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Quantitative Evaluation of Potassium Iodide Implementation Strategies for Emergency Preparedness and Response

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ABSTRACT

This study evaluates the effectiveness of potassium iodide (KI) distribution strategies in mitigating exposure to radioiodine during severe nuclear power plant accidents. This analysis quantitatively compares various KI distribution methods (pre-distributed versus stockpiles), including scenarios with and without KI administration. The results indicate that differences in distribution strategies impact the projected thyroid dose by at least an order of magnitude. The results also indicate that the timing of KI administration is critical, as expected. For scenarios involving delayed releases of significant quantities of radionuclides, evacuation is the most effective protection strategy regardless of KI distribution method. For scenarios involving rapid releases, retrieving KI from stockpiles can have a detrimental effect. Pre-distributed KI is potentially the most effective approach when used as a supplement to evacuation and sheltering. However, these model results are based on idealized conditions for KI distribution and administration; the actual benefits of KI prophylaxis are likely to be less than estimated in this report due to many variables. The results highlight the importance of considering the cost and rigor of different distribution programs and public compliance with emergency instructions. This report includes suggested research to explore KI distribution plans for advanced reactors.

ACKNOWLEDGEMENTS

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ACRONYMS AND TERMS

Acronym/Term	Definition
A-Thyroid	Acute thyroid dose
CD	Centralized dispensary
CRC	Community reception center
DD	Distributed dispensary
EPZ	Emergency Planning Zone
GE	General Emergency
ICRP	International Commission on Radiological Protection
ISLOCA	Interfacing Systems Loss of Coolant Accident
KI	potassium iodide
L-Thyroid	Lifetime thyroid dose
LTSBO	Long-Term Station Blackout
NAS	National Academy of Sciences
SAE	Site Area Emergency
SIP	sheltering-in-place
SOARCA	State-of-the-Art Reactor Consequence Analyses
STSBO	Short-Term Station Blackout
TED	Total effective dose
TISGTR	Thermally Induced Steam Generator Tube Rupture

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1. INTRODUCTION

Human exposure to radioiodine—whether through inhalation, external exposure, or ingestion of contaminated food products—can pose health risks, particularly to the thyroid when taken internally. This exposure can lead to radiation injury and increased risk of thyroid cancer and other related diseases. Nuclear reactors contain substantial amounts of radioactive iodine, and in the event of an accident that releases significant quantities of radioactive material into the environment, the surrounding public faces heightened risks of thyroid-related injuries and cancer [1]. Ingesting potassium iodide (KI) can mitigate these risks by effectively blocking the thyroid's uptake of radioactive iodine.

The U.S. Nuclear Regulatory Commission regulations in 10 CFR 50.47(b)(10) require the consideration of KI as a supplement to evacuation and sheltering. Additionally, Federal KI policy (67 FR 1355, dated January 10, 2002) recommends State and local authorities consider using KI for emergency workers, institutionalized persons and the general public. As such, emergency planning and response initiatives for nuclear power plants across the U.S often include KI distribution and ingestion plans. The effectiveness of KI in blocking radioiodine exposure is highly dependent on the timing of its administration relative to the first exposure to radioiodine, the availability of KI during an emergency, and whether the thyroid is already saturated with stable iodine before KI administration, among other factors. State and local emergency response plans across the U.S. feature different KI distribution strategies, which can significantly influence all aspects of administration and ingestion by the public during an accident.

Distribution methods can be categorized as either pre-distributed—where KI is administered before an accident occurs—or stockpiled, where KI is provided at fixed locations after an accident has begun. Each method has advantages and disadvantages concerning control of storage conditions, record keeping, resource requirements, and timing of ingestion. For instance, stockpiling does not work well in rare instances when evacuation would be impractical or delayed since the public may not be able to access the stockpile locations [1].

The optimal approach to KI distribution and ingestion remains uncertain [1] [2]. These uncertainties could lead to increased costs and nonradiological harm for no substantive increase in radiological protection. There are limited quantitative analyses on the efficacy of the various KI strategies. However, this uncertainty can be addressed through quantitative analyses using models such as the MACCS code [3], which can evaluate the efficacy of KI strategies in comparison to evacuation and sheltering. Given the variability in effectiveness among different distribution methods, this study aims to quantitively compare these strategies, including the scenario of not administering KI at all, to evaluate their potential effectiveness across various accident scenarios and to better inform KI use moving forward.

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2. METHODOLOGY

Version 4.2 of the MACCS code was used [3] to conduct this analysis. A majority of the modeling parameters replicate those described in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Surry integrated analysis [4]. Since the SOARCA analysis was completed over ten years ago, some model inputs were updated to be more consistent with recommendations in the MACCS technical bases for consequence analysis [5]. Specifically, the most up to date dose coefficient file was used as well as the Eimutis and Konicek dispersion look up tables, and the Regulatory Guide 1.145 plume meander model was turned on. The following sections summarize the pertinent inputs and assumptions used in this analysis.

2.1. Accident Scenarios

To evaluate the different distribution strategies for various accident scenarios, four source terms were analyzed, each with varying amounts of iodine released and atmospheric release timing. These source terms were taken from the SOARCA Surry integrated analysis and include: Short-Term Station Blackout (STSBO), Long-Term Station Blackout (LTSBO), Interfacing Systems Loss of Coolant Accident (ISLOCA), and Thermally Induced Steam Generator Tube Rupture (TISGTR).

Each accident scenario is described in detail in the SOARCA analysis [4]. A summary of the release characteristics for each source term is provided in Table 2-1. This table displays the release fractions for each chemical group and the atmospheric release start and end time. The ISLOCA scenario releases the most iodine and the LTSBO releases the least. The TISGTR scenario has the earliest release, starting roughly three hours after accident initiation and the LTSBO has the longest delay before release begins, with releases to the atmosphere not starting until 45 hours after accident initiation. It should be noted all four scenarios analyzed are the unmitigated release scenarios (i.e., the set of scenarios that the SOARCA study did not give credit for key operator actions that, if successfully completed, would prevent, reduce, or delay release). This is a highly unlikely scenario but a necessary and conservative modeling assumption to see clear implications of various KI strategies.

Table 2-1: Source term release fraction and atmospheric release timing comparison.

Scenario	Integral Release Fractions by Chemical Class									Atmospheric Release Timing	
	Xe	Cs	Ba	I	Te	Ru	Mo	Ce	La	Start (hr)	End (hr)
STSBO	5.18E-01	1.00E-03	0	6.00E-03	6.00E-03	0	0	0	0	25.5	48.0
TISGTR	5.92E-01	4.00E-03	0	9.00E-03	7.00E-03	0	1.00E-03	0	0	3.6	48.0
LTSBO	5.37E-01	0	0	3.00E-03	6.00E-03	0	0	0	0	45.3	72.0
ISLOCA	9.83E-01	2.00E-02	0	1.54E-01	1.32E-01	0	3.00E-03	0	0	12.8	48.0

2.2. Emergency Response

The sheltering and evacuation framework utilized in the Surry SOARCA analysis is used here to illustrate a realistic emergency response scenario. Based on this framework, a 10-mile Emergency Planning Zone (EPZ) was established around the site, along with a 20-mile evacuation movement zone. For all four accident scenarios, a consistent notification delay was applied. Specifically, upon the initiation of an accident, a Site Area Emergency (SAE) is declared within 15 minutes. Subsequently, a General Emergency (GE) is declared 1 hour and 45 minutes later, followed by the activation of sirens 45 minutes thereafter. This results in a cumulative notification delay of 2 hours and 45 minutes.

While the original SOARCA analyses contain multiple cohorts for various population groups, for simplicity, this analysis focuses on the public within 0-10 miles from the site. The sheltering and evacuation times used for each KI distribution scenario are described in more detail in the following section. Relative cohort parameters are provided in Table 2-2. The same shielding and exposure factors are applied for sheltering and mobilization activities. The network evacuation scheme used in SOARCA was also implemented as shown in Figure 2-1.

Table 2-2: General public cohort parameters.

<table>
<tr><th>Parameter</th><th colspan="4">Value</th></tr>
<tr><td>Evacuation Phase Durations</td><td colspan="4">Beginning: 0.25 hour
Middle: 9.25 hour</td></tr>
<tr><td>Evacuation Speeds</td><td colspan="4">Initial: 5 mph
Middle: 1 mph
Late: 20 mph</td></tr>
<tr><td>Shielding and Exposure Factors</td><td>Cloudshine
Normal: 0.68
Sheltering: 0.60
Evacuation: 1</td><td>Inhalation
Normal: 0.46
Sheltering: 0.33
Evacuation: 0.98</td><td>Groundshine
Normal: 0.26
Sheltering: 0.20
Evacuation: 0.50</td><td>Skin Deposition
Normal: 0.46
Sheltering: 0.33
Evacuation: 0.98</td></tr>
<tr><td>Breathing Rate</td><td colspan="4">2.66E-04 m^3/s</td></tr>
</table>

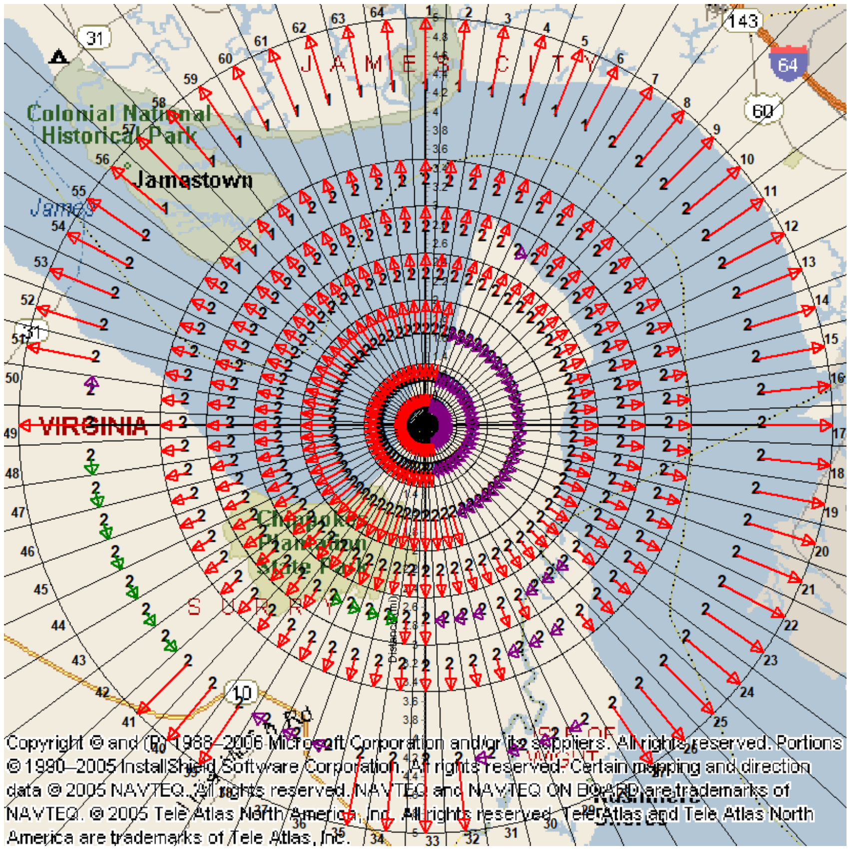


Figure 2-1: Network evacuation scheme (0-5 miles). Red indicates outer movement; purple, movement to the right; green, movement to the left.

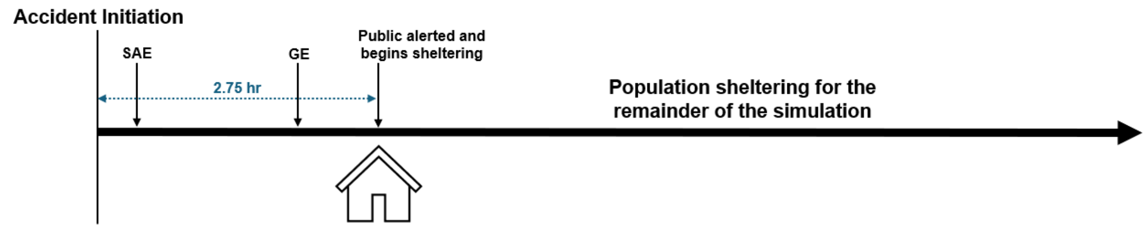
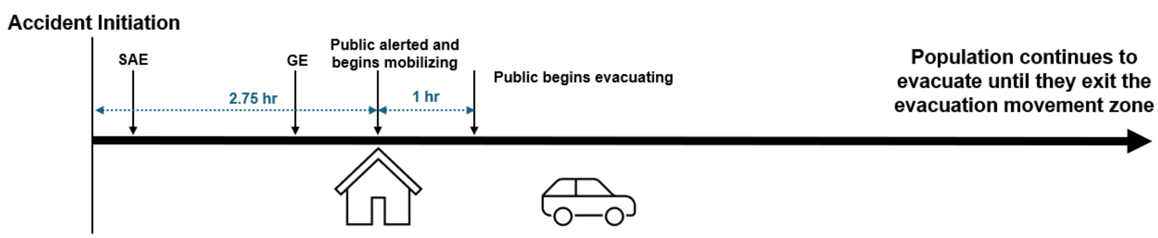
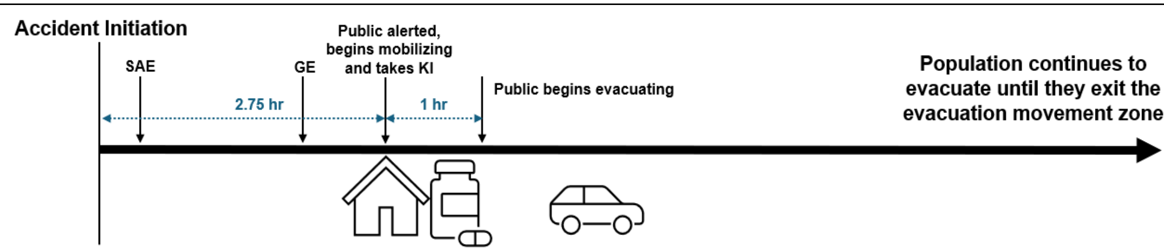
2.3. Potassium Iodide Distribution Scenarios

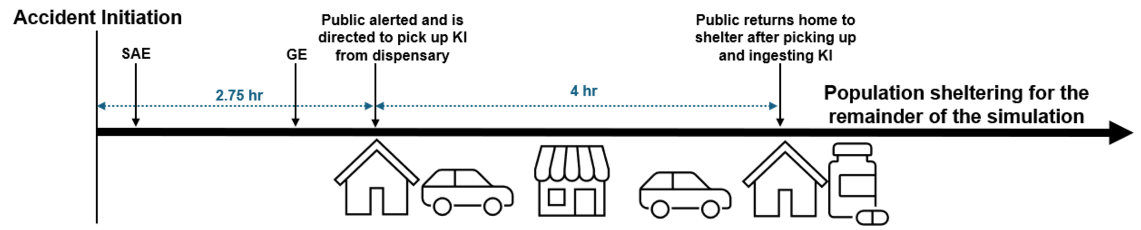
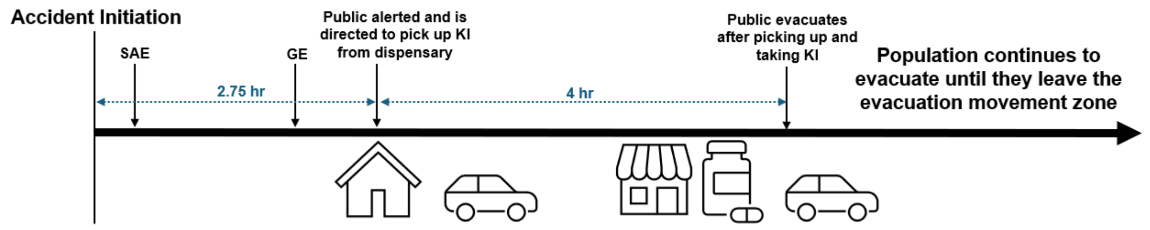
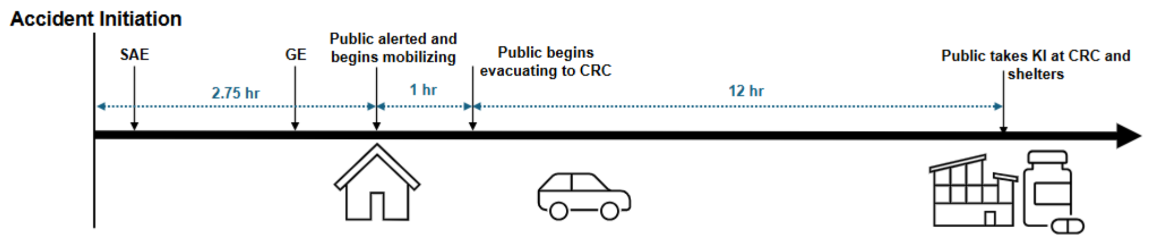
Four different KI distribution methods are assessed.

- No KI distribution.
- Pre-distribution of KI in which the public residing within the EPZ has already been provided KI prior to the accident.
- KI stockpile available at various distributed dispensary (DD) locations around the EPZ at the time of the accident. In this scenario, it is expected that the public would be directed to pick up the KI at one of the available locations upon notification of the accident.
- KI stockpile through a centralized dispensary (CD) at the community reception center (CRC) during the accident. The CRC is assumed to be a location the public is directed to evacuate to and is outside of the evacuation movement zone.

Depending on the accident scenario, evacuation may be impractical and sheltering-in-place (SIP) until the plume passes may be recommended. Therefore, both protective actions are assessed in this study. For the KI stockpile scenarios from a distributed dispensary, it is assumed it takes four hours for the public to pick up the KI before SIP or evacuating the EPZ. To demonstrate the effectiveness of different KI distribution methods in conjunction with plausible protective actions that may be implemented, seven cases were developed for comparison and are displayed in Table 2-3.

Table 2-3: KI distribution scenario actions for each case.

Case	Scenario Actions
1: No KI, SIP	
2: No KI, mobilization, subsequent evacuation	
3: Pre-distributed KI, SIP	
4: Pre-distributed KI, mobilization, subsequent evacuation	

Case	Scenario Actions
5: KI stockpile (DD), SIP	
6: KI stockpile (DD), mobilization, subsequent evacuation	
7: KI stockpile (CD), mobilization, subsequent evacuation	

2.4. Potassium Iodide Efficacy

The effectiveness of KI ingestion during an accident will depend on several factors including timing of ingestion and the degree of pre-existing stable iodine saturation of the thyroid gland. To roughly estimate the effectiveness of KI ingestion for the different distribution methods discussed above, Table 2.1 in the National Academy of Sciences (NAS) report on KI [1] was used to determine the percent efficacy based on assumed time of ingestion with respect to I-131 exposure. This was completed by extracting the arrival time of the plume segment of maximum risk for each accident scenario within 5 miles of the release location and comparing it to the assumed KI ingestion time after accident initiation for each distribution method analyzed. For Case 3 and 4, it is assumed the population will take the KI relatively quickly after accident notification (within two hours). For Case 5 and 6, it is assumed the population will take four hours after accident notification to pick up KI before ingestion. Lastly, based on assumed evacuation speeds, it will take the population approximately 12 hours to ingest KI after accident initiation to account for travel time to the CRC and any delay due to intake processing.

These timings in comparison to the plume arrival times for the different accident scenarios are represented in Figure 2-2. The STSBO and LTSBO scenarios are not shown as the plume arrival does not begin until much later at 25 hours and 45 hours after accident initiation, respectively. Given the earlier plume arrival times for the ISLOCA and TISGTR scenarios, the hours displayed in red roughly estimate the duration the public is exposed to I-131 (assuming they are within the plume path) before ingesting KI for the different distribution methods.

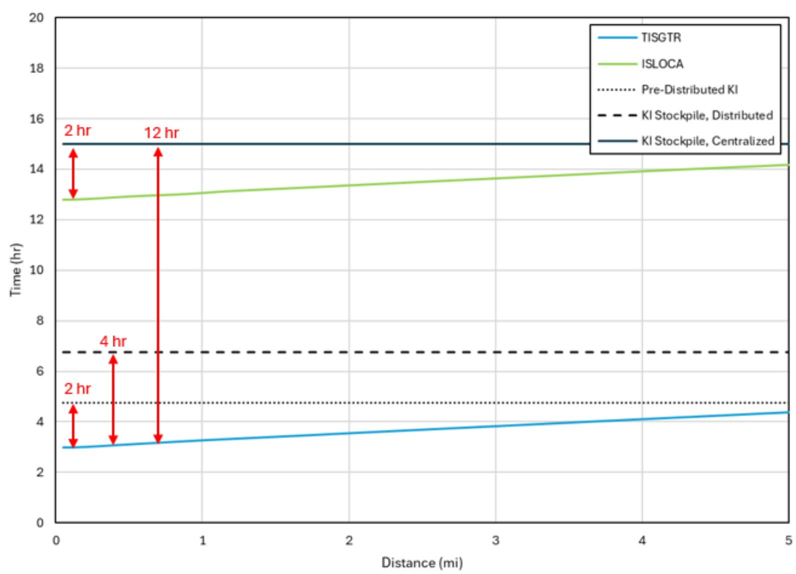


Figure 2-2: Assumed KI Ingestion timing versus plume arrival time.

Using the information displayed above in correlation with Table 2.1 from [1], the KI effectiveness factors applied to each case for each accident scenario are shown in Table 2-4. Some adjustments were made to account for longer delays in ingestion than the assumed timings. This was achieved by rounding the estimated KI effectiveness factor down to a lower threshold (e.g., reducing the calculated efficacy of 98% to 90%, 80% to 70%, etc.). Given the very delayed release start for the STSBO and LTSBO scenarios, the KI efficacy is assumed to be 90% for all cases to account for intake hours before expected I-131 exposure. For the ISLOCA source term, it is estimated that there will be roughly two hours of plume exposure before ingestion for Case 7, resulting in a lower KI efficacy for that case. For the TISGTR source term, it is estimated that there are roughly two hours of exposure before KI ingestion for Cases 3 and 4, four hours of exposure before ingestion for Cases 5 and 6, and 12 hours of exposure before ingestion for Case 7 (see Figure 2-2), which results in the decreasing KI efficacy shown in the table below for that source term. The KI effectiveness factors are applied in MACCS through reduction of the early phase thyroid doses from inhaled radioiodine.

Table 2-4: Assumed KI effectiveness factors for each case and source term.

Case	STSBO	LTSBO	ISLOCA	TISGTR
1	N/A	N/A	N/A	N/A
2	N/A	N/A	N/A	N/A
3	90%	90%	90%	70%
4	90%	90%	90%	70%
5	90%	90%	90%	50%
6	90%	90%	90%	50%
7	90%	90%	70%	30%

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3. MODELING RESULTS

This section presents the results for each accident scenario following the methodology outlined in the previous section. For comparison purposes, results are provided in terms of the mean total effective dose (TED), the acute thyroid dose (A-Thyroid), and lifetime thyroid dose (L-Thyroid) to an adult individual as a function of distance from the site. It is important to note that these results do not reflect the overall population within the 10-mile radius; rather, they pertain to an individual who is assumed to adhere strictly to the protective action decisions described earlier. If the entire population were considered, it is expected that a portion of the public would not follow these recommendations, potentially leading to different outcomes than those presented here.

The accident scenarios assessed in this analysis represent conservative, unmitigated cases, and the dose results reported here should be interpreted with caution. The purpose of this analysis is to evaluate the relative change in dose in response to KI distribution methods and protective actions. Therefore, all results are normalized based on the amount of I-131 released for each scenario. It was chosen to normalize the results by I-131 given its contribution to thyroid dose even though the doses reported encompass the entire source term, not just I-131. The I-131 air and ground concentrations at two and five miles from the site and tables with results normalized by I-131 time-integrated air concentrations are available in Appendix A.

3.1. STSBO Results

The results for the STSBO scenario (with atmospheric release beginning 25.5 hours after accident initiation), at distances of two and five miles for each case, are presented in Table 3-1. Additionally, the normalized doses for TED, A-Thyroid, and L-Thyroid as a function of distance are illustrated in Figure 3-1, Figure 3-2, and Figure 3-3, respectively. Due to the delayed release time associated with this scenario, all cases involving prompt evacuation result in zero dose (and are thus not visible graphically). In the SIP scenarios, the results for both pre-distributed KI and KI stockpiles are identical, as the assumed effectiveness factors for KI are the same. While not distributing KI and SIP (Case 1) results in the highest dose, the doses across all scenarios are generally within the same order of magnitude.

The results indicate that for significantly delayed releases (more than 24 hours after accident initiation), the most effective mitigation strategy is evacuation, regardless of whether a KI distribution method is implemented. In cases where evacuation is not possible, having KI either pre-distributed or readily available can be just as effective as obtaining it post-incident, pending additional factors that impact the effectiveness of KI besides timing of ingestion. As expected, having KI on hand can help reduce radiation dose. Nevertheless, decision-makers must carefully consider additional factors (e.g., cost, compliance) associated with KI distribution and ingestion in relation to the potential dose savings, which generally fall within the same order of magnitude with or without KI. For Case 7, cohort movement to a CD outside of the analysis area is functionally equivalent to evacuation, resulting in a normalized dose of zero.

Table 3-1: STSBO scenario results at 2 and 5 miles from the source.

Case	TED (Sv/Ci I-131)		A-Thyroid (Sv/Ci I-131)		L-Thyroid (Sv/Ci I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	1.91E-07	6.50E-08	6.17E-07	2.07E-07	1.71E-06	5.81E-07
2: No KI, Evac	0	0	0	0	0	0
3: Pre-Dist. KI, SIP	1.19E-07	4.09E-08	1.45E-07	4.97E-08	2.86E-07	9.74E-08
4: Pre-Dist. KI, Evac	0	0	0	0	0	0
5: KI Stockpile (DD), SIP	1.19E-07	4.09E-08	1.45E-07	4.97E-08	2.86E-07	9.74E-08
6: KI Stockpile (DD), Evac	0	0	0	0	0	0
7: KI Stockpile (CD)	0	0	0	0	0	0

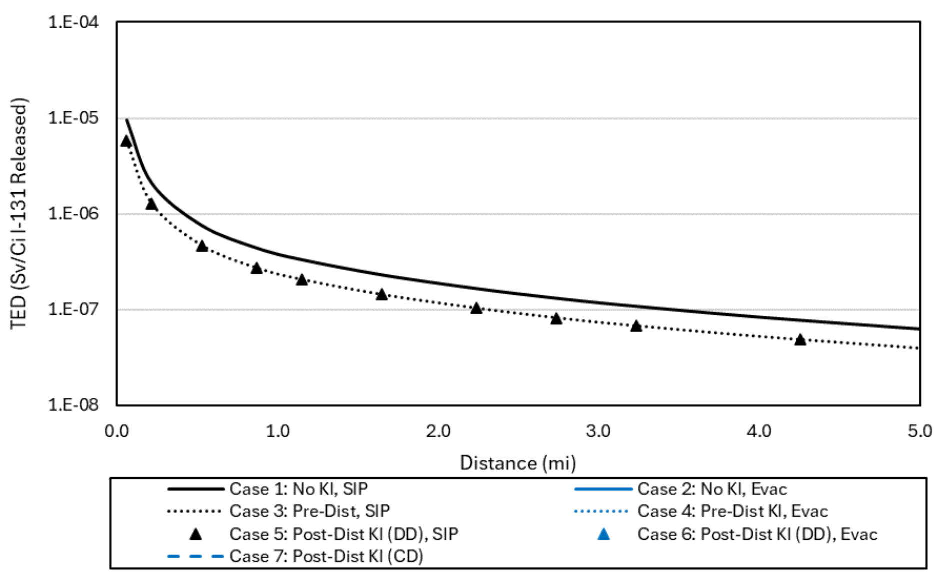

Figure 3-1: STSBO normalized TED dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

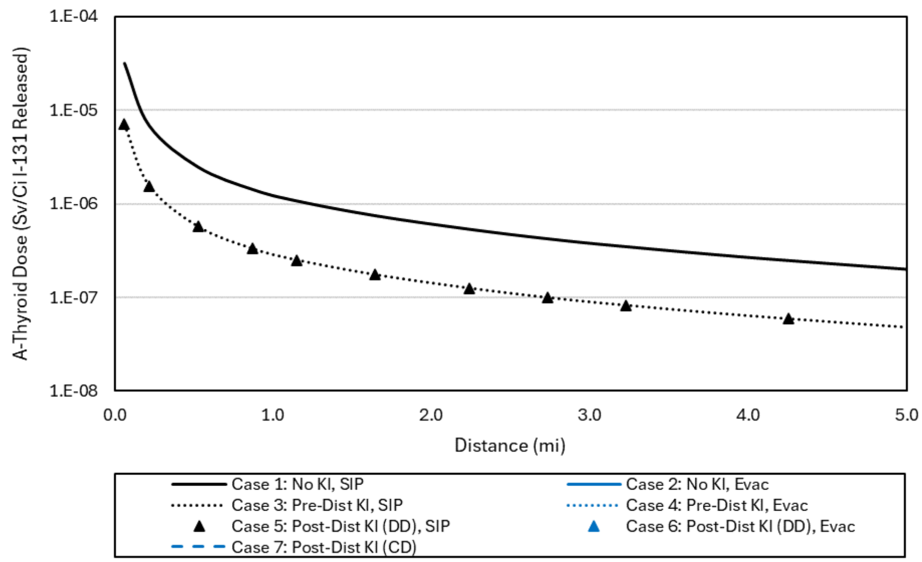

Figure 3-2: STSBO normalized A-Thyroid dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

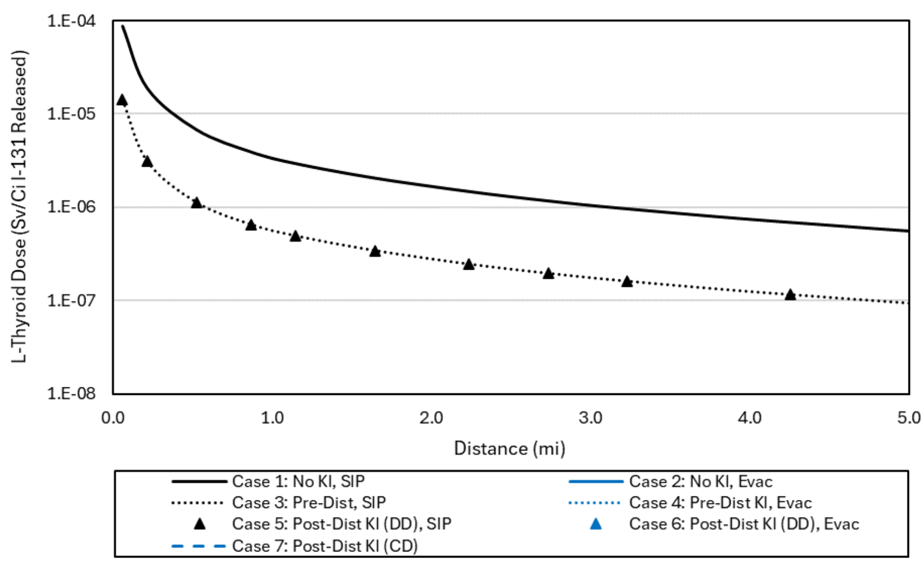

Figure 3-3: STSBO normalized L-Thyroid dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

3.2. LTSBO Results

The results for the LTSBO scenario (with atmospheric release beginning 45.3 hours after accident initiation), at distances of two and five miles for each case, are presented in Table 3-2. Additionally, the normalized doses for TED, A-Thyroid, and L-Thyroid as a function of distance are illustrated in Figure 3-4, Figure 3-5, and Figure 3-6, respectively. Given that the delayed release time for this scenario is even longer than that of the STSBO scenario, it can also be concluded here that evacuation is the most effective mitigation strategy, regardless of KI distribution method. If evacuation is not possible, having KI readily available can also reduce radiation dose; however, decision-makers should weigh additional factors of KI distribution and ingestion against potential dose savings. Normalized dose results of zero are not visible graphically.

Table 3-2: LTSBO scenario results at 2 and 5 miles from the source.

Case	TED (Sv/Ci I-131)		A-Thyroid (Sv/Ci I-131)		L-Thyroid (Sv/Ci I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	2.14E-07	7.37E-08	5.52E-07	1.87E-07	1.65E-06	5.57E-07
2: No KI, Evac	0	0	0	0	0	0
3: Pre-Dist. KI, SIP	1.46E-07	5.12E-08	1.56E-07	5.45E-08	3.10E-07	1.07E-07
4: Pre-Dist. KI, Evac	0	0	0	0	0	0
5: KI Stockpile (DD), SIP	1.46E-07	5.12E-08	1.56E-07	5.45E-08	3.10E-07	1.07E-07
6: KI Stockpile (DD), Evac	0	0	0	0	0	0
7: KI Stockpile (CD)	0	0	0	0	0	0

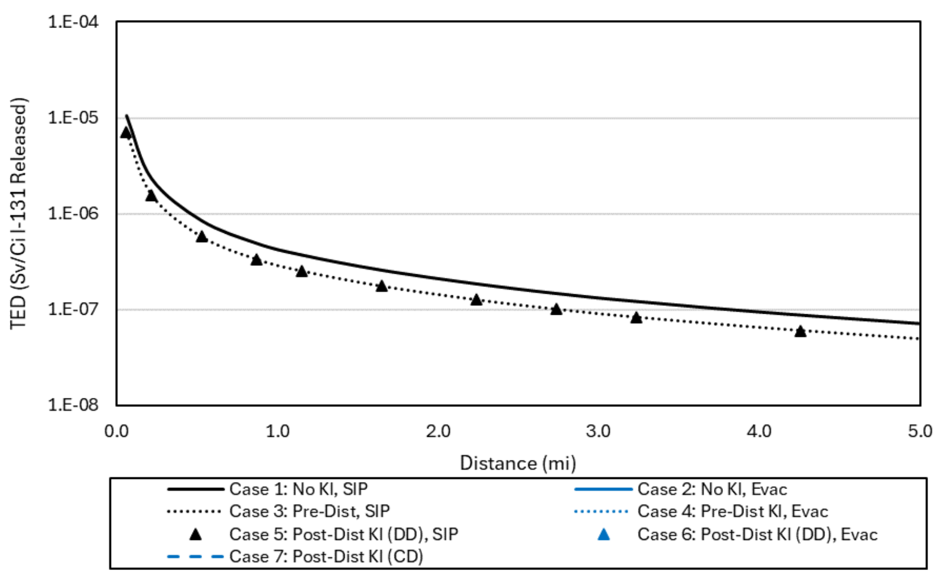

Figure 3-4: LTSBO normalized TED dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

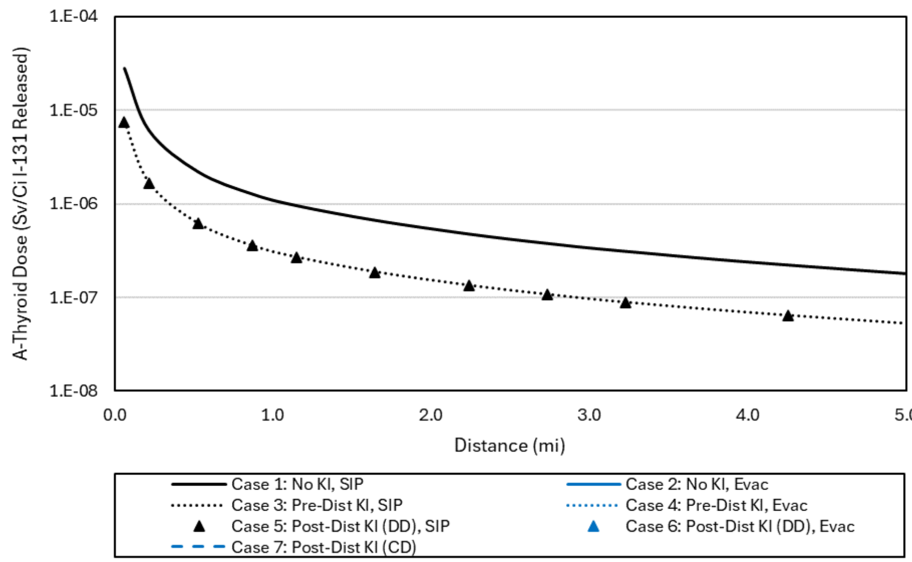

Figure 3-5: LTSBO normalized A-Thyroid dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

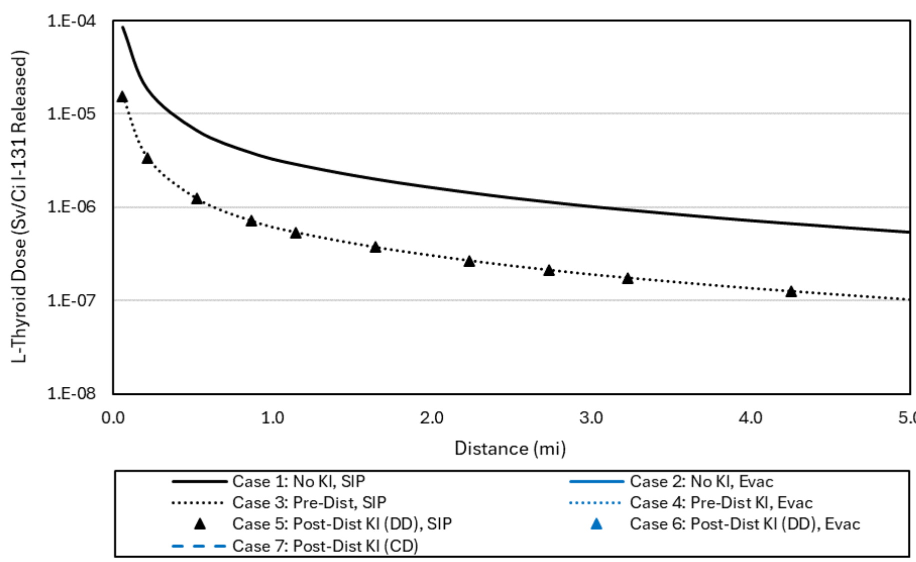

Figure 3-6: LTSBO normalized L-Thyroid dose as a function of distance. Due to the delayed release time associated with this scenario, all cases involving immediate evacuation result in zero dose (i.e. Cases 2, 4, 6, and 7 are not visible graphically).

3.3. ISLOCA Results

The results for the ISLOCA scenario (with atmospheric release beginning 12.8 hours after accident initiation), at distances of two and five miles for each case, are presented in Table 3-3. Additionally, the normalized doses for TED, A-Thyroid, and L-Thyroid as a function of distance are illustrated in Figure 3-7, Figure 3-8, and Figure 3-9, respectively. Like the STSBO and LTSBO scenarios, the evacuation cases demonstrate significantly greater effectiveness than the SIP approach, reducing the estimated dose by several orders of magnitude compared to SIP.

In the SIP cases, the results for both KI distribution methods are nearly identical to those where KI is not distributed at all. Comparing the results overall, the pre-distributed KI with immediate evacuation (Case 4) results in the lowest estimated dose, benefiting from the highest assumed effectiveness of KI. However, it is important to note that in this scenario, unlike the previous two accidents where all evacuation cases resulted in zero dose due to evacuees successfully evacuating before plume arrival, the evacuation cases here are reflective of radiation exposure. This is because individuals evacuating may be exposed to the plume while sitting in their cars during the evacuation process. Additionally, as more people begin to evacuate, road congestion further slows the evacuation resulting in potentially more exposure. This is graphically represented in Figure 3-7, Figure 3-8, and Figure 3-9 by the increase in dose for the evacuation cases at approximately 2.5 miles from the source. Nonetheless, most evacuation case results are also closely aligned, regardless of the KI distribution method, apart from Case 6.

In Case 6, the assumed delay for the public to retrieve KI from a stockpile before evacuating leads to a larger estimated dose, trending closer to the SIP results. This suggests that evacuating immediately without KI is more effective than waiting to pick up KI. Additionally, if it is anticipated that it will take longer than four hours for the public to collect KI from a local stockpile before evacuation, SIP until the plume passes may be more effective in terms of dose reduction for rapidly progressing accident scenarios.

In practical terms, results suggest that if individuals can evacuate in time, they should do so without stopping to collect KI locally, as having KI is irrelevant if they can leave quickly. Conversely, if evacuation is not an option and individuals must remain in the area, having KI available is slightly better for minimizing radiation dose, if taken in a timely manner.

Table 3-3: ISLOCA scenario results at 2 and 5 miles from the source.

Case	TED (Sv/Ci I-131)		A-Thyroid (Sv/Ci I-131)		L-Thyroid (Sv/Ci I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	6.61E-07	2.30E-07	2.73E-06	9.36E-07	6.54E-06	2.27E-06
2: No KI, Evac	1.99E-11	2.74E-11	9.71E-11	1.46E-10	2.38E-10	3.62E-10
3: Pre-Dist. KI, SIP	3.81E-07	1.34E-07	5.47E-07	1.90E-07	1.04E-06	3.62E-07
4: Pre-Dist. KI, Evac	9.57E-12	1.16E-11	1.60E-11	2.12E-11	3.44E-11	4.93E-11
5: KI Stockpile (DD), SIP	3.81E-07	1.34E-07	5.47E-07	1.90E-07	1.04E-06	3.62E-07
6: KI Stockpile (DD), Evac	3.13E-09	2.72E-09	5.95E-09	5.19E-09	1.44E-08	1.25E-08
7: KI Stockpile (CD)	1.19E-11	1.51E-11	3.41E-11	4.88E-11	7.96E-11	1.19E-10

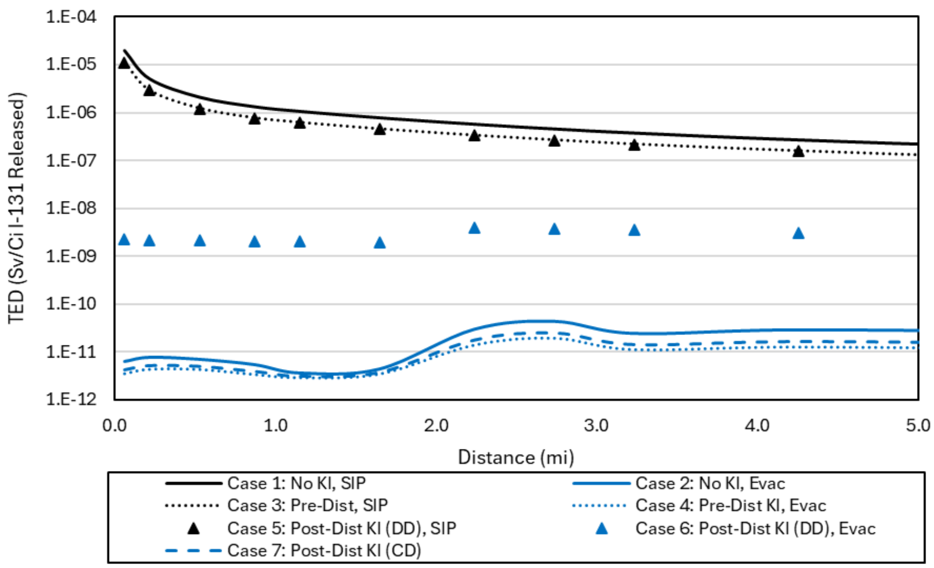

Figure 3-7: ISLOCA normalized TED dose as a function of distance.

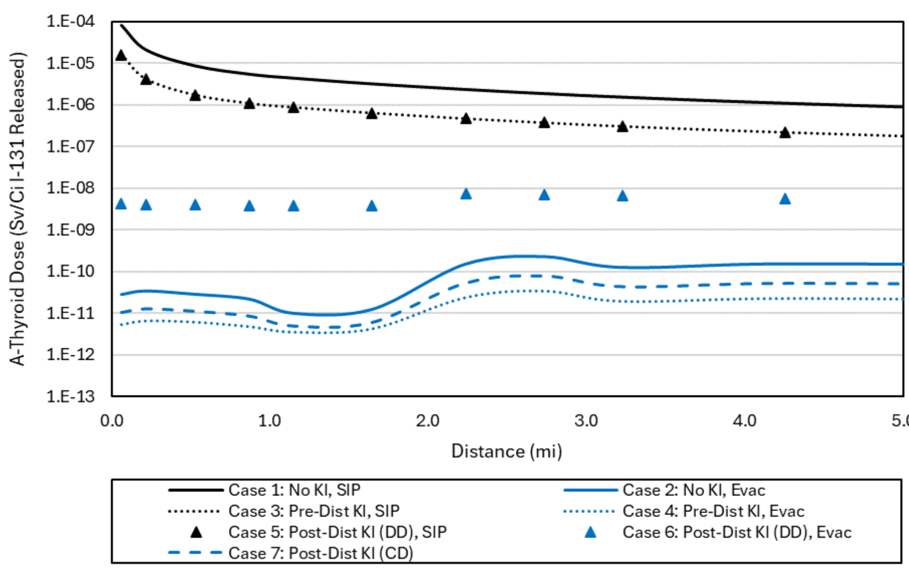

Figure 3-8: ISLOCA normalized A-Thyroid dose as a function of distance.

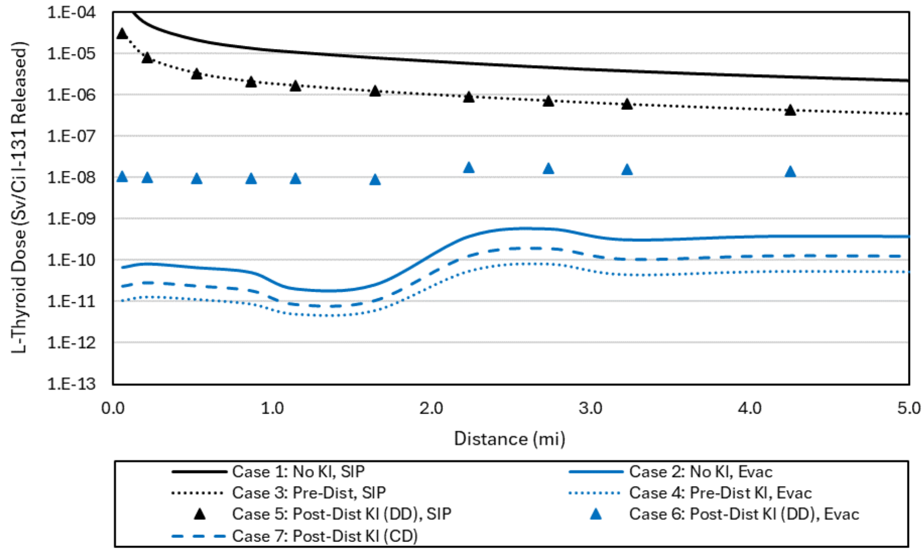

Figure 3-9: ISLOCA normalized L-Thyroid dose as a function of distance.

3.4. TISGTR Results

The results for the TISGTR scenario (with atmospheric release beginning 3.6 hours after accident initiation), at distances of two and five miles for each case, are presented in Table 3-4. Additionally, the normalized doses for TED, A-Thyroid, and L-Thyroid as a function of distance are illustrated in Figure 3-10, Figure 3-11, and Figure 3-12, respectively. Given that this scenario begins releasing radioactive material into the atmosphere approximately three hours after accident initiation, it produces similar results across the different cases, as evacuees may be exposed to the plume during most of the evacuation phase, resulting in dose estimates that are comparable to those who SIP. However, the same general trends observed for other accidents still apply. Specifically, for the TED dose results, the evacuation cases produce smaller dose estimates than the SIP cases although only by one order of magnitude. Additionally, Case 4 (evacuating with pre-distributed KI) produces the lowest estimated doses overall. Case 6 results are even closer to the SIP results than what was observed for the ISLOCA scenario, as the delay in picking up KI from stockpile leads to increased exposure to the plume during evacuation. This is because the estimated time to collect KI exceeds the release start time for this accident scenario.

However, for all other scenarios, similar trends were observed for the A-Thyroid and L-Thyroid dose estimates when compared to the TED dose. For this scenario, differing behavior is observed. The dose results for A-Thyroid and L-Thyroid at two and five miles are almost entirely within the same order of magnitude regardless of case. Additionally, Figure 3-11 and Figure 3-12 show that beyond the two mile mark, some of the evacuation cases begin to produce higher dose estimates than the SIP cases. This is because the evacuation is concurrent with the plume passage and shielding from buildings is more protective than shielding while in a vehicle. The difference between TED and thyroid specific dose is mainly because these results are due almost entirely to radioiodine exposure while the TED dose includes significant contributions from all radionuclides and the difference in KI distribution effectiveness can be better observed here.

Given the rapid release timing, there is less variation in dose estimates between different KI distribution methods compared to scenarios with no KI distribution, as well as between immediate evacuation and SIP, until the plume passes. As demonstrated in Figure 3-11 and Figure 3-12, at certain distances, it may be more advantageous to SIP, regardless of KI availability. For those closer to the source, evacuation can provide some dose savings; however, this benefit diminishes at greater distances. In scenarios without KI availability, individuals at closer distances do experience some dose savings from evacuation, but as distance increases, the doses converge with those of individuals SIP. Overall, dose savings due to KI ingestion appear to be negligible for the TISGTR.

Table 3-4: TISGTR scenario results at 2 and 5 miles from the source.

Case	TED (Sv/Ci I-131)		A-Thyroid (Sv/Ci I-131)		L-Thyroid (Sv/Ci I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	5.00E-07	1.64E-07	1.37E-06	4.56E-07	2.91E-06	9.79E-07
2: No KI, Evac	8.92E-08	6.84E-08	4.20E-07	3.18E-07	9.35E-07	7.10E-07
3: Pre-Dist. KI, SIP	4.16E-07	1.35E-07	5.81E-07	1.94E-07	1.09E-06	3.66E-07
4: Pre-Dist. KI, Evac	5.76E-08	4.43E-08	1.45E-07	1.10E-07	3.13E-07	2.38E-07
5: KI Stockpile (DD), SIP	4.64E-07	1.51E-07	9.36E-07	3.09E-07	1.90E-06	6.28E-07
6: KI Stockpile (DD), Evac	2.27E-07	9.52E-08	7.54E-07	3.05E-07	1.64E-06	6.77E-07
7: KI Stockpile (CD)	7.56E-08	5.80E-08	3.02E-07	2.29E-07	6.69E-07	5.08E-07

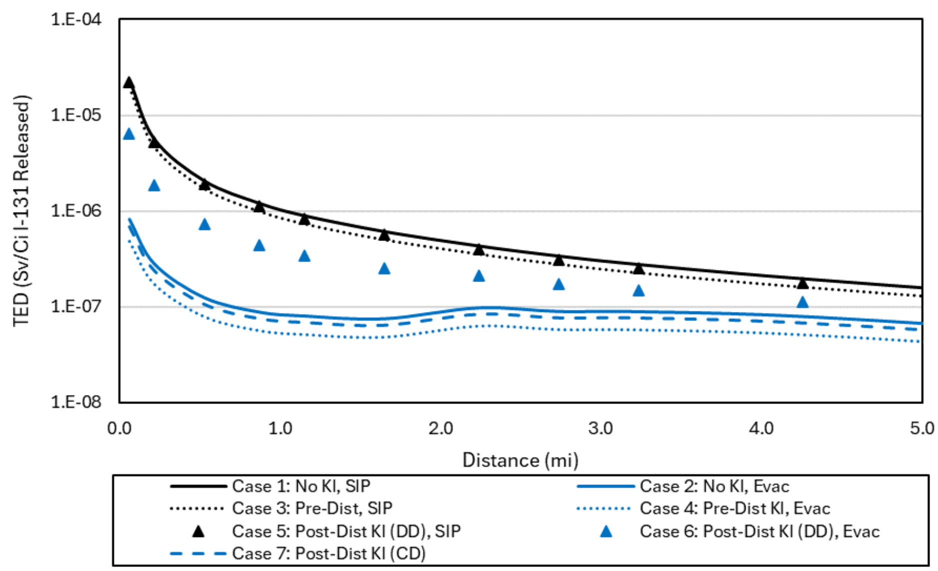

Figure 3-10: TISGTR normalized TED dose as a function of distance.

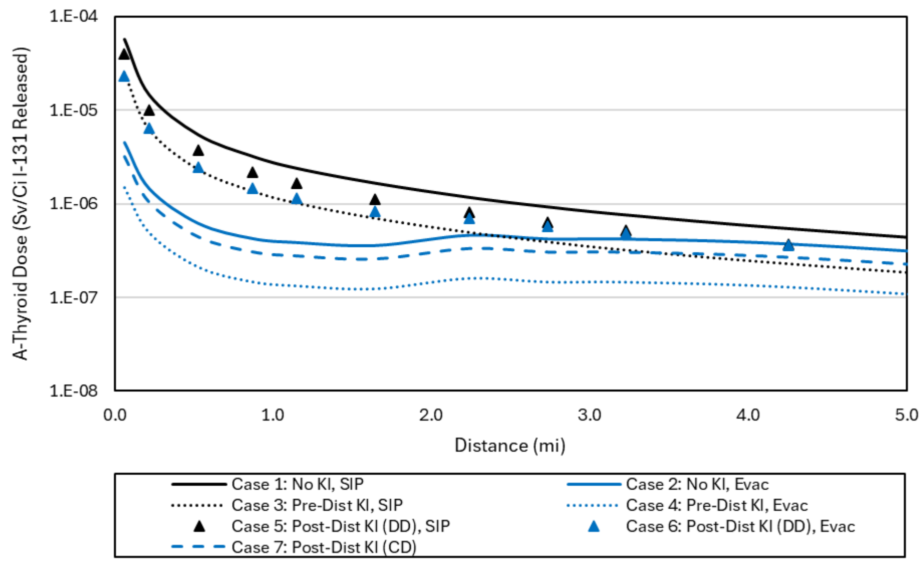

Figure 3-11: TISGTR normalized A-Thyroid dose as a function of distance.

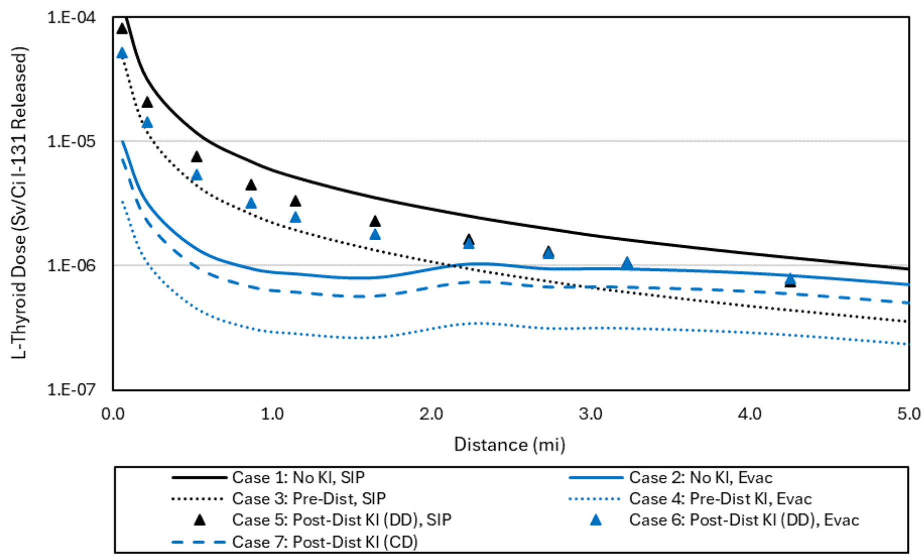

Figure 3-12: TISGTR normalized L-Thyroid dose as a function of distance.

3.5. Sensitivity Analyses

In addition to the results discussed above, two sensitivity analyses were completed to further assess the effectiveness of KI with respect to mobilization/sheltering timing and varying age group.

3.5.1. Mobilization Timing Sensitivity

Given the effectiveness of evacuation demonstrated in the results for each accident scenario above, a sensitivity analysis was conducted to vary the mobilization/sheltering time before evacuation, as the base case only assumed a one-hour mobilization time and it is plausible that the general public may take longer than one hour to evacuate or they may be directed by emergency response officials to wait for a period of time before evacuating. To observe the impact this may have for different source term magnitudes, a sensitivity analysis was completed for both the ISLOCA and the LTSBO. Due to the significant differences in release timing between the two scenarios, the LTSBO source term was modified in MACCS to align its release timing with that of the ISLOCA scenario, allowing for a more direct comparison between source term magnitudes rather than timing. All other relevant source term information for the LTSBO remained unchanged. Consequently, both scenarios were set to begin releasing radioactive material into the environment at 12.8 hours after the accident initiation.

Both a no KI scenario and a KI scenario were analyzed, with the KI effectiveness assumed to be 90%. The results were not normalized by the amount of I-131 released to facilitate a clear observation of the difference due to source term magnitudes.

Table 3-5 provides the estimated TED doses for both the ISLOCA and LTSBO scenarios (with modified release timing) across four different mobilization/sheltering times (noted as the SIP time in the table below), in addition to the original one-hour mobilization time, for both scenarios with and without KI.

The results demonstrate that if the mobilization or sheltering time exceeds the release start time, the results tend to align more closely with just SIP indefinitely (Cases 1 and 3). Additionally, a reduction in dose is observed when evacuation begins prior to the onset of the release for both the KI and no KI scenarios. If evacuation begins after beginning of release, results stay within the same order of magnitude. Furthermore, it is evident that the doses associated with the LTSBO scenario are consistently one to two orders of magnitude lower than those for the ISLOCA scenario, given the difference in total radioactive material released for each source term shown in Table 2-1.

Table 3-5: Mobilization timing sensitivity TED dose results.

Case	ISLOCA (Sv)		LTSBO (Sv) (modified source term)	
	2 miles	5 miles	2 miles	5 miles
No KI, 1 hr SIP	2.22E-04	3.05E-04	8.78E-06	6.68E-06
No KI, 4 hr SIP	8.75E-02	7.63E-02	1.58E-03	1.34E-03
No KI, 8 hr SIP	5.77E-01	4.63E-01	1.25E-02	1.06E-02
No KI, 16 h SIP	5.10E+00	1.97E+00	1.20E-01	5.15E-02
No KI, 24 hr SIP	5.27E+00	1.87E+00	1.17E-01	4.42E-02
KI, 1 hr SIP	1.06E-04	1.28E-04	5.22E-06	3.98E-06
KI, 4 hr SIP	3.47E-02	3.03E-02	9.61E-04	8.13E-04
KI, 8 hr SIP	2.27E-01	1.82E-01	7.63E-03	6.51E-03
KI, 16 hr SIP	2.07E+00	8.18E-01	7.52E-02	3.29E-02
KI, 24 hr SIP	2.27E+00	8.24E-01	7.51E-02	2.92E-02

3.5.2. Age Group Sensitivity

Thus far, all results discussed have focused exclusively on the adult age group. However, it is important to note that children's thyroids are more sensitive to iodine exposure, and the effectiveness of KI may differ between children and adults, potentially influencing the observations made in this report. Therefore, the purpose of this sensitivity analysis is to provide insight into the relative differences in dose estimates between adults and younger, more sensitive age groups using simplified assumptions.

To compare the two age groups, a simplified case was analyzed, assuming a one-hour release of 1 Ci of I-131 (with no other radionuclides considered). This analysis utilized dose coefficient information specific to adults and three-month-old infants from International Commission on Radiological Protection Publication (ICRP) Publication 60 [6]. For this assessment, evacuation was not factored in, and KI ingestion was excluded to yield the most conservative estimates. Additionally, a breathing rate of 3.33E-05 m^3/s was assumed for a three-month-old child (activity averaged), based on the information provided in ICRP Publication 66 [7].

Table 3-6 presents a comparison of the TED and L-Thyroid dose between adults and three-month-olds. Despite the younger age group's heightened sensitivity to iodine exposure, the resultant dose estimates for children remain within the same order of magnitude. Nonetheless, these findings offer valuable insights into the expected outcomes for children in the KI effectiveness analysis described in this report.

Table 3-6: Age group sensitivity results.

Age Group	TED (Sv/Ci I-131)		L-Thyroid (Sv/Ci I-131)	
	2 miles	5 miles	2 miles	5 miles
Adult	4.73E-07	1.36E-07	8.28E-06	2.38E-06
Three-Month-Old	5.64E-07	1.62E-07	1.00E-05	2.88E-06

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4. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this analysis was to quantitatively compare various KI distribution strategies, including the scenario of not administering KI at all, to evaluate their effectiveness across different nuclear accident scenarios. The analysis reveals that different KI distribution strategies can impact the projected thyroid dose by at least an order of magnitude. However, the timing of KI administration relative to exposure remains a crucial factor influencing outcomes.

Key findings from the analysis indicate that for scenarios involving very delayed releases, like the STSBO and LTSBO, evacuation emerges as the most effective strategy, regardless of the KI distribution method employed. In contrast, for rapid releases, delays associated with retrieving KI from stockpiles can be more detrimental than opting for immediate evacuation without KI. This is particularly evident when comparing Case 2 and Case 6 for the ISLOCA and TISGTR scenarios.

The study consistently demonstrates that pre-distributed KI, combined with immediate evacuation, is the most effective approach, especially when mobilization times are quick. However, it is important to consider the absolute value of dose savings, as the harmful non-radiological effects of unnecessary evacuation can outweigh the benefits in certain situations. The magnitude of the differences observed between sheltering and evacuation in the TISGTR and ISLOCA results further underscores the importance of context in decision-making. The absolute dose savings from KI ingestion should be contextualized with the cost and rigor of a distribution program.

Given the variability in effectiveness among different distribution methods, it is recommended that future analyses focus on identifying radioiodine inventory levels for advanced reactors that may be small enough to negate the need for a KI distribution plan. This study primarily concentrated on conservative light water reactor source terms from the SOARCA analysis; expanding the analysis to include other reactor types/size as well as mitigated accident scenarios could provide valuable insights. Additionally, further sensitivities for practical implications of emergency guidance should be conducted.

It is also important to note that the results in this analysis are based on individual cases where instructions are followed perfectly. In reality, a portion of the public may not adhere to these guidelines during an emergency, pre-distributed KI may be expired, lost, consumed at an incorrect time or not at all, impacted populations may be confused by emergency response instructions, etc. Therefore, a population-level perspective should be considered in future evaluations, as the impact of different KI distribution methods may yield different results when accounting for overall public compliance with KI administration.

In conclusion, this study provides a foundation for improving decisions related to KI distribution and highlights the need for ongoing research to address uncertainties in emergency response planning for nuclear power plant accidents.

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APPENDIX A. AIR AND GROUND CONCENTRATION RESULTS

This appendix displays the same information represented in Section 3 except they are normalized by the I-131 time-integrated air concentration at two and five miles from the site.

Table A-1: STSBO I-131 air and ground concentrations at 2 and 5 miles from the source.

Distance	I-131 Air Concentration (Bq-s/m^3)	I-131 Ground Concentration (Bq/m^2)
2 miles	8.32E+09	1.94E+07
5 miles	2.25E+09	5.03E+06

Table A-2: STSBO scenario air concentration normalized results at 2 and 5 miles from the source.

Case	TED (Sv/Bq-s/m^3 I-131)		A-Thyroid (Sv/Bq-s/m^3 I-131)		L-Thyroid (Sv/Bq-s/m^3 I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	9.86E-12	1.24E-11	3.19E-11	3.96E-11	8.86E-11	1.11E-10
2: No KI, Evac	0	0	0	0	0	0
3: Pre-Dist. KI, SIP	6.17E-02	7.81E-12	7.51E-12	9.49E-12	1.48E-11	1.86E-11
4: Pre-Dist. KI, Evac	0	0	0	0	0	0
5: KI Stockpile (DD), SIP	6.17E-02	7.81E-12	7.51E-12	9.49E-12	1.48E-11	1.86E-11
6: KI Stockpile (DD), Evac	0	0	0	0	0	0
7: KI Stockpile (CD)	0	0	0	0	0	0

Table A-3: LTSBO I-131 air and ground concentrations at 2 and 5 miles from the source.

Distance	I-131 Air Concentration (Bq-s/m^3)	I-131 Ground Concentration (Bq/m^2)
2 miles	4.27E+09	8.39E+06
5 miles	1.15E+09	2.18E+06

Table A-4: LTSBO scenario air concentration normalized results at 2 and 5 miles from the source.

Case	TED (Sv/Bq-s/m^3 I-131)		A-Thyroid (Sv/Bq-s/m^3 I-131)		L-Thyroid (Sv/Bq-s/m^3 I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	1.05E-11	1.35E-11	2.72E-11	3.42E-11	8.11E-11	1.02E-10
2: No KI, Evac	0	0	0	0	0	0
3: Pre-Dist. KI, SIP	7.20E-12	9.37E-12	7.66E-12	9.97E-12	1.53E-11	1.95E-11
4: Pre-Dist. KI, Evac	0	0	0	0	0	0
5: KI Stockpile (DD), SIP	7.20E-12	9.37E-12	7.66E-12	9.97E-12	1.53E-11	1.95E-11
6: KI Stockpile (DD), Evac	0	0	0	0	0	0
7: KI Stockpile (CD)	0	0	0	0	0	0

Table A-5: ISLOCA I-131 air and ground concentrations at 2 and 5 miles from the source.

Distance	I-131 Air Concentration (Bq-s/m^3)	I-131 Ground Concentration (Bq/m^2)
2 miles	2.47E+11	5.53E+08
5 miles	6.85E+10	1.46E+08

Table A-6: ISLOCA scenario air concentration normalized results at 2 and 5 miles from the source.

Case	TED (Sv/Bq-s/m^3 I-131)		A-Thyroid (Sv/Bq-s/m^3 I-131)		L-Thyroid (Sv/Bq-s/m^3 I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	2.97E-11	3.73E-11	1.23E-10	1.52E-10	2.94E-10	3.67E-10
2: No KI, Evac	8.97E-16	4.45E-15	4.37E-15	2.37E-14	1.07E-14	5.87E-14
3: Pre-Dist. KI, SIP	1.71E-11	2.17E-11	2.46E-11	3.08E-11	4.67E-11	5.87E-11
4: Pre-Dist. KI, Evac	4.30E-16	1.87E-15	7.21E-16	3.43E-15	1.55E-15	7.99E-15
5: KI Stockpile (DD), SIP	1.71E-11	2.17E-11	2.46E-11	3.08E-11	4.67E-11	5.87E-11
6: KI Stockpile (DD), Evac	1.41E-13	4.42E-13	2.68E-13	8.42E-13	6.49E-13	2.03E-12
7: KI Stockpile (CD)	5.36E-16	2.45E-15	1.53E-15	7.91E-15	3.58E-15	1.93E-14

Table A-7: TISGTR I-131 air and ground concentrations at 2 and 5 miles from the source.

Distance	I-131 Air Concentration (Bq-s/m^3)	I-131 Ground Concentration (Bq/m^2)
2 miles	1.33E+10	3.70E+07
5 miles	3.44E+09	8.99E+06

Table A-8: TISGTR scenario air concentration normalized results at 2 and 5 miles from the source.

Case	TED (Sv/Bq-s/m^3 I-131)		A-Thyroid (Sv/Bq-s/m^3 I-131)		L-Thyroid (Sv/Bq-s/m^3 I-131)	
	2 miles	5 miles	2 miles	5 miles	2 miles	5 miles
1: No KI, SIP	2.45E-11	3.10E-11	6.69E-11	8.64E-11	1.42E-10	1.85E-10
2: No KI, Evac	4.37E-12	1.29E-11	2.05E-11	6.01E-11	4.57E-11	1.34E-10
3: Pre-Dist. KI, SIP	2.03E-11	2.56E-11	2.84E-11	3.67E-11	5.34E-11	6.93E-11
4: Pre-Dist. KI, Evac	2.82E-12	8.39E-12	7.10E-12	2.08E-11	1.53E-11	4.50E-11
5: KI Stockpile (DD), SIP	2.27E-11	2.85E-11	4.58E-11	5.84E-11	9.31E-11	1.19E-10
6: KI Stockpile (DD), Evac	1.11E-11	1.80E-11	3.69E-11	5.77E-11	8.05E-11	1.28E-10
7: KI Stockpile (CD)	3.70E-12	1.10E-11	1.48E-11	4.33E-11	3.27E-11	9.61E-11

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