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EXAMINATION OF THE USE OF POTASSIUM IODIDE (KI) AS AN EMERGENCY PROTECTIVE MEASURE FOR NUCLEAR REACTOR ACCIDENTS

David C. Aldrich
Sandia National Laboratories
Albuquerque, New Mexico 87185

Roger M. Blond
U.S. Nuclear Regulatory Commission
Washington, DC 20555

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Sandia National Laboratories
Albuquerque, New Mexico 87185
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ABSTRACT

Following the recent accident at Three Mile Island, there has been a resurgence of interest in the use of thyroid blocking as an emergency protective measure for reactor accidents. An analysis has been performed to provide guidance to policymakers concerning the effectiveness of potassium iodide (KI) as a blocking agent in realistic accident situations, the distance to which (or area within which) it should be distributed, and its relative effectiveness compared to other available protective measures.

The analysis was performed using the Reactor Safety Study (WASH-1400) consequence model. Four categories of accidents were addressed: gap activity release accident (GAP), GAP without containment isolation, core melt with a melt-through release (Melt-Through), and core melt with an atmospheric release (Atmospheric). Thyroid dose calculations show that the GAP category does not pose a significant health hazard to the public at any distance from the reactor. For the GAP without containment isolation and Melt-Through categories, doses in excess of recommended protective action guidance levels (PAGs) (5-25 rem) are confined to areas within approximately 10 and 15 miles of the reactor, respectively. For the Atmospheric category, however, thyroid doses are likely to exceed PAGs out to 100's of miles.

A cost-benefit analysis for the use of KI was also performed. Cost-benefit ratios ($/thyroid nodule prevented) are given assuming that no other protective measures are taken. Uncertainties due to health effects parameters, accident probabilities and costs are assessed. The effects on predicted ratios of other potential protective measures, such as evacuation and sheltering, are addressed. The impact on children (critical population) is also evaluated. The estimated cost-benefit ratios are high, and it appears that the distribution of KI is only marginally cost-effective, at best.

Finally, using statistics provided in NCRP Report No. 55, a simple risk-benefit analysis showed the risk of adverse reaction posed by KI at the recommended action levels and dosages to be small compared to its potential benefits. However, several recent reports suggest that adverse reaction rates for some segments of the population may be higher than those estimated by the NCRP.

CONTENTS

Figures

Tables

Tables (cont'd)

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PROLOGUE

During the first few critical days of the accident at Three Mile Island, many spontaneous decisions were made concerning offsite emergency protective measures. The sense of the moment dictated action. Plans were conceived and implemented with little or no time available to determine the potential benefits and costs associated with alternatives. Specific plans were developed to evacuate the population within 20 miles of the reactor; the Governor ordered a five mile precautionary evacuation of pregnant women and small children; and Potassium-Iodide medication (KI) was manufactured and shipped to the area for possible distribution.

To provide an adequate planning basis for potential future accidents, it is necessary to determine how frequently they would occur; to estimate their anticipated impacts on the surrounding population; and to evaluate the potential benefits of alternative protective measures. Several studies have focused on these important questions.[1,2,3] It is also important to estimate the costs associated with various protective measure strategies. With this information (i.e., probability of accident occurrence; impact on public; benefit of various protective measures; and associated costs), a rational basis would be available to make planning decisions.

It is the intent of this report to focus on one emergency protective measure (Potassium Iodide) and present information needed to make a decision concerning a program for its use. There are many uncertainties associated with the information, methods, and techniques which are used in this analysis. As our knowledge and experience expands, the results and conclusions of this type of study should be reevaluated and, if necessary, changes should be made to the emergency planning strategy.

1. Introduction

Potential accidents at nuclear reactors, however unlikely, could result in substantial offsite radiation exposures, and pose a serious threat to the health and safety of the surrounding public. If an accident were sufficiently severe, the resulting radiological consequences could include immediate deaths and injuries, delayed cancer deaths, thyroid nodules, and long-term contamination of land and property.[1] Any immediate effects, even for the worst accidents, would probably be confined to areas relatively close to the reactor (a few tens of miles)[1,2] and could be significantly reduced by implementing immediate protective measures. However, cancer deaths and thyroid nodules could occur over much larger distances (100's of miles) and would therefore be less affected by immediate protective measures taken near the site.

The risk to the thyroid of exposed individuals posed by potential accidents is especially great for several reasons:

- Radioactive isotopes of iodine are produced in abundance by the fission process.
- Iodine and iodine compounds are normally quite volatile. Therefore, a sizeable fraction of core radioiodine inventories could be available for release to the atmosphere.
- Inhaled or ingested radioiodines are quickly absorbed into the bloodstream and concentrate preferentially in the thyroid.
- Iodines are eliminated from the thyroid with a relatively long biological half-life.

As a result, the radiation dose to the thyroid is likely to far exceed the dose to the rest of the body, and thyroid damage is likely to affect more individuals than any other accident-induced health effect.[1,3] Taken in large enough quantities, potassium iodide (KI) acts to block the absorption of radioiodines by the thyroid, reducing the thyroid dose. For this reason, KI has been discussed for many years as a potential protective measure for use in the event of a serious reactor accident.[4]*

The availability of KI would provide a supplemental strategy to be considered along with other possible protective measures. However, KI should not be considered a panacea for reactor accidents. Although its effective use could significantly reduce the number of thyroid nodules resulting from an accident, it would have no impact on long-term land contamination or immediate health effects, and only a moderate impact on delayed cancer deaths. Use of KI is also not the only protective action that will reduce thyroid dose, nor is it without its difficulties and problems:

- The drug is not completely risk free; adverse reactions are possible.
- Making KI available would involve a cost to society; dollars that perhaps could be used to reduce risk more effectively elsewhere.

* Potassium iodate, a drug similar to KI, has been distributed for use within a few miles of reactors in Great Britain.[5] A recent analysis by Beyea and von Hippel[3] recommends planning for the use of KI over much larger distances in the U.S., on the order of 100 or more miles from all reactors.

- There are serious storage and distribution logistical problems associated with ensuring that the public would receive the drug in sufficient time to be effective.
- It must be assured that any KI distribution strategy implemented would not reduce the effectiveness of other protective actions taken, e.g., if people are required to receive KI at a distribution center, they may be "caught" by the cloud while outdoors, and receive a higher dose than if they had stayed at home.

A timely decision on the potassium iodide issue is required of responsible policymakers. This report summarizes a study performed to provide them with technical guidance on that issue. It is intended (1) to provide insight concerning the effectiveness of KI in potential accident situations, (2) to help determine the merits of KI as an emergency protective option, (3) to establish the population and the distance to which (or area within which) it should be distributed, and (4) to determine under what conditions it should be implemented. Simple cost-benefit and risk-benefit analyses have been performed as part of this study. The effects of other protective measures, such as evacuation and sheltering, are assessed as well. Specific alternative strategies for stockpiling and distributing KI have not been addressed, although that would be essential to reduce costs and assure effectiveness before making KI available.

The analysis reported here was performed using the Reactor Safety Study (RSS) consequence model,[1] CRAC, for a range of potential reactor accidents. Four categories of accident releases are examined; from fuel pin gap activity release accidents to complete core meltdowns with containment failure directly to the atmosphere. It is important to note that there is a great deal of uncertainty in our knowledge of these releases and their probabilities, as well as dose-health effect relationships for the thyroid. In some cases, these uncertainties hinder our ability to provide definitive guidance. However, they are addressed to the extent possible in our analysis.

2. KI as a Protective Measure

Inhaled or ingested iodine is rapidly and almost completely absorbed into the bloodstream. Almost one third of the iodine concentrates in the thyroid where it has a biological half-life of approximately 120 days. The absorption of radioiodines by the thyroid is greatly reduced if body fluids are saturated with stable iodine prior to exposure.[4] The blocking effectiveness of stable iodine is shown in Figure 1 as a function of the time of administration. After a short-term exposure, the majority of radioiodine uptake by the thyroid occurs within 10-12 hours, and the initial administration of a blocking agent is therefore of little value beyond that time. Essentially complete curtailment (90% or greater) of radioiodine uptake by the thyroid requires that stable iodine be administered shortly before or immediately after the initiation of exposure. A block of 50 percent or more is attainable only during the first few hours after exposure.

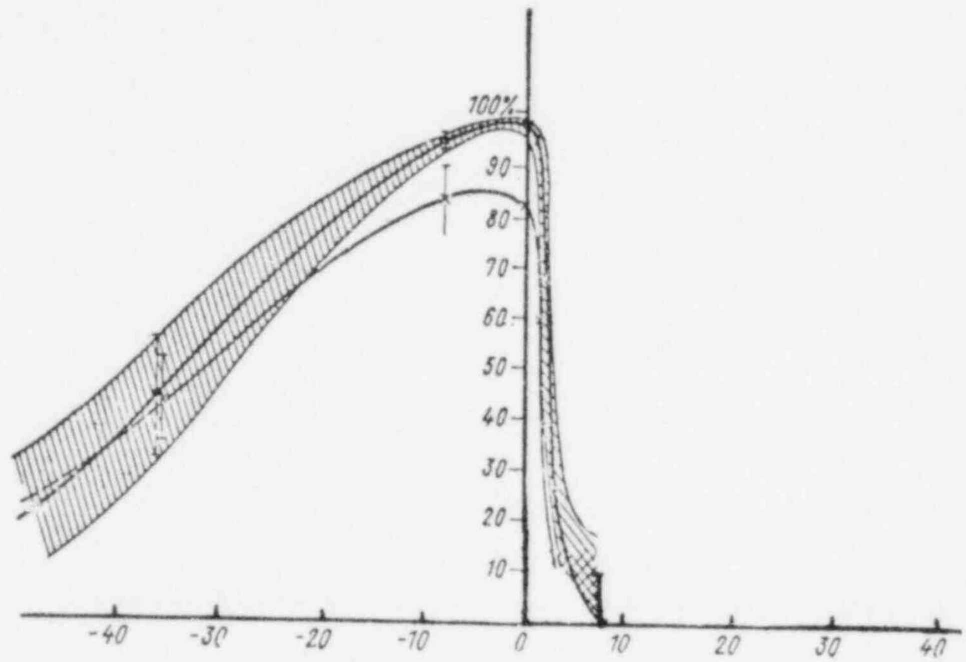

Figure 1. Percent of Thyroid Blocking Afforded by 100 mg of Stable Iodine as a Function of Time (in hours) of Administration Before or After a 1 µci Slug Intake of I-131.

Ref: Radioactive Iodine in the Problem of Radiation Safety (USSR) (1972), USAEC Translation Series, AEC-tr-7536. Available from NTIS, US Department of Commerce, Springfield, VA 22151.

Several chemical compounds of stable iodine are suitable as blocking agents, including potassium iodide (KI) and potassium iodate.* The Food and Drug Administration (FDA) has recommended and approved oral administration of potassium iodide (KI) in dosages of 130 mg (tablet or liquid form) as a blocking agent.[4,6] Continued administration of this daily dose appears to maintain an essentially complete block. A minimum of three to seven days administration would probably be required, and use of the drug is not expected to exceed 10 days.[6]

There is presently no definitive guidance concerning when, or under what conditions, KI should be used as a blocking agent. The NCRP recommends that it be considered for use if the projected thyroid dose** to an individual in the general public exceeds 10 rem.[4] Protective Action Guides (PAGs) promulgated by the EPA for projected thyroid dose range from 5 to 25 rem.[7] Protective action is recommended at the lower level for sensitive populations (pregnant women, children), or if there are no local constraints to providing protection at that level. Protective actions would be warranted in all cases if the projected dose exceeds the higher value. However, only evacuation

*Radiological emergency plans in Great Britain include thyroid-blocking using 100 mg tablets of potassium iodate, since in the British experience, the shelf-life of the iodate is appreciably longer than that of iodide tablets. The iodate form could be employed in the U.S. only by compliance with FDA requirements that include gathering the pertinent clinical data for the iodate.

**The projected thyroid dose is the estimated dose that would be received within a few days following the release if no protective actions are taken.

and controlled area access were discussed in the EPA document,[7] and the use of KI was not specifically cited as an appropriate protective measure.

There is considerable experience with the use of KI as a therapeutic drug.[4] It has been used for a number of years in high doses, and on a long-term basis, for the treatment of various pulmonary disorders. The reported incidence of adverse reactions to the drug is low, and the risk posed by the short-term use of the relatively low doses that would be involved with response to an accident is judged to be minimal. The NCRP[4] estimates the adverse reaction rate to be between 1×10^{-7} and 1×10^{-6} per dose, and concludes that the administration of KI would not result in significant immediate side effects, even if given to large segments of the population.*

Because the prompt administration of KI in the event of an accident is critical to its effectiveness as a protective measure, some method of rapid distribution to the public is required. There is little current definitive planning for such methods. Stockpiling supplies of KI in "distribution centers" such as schools, police stations, or firehouses has been recommended.[4] An alternative would be to provide each household with a sufficient supply for all members of the household. The feasibility and effectiveness of these and other alternative strategies, as well as their likely implementation costs, should be investigated.

*Note that warning would be given cautioning against the use of KI by individuals who are sensitive to iodine.

3. Accident Releases Considered

Release magnitudes for potential accidents of offsite significance range from relatively small releases of gap activity to the large releases predicted for full core-melt accidents in which the containment fails directly to the atmosphere.* The RSS[1] grouped this spectrum of reactor accidents into nine release categories for pressurized water reactors (PWR) with large dry containments and five for boiling water reactors (BWR) with Mark I containment. These categories are presented in Table 1 along with their estimated probabilities of occurrence, release magnitudes, and other parameters that characterize the release. It should be noted that, because of the lack of complete understanding of the physical processes associated with core-melting and the resulting release of radioactive material to the environment, there is a large degree of uncertainty and overlap in these groupings. There is also a significant uncertainty associated with their estimated probabilities,[8] a point which will be discussed later in this report.

*A large light water power reactor typically contains about 10 billion curies of radioactive material. The spectrum of potential accidents addressed in this study would release from 10^{-7} (1000 curies) to about one half (5 billion curies) of this radioactive material directly to the atmosphere.

Table 1. Summary of Release Categories Representing Hypothetical Nuclear Reactor Accidents (from Ref. 1)*

Release Category	Probability (reactor-yr^{-1})	Time of Release (hr)	Duration of Release (hr)	Warning Time for Evacuation (hr)	Elevation of Release (meters)(g)	Energy Release (10^6 Btu/hr)	Fraction of Core Inventory Released(a): Xe-Kr	Organic I(b)	I(b)	Cs-Rb	Te-Sb	Ba-Sr	Ru(c)	La(d)
PWR 1	9×10^{-7}(e)	2.5	0.5	1.0	25	20 and 520(e)	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A(f)	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR 1	1×10^{-6}	2.0	0.5	1.5	25	130	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
BWR 2	6×10^{-6}	30.0	3.0	2.0	0	30	1.0	7×10^{-3}	0.90	0.50	0.30	0.10	0.03	4×10^{-3}
BWR 3	2×10^{-5}	30.0	3.0	2.0	25	20	1.0	7×10^{-3}	0.10	0.10	0.30	0.01	0.02	4×10^{-3}
BWR 4	2×10^{-6}	5.0	2.0	2.0	25	N/A	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}
BWR 5	1×10^{-4}	3.5	5.0	N/A	150	N/A	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-14}	0	0

(a) Background on the isotope groups and release mechanisms is presented in Appendix VII.
(b) Organic iodine is combined with elemental iodines in the calculations. Any error is negligible since its release fraction is relatively small for all large release categories.
(c) Includes Ru, Rh, Co, Mo, Tc.
(d) Includes Y, La, Zr, Nb, Ce, Pr, Nd, Np, Pu, Am, Cm.
(e) Accident sequences within PWR 1 category have two distinct energy releases that affect consequences. PWR 1 category is subdivided into PWR 1A with a probability of 4×10^{-7} per reactor-year and 20×10^6 Btu/hr and PWR 1B with a probability of 5×10^{-7} per reactor-year and 520×10^6 Btu/hr.
(f) Not applicable.
(g) A 10 meter elevation is used in place of zero representing the mid-point of a potential containment break. Any impact on the results would be slight and conservative.

*The time of release is the time interval between the initiation of the accident and the release of radioactive material from the containment structure to the atmosphere. The duration of release is the period of time during which radioactive material is emitted to the atmosphere. The warning time for evacuation is the projected time interval between awareness of impending core melt and the release of radioactive material from the containment building. For those accidents in which core-melting does not occur, there is no projected warning time. Finally, the height of release and the energy content of the released plume influence the height to which the plume rises and, thus, the exposure to persons near the site.

For the purpose of this study, the PWR accident release spectrum has been grouped into 4 categories:*

	RSS Release Categories
1. Gap Activity Release Accident (GAP)	PWR9
2. Gap Activity Release Accident without Containment Isolation (GAP w/o Isolation)	PWR8
3. Core Melt with Melt-Through Release (Core Melt Melt-Through)	PWR6-7
4. Core Melt with Atmospheric Release (Core Melt Atmospheric)	PWR1-5

PWR9 represents a gap activity release accident in which only the activity initially contained within the gap between the fuel pellet and cladding would be released into the containment. All engineered safeguards are assumed to function properly. PWR8 is the same as PWR9, except that the containment fails to isolate properly on demand. Again, all other engineered safeguards, including containment sprays, are assumed to function properly. PWR categories 1 through 7 are accidents in which core melt is assumed to occur. PWR 6 and 7 are dominated by accident sequences involving containment failure by containment base mat melt-through. PWR1-5, on the other hand, consist of accidents in which containment failure is assumed to occur directly to the atmosphere as a result of either inadequate isolation of containment openings or penetrations, a reactor vessel steam explosion,

*These 4 categories are comprised of the RSS release categories from which they are defined, each weighted by its respective probability as calculated in the RSS.

hydrogen burning, or overpressure. To reduce the required time and cost of computation, BWR accidents have not been considered specifically in this analysis. However, the information and conclusions presented for large dry containment PWRs should be roughly applicable to other PWR designs and for BWRs as well, given a similar type of accident and mode of containment failure.*

4. Thyroid Dose and Health Effects Calculations

Dose to the thyroid is estimated as the sum of 1) external dose from the passing cloud (cloud exposure), 2) external dose from contaminated ground (ground exposure), 3) internal dose during the first 30 days from all inhaled radionuclides except I-131, and 4) internal dose during the first 30 days from inhaled I-131. Thyroid dose from ingestion via the grass-cow-milk-man pathway and chronic exposure has not been included in this analysis because those pathways would not require an immediate emergency response in the event of an accident.

*BWR5 represents the BWR gap activity release accident. BWR1-4 are accidents that involve core-melt. For the specific BWR design investigated in the RSS, the probability of containment failure by containment vessel melt-through is essentially zero, i.e., the containment is assumed to always fail directly to the atmosphere. BWR4 is dominated by accident sequences involving containment isolation failure in either the drywell or wetwell, whereas BWR1-3 are dominated by accidents in which the containment fails from either a steam explosion in the reactor vessel or containment, or from overpressure resulting in release through the reactor building or directly to the atmosphere. Other containment designs (e.g., PWR ice condenser, BWR Mark II or BWR Mark III) would have somewhat different probabilities for the various containment failure modes.

The dose received by a child's thyroid is likely to be different than that received by an adult for several reasons, including differences in thyroid mass, breathing rate, fractional iodine uptake, and metabolic rate. The RSS assumed age dose factors* of 1.0 for children of ages 0-1 years, 1.9 for ages 1-10 years, and 1.6 for ages 10-20 years. Somewhat higher factors (up to 5) have been assumed in other studies.[3,9]

There is considerable uncertainty concerning the effects of radiation exposure on the thyroid.[1,4,9] Thyroid nodules are the effect of primary concern and would typically be observed from 10 to 40 years after exposure.[1] A nodule is an abnormal growth that could be either benign or malignant (cancerous). Nodules that are thought to be possibly malignant would most likely be surgically removed.

Most thyroid cancers are well differentiated, slow growing, and relatively amenable to therapy. Their associated mortality rate is therefore much lower than that for most other forms of cancer. The RSS[1] conservatively assumed a 10 percent mortality rate for malignant thyroid nodules.

Based on the results of animal experiments and clinical data for humans, the RSS[1] assumed that internal irradiation of the thyroid by I-131 would be only 1/10th as effective as external x-rays in producing both benign and malignant nodules.**

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*Ratio of child to adult inhalation dose.

**On a purely radiological basis, it is thought that the more uniform distribution of dose within the thyroid from external irradiation might increase the efficiency of inducing clinical hypothyroidism.

3

This factor of 0.1 for I-131 dose was disputed by the American Physical Society (APS) study group on reactor safety,[9] which assumed a range of factors from 0.3 to 1.0. Because this issue remains unresolved, calculations have been performed in this analysis both with and without a 0.1 factor for I-131 dose effectiveness.

Sufficiently high radiation doses* would result in ablation of the thyroid with no subsequent risk of either benign or malignant nodules.[1] However, because of the high doses required, thyroid ablation is unlikely to occur except for persons very near the reactor following the most severe accidents. Ablation would probably require surgical removal of the thyroid, and the affected individual would need to take substitute hormone pills on a daily basis. Thyroid damage, including both nodules and ablation, has been addressed in this analysis.

The RSS calculation of the expected number of thyroid nodules per million person-rem** is reproduced in Table 2. The assumed total incidence rate is 334 thyroid nodules per 10^6 person-rem, of which 60 percent are benign and 40 percent are malignant. Although not specifically computed, a dose-effects coefficient for a child's thyroid can be derived from the RSS

*The RSS assumed that doses in excess of 5000 rem (50,000 rem from I-131) would result in thyroid ablation. A value of 3000 rem has been assumed in this analysis.

**Number of cases per million population per rem

Table 2. RSS Calculation of Expected Cases per Million Person-Rem of Benign and Cancerous Thyroid Nodules (from Ref. 1).

Age Group (years)	Fraction of Population	Life Expectancy (years)	Latent Period (years)	Years at Risk	Age Dose Factor[a]	Benign Nodules: Risk Coefficent[b]	Benign Nodules: Expected Cases[c]	Cancers: Risk Coefficient[b]	Cancers: Expected Cases[c]
0 - 0.99	0.014	71.3	10	30	1.0	8	3.4	4.3	1.8
1 - 10	0.146	69.4	10	30	1.9	8	66.6	4.3	35.8
11 - 20	0.196	60.6	10	30	1.6	8	75.3	4.3	40.5
21 - 30	0.164	51.3	10	30	1	4	19.7	4.3	21.1
31 - 40	0.118	42.0	10	30	1	4	14.2	4.3	15.2
41 - 50	0.109	32.6	10	22.6	1	4	9.9	4.3	10.6
51 - 60	0.104	24.5	10	14.5	1	4	6.0	4.3	6.5
61 - 70	0.080	17.1	10	7.1	1	4	2.3	4.3	2.4
71 - 80	0.044	11.1	10	1.1	1	4	0.1	4.3	0.2
80+	0.020	6.5	10	0	1	4	0	4.3	0
TOTAL							200		134

[a]Ratio of child to adult inhalation dose. See Tables VI-8-5 and 9-8 in reference 1.

[b]Number of cases per million population per rem per year.

[c]Expected cases per million person-rem.

data to be approximately a factor of 2 higher.* Beyea[3] assumes the RSS values as lower bounds, and upper bounds of 650 thyroid nodules per 10^6 person-rem for adults, and 6500 thyroid nodules per 10^6 person-rem for children.

Unless otherwise stated, the calculations performed in this study assume the RSS risk coefficient of 334 thyroid nodules per 10^6 person-rem. This corresponds to an assumed risk, or probability, of a thyroid nodule for an individual of 3.34×10^{-4}/rem, i.e., 100 rem to an individual implies a probability of contracting thyroid nodules of 3.34×10^{-2}. For this assumed coefficient, a dose to an individual of 3000 rem gives a thyroid nodule probability of approximately 1.0. Therefore, the following is assumed:

Thyroid Dose

$\leq$ 3000 rem	p(thyroid nodule) = $(3.34 \times 10^{-4}$/rem)(dose in rem)
$>$ 3000 rem	p(thyroid nodule) = 0 p(ablated thyroid) = 1.0

The effect of uncertainty in the thyroid dose-effect relationship is assessed by repeating some calculations using the upper bound values proposed by Beyea[3] and the APS.[9]

Thyroid Dose Calculations

A series of calculations was performed using CRAC,[1,10] to determine 1) the magnitude of the threat to the thyroid of

*For age group 1-10: (years at risk) (age dose factor) (risk coefficient) = 30 x 1.9 x (8 + 4.3) = 707 thyroid nodules per 10^6 person-rem (see Table 2).

exposed individuals, 2) the distance to which that threat is likely to be of concern, and 3) the relative contributions of different exposure pathways and radioisotopes to the thyroid dose, for each of the four accident categories defined in the previous section. All calculations were performed for a 3200 MWt PWR using one year of meteorological data taken from a single reactor site.* From the year's data, 91 different weather sequences were selected by stratified sampling[1] and used to generate probability distributions of thyroid dose versus distance. Breathing rate and shielding parameters appropriate for a person located outdoors[1,2,12] are assumed: breathing rate = 2.66×10^{-4} m^3/s, shielding factors = 1.0 (cloud exposure) and 0.7 (ground exposure).

For each accident category, Table 3 presents the mean thyroid dose that would be received by an exposed adult located outdoors at selected distances from the reactor. The corresponding dose to a child's thyroid would be approximately a factor of 2 higher. Table 4 presents the associated probability of thyroid damage for the same individuals. The values shown equal the doses in Table 3 multiplied by the RSS risk coefficient of 3.34×10^{-4} per person-rem to the thyroid.

*Site-to-site variations in meteorological histories have been shown to have little effect on the prediction of long-term public health effects.[11] Therefore, the use of meteorological data from a single site is considered sufficient for this study.

Table 3. Mean[a] Thyroid Dose[b] (rem) versus Distance for Exposed Adult Located Outdoors[c]
The mean thyroid dose for a child would be approximately a factor of 2 higher.[d]

	Accident Category			
Distance (miles)	GAP	GAP w/o Isolation	Core Melt Melt-Through	Core Melt Atmospheric
1	5.7×10^{-2}	55	25	1.3×10^{4}
5	4.0×10^{-3}	3.9	1.7	5.8×10^{3}
10	1.1×10^{-3}	1.1	5.2×10^{-1}	3.2×10^{3}
25	1.7×10^{-4}	1.7×10^{-1}	7.6×10^{-2}	1.1×10^{3}
50	4.2×10^{-5}	4.2×10^{-2}	2.0×10^{-2}	3.8×10^{2}
100	1.1×10^{-5}	1.1×10^{-2}	5.9×10^{-3}	1.0×10^{2}
150	3.8×10^{-6}	3.8×10^{-3}	2.0×10^{-3}	36
200	1.9×10^{-6}	1.9×10^{-3}	1.0×10^{-3}	16

[a] 91 weather sequences were used to calculate a probability distribution of dose at each distance. The mean doses presented are the mean of those distributions.

[b] Calculated doses include: dose from inhaled radionuclides from cloud passage, plus external dose due to the passing cloud plus 1-day exposure to ground contamination.

[c] Breathing rate = 2.66×10^{-4} m^3/s. Shielding factors = 1.0 (cloud exposure) and 0.7 (ground exposure).

[d] RSS[1] assumed age dose factor of 1.9 for children aged 1-10 (see Section 3).

Table 4. Conditional Probability[a] of Thyroid Damage[b] versus Distance for Exposed Adult Located Outdoors. Probabilities are conditional on the accident occurring. Probabilities would be approximately a factor of 2 higher for a child.[c]

	Accident Category			
Distance (miles)	GAP	GAP w/o Isolation	Core Melt Melt-Through	Core Melt Atmospheric
1	1.9×10^{-5}	1.8×10^{-2}	8.4×10^{-3}	0.6[d]
5	1.3×10^{-6}	1.3×10^{-3}	5.7×10^{-4}	0.7[d]
10	3.7×10^{-7}	3.7×10^{-4}	1.7×10^{-4}	0.7[d]
25	5.7×10^{-8}	5.7×10^{-5}	2.5×10^{-5}	0.4[d]
50	1.4×10^{-8}	1.4×10^{-5}	6.7×10^{-6}	1.3×10^{-1}
100	3.7×10^{-9}	3.7×10^{-6}	2.0×10^{-6}	3.3×10^{-2}
150	1.3×10^{-9}	1.3×10^{-6}	6.7×10^{-7}	1.2×10^{-2}
200	6.3×10^{-10}	6.3×10^{-7}	3.3×10^{-7}	5.3×10^{-3}

[a]No 0.1 effectiveness factor for I-131 dose is assumed. Values presented equal doses in Table 3 multiplied by assumed risk coefficient of 334 thyroid nodules per 10^6 person-rem to the thyroid.

[b]Thyroid damage includes thyroid nodules (both benign and cancerous) and ablated thyroids.

[c]See Section 3.

[d]Probabilities are less than 1.0 because for some accidents and weather conditions, the energy of release is sufficiently high to result in significiant plume rise. In these cases, the plume would travel over the heads of individuals near the reactor, and resulting thyroid doses would be low.

The probability of thyroid damage to an individual following a gap activity release accident (GAP) is extremely low, ranging from less than 2×10^{-5} (1 in 50,000) 1 mile downwind of the site to less than 4×10^{-9} (1 in 250,000,000) at 100 miles. Probabilities are somewhat higher for the GAP w/o Isolation and Core Melt Melt-Through accidents. Thyroid damage probabilities for the Core Melt Atmospheric accidents are much higher, and such accidents could pose significant health hazards to persons at distances of more than 100 miles from the site.* These results agree with those of previous studies.[2,3]

Fractional components of the mean thyroid dose are provided in Table 5 for selected distance intervals: 0-25 miles, 25-100 miles, and distances greater than 100 miles. Within these intervals, the relative contributions to thyroid dose will not differ significantly. The dose is divided into components for the inhalation of radioiodines, inhalation of non-radioiodines, cloud exposure and ground exposure. Radioiodine inhalation is further divided into components for I-131 and other iodines. It is evident from Table 5 that the thyroid dose is dominated by the inhalation of radioiodines for each of the four accident categories. Inhalation of I-131 alone

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*Caution must be used in interpreting the large distances indicated. The RSS consequence model assumes an invariant wind direction following the release of radioactive material. However, because of the time required by the cloud to travel large distances, it is likely that the wind direction will, in fact, shift and that the predicted dose levels would not be observed at the reported radial distance. Rather, the distance applies more closely to the distance along the trajectory of the released cloud.

Table 5. Fractional Components of Mean Thyroid Dose for Exposed Individual Located Outdoors

Distance Interval (miles)	Inhaled Radioiodines[a] I-131	Inhaled Radioiodines[a] Other Iodines	Inhaled Non-radioiodines[a]	Cloud Exposure[b]	Ground Exposure[c]
A. GAP					
0-25	0.67	0.25	0.02	0.03	0.03
25-100	0.70	0.22	0.02	0.04	0.02
>100	0.77	0.16	0.03	0.02	0.02
B. GAP w/o Isolation					
0-25	0.68	0.25	0.02	0.02	0.03
25-100	0.71	0.23	0.02	0.02	0.02
>100	0.78	0.16	0.02	0.02	0.02
C. Core Melt Melt-Through					
0-25	0.65	0.16	0.10	0.06	0.03
25-100	0.63	0.15	0.10	0.09	0.03
>100	0.63	0.09	0.09	0.16	0.03
D. Core Melt Atmospheric					
0-25	0.67	0.21	0.07	0.01	0.04
25-100	0.72	0.20	0.05	0.01	0.02
>100	0.77	0.16	0.05	0	0.02

[a] Breathing rate = 2.66 x 10^{-4} m^3/s.
[b] Shielding factor for exposure to cloud = 1.0.
[c] 1-day exposure to ground contamination. Shielding factor = 0.7.

accounts for 60-80 percent of the total dose, and other iodines contribute another 10-25 percent. Inhalation of non-radio-iodines, cloud exposure and ground exposure are all small contributors to total thyroid dose.

The probabilities of exceeding thyroid doses of 0.01 and 0.1 rem versus distance from the reactor are shown in Figure 2, conditional on the occurrence of a gap activity release accident (GAP). The probabilities are calculated for an exposed adult located outdoors. The selected dose levels, 0.1 and 0.01 rem, are far lower than any recommended action levels, and are still confined to areas very close to the reactor. Therefore, it is evident that the GAP accident does not pose a significant hazard to the public.

Figures 3 and 4 show the probability of exceeding thyroid doses of 1, 5, 10 and 25 rem versus distance for the GAP w/o Isolation and Core Melt Melt-Through accidents. The 5, 10 and 25 rem dose levels were chosen because they represent the range of action levels that have been recommended for the initiation of emergency protective measures. The 1 rem level was added as a lower bound for doses of interest. It is evident from these results that, for all practical purposes, projected thyroid doses of concern are confined to areas within a few 10's of miles of the reactor for these types of accidents, and in most cases to areas considerably closer. For the GAP w/o Isolation accidents, doses in excess of 5 rem are confined to about 10 miles; those in excess of 25 rem to about 5 miles. The

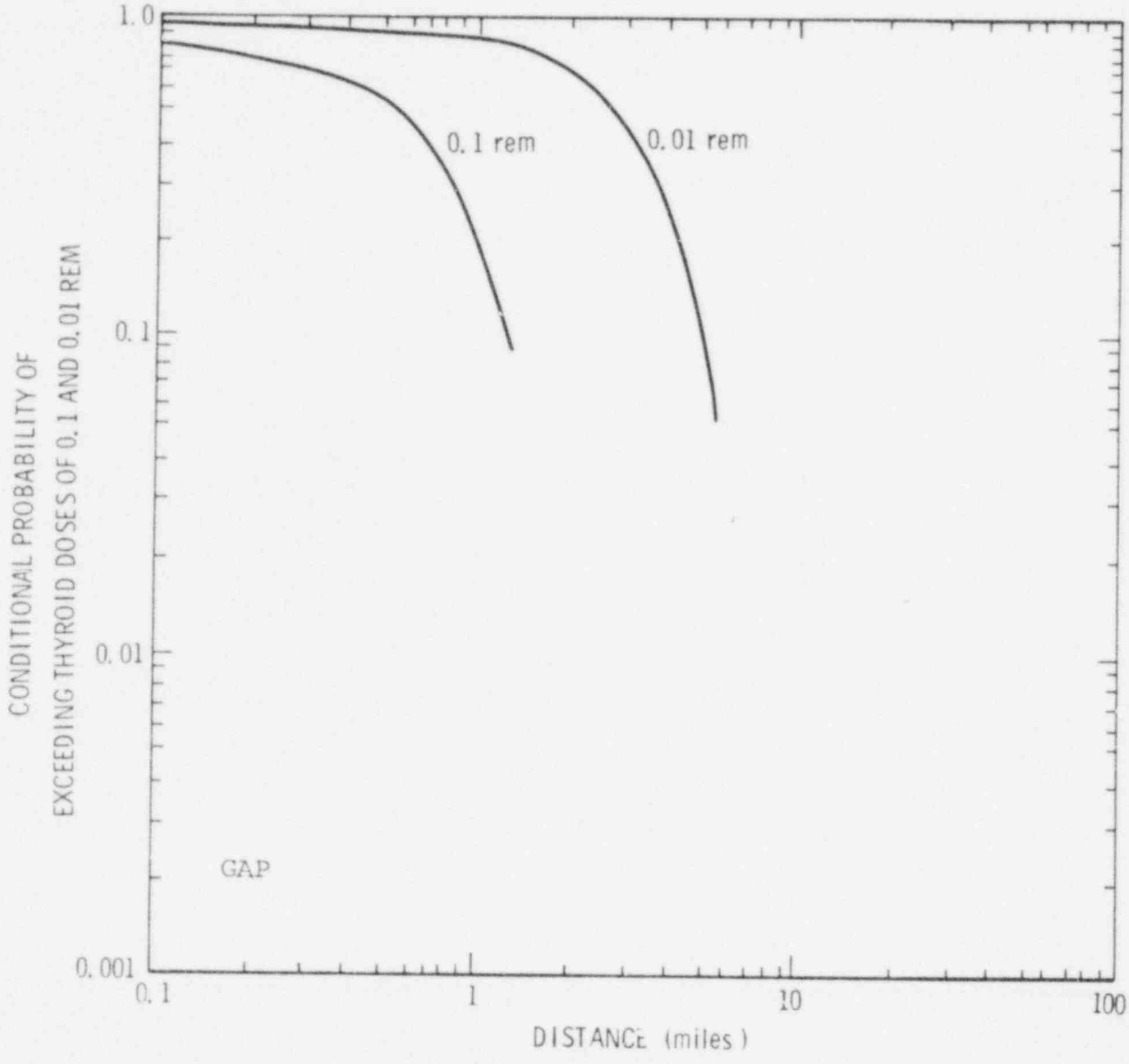

Figure 2. Conditional Probability of Exceeding Thyroid Doses of 0.01 and 0.1 rem versus Distance for an Exposed Adult Located Outdoors. Probabilities are Conditional on a Gap Activity Release Accident (GAP).

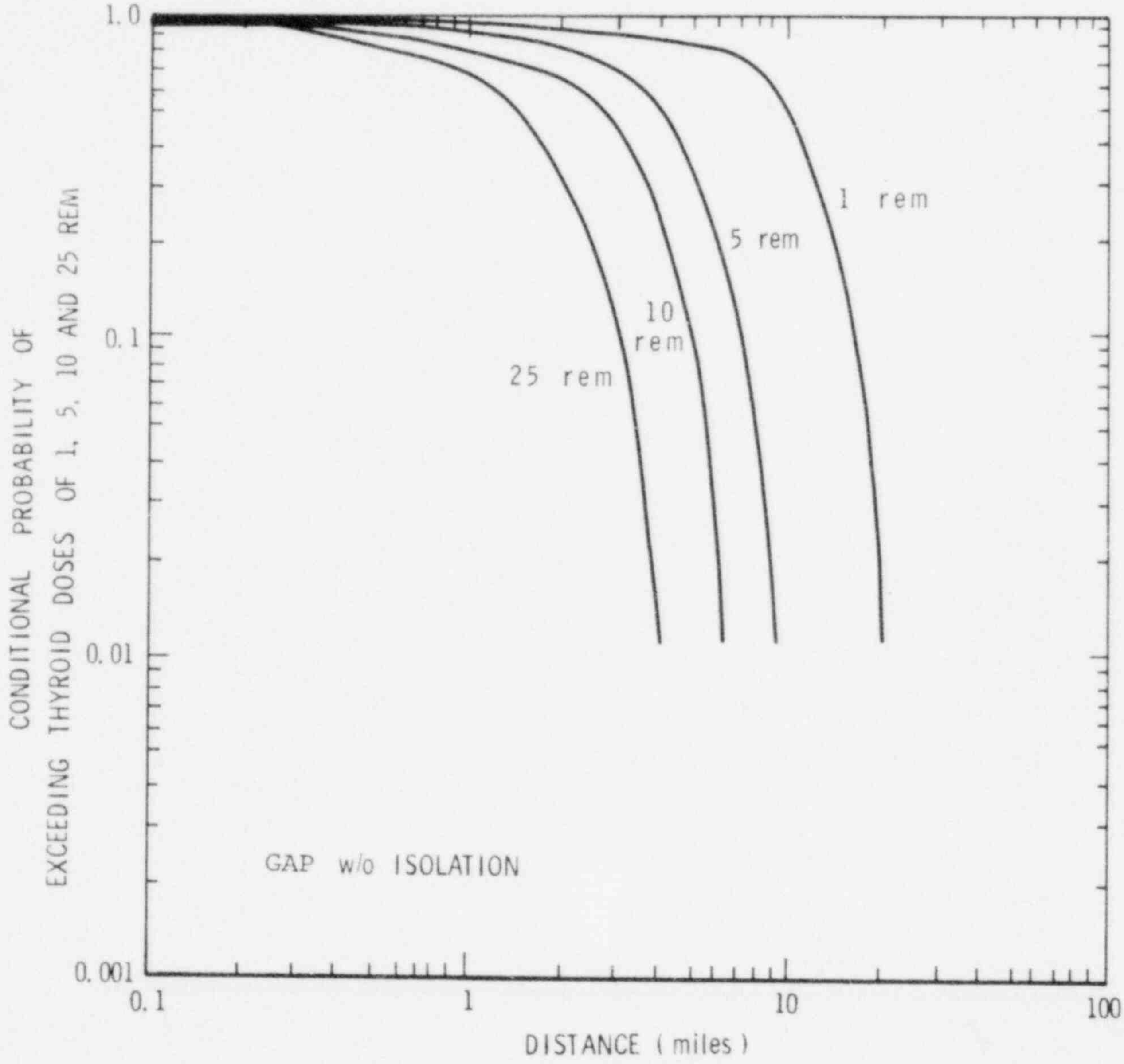

Figure 3. Conditional Probability of Exceeding Thyroid Doses of 1, 5, 10 and 25 rem for an Exposed Adult Located Outdoors. Probabilities are Conditional on a GAP w/o Isolation Accident.

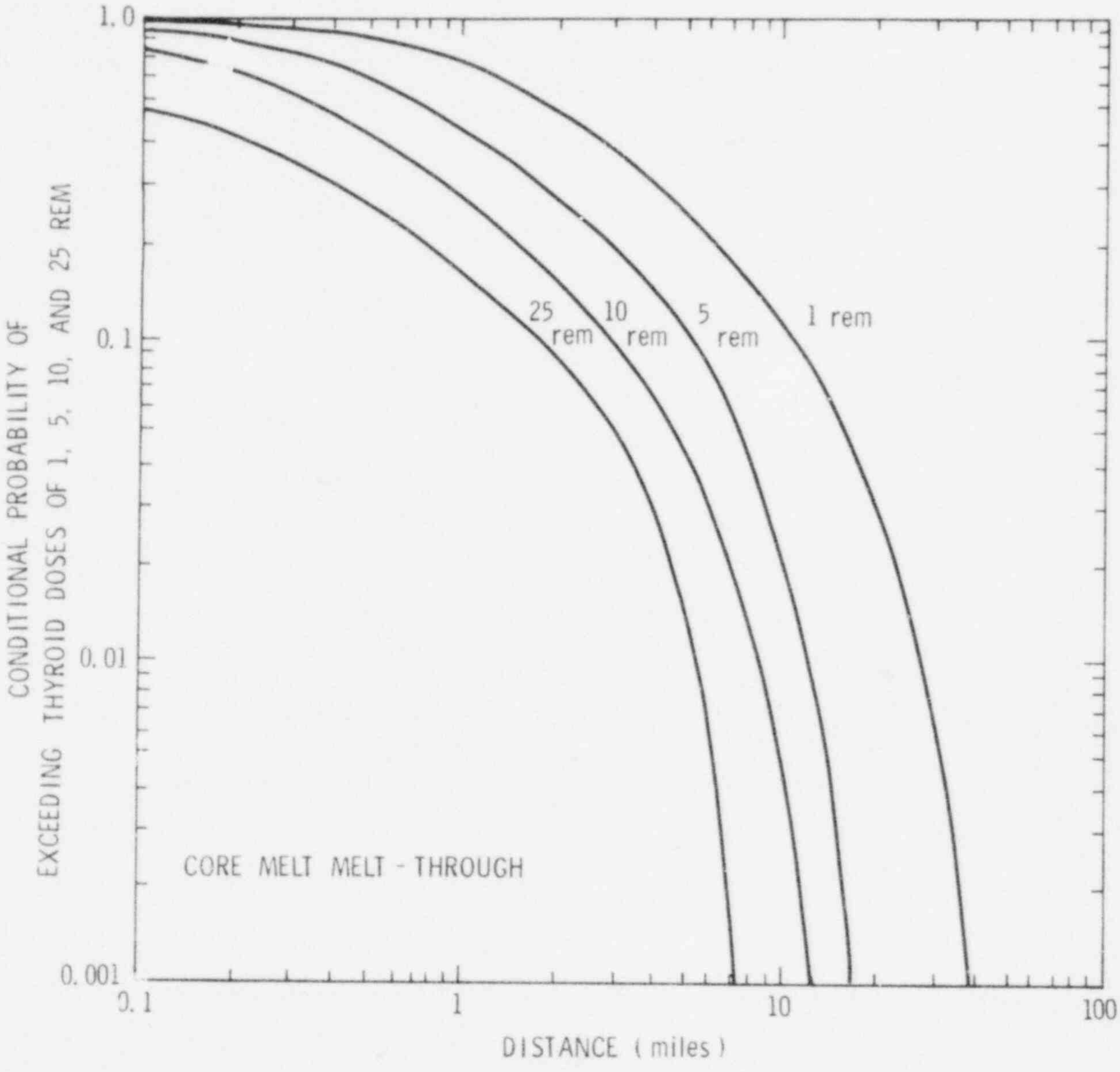

Figure 4. Conditional Probability of Exceeding Thyroid Doses of 1, 5, 10 and 25 rem for an Exposed Adult Located Outdoors. Probabilities are Conditional on a Core Melt Melt-Through Accident.

same dose levels are confined to approximately 15 and 7 miles, respectively, for the Core Melt Melt-Through category.

The conditional probabilities of exceeding thyroid doses of 1, 10 and 25 rem for the Core Melt Atmospheric category are shown in Figure 5. The thyroid dose levels of concern are likely to be exceeded at very large distances from the reactor (and correspondingly over very large areas) if this type of accident were to occur.

5. Other Protective Measures

It was shown in the previous section that, for each of the four accident categories addressed, the thyroid dose is dominated by the inhalation of radioiodines. Therefore, in order to be effective in reducing the thyroid dose and resulting health impacts, a protective measure must reduce the inhalation dose. KI does this by blocking the absorption of inhaled radioiodines by the thyroid. However, other protective measures, including both evacuation and sheltering, can also act to reduce inhalation dose.

Evacuation, which is the expeditious movement of the population, is considered to be the primary protective measure in most radiological emergency planning within the United States.[13,14,15,16] Evacuation could potentially be 100 percent effective in reducing all dose if accomplished before arrival of the radioactive cloud. On the other hand, it could be in-

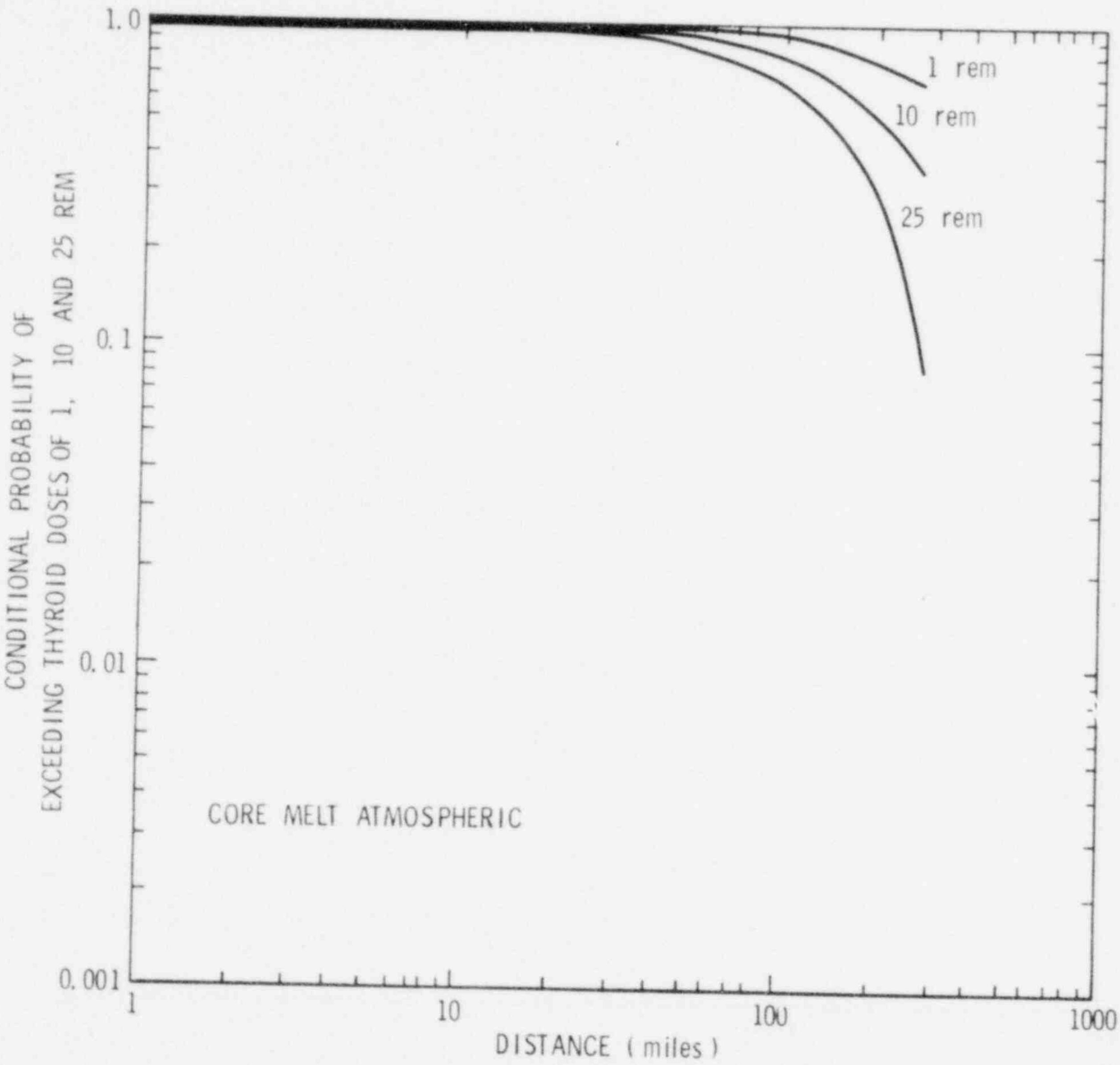

Figure 5. Conditional Probability of Exceeding Thyroid Doses of 1, 10 and 25 rem for an Exposed Adult Located Outdoors. Probabilities are Conditional on a Core Melt Atmospheric Accident.

effective in reducing inhalation doses if not initiated until after the cloud has passed.*

Sheltering might also provide some reduction in thyroid dose and could potentially be implemented at much larger distances than evacuation. Sheltering is the deliberate action by the public to take advantage of the protection against radiation exposure afforded by remaining indoors, away from doors and windows, during and after the passage of the cloud of radioactive material. The shielding inherent in normally inhabited structures offers some degree of protection against external penetrating radiation from airborne and surface-deposited radionuclides. Furthermore, the exclusion of a significant amount of airborne radioactive material from the interior of a structure, either by natural effects or by certain ventilation strategies, can reduce the amount of inhaled radionuclides as well.[17] A recent study[18] suggests that a factor of 2 reduction in inhalation dose can be assumed for sheltered individuals. That factor has been assumed in the following cost-benefit analysis.

Finally, other potential measures such as breathing through either respirators or common household items, e.g., handkerchiefs and towels,[19,20] may provide additional protection against dose

*Even in situations where the radioactive cloud has passed, evacuation could be valuable to reduce exposure to ground contamination. However, since thyroid dose is dominated by radioiodine inhalation, it would not be reduced significantly in this case. It is also possible that evacuating persons could receive increased inhalation doses if, for example, they remained in the cloud for a longer period of time or moved toward, rather than away from, the reactor while in the plume.

from inhalation of radionuclides. However, further research is required to determine their effectiveness in realistic accident situations, and they have not been addressed in this analysis.

6. Cost-Benefit Analysis

5

The decision to use potassium iodide (KI) as a protective measure should be based, at least in part, on its cost-effectiveness relative to other available protective or safety measures. To analyze the costs and potential benefits of KI, the following information is needed:

- Costs;
- Potential impact of accidents;
- Potential reduction in accident impacts; and
- Accident probabilities.

The cost of implementing a KI program would include: the purchase price of the KI in tablet or liquid form (both original and periodic replacement costs); costs for stockpiling, distributing and monitoring the status of the drug; and administrative expenses associated with the program. The potential impact of the accident is measured here by the mean number of thyroid nodules that would occur within selected distance intervals. The reduction in accident impact is measured as the difference between the number of thyroid nodules predicted if no protective actions are taken (normal activity) and the number predicted if various protective actions are implemented. Accident probabilities are expected occurrence rates per year of reactor operation. By combining the costs with the accident probabilities and the estimated reduction in effects, a cost-benefit ratio is generated. The cost-benefit ratio for KI is interpreted as the expected number of dollars required to prevent a single thyroid nodule.

The cost-benefit ratio has been evaluated for the GAP w/o Isolation, Core Melt Melt-Through, and Core Melt Atmospheric accident categories over selected distance intervals out to 200 miles from the reactor. Because few, if any, thyroid nodules are likely for the gap activity release accident (GAP), that category has not been addressed. Calculations were performed for a 3200 MWt PWR using CRAC in the same manner as described in Section 4. Several additional assumptions were made to facilitate the analysis and to allow the presentation of results in a concise and easily interpretable manner. All calculations assume that KI is 99 percent effective in reducing the dose to the thyroid from inhaled radioiodines. This is obviously a limiting case since it assumes that all affected individuals take the drug before or immediately after the cloud passes. A uniform population density of 100 persons per square mile was also assumed.* Results for real, or site-specific, population distributions can be estimated by scaling the 100 persons/mile^2 results within each distance interval. Finally, calculations were performed both with and without the 0.1 dose effectiveness factor for I-131 discussed in Section 4.

*Because costs are also assumed to be proportional to population density, this assumption does not impact the cost-benefit ratios calculated.

Costs

The stockpiling, distribution, monitoring, and administrative costs of a KI program would depend on the specific strategy of implementation and are difficult to estimate. Therefore only the original purchase and replacement costs of the drug are addressed in this analysis. The following assumptions are made:

1) Cost of KI per individual (14 tablets in a bottle) = $0.50.*
2) KI is replaced every five years (i.e., 5 year shelf life).**
3) KI is available for all persons within a given distance interval.
4) No redundancy of KI locations (i.e., no extra tablets are available).***

The cost per year to provide KI for all persons within an interval is therefore equal to the number of persons in the interval x $0.50/person x 1/5 years.

*This value is consistent with the price range ($0.41 to 0.75, depending on quantity) quoted by a U.S. drug firm that manufactures KI.

**KI tablets and solution currently approved by the U.S. Food and Drug Administration (FDA) for marketing bear 2-year expirations. However, improved product stability should be possible. Therefore, a 5-year shelf-life is assumed here.

***Considering the importance of prompt distribution and administration of KI, some redundancy of storage locations would be desirable. However, the extra cost from this redundancy has not been included here.

For the uniform population density of 100 persons/mile^2 assumed in this analysis, the number of persons located within selected distance intervals are as follows:

Distance Interval (miles)	No. Persons in Interval	Cumulative No. Persons
0-5	7,900	7,900
5-10	23,600	31,400
10-25	165,000	196,000
25-50	589,000	785,000
50-100	2,360,000	3,140,000
100-150	3,930,000	7,070,000
150-200	5,500,000	12,600,000

Using this information, the estimated annual cost for a KI program within each interval is given below.

Distance Interval (miles)	Cost($/year)
0-5	790
5-10	2,400
10-25	16,000
25-50	59,000
50-100	240,000
100-150	390,000
150-200	550,000

At the assumed cost of $0.10 per person per year, the annual cost to implement a KI program for the entire U.S. would be about $20 million.*

*Other distribution strategies, such as regional storage, could substantially reduce this cost. However, because of longer implementation times, the effectivenss of these strategies may also be reduced.

Potential Impact of the Accidents

The mean number of thyroid nodules* that would occur within selected distance intervals for the three accident categories addressed are given in Tables 6a, 6b and 6c. Results are presented separately for four protective measure combinations: 1) normal activity, i.e., no protective actions taken,** 2) normal activity plus 99 percent effective KI, 3) sheltering***, and 4) sheltering plus 99 percent effective KI. Although results are not specifically presented for evacuation, they would range from zero within all distance intervals to approximately those values shown for normal activity (see Section 5).

Potential Reduction in Thyroid Nodules

The potential reductions in the mean number of thyroid nodules that would result by the use of KI are presented in Table 7. The values provided were determined from those given in Tables 6a, 6b and 6c. As an example, for the GAP w/o Isolation accident, the mean number of nodules in the 0-5 mile interval is 1.77 for normal activity and 0.09 for normal activity plus

*For the Core Melt Atmospheric accident category, thyroid doses can be sufficiently high to result in ablated thyroids as well as nodules. Mean numbers of ablated thyroids in each distance interval are given in parentheses in Table 6c.

**Shielding factors = 0.75 (cloud exposure) and 0.33 (ground exposure). 1-day exposure to ground contamination (see reference 1).

***Shielding factors and ground exposure time are the same as for normal activity. 50 percent reduction in inhalation dose.

Table 6a. GAP w/o Isolation. Conditional Mean Number of Thyroid Nodules Within Selected Distance Intervals. A uniform population density of 100 persons/mile^2 is assumed. Risk coefficient = 334 thyroid nodules per 10^6 person-rem to thyroid.

Without 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	1.77	0.09	0.90	0.06
5-10	0.35	0.02	0.18	0.01
10-25	0.43	0.03	0.22	0.02
25-50	0.32	0.02	0.16	0.01
50-100	0.36	0.02	0.18	0.01
100-150	0.17	0.01	0.09	0.01
150-200	0.11	0.01	0.06	0

With 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	0.66	0.07	0.35	0.05
5-10	0.13	0.02	0.07	0.01
10-25	0.16	0.02	0.08	0.02
25-50	0.11	0.02	0.06	0.01
50-100	0.12	0.02	0.06	0.01
100-150	0.05	0.01	0.03	0.01
150-200	0.03	0.01	0.02	0

[a] Shielding factors = 0.75 (cloud exposure) and 0.33 (ground exposure). 1-day exposure to ground contamination.

[b] Shielding factors and ground exposure same as for normal activity. Inhalation reduction factor = 0.5.

Table 6b. Core Melt Melt-Through. Conditional Mean Number of Thyroid Nodules Within Selected Distance Intervals. A uniform population density of 100 persons/mile^2 is assumed. Risk coefficient = 334 thyroid nodules per 10^6 person-rem to thyroid.

Without 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	2.34	0.36	1.22	0.23
5-10	0.53	0.09	0.28	0.06
10-25	0.66	0.12	0.36	0.09
25-50	0.52	0.10	0.28	0.07
50-100	0.56	0.11	0.30	0.08
100-150	0.30	0.07	0.17	0.05
150-200	0.21	0.05	0.12	0.04

With 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	0.91	0.34	0.50	0.22
5-10	0.21	0.09	0.12	0.06
10-25	0.27	0.12	0.16	0.09
25-50	0.21	0.10	0.13	0.07
50-100	0.23	0.11	0.14	0.08
100-150	0.12	0.07	0.08	0.05
150-200	0.08	0.05	0.06	0.04

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[a]Shielding factors = 0.75 (cloud exposure) and 0.33 (ground exposure). 1-day exposure to ground contamination.

[b]Shielding factors and ground exposure same as for normal activity. Inhalation reduction factor = 0.5.

Table 6c. Core Melt Atmospheric. Condicional Mean Number of Thyroid Nodules (Albated Thyroids) Within Selected Distance Intervals. A uniform population density of 100 persons/mile^2 is assumed. Risk coefficient = 334 thyroid nodules per 10^6 person-rem to thyroid.

Without 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	81 (137)	49 (0)	76 (92)	31 (0)
5-10	192 (292)	81 (0)	210 (146)	48 (0)
10-25	1110 (610)	181 (0)	918 (102)	109 (0)
25-50	2110 (210)	193 (0)	1190 (30)	115 (0)
50-100	2970 (20)	234 (0)	1520 (0)	140 (0)
100-150	1580 (0)	119 (0)	802 (0)	70 (0)
150-200	992 (0)	76 (0)	503 (0)	45 (0)

With 0.1 dose effectiveness factor for I-131

Distance Interval (miles)	Normal Activity[a]	Normal Activity 99% KI	Sheltering[b]	Sheltering 99% KI
0-5	73 (73)	46 (0)	76 (25)	29 (0)
5-10	231 (63)	75 (0)	158 (8)	46 (0)
10-25	735 (31)	168 (0)	403 (3)	102 (0)
25-50	836 (22)	177 (0)	448 (0)	107 (0)
50-100	995 (0)	214 (0)	520 (0)	129 (0)
100-150	473 (0)	108 (0)	247 (0)	64 (0)
150-200	280 (0)	68 (0)	147 (0)	41 (0)

[a]Shielding factors = 0.75 (cloud exposure) and 0.33 (ground exposure). 1-day exposure to ground contamination.

[b]Shielding factors and ground exposure same as for normal activity. Inhalation reduction factor = 0.5.

Table 7. Potential Reduction in Mean Number of Thyroid Nodules (Ablated Thyroids) by Use of KI. 99% effective KI is assumed. Numbers are determined from Table 6.

Distance Interval (miles)	Without 0.1 dose effectiveness factor for I-131		With 0.1 dose effectiveness factor for I-131	
	Normal Activity	Sheltering	Normal Activity	Sheltering
GAP w/o Isolation				
0-5	1.68	0.84	0.59	0.30
5-10	0.33	0.17	0.11	0.06
10-25	0.40	0.20	0.14	0.06
25-50	0.30	0.15	0.09	0.05
50-100	0.34	0.17	0.10	0.05
100-150	0.16	0.08	0.04	0.02
150-200	0.10	0.06	0.02	0.02
Core Melt Melt-Through				
0-5	1.98	0.99	0.57	0.28
5-10	0.44	0.22	0.12	0.06
10-25	0.54	0.27	0.15	0.07
25-50	0.42	0.21	0.11	0.06
50-100	0.45	0.22	0.12	0.06
100-150	0.23	0.12	0.05	0.03
150-200	0.16	0.08	0.03	0.02
Core Melt Atmospheric				
0-5	32 (137)	45 (92)	27 (73)	47 (25)
5-10	111 (292)	162 (146)	156 (63)	112 (8)
10-25	929 (610)	809 (102)	567 (31)	301 (3)
25-50	1920 (210)	1080 (30)	659 (22)	341 (0)
50-100	2740 (20)	1380 (0)	781 (0)	391 (0)
100-150	1460 (0)	732 (0)	365 (0)	183 (0)
150-200	916 (0)	458 (0)	212 (0)	106 (0)

99 percent effective KI (Table 6a). The difference between these two numbers (1.68) is the reduction afforded by using KI.

Accident Probabilities

The probability of occurrence estimated by the RSS[1] for the accident categories addressed in this analysis can be obtained from the data in Table 1.

	RSS Categories	Estimated Probability (per reactor-year)
GAP	PWR9	4×10^{-4}
GAP w/o Isolation	PWR8	4×10^{-5}
Core Melt Melt-Through	PWR6-7	4.6×10^{-5}
Core Melt Atmospheric	PWR1-5	1.4×10^{-5}

The RSS probabilities were used with the results in Table 7 to determine the potential reduction in the mean number of thyroid nodules per year of reactor operation by implementing a KI strategy. Those values, which are shown in Table 8, include contributions from all 3 of the accident categories considered.* Note that the contribution from the Core Melt Atmospheric category dominates (95-100%).

*The expected reduction per reactor year = $\sum_i$ (potential reduction)$_i$ (accident probability)$_i$, where i is the accident category.

Table 8. Potential Reduction[a] per Year of Reactor Operation in Mean Number of Thyroid Nodules[b] by Use of KI. 99% effective KI is assumed. RSS probabilities are assumed.

Distance Interval (miles)	Without 0.1 dose effectiveness factor for I-131		With 0.1 dose effectiveness factor for I-131	
	Normal Activity	Sheltering	Normal Activity	Sheltering
0-5	2.5×10^{-3}	2.0×10^{-3}	1.4×10^{-3}	$1.0 \times 10^{-}$
5-10	5.7×10^{-3}	4.3×10^{-3}	3.1×10^{-3}	1.7×10
10-25	2.2×10^{-2}	1.3×10^{-2}	8.4×10^{-3}	$4.3 \times 10^{-}$
25-50	3.0×10^{-2}	1.6×10^{-2}	9.5×10^{-3}	$4.8 \times 10^{-}$
50-100	3.9×10^{-2}	1.9×10^{-2}	1.1×10^{-2}	$5.5 \times 10^{-}$
100-150	2.0×10^{-2}	1.0×10^{-2}	5.1×10^{-3}	$2.6 \times 10^{-}$
150-200	1.3×10^{-2}	6.4×10^{-3}	3.0×10^{-3}	$1.5 \times 10^{-}$

[a]Reductions calculated from values in Table 7.

$$\text{Expected reduction per reactor-year} = \sum_i (\text{potential reduction})_i \, (\text{accident probability})_i,$$ where i is the accident category.

[b]Includes ablated thyroids.

The uncertainties in the probabilities used above are large. Error bounds of factors of 1/5 and 5 on the values above were estimated in the RSS. In 1978, the risk assessment review group (Lewis Committee),[8] chartered by NRC to review the Reactor Safety Study, concluded "We are unable to determine whether the absolute probabilities of accident sequences in WASH-1400 are high or low, but we believe that the error bounds on those estimates are, in general, greatly understated." Operating experience data for light water reactors (LWR) can also be used to estimate an <u>upper bound</u> for the probability of core melt.[21] Through the end of 1979, there had been approximately 450 years of LWR experience in the U.S., without a core melt event.*[22] Assuming a χ^2 distribution for such potential events, it can be shown that the probability of core melt is less than 1.5×10^{-3} with 50 percent confidence, and less than 6.7×10^{-3} with 95 percent confidence.**[21] These upper bound probabilities are approximately factors of 25 and 100 times the RSS values above ($4.6 \times 10^{-5} + 1.4 \times 10^{-5} = 6.0 \times 10^{-5}$).

Cost-Benefit Ratio

Combining the estimated costs and the results in Table 8, estimated cost-benefit ratios for the use of KI are presented

*Although the accident at Three Mile Island involved serious core damage, it was not a core melt event.

**Worldwide LWR experience through 1979 was closer to 1000 reactor-years.[21] Using this value rather than 450 years results in probability estimates of 7×10^{-4} with 50 percent confidence, and 3×10^{-3} with 95 percent confidence.

in Table 9 in terms of $ per nodule prevented, i.e., the expected number of dollars required to prevent a single thyroid nodule. The estimated ratios range from 3.2×10^5 $/nodule prevented (for the 0-5 mile interval, normal activity, and no 0.1 dose effectiveness factor for I-131) to 3.7×10^8 $/nodule prevented (f : the 150-200 mile interval, sheltering and 0.1 I-131 dose effectiveness factor).

Sensitivities

Table 10 summarizes a cost-benefit analysis performed specifically for the use of KI by children. The risk coefficient assumed, 668 per 10^6 person-rem,* is a factor of 2 higher than that assumed in Table 9. Other assumptions include: no 0.1 dose effectiveness factor for I-131, RSS accident probabilities, normal activity, and a uniform population density of 100 persons/mile^2. Only the Core Melt Atmospheric accident category was addressed. However, as shown earlier, this has a negligible effect on the predicted results. The cost-benefit ratios in Tables 9 and 10 are not significantly different for the intervals close to the reactor. This is because the doses within those intervals are sufficiently high to result in thyroid nodules for essentially all exposed individuals, regardless of the coefficient assumed. At larger distances, the cost-benefit ratio in Table 10 is a factor of 2 lower, as expected.

*This is also very close to the risk coefficient assumed by Beyea for adults (see Section 4).[3]

Table 9. Estimated Cost-Benefit Ratios for Use of KI ($ per nodule prevented[a]) 99% effective KI is assumed. RSS probabilities are assumed.

Distance Interval (miles)	Without 0.1 dose effectiveness factor for I-131: Normal Activity	Without 0.1 dose effectiveness factor for I-131: Sheltering	With 0.1 dose effectiveness factor for I-131: Normal Activity	With 0.1 dose effectiveness factor for I-131: Sheltering
0-5	3.2×10^{5}[b]	4.0×10^{5}	5.6×10^{5}	7.9×10^{5}
5-10	4.2×10^{5}[c]	5.6×10^{5}	7.7×10^{5}	1.4×10^{6}
10-25	7.3×10^{5}[d]	1.2×10^{6}	1.9×10^{6}	3.7×10^{6}
25-50	2.0×10^{6}[e]	3.7×10^{6}	6.2×10^{6}	1.2×10^{7}
50-100	6.2×10^{6}[f]	1.3×10^{7}	2.2×10^{7}	4.4×10^{7}
100-150	2.0×10^{7}[f]	3.9×10^{7}	7.6×10^{7}	1.5×10^{8}
150-200	4.2×10^{7}[f]	8.6×10^{7}	1.8×10^{8}	3.7×10^{8}

[a]Includes both nodules and ablated thyroids. Approximately 4% of the thyroid nodules will be fatal.
[b]Approximately 80% of the reduced thyroid damage cases are ablated thyroids, 19% are nodules and 1% are thyroid cancer fatalities (from Table 7).
[c]Approximately 70% are ablated thyroids, 29% are nodules and 1% are thryoid cancer fatalities.
[d]Approximately 40% are ablated thyroids, 58% are nodules and 2% are thyroid cancer fatalities.
[e]Approximately 10% are ablated thyroids, 86% are nodules and 4% are thyroid cancer fatalities.
[f]Approximately 96% are nodules and 4% are thyroid cancer fatalities.

Table 10. Cost-Benefit Analysis for Use of KI by Children. Assumptions: risk coefficient = 668 thyroid nodules per 10^6 person-rem to thyroid,[a] no 0.1 dose effectiveness factor for I-131, Core Melt Atmospheric accident category only, RSS accident probabilities.

Distance Interval (miles)	Thyroid Nodules[b] (mean)[c] Normal Activity	Normal Activity 99% KI	Potential Reduction[c]	Reduction (nodules/yr)[c]	Cost-Benefit Ratio ($/nodule prevented)
0-5	270	91	179	2.5×10^{-3}	3.2×10^{5}
5-10	625	157	468	6.5×10^{-3}	3.7×10^{5}
10-25	2510	361	2150	3.0×10^{-2}	5.3×10^{5}
25-50	4190	386	3800	5.3×10^{-2}	1.1×10^{6}
50-100	5930	467	5460	7.6×10^{-2}	3.2×10^{6}
100-150	3170	238	2930	4.1×10^{-2}	9.5×10^{6}
150-200	1980	151	1830	2.6×10^{-2}	2.1×10^{7}

---

[a] Includes age dose factors and risk coefficients from RSS (see Section 3).
[b] Includes both nodules and ablated thyroids.
[c] Assumes a uniform population density of 100 persons/mile^2.

Finally, Table 11 summarizes an identical analysis performed for children using the APS upper bound risk coefficient of 6500 thyroid nodules per 10^6 person-rem to the thyroid. In this case, the estimated cost-benefit ratios range from 4.9×10^5 \$/nodule prevented within 0-5 miles to 2.2×10^6 \$/nodule prevented within 150-200 miles. Note that the ratio for the 0-5 mile interval is actually higher than in Tables 9 and 10.*

The cost-benefit ratios given in each of the preceding tables were calculated for selected distance intervals from a single reactor. However, if there were two reactors at a particular site, the probability of an accident at that site would be twice as high and the cost-benefit ratio for each distance interval would be a factor of 2 lower. Similarly, in many areas of the U.S., several reactors at different sites may contribute to an individual's risk of thyroid damage. The extent to which this would reduce the cost-benefit ratio for KI depends on a number of factors, including the specific location with respect to neighboring plants, wind direction frequencies, reactor power levels, etc. For example, there are approximately 13 reactors** currently operating within 200 miles of New York City. Using

*For this assumed risk coefficient, the thyroid dose is still high enough to cause significant numbers of thyroid nodules, even with 99% effective KI.

**Reactors (power level ≥ 200 MWe) within 25-50 mile interval: Indian Point 2 and 3; 50-100 miles: Oyster Creek, Haddam Neck, Millstone 1 and 2; 100-150 miles: Salem, Vermont Yankee, Peach Bottom 2 and 3; 150-200 miles: Three Mile Island 1 and 2, Pilgrim.

POOR ORIGINAL

Table 11. Cost-Benefit Analysis for Use of KI by Children. Assumptions: APS[a] upper-bound risk coefficient for children of 6500 thyroid nodules per 10^6 person-rem to thyroid,[b] no 0.1 dose effectiveness factor for I-131, Core Melt Atmospheric accident category only, RSS accident probabilities.

Distance Interval (miles)	Thyroid Nodules[c] (mean)[d]				
	Normal Activity	Normal Activity 99% KI	Potential Reduction[d]	Reduction (nodules/yr)[d]	Cost-Benefit Ratio ($/nodule prevented)
0-5	374	262	112	1.6×10^{-3}	4.9×10^{5}
5-10	1020	586	434	6.1×10^{-3}	3.9×10^{5}
10-25	5590	2430	3160	4.4×10^{-2}	3.6×10^{5}
25-50	12,600	3500	9100	1.3×10^{-1}	4.5×10^{5}
50-100	31,600	4530	27,100	3.8×10^{-1}	6.3×10^{5}
100-150	28,400	2320	26,100	3.7×10^{-1}	1.1×10^{6}
150-200	19,300	1470	17,800	2.5×10^{-1}	2.2×10^{6}

[a] American Physical Society [8].
[b] Includes age dose factor of 5.0.
[c] Includes both nodules and ablated thyroids.
[d] Assumes a uniform population density of 100 persons/mile^2.

the data provided in Table 9 above, and ignoring wind direction frequencies and differences in reactor power level and design, the cost-benefit ratio specific to New York City can be estimated to be approximately a factor of 4 lower than if only the nearest reactor (Indian Point 1 or 2) was considered alone.* Similarly, for the city of Chicago (which has more than 10 operating plants within 200 miles), the cost-benefit ratio is approximately five times lower than the ratio if only a single reactor was considered.

7. Risk-Benefit Analysis

As discussed in Section 2, the risk posed by the use of KI as an emergency protective measure for reactor accidents was judged by the NCRP to be minimal. Nevertheless, a brief analysis is presented here to determine under what conditions, if any, the risk posed by the drug might outweigh its potential benefits.

Assuming a risk of adverse reaction of 10^{-6} per 130 mg tablet of KI (see Section 2) and that a total of 10 tablets would be administered to each person following an accident, the risk posed to that person by the drug equals 10^{-5}. To estimate the thyroid dose for which the potential benefit (reduced risk

*From Table 9, for normal activity and no 0.1 I-131 dose effectiveness factor, NYC cost-benefit ratio for a single Indian Point reactor = 2.0×10^6 \$/thyroid nodule. Including all 13 reactors:

$$\frac{1}{\text{cost-benefit ratio}} = \frac{2}{2.0\times10^6} + \frac{4}{6.2\times10^6} + \frac{4}{2.0\times10^7} + \frac{3}{4.2\times10^7}$$

and cost-benefit ratio = 5.2×10^5 \$/thyroid nodule.

of nodule occurrence) and risk of KI are equivalent, the following additional assumptions are made: risk coefficient for individual = 3.34×10^{-4}/rem, no 0.1 dose effectiveness factor for I-131, and 99 percent effective* use of KI reduces total thyroid dose by 90 percent.** Then $10^{-5} = 0.9 \times (3.34 \times 10^{-4}\text{/rem}) \times$ (equivalent dose), and the equivalent dose = 3×10^{-2} rem. What if other assumptions are made? Higher risk coefficients, such as those for children (see Section 3), would result in lower predicted equivalent doses. The administration of KI to everyone within 360° of a site, rather than only to exposed persons, would increase the equivalent dose. For example, if the radioactive plume was 15° wide, the equivalent dose would be a factor of 24 (i.e., 360/15) higher*** (= 0.8 rem). Assuming only 50 percent effective KI (rather than 99%), as well as 360° administration, the equivalent dose would become 2 rem. Finally, if a 0.1 dose effectiveness factor for I-131 is also assumed, the equivalent dose is increased to approximately 5 rem.****

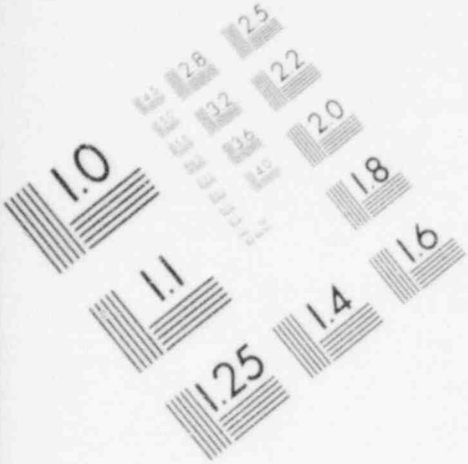
---

*99 percent reduction in dose from inhaled radioiodines.

**Actual percentage reduction depends on the composition of the release. For the accident categories addressed in this study, roughly 90 percent of the thyroid dose is due to inhaled radioiodines (see Table 5).

***24 times as many individuals would now take the drug. The adverse reaction risk would therefore be 24 times higher.

****I-131 contributes approximately 75 percent of the dose from inhaled iodines (see Table 5). With a 0.1 dose effectiveness factor, the effective dose from inhaled iodines is reduced by a factor of $(0.75)(0.1) + (0.25) = 0.33$. The potential benefit of 50 percent effective KI = $0.9\ (0.33)(0.5)(3.34 \times 10^{-4})$(equivalent dose). Setting this equal to $24\ (10^{-5})$, the equivalent dose = 5 rem.



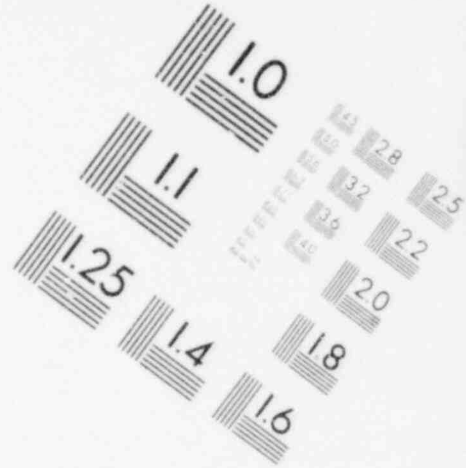
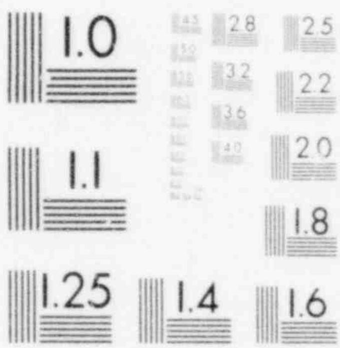


IMAGE EVALUATION
TEST TARGET (MT-3)



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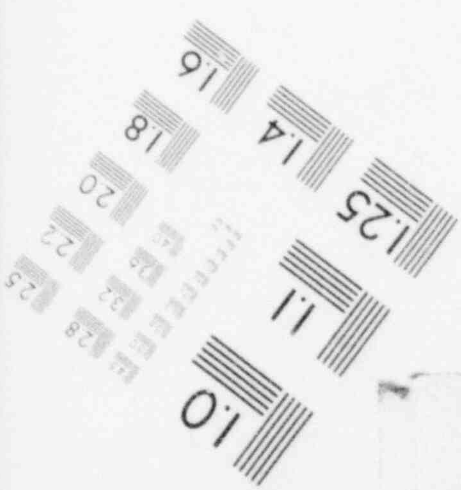
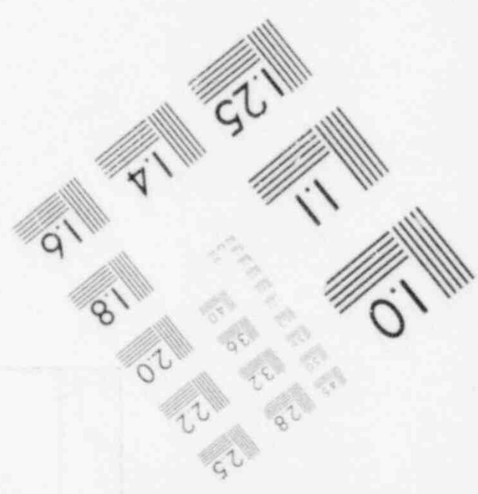
MICROCOPY RESOLUTION TEST CHART





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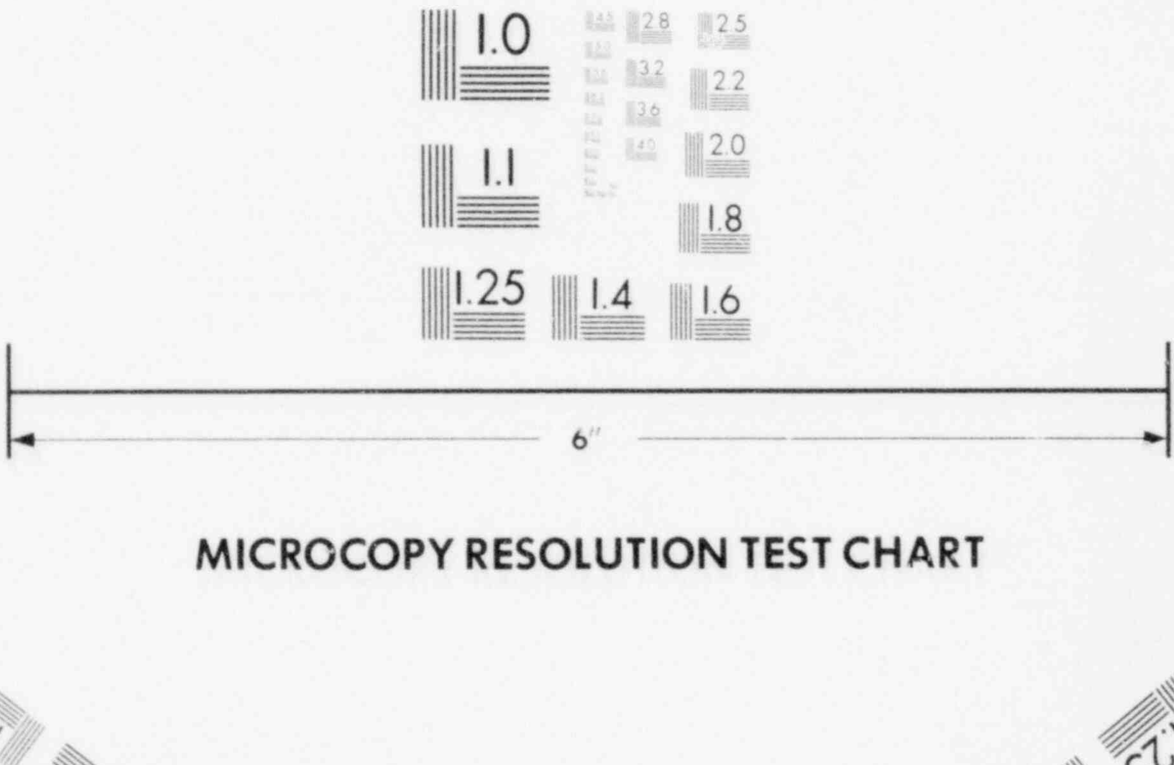

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The range of equivalent doses calculated above for various assumptions are all below the level recommended by the NCRP for use of KI (10 rem, see Section 2). Therefore, at the recommended level, the risk posed by the drug does appear to be small compared to its potential benefits.* However, several recent reports suggest that the risk associated with the drug may be significantly higher than 10^{-6} per dose for certain segments of the population.[23,24] If this is confirmed, the risk-benefit conclusion for KI would have to be reassessed.

8. Summary, Conclusions and Recommendations

This study was undertaken to provide guidance to policy-makers concerning the use of potassium iodide (KI) as an emergency protective measure for reactor accidents. Although the effective use of KI could significantly reduce the number of thyroid nodules resulting from a serious accident, it would have no, or only minor, impact on other accident consequences; including immediate deaths or injuries, delayed cancer deaths, and long-term land contamination. Therefore, the availability of KI would provide only a supplemental strategy to be considered along with other possible protective measures.

The study was performed using the Reactor Safety Study (WASH-1400) consequence model, CRAC. Four categories of accidents were addressed: gap activity release accidents (GAP), GAP without

*If the adverse reaction risk was 10^{-7} rather than 10^{-6} per dose (see Section 2), the risk posed by KI would be minimal compared to its potential benefits.

containment isolation (GAP w/o Isolation), core melt with a melt-through release (Core Melt Melt-Through) and core melt with an atmospheric release (Core Melt Atmospheric). A series of thyroid dose calculations showed that the GAP category does not pose a significant health hazard to the public at any distance from the reactor. For the GAP w/o Isolation and Core Melt Melt-Through categories, doses in excess of recommended protective action guidance levels (PAGS)(5-25 rem) are confined to areas within approximately 10 and 15 miles of the reactor, respectively. For the Core Melt Atmospheric category, however, thyroid doses are likely to exceed PAGs out to 100's of miles.

A cost-benefit analysis for the use of KI was also performed, the results of which are summarized in Table 12. Cost-benefit ratios ($ per thyroid nodule prevented) are presented for selected distance intervals, assuming that no other protective measures are taken. The effect of evacuation and sheltering on the predicted ratios is shown in Table 9 and is discussed in Section 5. Evacuation has the potential to be 100% effective in reducing all dose if accomplished before arrival of the radioactive cloud. Sheltering was assumed in this analysis to provide a factor of 2 reduction in thyroid dose. Therefore, in both cases, the thyroid dose reduction afforded by the supplemental use of KI would be reduced, and the KI cost-benefit ratios presented in Table 12 would be correspondingly increased.

The uncertainties in the estimated cost-benefit ratios are very large. Key assumptions made in deriving the ratios are noted in Table 12. The KI was conservatively assumed to be 99%

Table 12. Summary Table for KI Cost-Benefit Analysis[a,b] (from Table 9)

Distance Interval (miles)	Normal Activity Cost-Benefit Ratio ($/thyroid nodule prevented
0-5	3×10^5
5-10	4×10^5
10-25	7×10^5
25-50	2×10^6
50-100	6×10^6
100-150	2×10^7
150-200	4×10^7

[a]Key Assumptions

1. 99% effective KI (i.e., all persons take drug before cloud passes).
2. No other protective measures are taken.
3. WASH-1400 accident probabilities.
4. Estimated cost of KI program = $0.10 per person per year. Assumed cost includes only the purchase price of KI, i.e., no costs for distribution, monitoring and administrative expenses.
5. Only 1 reactor (3200 MWt PWR) within 200 miles.
6. WASH-1400 dose-effects coefficients (no 0.1 effectiveness factor for I-131 dose).

[b]Uncertainties are large and scale approximately linearly with assumed KI effectiveness, accident probabilities, cost, multiple reactors, and dose-effects coefficients.

effective (i.e., all persons take the drug before the cloud passes). Realistic effectiveness values could be significantly smaller. WASH-1400 accident probabilities were assumed. Probability uncertainties have been estimated to be at least an order of magnitude (see Section 6). Estimated costs for a KI program were conservatively based on only the purchase price of the drug and did not include costs for distribution, monitoring, and administrative expenses. The ratios presented in Table 12 are appropriate if there is only a single reactor within 200 miles. Many actual sites would be influenced by several reactors, and cost-benefit ratios could be reduced by factors of 2 to 5 (see Section 6). Uncertainties in dose and health effects parameters are also large and could result in either higher or lower cost-benefit ratios.

To some extent, the large uncertainties in the above assumptions hinder our ability to provide definitive guidance. Nevertheless, for the assumptions made, the calculated cost-benefit ratios are high; and even including uncertainties, KI appears to be only marginally cost-effective, at best.*

Finally, using statistics provided by the NCRP[4], a simple risk-benefit analysis showed the risk of adverse reaction posed by KI at the recommended action levels and dosages to be small compared to its potential benefits. However, several recent

*Although the total cost associated with a case of thyroid nodules was not specifically addressed, an approximate upperbound of $17,000 can be inferred from the information presented in reference 25 assuming 1) average hospital care costs of $2,000, 2) that hospital costs are 60% of all direct costs, and 3) that indirect costs (economic losses due to mortality and morbidity) are 4 times higher than direct costs.

reports suggest that there is a significantly higher risk associated with use of the drug among certain segments of the population.[23,24] If this is confirmed, the risk-benefit conclusion for KI would have to be reassessed.

Based on the above analysis, the following additional recommendations and comments are made:

- The risk of thyroid nodules was shown to be dominated by the large releases associated with core melt accidents in which the containment fails directly to the atmosphere. Therefore, if design modifications, such as filtered containment venting systems, are implemented to reduce the likelihood of those releases, the potential benefit of KI could be substantially reduced.
- Before any KI program is implemented, specific alternative strategies for stockpiling and distributing the drug should be examined to reduce costs and assure effectiveness.
- The use of common household items (e.g., handkerchiefs and towels) as respiratory filters may provide significant additional protection against dose due to inhaled radionuclides and should be considered further in the development of protective strategies.
- If a KI program is implemented, responsible government agencies should give priority to establishing guidance (PAGs) concerning when, or under what conditions, the drug should be used.

- Finally, whether or not a public KI program is implemented, it might be wise to have sufficient quantities of the drug available at or near reactor sites for use by 1) site personnel, 2) offsite emergency response personnel, and 3) controlled populations in offsite institutions (e.g., hospitals, prisons) where immediate evacuation would be difficult or infeasible.

8

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DISTRIBUTION:

Roger Blond (50)
Probabilistic Analysis Staff
Office of Nuclear Regulatory Research
USNuclear Regulatory Commission
Washington, DC 20555

A. Bayer
INR-Kernforschungszentrum Karlsruhe
75 Karlsruhe 1
Postfach 3640
West Germany

Douglas Cooper
Department of Environmental Health Physics
Harvard School of Public Health
663 Huntington Avenue
Boston, MA 02215

Keith Woodward
Picard & Lowe Associates
1200 18th Street NW
Washington, DC 20036

Joseph Logsdon
US Environmental Protection Agency
AW 461
401 M Street NW
Washington, DC 20024

S. Chakraborty
Abteilung fur die Sicherheit der Kernanlagen
Eidgenossisches Amt fur Energiewirtschaft
CH-5303 Wurenlingen
Switzerland

N. Rasmussen
Nuclear Engineering Department
Massachusetts Institute of Technology
Cambridge, MA 02139

Dr. Ulf Tveten
Institutt for Atomenergi
PO Box 40
2007 Kjeller
Norway

Dr. Seppo Vuori
Valtion Teknillinen Tutkimuskeskus
Statens Tekniska Forskningscentral
Helsinki
Finland

Dr. Rosalyn S. Yalow
Montefiore Hospital and Medical Center
111 East 210th Street
Bronx, NY 10467

Dr. Frank von Hippel
Center for Environmental Studies
Princeton University
Princeton, NJ 08544

Dr. Thomas Fearon
National Councail on Radiation
Protection and Measurements
7910 Woodmont Avenue, Suite 1016
Washngton, DC 20014

Prof. Richard Wilson
Department of Physics
Harvard University
Cambridge, MA 02138

H. Arnold
Secretary of Health
Commonwalth of Pennsylvania
802 Health and Welfare Bldg.
Harrisburg, PA 17120

Dr. H. L. Gjorup
Health Physics Department
Riso National Laboratory
DK-4000 Roskilde
Denmark

Prof. Niel Wald
Graduate School of Public Health
University of Pittsburgh
RC510 Scaife Hall
Pittsburgh, PA 15261

Brian Grimes (10)
Office of Nuclear Reactor Regulatory
US Nuclear Regulatory Commission
545 Phillips
Washington, DC 20555

J. Schutz-Larsen
Arvebiologisk Institut
Tagensverj 14
KD-2200 Copenhagen N
Denmark

Bernard Cohen
University of Pittsburgh
Faculity of Arts and Sciences
Department of Physics
Pittsburgh, PA 15260

Pfo. Dade Moeller (3)
Department of Environmental Health Physics
Harvard School of P[illegible]lic Health
663 Huntington Avenue
Boston, MA 02215

Dr. Bernard Shleien (5)
Bureau of Radiological Health
HFX-460
5600 Fishers Lane
Rockville, MD 20857

Dr. Eugene L. Saenger
Eugene L. Saenger Radioisotope Laboratory
Cincinnati General Hospital
234 Goodman Street
Cincinnati, OH 45267

Dr. F. Horsch
Projekt Nukleare Sicherheit
Kernforschungszentrum Karlsruhe GmbH
Postfach 3640
D-7500 Karlsruhe 1
West Germany

Mr. T. Iijima
Division of Reactor Safety Evaluation
Tokai Research Establishment
Japan Atomic Energy Research Institute
Tokai-mura
Ibaraki-ken 911 13
Japan

Jim Martin
Probabilistic Analysis Staff
US Nuclear Regulatory Commission
Washington, DC 20555

Dr. G. N. Kelly (3)
National Radiological Protection Board
Harwell, Didcot
Oxfordshire OX 11 ORQ
England

Mr. C. Devillers
Chef du Service d'Etudes de Surete
Radiologique et des Sites
Centre d'Etudes Nucleaires
BP No. 6
F-92260 Fontenay-aux-Roses
France

E. C. Watson
Battelle Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

Dr. Ian Wall
Nuclear Safety and Analysis Department
Electric Power Research Institute
3412 Hillview Avenue
PO Box 10412
Palo Alto, CA 94303

Pfo. Yasushi Nishiwaki
Jagdschlossgasse 91
A-1130 Vienna
Austria

Dr. Jan Beyea
National Audubon Society
950 Third Avenue
New York, NY 10022

Harold Collins (100)
Office of State Programs
US Nuclear Regulatory Commission
7713 MNBB
Washington, DC 20555

Dr. G. D. Kaiser
United Kingdom ATomc Energy Authority
Safety and Reliability Directorate
Wigshaw Lane
Dulcheth
Warrington WA 3 4NE
Chesnire
England

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