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RADIATION PROTECTION: AN ANALYSIS OF THYROID BLOCKING

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Abstract

An analysis has been performed to provide guidance to policymakers concerning the effectiveness of potassium iodide (KI) as a thyroid blocking agent in potential reactor 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, and core melt with an atmospheric release. Cost-benefit ratios (US $/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 of other potential protective measures, such as evacuation and sheltering, and the impact on children (critical population) are evaluated. Finally, risk-benefit considerations are briefly discussed.

1. Introduction

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. This paper summarizes a study [1] performed at the request of the U.S. Nuclear Regulatory Commission to provide technical guidance on that issue. The objectives of the study were to determine 1) the effectiveness of potassium iodide (KI)[1] as a thyroid blocking agent in realistic

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[1] Radiological emergency plans in Great Britian include thyroid blocking using tablets of potassium iodate which, in the British experience, have an appreciably longer shelf-life than iodide tablets. The iodate form could be employed in the U.S. only by compliance with Food and Drug Administration (FDA) requirements that include gathering pertinent clinical data on the use of the drug.

accident situations, 2) the distance to which (or area within which) it should be distributed, 3) the conditions under which it should be implemented, and 4) its relative effectiveness compared to other available protective measures. The analysis was performed using the Reactor Safety Study (WASH-1400) consequence model [2,3], CRAC, for a range of potential reactor accidents; from fuel pin gap activity release accidents to complete core meltdowns with containment failure directly to the atmosphere. 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. To some extent, these uncertainties hinder our ability to provide definitive guidance. However, they are addressed to the extent possible in our analysis.

2. Background

2.1 Potassium Iodide (KI) as Protective Measure

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. Taken in large enough quantities, KI acts to block the absorption of radioiodines by the thyroid, reducing the thyroid dose.[2] 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]. However, use of KI is not the only protective action that will reduce thyroid dose, nor is it without its difficulties and problems:

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[2] The effectiveness of the block is strongly influenced by how rapidly the KI is administered. Essentially complete curtailment (90% or greater) of radioiodine uptake by the thyroid requires that the drug 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 [4].

-- 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.

-- There are serious 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.

There is presently no definitive guidance in the U.S. 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 [5]. 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 and controlled area access were discussed in the EPA document, and the use of KI was not specifically cited as an appropriate protective measure.

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. An alternative would be to provide each household with a sufficient supply for all members of the household. The feasibility, effectiveness and implementation costs of these and other alternative strategies should be investigated.

2.2 Thyroid Health Effects

There is considerable uncertainty concerning the effects of radiation exposure on the thyroid [2,4,6]. Thyroid nodules are the effect of primary concern and would typically be observed from 10 to 40 years after exposure. 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. WASH-1400 conservatively assumed a 10 percent mortality rate for malignant thyroid nodules.

Based on the results of animal experiments and clinical data for humans, WASH-1400 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.[3] This factor of 0.1 for I-131 dose was disputed by the American Physical Society (APS) study group on reactor safety [6], which assumed a range of factors from 0.3 to 1.0. Because this issue remains unresolved, calculations were performed in this analysis both with and without a 0.1 factor for I-131 dose effectiveness.

Sufficiently high radiation doses[4] would result in ablation of the thyroid with no subsequent risk of either benign or malignant nodules. 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.

WASH-1400 assumed an incidence rate of 334 thyroid nodules per 10^6 person-rem, of which 60 percent are benign and 40 percent are malignant. The dose-effects coefficient for a child's thyroid can be derived from WASH-1400 data to be approximately a factor of 2 higher. Others [7] have assumed incidence rates as high as 650 thyroid nodules per 10^6 person-rem for adults, and 6500 thyroid nodules per 10^6 person-rem for children. The calculations performed in this study assume the WASH-1400 risk coefficient of 334 thyroid nodules per 10^6 person-rem. The effect of uncertainty in the thyroid dose-effect relationship was assessed by repeating some calculations using the highest incidence rates proposed.

2.3 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. WASH-1400 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.

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[3] 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.

[4] On the order of 3000 to 5000 rem [1].

For the purpose of this study, the PWR accident release spectrum was further grouped into four categories:

	WASH-1400 Release Categories
1. Gap Activity Release Accident (GAP)	PWR9
2. Gap Activity Release Accident without Containment Isolation (GAP without 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, hydrogen burning, or overpressure. To reduce the required time and cost of computation, BWR accidents were not 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.

3. Results and Conclusions

3.1 Thyroid Dose Calculations

A series of calculations was performed using CRAC [2,3] to determine 1) the magnitude of the threat to the thyroid of 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 [2] and used to generate probability distributions of thyroid dose versus distance. Breathing rate and shielding parameters appropriate for a person located outdoors were assumed: breathing rate = 2.66×10^{-4} m^3/s, shielding factors

= 1.0 (cloud exposure) and 0.7 (ground exposure). Thyroid dose was 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 was not included because those pathways would not require an immediate emergency response in the event of an accident.

The probabilities of exceeding thyroid doses of 0.01 and 0.1 rem versus distance from the reactor are shown in Figure 1A, conditional on the occurrence of a gap activity release accident (GAP). 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 1B and 1C show the probability of exceeding thyroid doses of 1, 5 10 and 25 rem versus distance for the GAP without Isolation and Core Melt Melt-Through accidents. The 5, 10 and 25 rem dose levels represent the range of action levels that have been recommended in the US 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 kilometers (10's of miles) of the reactor for these types of accidents, and in most cases to areas considerably closer. For the GAP without Isolation accidents, doses in excess of 5 rem are confined to about 16 kilometers (10 miles); those in excess of 25 rem to about 8 kilometers (5 miles). The same dose levels are confined to approximately 24 and 11 kilometers (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 1D. 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.

Further analysis indicated that the thyroid dose is dominated by the inhalation of radioiodines for each of the four accident categories. Inhalation of I-131 alone accounts for 60-80 percent of the total dose, and other iodines contribute another 10-25 percent. Inhalation of non-radioiodines, cloud exposure and ground exposure are all small contributors to total thyroid dose.

3.2 Cost-Benefit Analysis

The decision to use 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 reduction in accident impacts afforded by the use of KI; 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 benefit of KI would be a reduction in the number of thyroid nodules that would occur following a major release of radioactive material. 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 results of our analysis are summarized in Table I in terms of cost-benefit ratios (US $ per thyroid nodule prevented) for selected distance intervals from a single 3200 MWt PWR. The uncertainties in the estimated ratios are very large. Key assumptions made in their derivation are noted in the table. Calculations were performed using CRAC in the same manner as described in the preceeding section. The KI was conservativel assumed to be 99% effective in reducing thyroid dose from inhaled radioiodines (i.e., all persons take the drug before or immediately after the cloud passes). Realistic effectiveness values could be significantly smaller. WASH-1400 accident probabilities were assumed.[5] Probability uncertainties have been estimated to be at least an order of magnitude [1]. Stockpiling, distribution, monitoring and administrative costs for a KI program would depend on the specific strategy of implementation

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[5] WASH-1400 probabilities: GAP (PWR9) $4\text{x}10^{-4}$, GAP without Isolation (PWR8) $4\text{x}10^{-5}$, Core Melt Melt-Through (PWR6-7) $4.6\text{x}10^{-5}$, and Core Melt Atmospheric (PWR1-5) $1.4\text{x}10^{-5}$ per reactor-year. Note that even though the probability of the Core Melt Atmospheric (PWR1-5) category is small, it dominates (95-100%) the risk of thyroid nodules.

and are difficult to estimate. Therefore, only the original purchase and replacement costs of the drug were included in this analysis.[6] The ratios presented in Table I are appropriate if there is only a single reactor within 200 miles. Many actual locations would be influenced by several reactors, and cost-benefit ratios could be reduced by factors as high as 5 in the US [1].

Uncertainties in dose and health effects parameters are also large and could result in either higher or lower cost-benefit ratios. The values in Table I assume WASH-1400 dose-effects coefficients without a 0.1 effectiveness factor for I-131 dose. If the 0.1 factor is assumed, the estimated ratios range from $6x10^5$ \$/nodule prevented within 0-8 km to $2x10^8$ \$/nodule prevented within 240-320 km. Using the upper bound risk coefficient of 6500 thyroid nodules per 10^6 person-rem for children [7] (no 0.1 I-131 dose effectiveness factor), the estimated ratios range from $5x10^5$ \$/nodule prevented within 0-8 km to $2x10^6$ \$/nodule prevented within 240-320 km.

Finally, the cost-benefit ratios in Table I assume that no other protective actions are taken. However, other protective measures, including both evacuation and sheltering, can also act to reduce thyroid dose. Evacuation has the potential to be 100% effective in reducing all dose if accomplished before arrival of the radioactive cloud. On the other hand, it could be ineffective 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 [8]. Therefore, in either case, the thyroid dose reduction afforded by the supplemental use of KI could be reduced, and the KI cost-benefit ratios presented in Table I could be correspondingly increased.

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.

3.3 Risk-Benefit Considerations

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-

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[6] The estimated cost of \$0.10 (US) per person per year assumes a purchase price of \$0.50 per individual (14 tablets in a bottle) and a shelf-life of five years.

term use of the relatively low doses that would be involved with response to an accident has been judged by some to be minimal. The NCRP [4] estimated the adverse reaction rate to be between $1x10^{-7}$ and $1x10^{-6}$ per dose, and concluded that the administration of KI would not result in significant immediate side effects, even if given to large segments of the population. Using the values proposed by the NCRP, 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 [1]. However, several recent reports [9,10] suggest that there may be a significantly higher risk associated with use of the drug among certain segments of the population. If this is confirmed, the risk-benefit conclusion for KI would have to be reassessed.

4. Comments and Recommendations

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

- 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 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 (e.g., 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.

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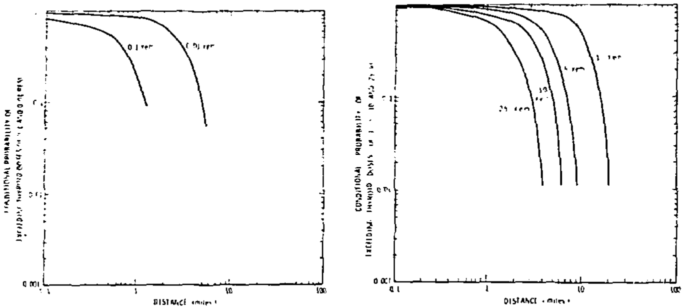
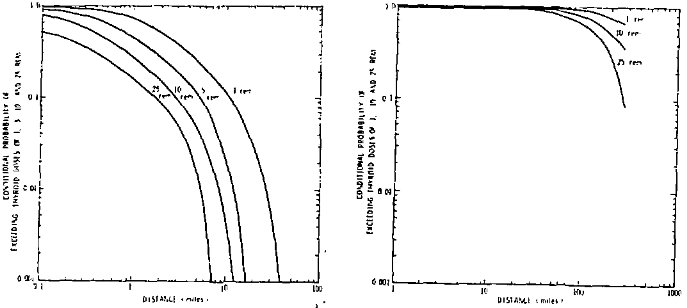


1A. GAP

1B. GAP without Isolation



1C. Core Melt Melt-Through

1D. Core Melt Atmospheric

Figure 1. Conditional Probability of Exceeding Indicated Thyroid Doses for an Exposed Adult[a] Located Outdoors. Probabilities are Conditional on Either a Gap Activity Release (GAP) (1A), GAP without Isolation (1B), Core Melt Melt-Through (1C), or Core Melt Atmospheric (1D) Accident.

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[a] The dose for an exposed child would be approximately a factor of 2 higher because of differences in thyroid mass, breathing rate, fractional iodine uptake, and metabolic rate [2].

Table I. Summary Table for KI Cost-Benefit Analysis[a,b]

Distance Interval (kilometers)	(miles)	Cost-Benefit Ratio (US $/thyroid nodule prevented)
0-8	0-5	3×10^5
8-16	5-10	4×10^5
16-40	10-25	7×10^5
40-80	25-50	2×10^6
80-160	50-100	6×10^6
160-240	100-150	2×10^7
240-320	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.