (At present, however, national policy is in a state of flux and no fuel from civilian reactors is being reprocessed. Spent fuel is being stored at each reactor site and the short-lived radioiodines in this fuel will decay completely if the storage period is long.)

Fuel that has been stored for 150 days would contain about 2.2 mCi ^{131}I per metric ton of fuel and, in the event of an accident involving rupture of a cask during transportation, only a fraction of this radioiodine would be released. Most of the radioiodine would be retained in the matrix of the UO_2 fuel, and not all the fuel would be exposed. It is estimated that only about 2 percent of the radioiodine (0.04 mCi/metric ton) would be available for release.

At the fuel reprocessing plant, the amount of radioiodine available for release in the event of an accident is limited by the rate at which the fuel is processed. The potential for massive radioiodine releases in the course of spent fuel transportation or reprocessing is thus orders of magnitude less than that for operating power reactors.

4. The Use of Thyroid Blocking Agents as Countermeasures Against Irradiation

Immediate "post-hoc" medication represents the most direct approach to prevent accumulation of radioiodine in the thyroid gland for a large population outside the plant. This step can be accomplished by blockade of iodide trapping or by stimulation of iodine release from the gland.

In normal individuals a single bolus of radioiodine is accumulated in the thyroid in large part over a 12-hour interval and at a continuing but slower rate over the next 12-hour period. Of the total amount taken into the body, 10–40 percent will be retained. Therefore, initial administration of a blocking agent will be of some value even as long as 24 hours after the accident. However, marked curtailment of radionuclide uptake (and therefore retention) can best be achieved by administration of the blocking agent almost immediately (probably within two hours). People closer to the reactor should therefore receive the blocking agent sooner than those farther away.

Once the radioiodine has been trapped in the thyroid, it will be metabolized into organic compounds and will reside in the gland for an interval sufficiently long to allow for considerable local irradiation. While there are agents, such as the thiourylenes, the thiocarbamides, and thyroid stimulating hormone (TSH), that will shorten the biological half-life of the radionuclide captured by the thyroid (Blum and Eisenbud, 1968), the benefit obtained from their use will be minimal at best and the problems of dispensing such drugs and possible toxic reactions from them become of concern.

With the types of accidents considered (Section 3.2.2), most immediate human contamination from radioiodine will be by inhalation. Since absorption from alveolar air to blood is extremely rapid and complete, radioiodine retention from inhalation becomes identical to that resulting from ingestion.

4.1 Thyroid Blocking Agents

Agents that block accumulation of radioiodine by the thyroid gland

belong to one of two classes. In the first class are the standard organic antithyroid agents that are used clinically, such as propylthiouracil or methimazole. These substances prevent the synthesis of organic compounds of iodine and thereby reduce both the peak uptake and retention. With administration of these agents there is also a rapid loss of the radioiodide that has accumulated because it is in fairly rapid equilibrium with the serum iodide. However, the reduction in uptake is incomplete (Taurog *et al.*, 1947; Alexander *et al.*, 1969) and, with a large ^{131}I burden, even its brief stay in the thyroid would be undesirable. The additional fact that these drugs may have serious side effects suggests that other agents are preferable.

The second group of blocking agents are ionic, and these act on the transport of iodide into and out of the thyroid. When given in sufficient amounts, entry of radioiodide into the gland can be virtually prevented (1 percent at 24 hours) (Pochin and Barnaby, 1962; Ramsden *et al.*, 1967).

The members of this group of drugs are all anions related to each other on the basis of their ionic size (partial molar ionic volume), and they appear to compete for the iodide carrier of the transport mechanism and may also accelerate efflux of accumulated iodide (Wolff, 1964, 1972). In addition to iodide, the following anions can be considered: thiocyanate (SCN^-), tetrafluoroborate (BF_4^-), perrhenate (ReO_4^-), perchlorate (ClO_4^-) and iodate (IO_3^-). These anions appear to have no clearcut advantage over iodide because: (1) thiocyanate is relatively more toxic; (2) there is too little experience with fluoroborate; (3) perrhenate is too expensive; and (4) perchlorate, although more potent than iodide on a molar basis, has been removed from clinical practice because of fatal cases of bone marrow suppression. Iodate is considered further in Section 4.4, but iodide appears to be the most useful member of this group.

4.2 Pharmacology of the Blocking Action of Iodide

Iodide, or a compound that can be converted to iodide, acts on the thyroid in five different ways: (1) as substrate; (2) by suppression of the release of organic iodine from the gland (Goldsmith *et al.*, 1958); (3) by inhibition of organic iodine formation (which, although useful for blocking, is generally short-lived in euthyroid subjects) (Wolff, 1969); (4) by saturation of the iodide transport system which occurs with a K_m (half saturation) of 2–4 $\times$ 10^{-5} millimols/liter (Wolff, 1964), the saturation mechanism effectively abolishing entry of ^{131}I (except

for that entering the gland by diffusion) at an intrathyroidal iodide concentration of 0.5–1.0 millimols/liter; and (5) by the formation of an organic iodine compound that inhibits the further uptake of ^{131}I, although the nature of this compound is obscure (Ingbar, 1972). However, essentially complete blocks of uptake can be obtained at serum inorganic iodide concentrations of 10–20 μg/100 ml of serum (Blum and Eisenbud, 1967).

The onset of inhibition is rapid and is readily demonstrated 30 minutes after oral administration (Blum and Eisenbud, 1967; Cronquist *et al.*, 1971). An important factor in obtaining satisfactory acute blocks of radioiodine uptakes is the speed of iodide administration after exposure to radioiodine. It is clear from standard uptake curves that, after a single pulse of radioiodine, the bulk of it has entered the gland by 10–12 hours and little benefit may be expected by blocking beyond this time. A substantial benefit (e.g., a block of 50 percent) is attainable only during the first 3–4 hours. It is therefore questionable whether monitoring before iodide administration would be practical. For more prolonged ^{131}I exposure, iodide will, of course, be useful at any time during the exposure and hence should still be given even if the drug was not given shortly after the release of radioactivity.

4.3 Chemical Form

Iodide (as KI) is eminently suitable for thyroid blocking purposes. The use of tablets would provide a stable form of KI for storage and would be less expensive than encapsulation, providing that the tablets were stored in tightly sealed containers so as to exclude moisture (Cole, 1972). For infants, the KI tablets could be dissolved in milk or orange juice.

4.4 Dosage and Frequency

Various studies have established that for adequate suppression an initial dose of 130 mg of KI/day, equivalent to 100 mg of iodide, is required (Figure 4) (Blum and Eisenbud, 1967; Ramsden *et al.*, 1967). The decay of the inhibitory effect after cessation of iodide is relatively slow (Blum and Eisenbud, 1967; Ramsden *et al.*, 1967; Johnson, 1963), and continuation with this daily dose appears to result in an adequate

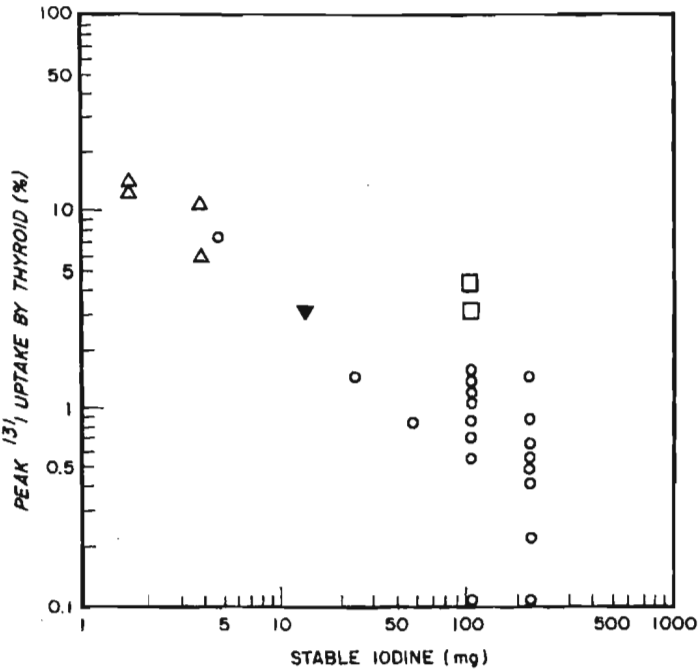

Fig. 4. Effect of single dose of stable iodine on the percent peak uptake of ^{131}I by the thyroid gland. □ – Adams and Bonnel (1962); ○ – Blum and Eisenbud (1967); △ – Cuddihy (1964); ▼ – Hamilton (1942).

block. Such daily doses are suggested to an accumulated limit of about 1 to 1.5 grams of iodide.

A survey of the literature indicates that toxic effects of iodides are not noted with doses of 100 mg of iodide (130 mg of KI) per day given to children over a course of years and that iodide goiter will result only after daily doses of several hundred milligrams of iodide administered for years (Saxena *et al.*, 1962). Consequently, oral doses of 130 mg of potassium iodide daily for 3 to 10 days would not be expected to produce toxicity even in the young. Since the glands are smaller and hence more sensitive per unit radioactivity taken up, and since they may be more sensitive to radiation-induced malignant change (Robbins *et al.*, 1967), it seems reasonable to supply adult doses to children.

For accuracy of administration, ease of distribution, and precise dosage, the use of a single dose form is a most desirable goal.

Blocking doses of 130 mg of potassium iodide per day for 3–7 days can be administered to pregnant women. Those pregnant women who are receiving large doses of iodide throughout pregnancy (300 mg or

more daily) should be warned by their obstetricians about the possibility of iodide goiter of the newborn (Wolff, 1969). Since radioiodine is secreted into human milk, nursing mothers should be advised to utilize suitable substitutes whenever possible to prevent accumulation of radioiodine by the infant. If such substitution is not possible, then iodide prophylaxis of mother and infant should be considered.

There are two acceptable forms of crystalline iodide in the U.S. Pharmacopeia, Sodium Iodide (NaI) U.S.P., and Potassium Iodide (KI) U.S.P. Potassium iodide in solution is available as (1) Strong Iodine Solution, U.S.P. (Compound Iodine Solution, Lugol's Solution) consisting of 5 percent elemental iodine and 10 percent KI in aqueous solution and (2) Potassium Iodide U.S.P. Solution, a saturated aqueous solution containing about 1 g/ml of KI.

Since the recommended daily dosage is 100 mg of iodide, it is necessary to develop an appropriate form to be stockpiled for emergency use only in the event of release of radioiodines from a power reactor or from other sources of similar magnitude. The U.S. Food and Drug Administration (FDA) is reviewing this problem and will publish in the Federal Register a notice to establish requirements for the manufacture of 130 mg potassium iodide tablets that can be stockpiled for emergency use. These requirements will be limited to manufacturing and analytical controls, stability requirements, and other manufacturing information, but will not require clinical studies. It will be necessary to inspect these tablets and their packaging at yearly or other appropriate intervals to assure that there is no loss of potency. Until such tablet forms become available, it will be possible to produce ampoules of dark glass containing 130 mg of KI to provide this recommended prophylaxis.

In Great Britain this kind of prophylaxis is provided by 100 mg tablets of potassium iodate, since in the British experience, the shelf-life of the iodate is appreciably longer than that of tablets of iodide. The iodate tablets are packaged in sealed foil. This iodate form could be employed in the United States only by compliance with FDA requirements that include assembling the pertinent clinical data for the iodate.

A 130-mg potassium iodide tablet will be scored across its center to provide 65-mg doses of KI, yielding 50 mg of iodide for infants, although the 100-mg daily dose of iodide is regarded as safe. If the liquid form is used, the dose to infants can be reduced to half by using half the volume.

4.5 Side Reactions

The frequency of reactions to iodide can be estimated. There are 6

pharmaceutical firms supplying Lugol's solution and USP iodide. One of these manufacturers indicates that his firm supplies about 43.2×10^6 therapeutic doses of 300 mg of USP potassium iodide solution per year and that this company has not received any reports of reactions to iodide in the past 5 years.

Another pharmaceutical manufacturer in 1975 supplied 4.9×10^6 doses of 300 mg of potassium iodide. If each of these 300-mg doses were actually taken by a patient there would be about 48×10^6 doses consumed in the U.S. per year. This figure is obviously an understatement of the amount of iodide administered. It represents only 2 of 6 suppliers of KI and does not represent the many other drugs containing therapeutic levels of iodide or iodine-containing substances used medically. Nevertheless, it can be assumed to be a minimum denominator.

The Division of Drug Experience of the FDA supplied all reported instances of adverse reactions to iodides and iodine from 1969 through 1975. There were 168 reported but unverified reactions ranging from abnormalities of blood count to several severe reactions characteristic of the findings of iodism. In 86 cases one or more other drugs were administered. One reported death was associated with a dose of 15 mg of potassium iodide. Assuming 168 reactions in 7 years or 24 reactions per year, and assuming that all of these reactions are due solely to iodide from the two sources noted above, the reaction rate can be estimated as $24/48 \times 10^6$ or 5×10^{-7} reactions per year. Even with the under-reporting of complications of iodide therapy in a presumably ill population, as well as the obvious underreporting of 300-mg doses of iodide, the above rate represents only a 7th order risk, i.e., between 1×10^{-7} and 10×10^{-7} at a daily therapeutic level of administration. This calculation indicates that the administration of a daily iodide dose of about one third of the recommended daily therapeutic dose listed in the 1975 U.S.P., even to large segments of the relatively healthy U.S. population, will not result in significant immediate toxicity or chronic iodism.

An additional indication of the lack of toxicity of stable iodide in relation to radioiodine is illustrated by an FDA approved radiopharmaceutical, ^{125}I-labeled fibrinogen as described in the package insert of April 1976. For an intravenous dose of 100 μCi of ^{125}I-labeled fibrinogen, the patient is to receive 250 mg of KI 24 hours before the radioactivity is administered and subsequently 300 mg of KI daily for 10 days after one injection or for three weeks if repeated injections of labeled fibrinogen are given (Abbott Laboratories, 1976).

For other radiopharmaceuticals containing either ^{125}I or ^{131}I, adequate blocking doses of iodide vary from 250 to 750 mg of KI over a

period of 1 day before administration of the labeled compound to 3 days after administration.

Although there are many individual reports of complications of iodide administration in the medical literature, these are anecdotal in that they list a number of cases with the complications, but do not give the number of patients taking iodides from which the cases demonstrating abnormalities are drawn.

4.5.1 *Thyrotoxicosis*

Induction of thyrotoxicosis (Jodbasedow) has been observed in the prophylactic treatment of iodine deficiency goiter but is likely to be uncommon in iodine sufficient areas like the United States. Nevertheless, iodine-induced goiter may occur in areas of sufficient iodine intake and should be looked for (Vagenakis *et al.*, 1972). The incidence of nodular goiter in the United States is approximately 4 percent. Such patients would have an increased risk of thyrotoxicosis if they received large doses of iodides for periods of several weeks or longer. They should be monitored at intervals of 4 weeks if the radioiodine alert is prolonged.

4.5.2 *Iodide Goiter*

Iodide goiter is rare after only a few weeks of iodide administration for limited periods of blocking. Respiratory obstruction of the infant by an enlarged thyroid should be looked for during delivery of women treated with iodide for any substantial period during pregnancy (Wolff, 1969). Moreover, patients with thyroiditis or other known parenchymal tissue damage (e.g., post radiation, etc.), or with low thyroid reserve for unknown reasons, should be watched for a propensity to suffer iodide myxedema.

4.5.3 *Hypothyroidism with Goiter*

This complication of iodide ingestion is rare. It is a distinct risk, however, in patients who have been treated for thyrotoxicosis with radioiodine or surgery in the past or who have had Hashimoto's thyroiditis and, in addition, received iodide for several weeks or longer.

4.5.4 *Iodide Parotitis*

Iodide parotitis is an uncommon complication resembling the swelling of the salivary gland as found in mumps (Wolff, 1969).

4.5.5 *Cutaneous Iodism*

This complication is found rarely in individuals who ingest large doses of iodine over long periods. There results a typical pustular acneiform eruption.

4.5.6 *Systemic Manifestations*

Even less common than the changes listed above are fever, generalized skin rash, arthralgia, inflammatory joint involvement, and changes in the hair and nails. These developments are indications for discontinuing prophylactic iodine therapy. Evacuation of the subject from the contaminated area or avoidance of foodstuffs contaminated with ^{131}I would then be required.

4.5.7 *Monitoring for Effects of Iodide*

Since the risks of undesired reactions to iodine vanish within a few days after discontinuing iodide ingestion, there is no indication for monitoring beyond a few days after stopping the prophylactic program.

4.6 Distribution

Since effectiveness against thyroid uptake of radioiodines depends on the almost instant availability of blocking agents, every available appropriate outlet should be considered as a stockpiling and distribution point. In determining such stations, consideration should be given to population concentrations in relation to the facility.

Stockpiling and distribution centers can include the nuclear facility, firehouses, police stations, hospitals, clinics, factories, office buildings, municipal buildings, schools, physicians' and dentists' offices, pharmacies, and other facilities where normal medical emergency services are usually available. This report does not develop details of stockpiling and distribution since, if these methods are to be used, the implementation is best determined by local authorities and the operators of the nuclear facility.

Since early access to blocking agents is of utmost importance and the blocking agents are inexpensive, redundancy is desirable and wastage is not a prime consideration. Supplies of potassium iodide

can be stored in a variety of places, including homes, especially for those distant from the previously listed distribution centers, and those who anticipate difficulty in reaching such centers because of lack of transportation, difficulty in ambulation, traffic congestion, or weather conditions.

4.7 Monitoring the Effectiveness of Iodide Blocking After a Radiation Accident

In the event of an accident accompanied by the release of radioiodine, it would be desirable to monitor some people in the exposed population in order to estimate the extent of involvement and the effects of prophylaxis and therapy. Monitoring may consist of periodic assay of the residual radioactive iodine in the thyroid gland, determining the effectiveness of thyroid blocking, appraisal of the tolerance of the exposed persons to the countermeasure medication, and long-term clinical follow-up for radiation damage.

The purpose of all of these monitoring efforts includes a determination of the effectiveness of the actual program and the collection of data to ascertain whether subsequent programs need to be more or less stringent.

4.7.1 *Radiation Dosage*

Some indication of thyroid exposure should be obtained either on the whole population or, if the numbers are too large, on a suitably selected sample. This determination can be done at nearby existing facilities, or portable counting units could be quickly transported into the area. Levels of radioactivity in exposed persons should be measured *in vivo* at approximately weekly intervals for four to six weeks until the level of radioactivity has fallen to negligible levels. Alternatively, urine can be measured for ^{131}I either in 24-hour collections, or by measuring the excretion per gram of creatinine in spot samples. These measurements would provide information regarding the absorbed dose to the thyroid and, indirectly, the absorbed dose to the whole body, and would also indicate whether all the radioiodine was received in a single dose within a short period of time or whether increments of radioiodine were being added with time. Furthermore, this monitoring would give some indication of the effectiveness of the prophylactic medication.

4.7.2 *Effectiveness of Program*

In order to ensure that exposed persons would be ingesting the prophylactic medication in adequate amounts and according to the prescribed program, a system of monitoring either for iodine blood levels or urine excretion rates should be instituted. Adequate blocking can be achieved either by ensuring that the serum level of total iodide is greater than 10 micrograms per 100 ml or that urinary excretion is greater than 50 milligrams of iodide per 24 hours or greater than 50 milligrams per gram of creatinine. Measurements of iodide in 24-hour urine collections or determination of the micrograms of iodide excreted per gram of creatinine in a morning fasting urine specimen can be used to evaluate the degree of prophylaxis. For children, these limits can be scaled downward according to weight. If the population sample is small, these measurements can be made on the entire group, or they can be made on an appropriate sample of the exposed population. Weekly measurements would be desirable until the stable iodide given for prophylaxis has been stopped.

4.7.3 *Side Effects of Program*

Possible complications of iodide ingestion are discussed in Section 4.5. Such manifestations would be expected to be negligible under the dosage regimen proposed here. Nevertheless, public health or civil defense authorities should have individuals suspected of such changes examined by a physician.

4.7.4 *Monitoring Early and Late Radiation Effects*

Concern for the health of significantly exposed persons after a radiation accident should ideally extend throughout the lifetime of the individual. Experience after exposures in the Pacific Islands and in the United States has shown that important thyroid damage may become clinically apparent many years after exposure (Conard *et al.*, 1975; Refetoff *et al.*, 1975; Safa *et al.*, 1975).

Surveillance must include both thyroid structure and function and the whole body. If radiation dose estimates indicate a whole body exposure of more than 30 rad, lymphocyte counts should be obtained frequently during the first few days and at increasing intervals later depending on the estimated dose. With larger doses, more intensive early study would be indicated. In addition, chromosome analysis

and aberration scoring at least once are indicated, with confirmatory repetition if the aberration frequency suggests that high doses were received. Persons receiving high doses (>25 rad to the gonads) should be warned to avoid procreation for several months after termination of the emergency (NCRP, 1971; NCRP, 1974).

There is little justification for monitoring thyroid structure and function if the estimated thyroid dose is less than 100 rad. If the thyroid receives more than 100 rad, an estimate of residual thyroid function should be made, within two or three months after exposure, by measurements of plasma T_4 and TSH by radioimmunoassay. At six months to yearly intervals thereafter, measurements of plasma T_4 and a clinical estimate of thyroid function should be made.

5. Evacuation as an Alternative Countermeasure

Recent analyses of many civilian accidents have demonstrated that large groups (several thousand people) can be evacuated rapidly and safely from an area without civil disturbance (Haus and Sell, 1974). The current worldwide record of operation of nuclear power reactors has indicated their safety especially in relation to contamination with radioiodine. There are considerable logistical problems involved in stockpiling and distributing iodides, both from the viewpoint of cost and adequacy of shelf life and from the viewpoint of the potency of drug forms acceptable within the United States. For these reasons it is desirable to consider the use of regional evacuation in determining the most efficacious methods for protection of the population in the event of a release of radioiodine.

Evacuation of the public after an accident involving a nuclear facility is an integral part of an overall emergency plan. Since evacuation must always be considered as a possibility in the event of such an accident, an established well-thought-out procedure that is widely distributed at local and state levels will include health officials, emergency personnel and citizens. Proper training of emergency personnel, including periodic drills carried out by these individuals, is desirable.

Emergency evacuation plans should outline specific geographic areas by highway, road, or street boundaries, and include routes of evacuation, location of facilities providing temporary food and shelter, degree of media participation, and pre-printed instructions and maps including the above information, to be handed out door-to-door, if necessary, by emergency personnel.

Since the greatest savings in absorbed dose to the thyroid gland may be achieved in the first few hours, and only meager surveillance data as to the extent of release may be available, a pre-determined series of steps or alerts should also be part of the procedure. These alerts, predicated on the severity of the radionuclide release, will determine what precautions persons living in the specified geographic areas would take – either remaining indoors, taking potassium iodide, being evacuated, or any combination of the three.

Past experience with evacuation procedures used in other types of emergencies, e.g., fuel fires, floods, release of propane and chlorine gases, indicates that the public is almost totally reliant on police, firemen, and civil defense workers for direction. Consequently, it is important that emergency personnel be trained in all phases of evacuation work, and that they properly coordinate their activities with radio and television stations in their areas whose participation in these circumstances is essential.

In weighing the benefit versus risk of evacuation, there are many factors to consider. Beginning with the initial estimate of contamination given by the nuclear power facility, some of the more obvious risks and problems have to be considered, individually and collectively, before a decision is made to institute mass evacuation. These considerations include the weather, the time of day, vehicle accident and personal injury potential, availability of transportation, availability of suitable shelter in a "safe" area, time between the accident and the order to evacuate, movement of children from schools, and movement of sick and infirm from hospitals and nursing homes and the potential for increased uptake of released radionuclides due to exertion and excitement associated with evacuation.

6. Summary and Recommendations

6.1 General Principles

A major protective action to be considered after a serious accident at a nuclear power facility involving the release of radioiodine is the use of stable iodide as a thyroid blocking agent to prevent thyroid uptake of radioiodines.

For greatest effectiveness, the blocking agent should be administered within a few hours after an accident. Since reliable radiation monitoring data may not be available that quickly, the decision to administer stable iodide should be based on a pre-planned estimate of the probable degree of contamination from the accident.

If the initial estimate at the facility indicates that thyroid total absorbed doses[2] of 10–30 rad or more are projected, the blocking agent should be administered immediately to employees at the facility and to other support personnel coming to or working near the facility.

If the estimate of thyroid total absorbed dose is less than 10 rad, it may be preferable to consider instructing people to remain indoors and to await further instructions, before deciding to administer blocking agents. If the estimates of the total thyroid absorbed dose exceed 10 rad, blocking agents should be considered.

Based on information supplied by the facility operator as to the magnitude of the accident, either the responsible physician for the facility or state and local officials should consider prompt administration of the blocking agent (without making absorbed dose estimates) to emergency personnel who respond to the accident. This group includes police officers, firemen, physicians, health physicists, nurses, ambulance drivers and paramedical personnel. These people would be considered a "high-risk" group.

For people beyond the immediate vicinity of the reactor, the decision to administer stable iodide, to instruct them to remain indoors,

[2] Total absorbed dose is the cumulated absorbed dose resulting, in this case, from the inhalation of radioiodines during a particular exposure period. The quantity dose commitment does not apply to this situation.

or to evacuate them would depend on the type of accident, on preplanned estimates of release, on wind direction and, later, on monitoring data as they become available (USNRC, 1975).

6.2 The Use of Potassium Iodide

Potassium iodide can and may be stocked at the nuclear facility, firehouses, police stations, hospitals, clinics, factories, office buildings, municipal buildings, physicians' and dentists' offices, pharmacies, and other locations where normal emergency medical services are usually available.

A daily dose of 130 mg of potassium iodide (1 tablet) will provide adequate blocking for each person. A half tablet may be given to children under one year of age. One tablet should be taken each day until the public is advised that the emergency is ended. Only one 130-mg tablet daily is needed and more will not be helpful. The first dose should be taken as soon after the warning as possible. Instructions for the cessation of iodide administration is the responsibility of public health authorities. The need for blocking agents is estimated as being required for 3–7 days and probably no longer than 10 days for a total dose of about 1 gram.

Potassium iodide need be taken only by individuals who are in the area of contamination. Instructions of public health officials should be followed carefully.

The short- and long-term consequences of inhalation of radioactive iodine are far less than the possible injury that might result from individual or mass panic arising from efforts to obtain the blocking agent, and this modicum of common sense should be remembered by each person.

6.3 Evacuation

An extensive review of mass evacuation has been carried out by the Environmental Protection Agency (Haus and Sell, 1974). This study shows clearly that masses of up to 150,000 persons have been evacuated safely in natural or potential man-made disasters. These evacuations have been carried out within hours without loss of life, panic or looting. Based on these experiences, urban as well as rural populations can be evacuated promptly and safely.

6.4 Milk Control

Contamination by radioiodine may involve regional milksheds for several days following a release. Some consideration of this subject can be found in Appendix C even though this topic is somewhat beyond the scope of this report.

Appendix A

Method of Calculation of the Inventory of a Nuclide in an Operating Reactor

The inventory of a given radionuclide in an operating reactor can be approximated as follows[3]

$$q_{ti} = \frac{(P_t)\,(3.2 \times 10^{16})\,\gamma_i\,(1 - e^{-\lambda_i t})}{3.7 \times 10^{10}} \tag{1}$$

$$= 0.87 \times 10^6\, P_t\, \gamma_i\, (1 - e^{-\lambda_i t}), \tag{2}$$

where q_{ti} = the activity of a given nuclide i (Ci) at time t seconds after the start of steady state reactor operation
P_t = thermal power level (MW_t)
γ_i = the fission yield of nuclide i (atoms/fission)
λ_i = decay constant for nuclide i (s^{-1})
3.2×10^{16} = fission rate per unit power level ($s^{-1}\,P_t^{-1}$)
3.7×10^{10} = disintegration rate per unit activity ($s^{-1}\,Ci^{-1}$).

When the reactor has operated for so long a period that t is much greater than λ_i^{-1}, the nuclide reaches its saturation or equilibrium activity and the above formula can be expressed as:

$$q_{si} = 0.87 \times 10^6\,(P_t)\,\gamma_i \tag{3}$$

where q_{si} = the saturation inventory of nuclide i (Ci).

[3] See footnote b in Table 7 (page 16).

Appendix B

Summary of Dose Calculations for Loss-of-Coolant Accident in Light Water Reactors

B.1 Introduction

The following is a brief presentation of the calculations for estimating the dosimetric consequences of a postulated loss-of-coolant accident with conservative and realistic values for release of fission products and assumptions about their transport. These calculations are made for a typical pressurized water reactor (PWR) and a typical boiling water reactor (BWR). These calculations are intended to serve as illustrations to indicate the effect of varying the assumptions; they are not intended to represent the exact upper and lower bounds on consequences for each case. The terms "upper and lower bounds" are used in the 1975 USNRC report (q.v.) and are essentially similar to the terms "conservative and realistic." The conservative calculation consists of assumptions (model and meteorology) similar to those used in the safety evaluation of a nuclear power plant while the realistic calculation consists of assumptions similar to those used in the preparation of an environmental statement for such a plant.[4]

B.2 Basic Model and Nuclide Data

The basic model used to estimate activity released from a primary containment is as follows:

$$\frac{dA^{i}_{pc}(t)}{dt} = \lambda_i A^{i}_{pc}(t) - \lambda_p A^{i}_{pc}(t), \tag{4}$$

[4] See Section 3.2.3 (page 17) for definitions of "conservative" and "realistic".

where $A^i_{pc}(t)$ = activity of nuclide i in the primary containment at time t
λ_i = decay constant for nuclide i
λ_p = primary containment leak constant.

The activity released from the containment[5] over any time interval t_1 to t_2 is

$$A^i_R(t_1, t_2) = \lambda_p \int_{t_1}^{t_2} A^i_{pc}(t)\, dt \tag{5}$$

Yield data and decay constants are taken from Blomeke and Todd (1957); dose conversion data are taken from the report prepared by ICRP Committee II (ICRP, 1960) and Lederer *et al.* (1967).

B.3 PWR Calculations

B.3.1 *Conservative Model*

Table 8 presents the basic assumptions for both the conservative and realistic cases. These assumptions are for a typical single containment PWR with sodium hydroxide as a spray additive. The basic model (Eq. 4) is used to estimate the activity released from the containment. The iodine removal by the chemical sprays is treated as a "dose reduction factor," each factor being calculated for each time interval assuming exponential removal. A "cutoff" time is calculated for each iodine form using the iodine spray reduction limits from Table 8. After this cutoff time, the removal function of the spray is assumed to stop. The activity calculated as released over the appropriate time interval is reduced by an "average dose reduction factor" which has been determined by weighting the individual dose reduction factors for each iodine form by its original fraction.

B.3.2 *Realistic Model*

The realistic model differs from the conservative model in the assumptions and calculations shown in Table 8. The spray removal due to physical scrubbing of iodine from the containment atmosphere

[5] Assuming that λ_p remains constant and that no conditions other than decay and leakage affect the availability of the nuclides for leakage.

TABLE 8—*Basic assumptions for typical PWR calculations*

	Conservative	Realistic
Power Level (MW_t)	3570	3570
Primary Containment Leak Rate (percent/d)	0.1 for <24 hours 0.05 for >24 hours	0.05 for <24 hours 0.025 for >24 hours
Operating Time (years)	3.0	3.0
Fraction of Core Inventory Available for Release (percent)		
Iodine	25	2.0
Noble Gases	100	2.0
Spray Effectiveness on Iodine, Dose Reduction Factor:		
0– 2 Hours	8	20
0– 8 Hours	14	20
8– 24 Hours	20	20
24– 96 Hours	20	20
96–720 Hours	20	20
Iodide Spray Reduction Limits (ratio of initial to final concentration):		
Elemental	100	N.A.[a]
Particulate	100	N.A.
Organic	1	N.A.
Composition of Iodine (percent):		
Elemental	91	N.A.
Organic	4	N.A.
Particulate	5	N.A.

[a] N.A. = not applicable (see Appendix B.3.2).

and the effect of the chemical additive are assumed to result in a constant combined dose reduction factor of 20. These assumptions are based on those recommended to applicants for their assessment of the consequences of a large loss-of-coolant accident in their environmental reports (USNRC, 1974).

B.4 BWR Calculations

B.4.1 *Conservative Model*

The basic assumptions for the conservative and realistic models

TABLE 9—*Basic assumptions for typical BWR calculations*

	Conservative	Realistic
Power Level (MW_t)	3458	3458
Primary Containment Leak Rate (percent/d)	0.5	0.25
Operating Time (years)	3.0	3.0
Fraction of Core Inventory Available for Release (percent):		
Iodine	25	0.04
Noble Gases	100	0.2
Composition of Iodine (percent):		
Elemental	91	91
Organic	4	4
Particulate	5	5
Exhaust Filter Efficiencies for Iodine (percent):		
Elemental	95	99
Organic	90	99
Particulate	95	99
Mixing of Primary Containment Leakage in Reactor Building (percent)	N.A.[a]	50
Total Flow to Volume Ratio in Reactor Building Mixing System (min^{-1})	N.A.	0.038
Ratio of Exhaust Flow to Total Flow	N.A.	0.018

[a] N.A. = not applicable.

are given in Table 9. The conservative model assumes that all the primary containment leakage goes directly to the standby gas treatment system filters where part of the iodine, but none of the noble gases, is removed. The dose reduction effect of the filter is applied to the activity leaking from the containment in the same manner as is the spray dose reduction factor used for the PWR.

B.4.2 *Realistic Model*

The realistic model assumes some mixing in the reactor building. The leakage from the primary containment is assumed to go directly to the exhaust header from the reactor building where 1.8 percent of it is exhausted through the standby gas treatment system filter, and the balance (98.2 percent) is returned to the reactor building where it is effectively mixed in 50 percent of the reactor building air volume. This split between exhaust and return flow is assumed to continue throughout the course of the accident.

B.5 Breathing Rates and χ/Q Values

Standard Regulatory Guide 1.3 or 1.4 (USAEC, 1974a; USAEC,

TABLE 10—*Estimates of total thyroid absorbed doses from ^{131}I–^{135}I for a postulated loss-of-coolant accident*

Distance, mi	Time After Release, hours				
	2	8	24	96	720
	Dose[a]				
	Conservative Estimate, rad				
PWR					
0.5	110	230	280	320	350
1	50	110	120	140	150
2	21	45	51	55	58
5	6.3	14	15	16	17
10	2.6	5.6	6.2	6.6	6.7
20	1.2	2.5	2.8	2.9	3.0
30	0.8	1.6	1.8	1.9	1.9
40	0.6	1.2	1.3	1.4	1.4
50	0.4	1.0	1.0	1.1	1.1
BWR					
0.5	210	790	1100	1500	1700
1	100	370	460	580	660
2	42	150	180	230	250
5	13	47	54	65	71
10	5.2	19	22	26	28
20	2.3	8.7	9.9	13	13
30	1.5	5.6	6.3	7.2	7.7
40	1.1	4.2	4.7	5.3	5.7
50	0.9	3.3	3.7	4.2	4.5
	Realistic Estimate, millirad				
PWR					
0.5	110	210	490	810	1100
1	53	100	200	300	400
2	22	41	73	110	140
5	6.7	12	20	28	36
10	2.8	5.1	8.3	12	15
20	1.2	2.3	3.6	4.9	6.1
30	0.8	1.5	2.3	3.0	3.7
40	0.6	1.1	1.7	2.2	2.6
50	0.5	0.9	1.3	1.7	2.1
BWR					
0.5	0.21	1.1	5.1	17	29
1	0.10	0.55	1.8	5.4	9.2
2	0.04	0.22	0.66	1.9	3.2
5	0.01	0.06	0.18	0.49	0.79
10	0.005	0.03	0.07	0.19	0.30
20	0.002	0.01	0.03	0.08	0.12
30	0.001	0.008	0.02	0.05	0.07
40	0.001	0.006	0.01	0.03	0.05
50	0.001	0.005	0.008	0.02	0.04

[a] The contributions to the total absorbed dose in the first few days from the various radioiodine nuclides are approximately as follows: ^{131}I – 60 percent; ^{133}I – 30 percent; $^{132, 134, 135}I$ – 10 percent. The contribution at later times is almost all due to ^{131}I because of the more rapid decay of the other iodines.

The absorbed dose to the whole body due to external radiation from the plume is less than the thyroid total absorbed dose generally by about one or two orders of magnitude.

1974b) assumptions for breathing rates are used for the conservative case, and a constant rate of 2.32×10^{-4} m³/s (ICRP, 1960) is used for the realistic case. For the conservative case, the χ/Q[6] values given in Regulatory Guides 1.3 and 1.4 for ground level releases are used (Figures 3(A) and 3(B) of USAEC, 1974a and Figures 2(A) and 2(B) of USAEC, 1974b). A building wake factor is applied to the 0–8 hour value out to five miles assuming a value for $0.5A$[7] of 1000 m² (see Figure 2 of USAEC, 1974a or Figure 1 of USAEC, 1974b). For the realistic case, the same building wake factors are assumed; however, the χ/Q values are reduced by factors 10, 20, 10, 5 and 3 for the 0–2 hour, 0–8 hour, 8–24 hour, 24–96 hour, and 96–720 hour time periods, respectively, in order to approximate 50 percentile meteorological conditions. Because the Pasquill model for predicting χ/Q values is not considered adequate beyond about 5 or 6 miles, the extrapolation of the χ/Q values (and resulting total absorbed dose) to 50 miles is not particularly accurate.

B.6 Results

With the methods described in Regulatory Guides 1.3 and 1.4 (USAEC, 1974a; USAEC, 1974b), the total absorbed doses for iodine are estimated. Summarized versions of these results are shown in Table 10 for the assumptions given in Tables 8 and 9. These calculations are presented for illustrative purposes only, depend on the assumptions described above, and do not relate to any particular power reactor and its site.

[6] χ/Q = concentration at a point of interest (Ci/m³) relative to the release rate at the source (Ci/s).

[7] The quantity A is the minimum cross-sectional area of the building and the curves in the Regulatory Guides are identified in terms of the quantity $0.5A$, where 0.5 corresponds to the shape factor. The quantity A is not to be confused with the quantities $A\downarrow_{pc}$ and $A\downarrow_{k}$ which appear in equations 4 and 5.

Appendix C

Milk Control

Countermeasures to avoid milk contamination and the risk of radiation exposure to milk users resulting from a nuclear facility accident must be implemented immediately after such an accident if they are to be effective. The protective actions to be considered require breaking the cycle through which contamination spreads—namely, the pasture-cow-milk-man pathway.

Since the potential for accidental radiation exposure of the population through milk may extend for many miles from the accident site; and since the magnitude of exposure through milk may be 400–700 times greater than through inhalation, the need for appropriate protective action is of paramount importance (Lengemann and Thompson, 1963; Bernhardt *et al.*, 1971).

First, a pre-determined emergency communications plan must be set in motion on an area-by-area basis whereby dairy farmers in the affected land area are alerted immediately and instructed by the appropriate state and local officials to move their cattle from pasture to stored feed. This breaks the cycle of transmission of radioactivity contamination at the root and must be accomplished immediately.

Within 48–72 hours, contaminated land areas can be identified by ground and aerial surveillance. Only those farmers in contaminated land areas would be required to keep their cattle on stored feed. This obviously reduces the possibility of fluid milk contamination.

In order to provide surveillance of all milk produced in the affected area, state or local sanitarians or milk control specialists should be immediately assigned to one or more of the milk receiving or processing plants likely to receive milk from contaminated farms. The sanitarians would be responsible for:

(1) Establishing immediate liaison with the industry and the officials responsible for taking protective actions.
(2) Identifying the dairy farms in the affected area shipping milk to the plant and determining if the cattle on these farms have been placed on stored feed.
(3) Providing drivers of bulk milk tanks with guidelines and

requirements covering protective actions in effect and instructing them not to accept milk from farmers having cattle on pasture in the affected area.

(4) Assisting the industry in establishing a procedure for collection of contaminated milk in excess of acceptable levels and diversion to a non-fluid milk processing plant.

(5) Ensuring that the processed milk products containing unacceptable levels be stored to await decay of radioiodines and monitoring of these products prior to release for public consumption.

(6) Initiating a sampling program, including the collection of representative samples of the finished product and the sampling of raw milk as needed and based upon capacity of the laboratory to handle samples.

If it has been determined through monitoring and sampling that some fluid milk has been contaminated, then appropriate local officials should request the milk industry to import uncontaminated fluid milk and/or only powdered and canned milk products. Children, lactating mothers and pregnant women can be placed on evaporated or powdered dry skim milk until imported fluid milk is brought in. Uncontaminated refrigerated fluid milk, frozen whole milk concentrate and canned sterile whole milk can also be used.

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The NCRP

The National Council on Radiation Protection and Measurements is a nonprofit corporation chartered by Congress in 1964 to:

1. Collect, analyze, develop, and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities, and units, particularly those concerned with radiation protection;
2. Provide a means by which organizations concerned with the scientific and related aspects of radiation protection and of radiation quantities, units, and measurements may cooperate for effective utilization of their combined resources, and to stimulate the work of such organizations;
3. Develop basic concepts about radiation quantities, units, and measurements, about the application of these concepts, and about radiation protection;
4. Cooperate with the International Commission on Radiological Protection, the International Commission on Radiation Units and Measurements, and other national and international organizations, governmental and private, concerned with radiation quantities, units, and measurements and with radiation protection.

The Council is the successor to the unincorporated association of scientists known as the National Committee on Radiation Protection and Measurements and was formed to carry on the work begun by the Committee.

The Council is made up of the members and the participants who serve on the fifty-six Scientific Committees of the Council. The Scientific Committees, composed of experts having detailed knowledge and competence in the particular area of the Committee's interest, draft proposed recommendations. These are then submitted to the full membership of the Council for careful review and approval before being published.

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Currently, the following Scientific Committees are actively engaged in formulating recommendations:

SC-1: Basic Radiation Protection Criteria
SC-7: Monitoring Methods and Instruments
SC-11: Incineration of Radioactive Waste
SC-18: Standards and Measurements of Radioactivity for Radiological Use
SC-23: Radiation Hazards Resulting from the Release of Radionuclides into the Environment
SC-24: Radionuclides and Labeled Organic Compounds Incorporated in Genetic Material
SC-25: Radiation Protection in the Use of Small Neutron Generators
SC-26: High Energy X-Ray Dosimetry
SC-28: Radiation Exposure from Consumer Products
SC-30: Physical and Biological Properties of Radionuclides
SC-31: Selected Occupational Exposure Problems Arising from Internal Emitters
SC-32: Administered Radioactivity
SC-33: Dose Calculations
SC-34: Maximum Permissible Concentrations for Occupational and Non-Occupational Exposures
SC-37: Procedures for the Management of Contaminated Persons
SC-38: Waste Disposal
SC-39: Microwaves
SC-40: Biological Aspects of Radiation Protection Criteria
SC-41: Radiation Resulting from Nuclear Power Generation
SC-42: Industrial Applications of X Rays and Sealed Sources
SC-44: Radiation Associated with Medical Examinations
SC-45: Radiation Received by Radiation Employees
SC-46: Operational Radiation Safety
SC-47: Instrumentation for the Determination of Dose Equivalent
SC-48: Apportionment of Radiation Exposure
SC-50: Surface Contamination
SC-51: Radiation Protection in Pediatric Radiology and Nuclear Medicine Applied to Children
SC-52: Conceptual Basis of Calculations of Dose Distributions
SC-53: Biological Effects and Exposure Criteria for Radiofrequency Electromagnetic Radiation
SC-54: Bioassay for Assessment of Control of Intake of Radionuclides
SC-55: Experimental Verification of Internal Dosimetry Calculations
SC-56: Mammography

In recognition of its responsibility to facilitate and stimulate cooperation among organizations concerned with the scientific and related aspects of radiation protection and measurement, the Council has created a category of NCRP Collaborating Organizations. Organizations or groups of organizations which are national or international in scope and are concerned with scientific problems involving radiation quantities, units, measurements and effects, or radiation protection may be admitted to collaborating status by the Council. The present Collaborating Organizations with which the NCRP maintains liaison are as follows:

American Academy of Dermatology
American Association of Physicists in Medicine
American College of Radiology
American Dental Association
American Industrial Hygiene Association
American Insurance Association
American Medical Association
American Nuclear Society
American Occupational Medical Association
American Podiatry Association
American Public Health Association
American Radium Society
American Roentgen Ray Society
American Society of Radiologic Technologists
American Veterinary Medical Association
Association of University Radiologists
Atomic Industrial Forum
College of American Pathologists
Defense Civil Preparedness Agency
Genetics Society of America
Health Physics Society
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National Electrical Manufacturers Association
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United Stated Energy Research and Development Administration
United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Service

The NCRP has found its relationships with these organizations to be extremely valuable to continued progress in its program.

The Council's activities are made possible by the voluntary contribution of the time and effort of its members and participants and the generous support of the following organizations:

Alfred P. Sloan Foundation
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United States Environmental Protection Agency
United States Navy
United States Nuclear Regulatory Commission
United States Public Health Service

To all of these organizations the Council expresses its profound appreciation for their support.

Initial funds for publication of NCRP reports were provided by a grant from the James Picker Foundation and for this the Council wishes to express its deep appreciation.

The NCRP seeks to promulgate information and recommendations based on leading scientific judgment on matters of radiation protection and measurement and to foster cooperation among organizations concerned with these matters. These efforts are intended to serve the public interest and the Council welcomes comments and suggestions on its reports or activities from those interested in its work.

NCRP Publications

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The currently available publications are listed below.

Proceedings of the Annual Meeting

No.	Title
1	*Perceptions of Risk,* Proceedings of the Fifteenth Annual Meeting, Held on March 14–15, 1979 (Including Taylor Lecture No. 3) (1980)
2	*Quantitative Risk in Standards Setting,* Proceedings of the Sixteenth Annual Meeting, Held on April 2–3, 1980 (Including Taylor Lecture No. 4) (1981)
3	*Critical Issues in Setting Radiation Dose Limits,* Proceedings of the Seventeenth Annual Meeting, Held on April 8–9, 1981 (Including Taylor Lecture No. 5) (1982)
4	*Radiation Protection and New Medical Diagnostic Procedures,* Proceedings of the Eighteenth Annual Meeting, Held on April 6–7, 1982 (Including Taylor Lecture No. 6) (1983)
5	*Environmental Radioactivity,* Proceedings of the Nineteenth Annual Meeting, Held on April 6–7, 1983 (Including Taylor Lecture No. 7) (1984)
6	*Some Issues Important in Developing Basic Radiation Protection Recommendations,* Proceedings of the Twentieth Annual Meeting, Held on April 4–5, 1984 (Including Taylor Lecture No. 8) (1985)
7	*Radioactive Waste,* Proceedings of the Twenty-first Annual Meeting, Held on April 3–4, 1985 (Including Taylor Lecture No. 9) (1986)

8 *Nonionizing Electromagnetic Radiation and Ultrasound,* Proceedings of the Twenty-second Annual Meeting, Held on April 2–3, 1986 (Including Taylor Lecture No. 10) (1988)

9 *New Dosimetry at Hiroshima and Nagasaki and Its Implications for Risk Estimates,* Proceedings of the Twenty-third Annual Meeting, Held on April 5–6, 1987 (Including Taylor Lecture No. 11) (1988).

10 *Radon,* Proceedings of the Twenty-fourth Annual Meeting, Held on March 30–31, 1988 (Including Taylor Lecture No. 12) (1989).

11 *Radiation Protection Today—The NCRP at Sixty Years,* Proceedings of the Twenty-fifth Annual Meeting, Held on April 5–6, 1989 (Including Taylor Lecture No. 13) (1990).

Symposium Proceedings

The Control of Exposure of the Public to Ionizing Radiation in the Event of Accident or Attack, Proceedings of a Symposium held April 27–29, 1981 (1982)

Lauriston S. Taylor Lectures

No.	Title and Author
1	*The Squares of the Natural Numbers in Radiation Protection* by Herbert M. Parker (1977)
2	*Why be Quantitative About Radiation Risk Estimates?* by Sir Edward Pochin (1978)
3	*Radiation Protection—Concepts and Trade Offs* by Hymer L. Friedell (1979) [Available also in *Perceptions of Risk,* see above]
4	*From "Quantity of Radiation" and "Dose" to "Exposure" and "Absorbed Dose"—An Historical Review* by Harold O. Wyckoff (1980) [Available also in *Quantitative Risks in Standards Setting,* see above]
5	*How Well Can We Assess Genetic Risk? Not Very* by James F. Crow (1981) [Available also in *Critical Issues in Setting Radiation Dose Limits,* see above]
6	*Ethics, Trade-offs and Medical Radiation* by Eugene L. Saenger (1982) [Available also in *Radiation Protection and New Medical Diagnostic Approaches,* see above]

7 *The Human Environment-Past, Present and Future* by Merril Eisenbud (1983) [Available also in *Environmental Radioactivity*, see above]

8 *Limitation and Assessment in Radiation Protection* by Harald H. Rossi (1984) [Available also in *Some Issues Important in Developing Basic Radiation Protection Recommendations*, see above]

9 *Truth (and Beauty) in Radiation Measurement* by John H. Harley (1985) [Available also in *Radioactive Waste*, see above]

10 *Nonionizing Radiation Bioeffects: Cellular Properties and Interactions* by Herman P. Schwan (1986) [Available also in *Nonionizing Electromagnetic Radiations and Ultrasound*, see above]

11 *How to be Quantitative about Radiation Risk Estimates* by Seymour Jablon (1987) [Available also in *New Dosimetry at Hiroshima and Nagasaki and its Implications for Risk Estimates*, see above]

12 *How Safe is Safe Enough?* by Bo Lindell (1988) [Available also in *Radon*, See above]

13 *Radiobiology and Radiation Protection: The Past Century and Prospects for the Future* by Arthur C. Upton (1989) [Available also in *Radiation Protection Today—The NCRP at Sixty Years*, See above]

14 *Radiation Protection and the Internal Emitter Saga* by J. Newell Stannard (1990)

NCRP Commentaries

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1	*Krypton-85 in the Atmosphere—With Specific Reference to the Public Health Significance of the Proposed Controlled Release at Three Mile Island* (1980)
2	*Preliminary Evaluation of Criteria for the Disposal of Transuranic Contaminated Waste* (1982)
3	*Screening Techniques for Determining Compliance with Environmental Standards* (1986), Rev. (1989)
4	*Guidelines for the Release of Waste Water from Nuclear Facilities with Special Reference to the Public Health Significance of the Proposed Release of Treated Waste Waters at Three Mile Island* (1987)
5	*Living Without Landfills* (1989)
6	*Radon Exposure of the U.S. Population—Status of the Problem* (1991)

NCRP Reports

No.	Title
8	*Control and Removal of Radioactive Contamination in Laboratories* (1951)
22	*Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure* (1959) [Includes Addendum 1 issued in August 1963]
23	*Measurement of Neutron Flux and Spectra for Physical and Biological Applications* (1960)
25	*Measurement of Absorbed Dose of Neutrons and Mixtures of Neutrons and Gamma Rays* (1961)
27	*Stopping Powers for Use with Cavity Chambers* (1961)
30	*Safe Handling of Radioactive Materials* (1964)
32	*Radiation Protection in Educational Institutions* (1966)
35	*Dental X-Ray Protection* (1970)
36	*Radiation Protection in Veterinary Medicine* (1970)
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38	*Protection Against Neutron Radiation* (1971)
40	*Protection Against Radiation from Brachytherapy Sources* (1972)
41	*Specifications of Gamma-Ray Brachytherapy Sources* (1974)
42	*Radiological Factors Affecting Decision-Making in a Nuclear Attack* (1974)
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50	*Environmental Radiation Measurements* (1976)
51	*Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities* (1977)
52	*Cesium-137 from the Environment to Man: Metabolism and Dose* (1977)
53	*Review of NCRP Radiation Dose Limit for Embryo and Fetus in Occupationally Exposed Women* (1977)
54	*Medical Radiation Exposure of Pregnant and Potentially Pregnant Women* (1977)

55 *Protection of the Thyroid Gland in the Event of Releases of Radioiodine* (1977)
57 *Instrumentation and Monitoring Methods for Radiation Protection* (1978)
58 *A Handbook of Radioactivity Measurements Procedures*, 2nd ed. (1985)
59 *Operational Radiation Safety Program* (1978)
60 *Physical, Chemical, and Biological Properties of Radiocerium Relevant to Radiation Protection Guidelines* (1978)
61 *Radiation Safety Training Criteria for Industrial Radiography* (1978)
62 *Tritium in the Environment* (1979)
63 *Tritium and Other Radionuclide Labeled Organic Compounds Incorporated in Genetic Material* (1979)
64 *Influence of Dose and Its Distribution in Time on Dose-Response Relationships for Low-LET Radiations* (1980)
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77 *Exposures from the Uranium Series with Emphasis on Radon and its Daughters* (1984)

78 *Evaluation of Occupational and Environmental Exposures to Radon and Radon Daughters in the United States* (1984)
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81 *Carbon-14 in the Environment* (1985)
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83 *The Experimental Basis for Absorbed-Dose Calculations in Medical Uses of Radionuclides* (1985)
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92 *Public Radiation Exposure from Nuclear Power Generation in the United States* (1987)
93 *Ionizing Radiation Exposure of the Population of the United States* (1987)
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102 *Medical X-Ray, Electron Beam and Gamma-Ray Protection For Energies Up To 50 MeV (Equipment Design, Performance and Use)* (1989)

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Volume XIX. NCRP Reports Nos. 101, 102, 103, 104

(Titles of the individual reports contained in each volume are given above).

The following NCRP Reports are now superseded and/or out of print:

No.	Title
1	*X-Ray Protection* (1931). [Superseded by NCRP Report No. 3]
2	*Radium Protection* (1934). [Superseded by NCRP Report No. 4]
3	*X-Ray Protection* (1936). [Superseded by NCRP Report No. 6]
4	*Radium Protection* (1938). [Superseded by NCRP Report No. 13]
5	*Safe Handling of Radioactive Luminous Compounds* (1941). [Out of Print]
6	*Medical X-Ray Protection Up to Two Million Volts* (1949). [Superseded by NCRP Report No. 18]
7	*Safe Handling of Radioactive Isotopes* (1949). [Superseded by NCRP Report No. 30]
9	*Recommendations for Waste Disposal of Phosphorus-32 and Iodine-131 for Medical Users* (1951). [Out of Print]
10	*Radiological Monitoring Methods and Instruments* (1952). [Superseded by NCRP Report No. 57]
11	*Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water* (1953). [Superseded by NCRP Report No. 22]
12	*Recommendations for the Disposal of Carbon-14 Wastes* (1953). [Superseded by NCRP Report No. 81]
13	*Protection Against Radiations from Radium, Cobalt-60 and Cesium-137* (1954). [Superseded by NCRP Report No. 24]
14	*Protection Against Betatron—Synchrotron Radiations Up to 100 Million Electron Volts* (1954). [Superseded by NCRP Report No. 51]
15	*Safe Handling of Cadavers Containing Radioactive Isotopes* (1953). [Superseded by NCRP Report No. 21]
16	*Radioactive Waste Disposal in the Ocean* (1954). [Out of Print]
17	*Permissible Dose from External Sources of Ionizing Radiation* (1954) including *Maximum Permissible Exposure to Man, Addendum to National Bureau of Standards Handbook 59* (1958). [Superseded by NCRP Report No. 39]
18	*X-Ray Protection* (1955). [Superseded by NCRP Report No. 26]
19	*Regulation of Radiation Exposure by Legislative Means* (1955). [Out of Print]

20 *Protection Against Neutron Radiation Up to 30 Million Electron Volts* (1957). [Superseded by NCRP Report No. 38]

21 *Safe Handling of Bodies Containing Radioactive Isotopes* (1958). [Superseded by NCRP Report No. 37]

24 *Protection Against Radiations from Sealed Gamma Sources* (1960). [Superseded by NCRP Report Nos. 33, 34, and 40]

26 *Medical X-Ray Protection Up to Three Million Volts* (1961). [Superseded by NCRP Report Nos. 33, 34, 35, and 36]

28 *A Manual of Radioactivity Procedures* (1961). [Superseded by NCRP Report No. 58]

29 *Exposure to Radiation in an Emergency* (1962). [Superseded by NCRP Report No. 42]

31 *Shielding for High Energy Electron Accelerator Installations* (1964). [Superseded by NCRP Report No. 51]

33 *Medical X-Ray and Gamma-Ray Protection for Energies up to 10 MeV*—Equipment Design and Use (1968). [Superseded by NCRP Report No. 102]

34 *Medical X-Ray and Gamma-Ray Protection for Energies Up to 10 MeV—Structural Shielding Design and Evaluation* (1970). [Superseded by NCRP Report No. 49]

39 *Basic Radiation Protection Criteria* (1971). [Superseded by NCRP Report No. 91]

43 *Review of the Current State of Radiation Protection Philosophy* (1975). [Superseded by NCRP Report No. 91]

45 *Natural Background Radiation in the United States* (1975). [Superseded by NCRP Report No. 94]

48 *Radiation Protection for Medical and Allied Health Personnel* [Superseded by NCRP Report No. 105]

56 *Radiation Exposure from Consumer Products and Miscellaneous Sources* (1977). [Superseded by NCRP Report No. 95]

58 *A Handbook on Radioactivity Measurement Procedures.* [Superseded by NCRP Report No. 58, 2nd ed.]

Other Documents

The following documents of the NCRP were published outside of the NCRP Reports and Commentaries series:

"Blood Counts, Statement of the National Committee on Radiation Protection," Radiology 63, 428 (1954)

"Statements on Maximum Permissible Dose from Television Receivers and Maximum Permissible Dose to the Skin of the Whole Body," Am. J. Roentgenol., Radium Ther. and Nucl. Med. 84, 152 (1960) and Radiology 75, 122 (1960)

Dose Effect Modifying Factors In Radiation Protection, Report of Subcommittee M-4 (Relative Biological Effectiveness) of the National Council on Radiation Protection and Measurements, Report BNL 50073 (T-471) (1967) Brookhaven National Laboratory (National Technical Information Service, Springfield, Virginia).

X-Ray Protection Standards for Home Television Receivers, Interim Statement of the National Council on Radiation Protection and Measurements (National Council on Radiation Protection and Measurements, Washington, 1968)

Specification of Units of Natural Uranium and Natural Thorium (National Council on Radiation Protection and Measurements, Washington, 1973)

NCRP Statement on Dose Limit for Neutrons (National Council on Radiation Protection and Measurements, Washington, 1980)

Control of Air Emissions of Radionuclides (National Council on Radiation Protection and Measurements, Bethesda, Maryland, 1984)

Copies of the statements published in journals may be consulted in libraries. A limited number of copies of the remaining documents listed above are available for distribution by NCRP Publications.

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