ABSTRACT

Hase, Jackson. Methodology for Evaluating Non-LWR Risk Metrics and Optimizing the Exclusion Area Boundary (Under the direction of Dr. Mihai A. Diaconeasa).

Exclusion Area Boundaries (EABs) represent where nuclear power plant (NPP) owners have full jurisdiction, and only authorized personnel are allowed to enter. As advanced non-light water reactors (non-LWRs) take center stage in nuclear energy, featuring increased passive safety features, it may be possible to shrink the EAB, allowing for reactors to take up less land while simultaneously increasing the public's safety. Reactor licensing regulations and targets are aimed towards protecting the health of an individual in the public and the environment by meeting the current safety goals, which require extravagant computations to evaluate risk metrics. The risk metrics of concern are as follows: the mean frequency of exceeding a site boundary dose of 100 mrem from all LBEs should not exceed 1 event per plant-year [1], the average individual risk of early fatality (EF) within 1 mile of the EAB should not exceed 5×10^{-7} per plant-year [2], and the average individual risk of latent cancer fatalities (LCF) within 10 miles of the EAB should not exceed 2×10^{-6} per plant-year [2]. One regulation being evaluated is that of the Nuclear Regulatory Committee's (NRC's) 10 CFR 50 [3] which limits the radiation exposure experienced by occupants in the control room during any accident to 5 rem. This thesis presents an optimization approach to evaluate and ensure that these safety goals are met, establishing a more efficient design process to support the licensing of advanced reactors. This is accomplished by evaluating the risk metrics at optimally determined bounding EAB distances, where if the metrics are satisfied, the need for complex computations of radiation dispersion over miles can be avoided entirely. This thesis also explores the possibility of minimizing the EAB, which is incredibly useful as small modular reactors (SMRs) and microreactors (μRs) are being designed. This is done by evaluating

the atmospheric dispersion factors at the EAB, using the factors to compute the doses of each release category, and using the release categories to calculate the consequences of licensing basis events (LBEs) and multiple risk metrics. Therefore, the risk metrics depend on the EAB distance, making it possible to determine the minimal distance required at which the metrics are satisfied. A case study performed on a standard modular high temperature gas-cooled reactor (MHTGR) shows that these three goals and control room standard can be met at the EAB, and furthermore that the EAB can be minimized to just under 50 meters from the reactor building, a major reduction from the typical 425 meter distance.

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Methodology for Evaluating Non-LWR Risk Metrics and Optimizing the Exclusion Area Boundary

by

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DEDICATION

To my fiancé, Brooke, whose love, patience, and unwavering support have been my greatest source of strength. To my family, who have always believed in me and encouraged me to pursue my dreams. To my advisor, Dr. Mihai Diaconeasa, for his invaluable guidance and mentorship. And above all, to God, who granted me strength when I felt weak, wisdom when I felt lost, and perseverance when the path seemed uncertain. Without His grace, this journey would not have been possible.

BIOGRAPHY

Jackson Hase was born in 2001 in Newport Beach, California, to Jason and Jeni Hase. At age seven, his family moved to Matthews, North Carolina, where he spent the rest of his childhood. He completed the pre-engineering program at Central Academy of Technology and Arts (CATA) before earning his high school diploma. Jackson then pursued a Bachelor degree in Nuclear Engineering at North Carolina State University, graduating in 2024. He continued at the same institution for a Master in Science of Nuclear Engineering, specializing in Probabilistic Risk Assessment (PRA).

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CFR	Code of Federal Regulations
DCF	Dose Conversion Factor
EAB	Exclusion Area Boundary
EF	Early Fatality
ESQ	Event Sequence Quantification
F-C	Frequency-Consequence
LBE	Licensing Basis Event
LCF	Latent Cancer Fatality
LWR	Light Water Reactor
MHTGR	Modular High Temperature Gas-cooled Reactor
MST	Mechanistic Source Term
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Committee
PRA	Probabilistic Risk Assessment
QHO	Quantitative Health Objective
SMR	small modular reactor
SSCs	structures, systems, and components
TI-RIPB	technology-inclusive, risk-informed, and performance-based
μRs	microreactors

CHAPTER 1. Current Processes for Meeting Cumulative Risk Metrics

1.1. Licensing Goals for non-LWRs

The Nuclear Energy Institute (NEI) developed NEI 18-04 [4] to streamline and standardize the licensing process for non-Light Water Reactor (non-LWRs) and reduce regulatory uncertainties and increase safety. The guidelines are designed to be technology-inclusive, risk-informed, and performance-based (TI-RIPB). In other words, deterministic safety analysis is combined with Probabilistic Risk Assessment (PRA) so a variety of advanced reactor technologies can be assessed to meet risk and safety targets. It is important to note that compliance with NEI 18-04 is not a requirement, but rather it serves as a framework that aligns with the Nuclear Regulatory Commission (NRC) licensing processes to simplify and clarify the development of safety cases for non-LWR technologies.

The guidelines outline a process for determining and evaluating Licensing Basis Events (LBEs). LBEs are to be evaluated against a Frequency-Consequence (F-C) Target (as shown in Figure 1), as well as three cumulative risk metrics, of which come from the Code of Federal Regulations (CFR), specifically 10 CFR 20 [1], and are evaluated as Quantitative Health Objectives (QHOs). These metrics include:

- The total mean frequency of exceeding a site boundary dose of 100 mrem from all LBEs should not surpass 1 event per plant-year. This criterion ensures that the full spectrum of LBEs—ranging from high-frequency, low-consequence events to low-frequency, high-consequence events—is considered. The 100 mrem threshold is derived from the annual cumulative exposure limits specified in 10 CFR 20 [1].
- The average individual risk of early fatality (EF) within 1 mile of the EAB, based on mean frequency and consequence estimates from all LBEs, shall not exceed 5×10^{-7} per

plant-year. This limit ensures compliance with the NRC safety goal QHO [2] for EF risk.

- The average individual risk of latent cancer fatalities (LCF) within 10 miles of the EAB, based on mean frequency and consequence estimates from all LBEs, shall not exceed 2×10^{-6} per plant-year. This limit ensures compliance with the NRC safety goal QHO for LCF risk.

Besides evaluating the integrated plant risk against QHOs and 10 CFR 20 limits, individual LBEs, as well as structures, systems, and components (SSCs) can be evaluated against the same F-C target and risk metrics to determine their respective risk-significance. Per NEI 18-04, LBEs are classified as risk-significant if the LBE site boundary dose exceeds 2.5 mrem over 30 days and the frequency of the dose is within 1% of the F-C Target (Figure 1). SSCs are classified as risk-significant if the SSC function is necessary to keep any LBEs inside the F-C Target, or if the total frequency of LBEs with the SSCs failed is within 1% of any of the three cumulative risk targets.

One can see that these three cumulative risk metrics play a crucial role in reactor licensing as the integrated plant risk, LBEs, and SSCs are dependent on these objectives to one degree or another. The process of determining LBEs as outlined by NEI 18-04 is displayed in Figure 2: Process for Selecting and Evaluation Licensing Basis Events [4]. This report will focus primarily on event 7b.

Besides these risk metrics, the NRC's 10 CFR 50.67(b)(2)(iii) [3] limits the radiation exposure experienced during any accident to 5 rem for occupants in the control room. Therefore, this metric will also be measured to ensure the safety of individuals on or within the EAB.

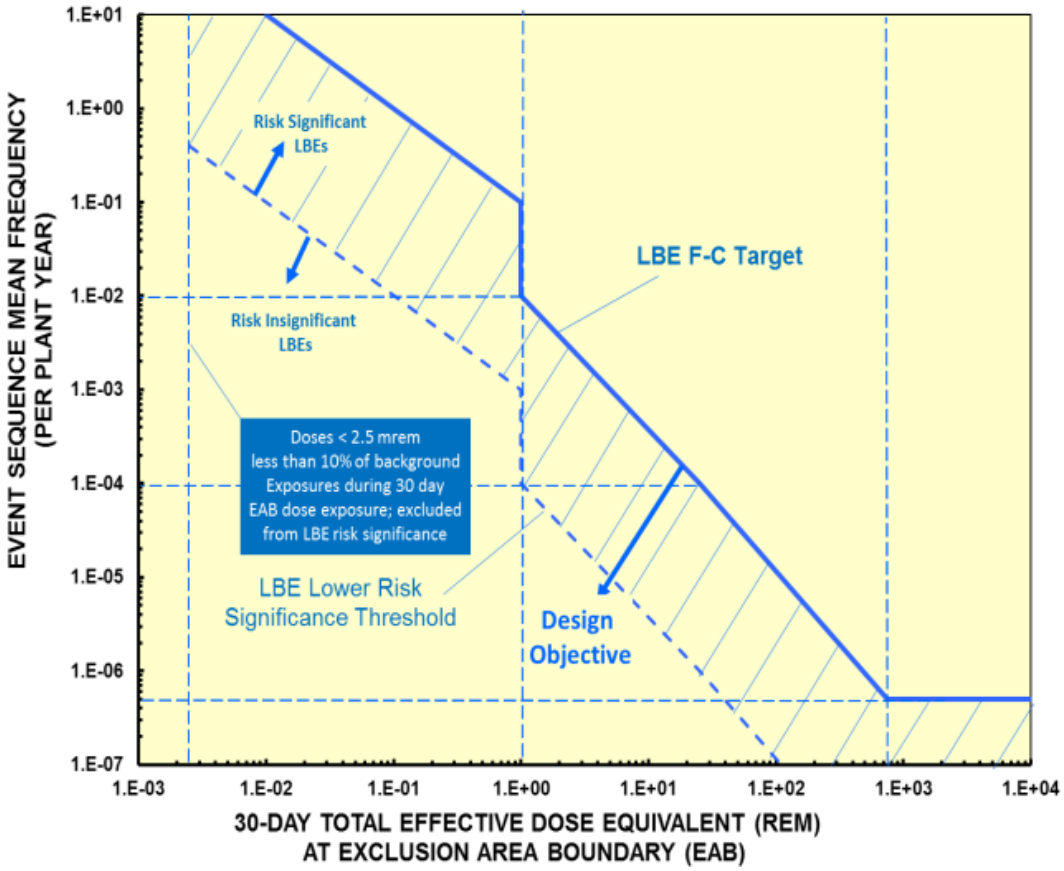

Figure 1: Frequency-Consequence Target with Hatch for Defining Risk-Significant LBEs [4]

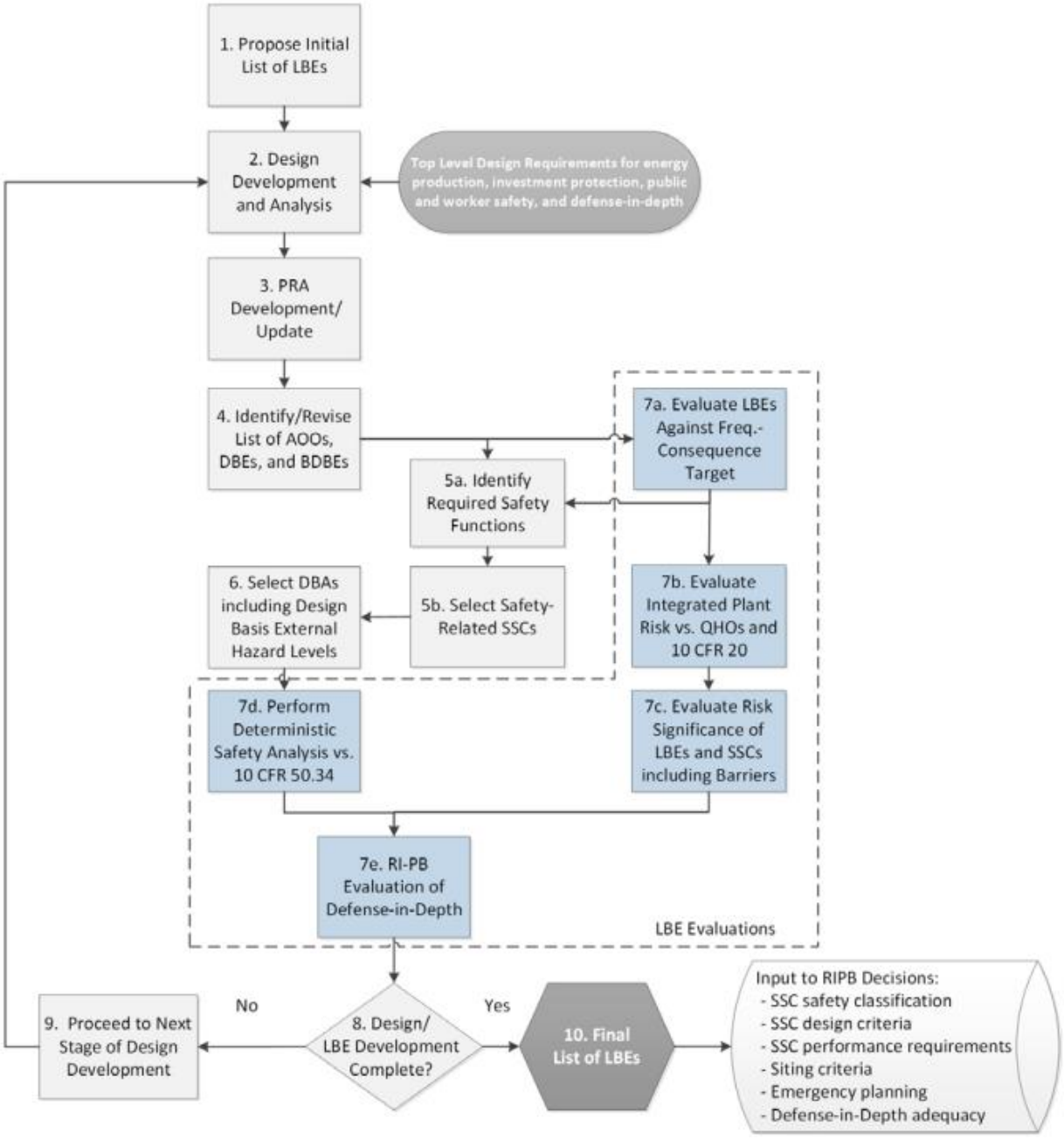

Figure 2: Process for Selecting and Evaluation Licensing Basis Events [4]

1.2. Calculations to Meet Criterion

This section outlines the methodology used to evaluate integrated plant risk against the three cumulative risk metrics presented by QHO and 10 CFR 20.

1.2.1. Evaluation of Cumulative Risk Targets for Integrated Risk of All LBEs

Per 10 CFR 20 [1], the total mean frequency of exceeding a site boundary dose of 100 mrem from all LBEs should not surpass 1 event per plant-year. Thus, the mean frequencies of all LBEs that have a mean dose consequence greater than 100 mrem at the site boundary are summed together. The resulting integrated risk must be less than 1/p-y to comply with licensing requirements. This is accomplished by utilizing equation (1) for LBE "i".

$$\sum_{i}^{LBEs > 100\ mrem} Frequency_i = Cumulative\ Risk\ \left[\frac{Events}{Plant - Year}\right] \quad (1)$$

1.2.2. Evaluation of Early Fatalities

The average individual risk of early fatality (EF) within 1 mile of the EAB, based on mean frequency and consequence estimates from all LBEs, shall not exceed 5×10^{-7} per plant-year, in order to comply with the NRC safety goal QHO [2] for EF risk.

To evaluate this metric, one must first understand how EFs may occur. Acute deaths only occur for doses above 100 rem, as shown in Figure 3. The mean lethal dose of radiation required to kill 50% of humans at 60 days (LD50/60) is about 350-400 rem without significant supportive care, and about 500-600 rem when antibiotics and transfusion support are provided. [5]

Because it is impossible for acute deaths to occur at doses below 100 rem, LBEs with a dose release less than 100 rem can be completely ignored in this calculation. Therefore, summing the mean frequencies of all LBEs "i" with a mean dose consequence higher than 100 rem at the

EAB will yield the frequency of EFs at the EAB. It is worth noting that this is a very conservative estimate. At doses of 100 rem, most people would survive, even without treatment. For a more realistic approach, only LBEs with a dose of about 500 rem could be considered, as that is the mean value of lethal dose as shown in Figure 3.

$$\sum_{i}^{LBEs > 100\ rem} Frequency_i = Cumulative\ Risk\ \left[\frac{EF}{Plant - Year}\right] \quad (2)$$

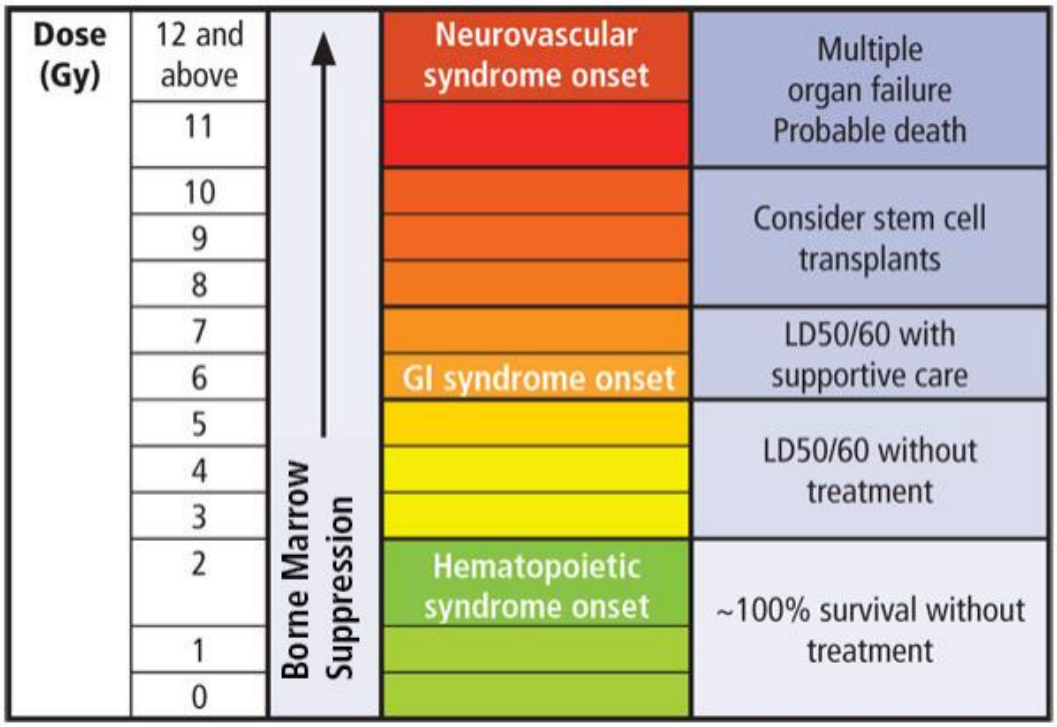

Figure 3: Radiation Effects [5]

1.2.3. Evaluation of Latent Cancer Fatalities

BEIR VII estimates that approximately 1% of individuals would develop cancers from a dose of 10 rem [6]. The Linear No-Threshold Model suggests the risk of cancer increases linearly with dose, at a factor of about 5% per 100 rem (or 0.05% per rem). Therefore, to determine the

probability of a person developing cancer due to an LBE, all LBEs will be considered and they will be weighted by a factor of 0.0005 per rem. This considers that there is a greater likelihood of LCFs occurring for LBEs with higher doses, but that there is still a small chance of cancer even if the dose is below 10 rem.

$$\sum_{i}^{All\ LBEs} Frequency_i * Dose_i * 0.0005 = Cumulative\ Risk\ \left[\frac{LCF}{Plant - Year}\right] \quad (3)$$

To comply with the NRC safety goal QHO for LCF risk, the average individual risk of latent cancer fatalities (LCF) within 10 miles of the EAB is limited to 2×10^{-6} per plant-year, based on mean frequency and consequence estimates from all LBEs.

1.2.4. Determining Site Boundary Atmospheric Dispersion Factor (χ/Q)

RG 1.145 [7] recommends using averaged hourly weather data specific to the plant site to calculate χ/Q. To keep this methodology more general, meteorological conditions are conservatively assumed, such that atmospheric mixing and dispersion are minimized and there is a greater release concentration downwind. For this approach, a stability class of F (stable atmospheric conditions) and a wind speed of 1 m/s are selected.

According to RG 1.145 [7], when the wind speed at the 10-meter level is less than 6 m/s and there are stable atmospheric conditions (classes D, E, F, and G), the following equations are used to determine the χ/Q values for relative ground-level concentrations at the plume centerline:

$$\frac{\chi}{Q} = \frac{1}{U\left(\pi\sigma_y\sigma_z + \frac{A}{2}\right)} \quad (4)$$

$$\frac{\chi}{Q} = \frac{1}{U\left(3\pi\sigma_y\sigma_z\right)} \quad (5)$$

$$\frac{\chi}{Q} = \frac{1}{U(\pi \Sigma_y \sigma_z)} \quad (6)$$

where

χ/Q is relative concentration $[s/m^3]$,

U is the wind speed at 10 meters above plant grade [m/s],

σ_y is the lateral plume spread [m], (Figure 1 of RG 1.145 [7])

σ_z is the vertical plume spread [m], (Figure 2 of RG 1.145 [7])

A is the smallest vertical-plane cross-sectional area of the reactor building $[m^2]$,

Σ_y is the lateral plume spread with meander and building wake effects, where $\Sigma_y = M\sigma_y$ for distances less than 800 meters, where M is the meander correction factor obtained from RG 1.145 Fig. 3 [7].

Values for σ_y and σ_z come from Figures 1 and 2 of RG 1.145 [7]. Using the three equations for χ/Q, the values from equations (4) and (5) are compared and the higher value selected. This value is then compared with the value from equation (6), and the lower value of these two is selected as the appropriate χ/Q value, in accordance with RG 1.145 [7]. By utilizing this process, the atmospheric dispersion factor can be calculated based on the ground distance from the plume centerline, which for many of the computations in this report is equivalent to the EAB.

1.2.5. Determining Control Room Dispersion Factor (χ/Q)

Because the χ/Q calculations from RG 1.145 apply at the EAB and the control room must be within the EAB, different calculations are used to evaluate the atmospheric dispersion factor for the control room. Alternative methods for determining χ/Q values at the control room are

addressed in RG 1.194 [8]. The χ/Q value for a single point source on a surface, or when a single point receptor has a difference in elevation of less than 30% of the upwind building height (typically the containment), is estimated by using equation (5), which takes building wake into consideration. When there are many points of activity on a surface and a single point receptor, or if the difference in elevation between the source and receptor is more than 30% of the building height, equation (7) is used.

$$\frac{\chi}{Q} = \left[U\left(\pi\sigma_y\sigma_z + \frac{A}{K+2}\right)\right]^{-1} \tag{7}$$

where

$K = \frac{3}{(s/d)^{1.4}}$,

s is the shortest distance between the building surface and receptor location [m],

d is the diameter or width of the building [m].

This equation simply evaluates the atmospheric dispersion factor at the control room distance and does not consider how radiation may enter the control room building. Essentially, we assume a worst-case scenario in which a control room occupant is outside without radiation shielding during an accident, making this a highly conservative assumption.

1.2.6. Dispersion Reduction Factor

Reference [9] compares the equations seen in RG 1.145 for χ/Q to observed values, as shown below in Figure 4. It is seen that at wind speeds of 1 m/s (as was assumed), the RG 1.145 equations overestimate the concentration by at least a factor of 10. Therefore, to remain conservative, a reduction factor of 4 will be used for the RG 1.145 calculated dispersion factors due to known conservatism in the equations, which is valid for distances < 1200 meters.

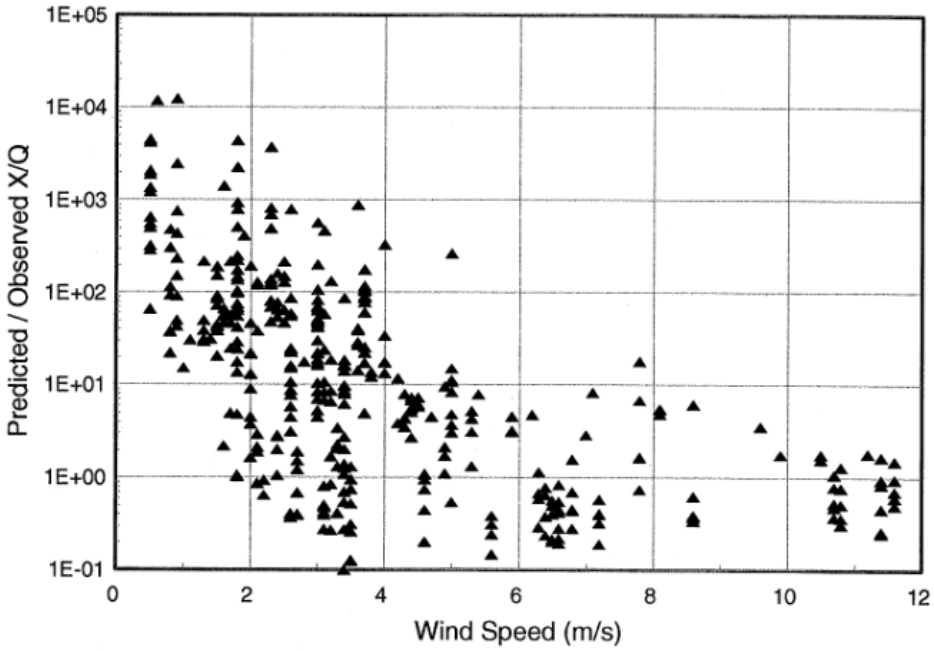

Figure 4: Variation in the ratios of concentrations predicted by an open-terrain dispersion model to observed centerline concentrations in wakes as a function of wind speed. [9]

In the same study, the RG 1.145 equations were compared to observed χ/Q values for the full ground-level data set, applicable to the control room, as seen below in Figure 5. There appears to be no correlation with wind speed and model bias, therefore no control room reduction factor will be assumed.

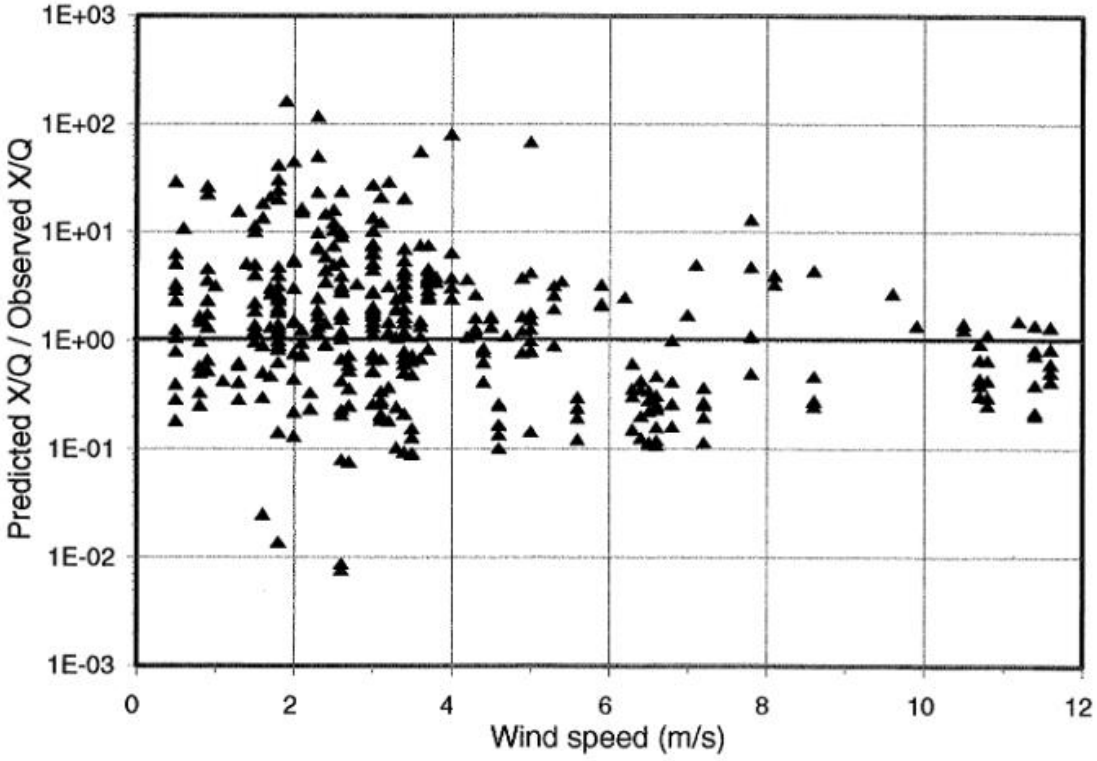

Figure 5: Variation in the ratio of revised model concentration predictions to observed concentrations as a function of wind speed for the full ground-level data set. [10]

1.2.7. Mean Dose for LBEs

This methodology assumes that mechanistic source term (MST) analysis has already been completed, such that the containment response, source term generation after radioactive release, and the cumulative release to the environment of each radioactive isotope for every release category is determined. Each LBE is mapped to a specific release category. The mean dose for each release category is determined by the following calculation:

$$D_i = \sum_{j=1}^{J} Q_{ij} f_{ij}(t; \varsigma_{1,j;}\varsigma_{2,j;\ldots}) C_j \frac{\chi}{Q} \tag{8}$$

where

D_i is the dose of release category "i",

J is the total number of nuclides released,

Q_{ij} is the initial activity for nuclide "j" in release category "i",

$f_{ij}(t; \varsigma_{1,j;}\varsigma_{2,j;\ldots})$ is the fractional reduction in nuclide "j" due to buildup, decay, settling, plateout, and other processes involving physical parameters,

C_j is the dose conversion factor for nuclide "j", taken from [11]

1.3. Problems Associated with the Current Processes

As seen in Figure 2, the process of determining LBEs and ultimately licensing a reactor is an iterative process. This produces some challenges, as the process may be iterated through five, ten, or even more times. This can be an incredibly time-consuming process, which in turn leads to being a cost-heavy process. There is also the issue of error propagations through iteration, which can lead to inaccurate results if not performed with extreme caution.

As seen in the equations in 1.2, evaluating the dose release to the public from a nuclear plant accident is no easy feat. Even utilizing advanced coding tools like MACCS or MELCOR can take hours to accurately model accident progression, dispersion, and dose effects [12]. The main contributor to this elaborate modeling scheme is the distance from the accident, as for greater distances there are more variables such as building wake, wind speed, dispersion, release height, ground deposition, cloud shine, population distribution, and more. These variables each have their own set of parameters as well, which can be dependent on one another, leading to this extremely intricate process to accurately evaluate public dose.

This presents the desire for a simplified process. If conservative assumptions can be made while simultaneously satisfying the licensing targets discussed in 1.1, this process of evaluating public dose could be greatly streamlined. If the EF and LCF frequency limits were met at the EAB, there would be no need to evaluate the cumulative risk within the 1-mile and 10-mile mark, respectively. In the scenario that these risk metrics were not even remotely close to being surpassed at the EAB, then the boundary can be shrunk, allowing for the public to reside in closer proximity to the nuclear power plant (NPP). This proves incredibly useful for small modular reactors (SMRs) which may be in population-dense urban cities. Furthermore, streamlined and conservative methodology means modeling scenarios could take seconds or minutes instead of hours, leading to more money being saved, less risk to the public, and quicker reactor licensing.

CHAPTER 2. Proposed Optimization Methodology for Evaluation at EAB

This section serves to simplify the equations above for evaluating EFs and LCFs at the EAB, rather than within 1 mile and 10 miles (respectively) of the site boundary. The evaluation of cumulative risk targets (1.2.1) for integrated risk of all LBEs is already required to be taken at the site boundary, therefore there is no further need to simplify that methodology.

2.1. Evaluating EAB Atmospheric Dispersion Factor (χ/Q)

The process outlined in 1.2.4 utilizes charts to derive values for σ_y and σ_z to calculate χ/Q. However, to make calculations more automated rather than observing a chart and finding an appropriate value for every iteration of EAB distance, equations for the directional plume spread are constructed. Reference [13] presents a method to derive analytical expressions for σ_y and σ_z as a function of distance from the source and meteorological variables σ_θ. By assuming that there is 0 standard deviation of azimuthal wind direction, and that Stability Class F is maintained, keeps calculations conservatively consistent and leads to the expressions below:

$$\sigma_y = 0.0722x^{0.9031} \tag{9}$$

$$\sigma_z(x < 100m) = 0.053x^{0.814} \tag{10}$$

$$\sigma_z(100m < x < 1000m) = 0.086x^{0.74} - 0.35 \tag{11}$$

By following the methodology outlined in 1.2.4 and incorporating these relationships for $\sigma_y \; and \; \sigma_z$, the conservative value for χ/Q can automatically be calculated based on the EAB distance x. This will ultimately be the driving force of the methodology, as the atmospheric dispersion factor is the only equation being used which is dependent on distance. A smaller distance leads to a higher dispersion factor, which results in a higher concentration of dose in the nearby area, and vice versa.

2.2. Evaluating Early Fatalities at the EAB

By utilizing the χ/Q obtained for the respective EAB, (8) enables for the calculation of the dose for each release category. (2) is used to determine the frequency of EFs. With the utilization of computational software (such as Microsoft Excel), the frequency of EFs can be observed over a variety of EABs. This enables one to determine the minimum EAB distance required at which the frequency of EFs satisfies the QHO of 5×10^{-7} per plant-year.

2.3. Evaluating Latent Cancer Fatalities at the EAB

This approach is the same as 2.2, however the QHO of 2×10^{-6} per plant-year for LCFs must be satisfied. Because standard practice is evaluating LCFs within a 10-mile radius, a more realistic approach would consider the population density distribution. However, because we are aiming to minimize the EAB, the population density becomes less prevalent, especially for distances less than 400 m.

2.4. EAB Optimization Approach Using Microsoft Excel

The goal of this methodology is that anyone looking to optimize the EAB of a specific NPP site can follow this process to determine the plant-specific optimal EAB with only a few provided parameters. It is assumed that Event Sequence Quantification (ESQ) and Mechanistic Source Term (MST) analysis has already been performed, such that the LBE frequencies and cumulative release to the environment for every release category are known. Equation (8) displays how to calculate the dose for each release category, which is dependent on initial activity, fractional reduction factors, dose conversion factors, and χ/Q. MST anlysis provides the values for initial activity. Fractional reduction factors ($\varsigma_{i,j;}$) are specific to nuclide "j" and release category "i" due to buildup, decay, settling, plateout, and other processes involving the physical parameters [14]. The dose conversion factors for each nuclide (C_j) are taken from reference [11]. This leaves only χ/Q,

which is evaluated at the EAB by using equations (4), (5), and (6), with the appropriate methodology discussed in 1.2.4, where σ_y and σ_z are derived from equations (9), (10), and (11). The result of χ/Q calculated is divided by the dispersion reduction factor in order to provide a more realistic value for χ/Q, while still remaining conservative.

To incorporate this strategy into Excel, one must first input the appropriate constants for equations (4), (5), and (6), including U, A, C, σ_y, σ_z, M, and reduction factors, where σ_y and σ_z utilize equations (9), (10), and (11), which are dependent on a cell representative of the EAB distance. Next, χ/Q can be evaluated by utilizing the appropriate logic discussed in 1.2.4 and dividing by the reduction factor, so that χ/Q can be determined for any EAB distance simply by changing the EAB distance cell.

The release to the environment established in the ESQ should be input into Excel, organized by release categories as the columns and nuclides as the rows. By making a column of the dose conversion factors (DCFs) aligning with each appropriate nuclide, the dose of each nuclide for each release category can easily be determined by utilizing equation (8). By summing up the doses of every nuclide, the total effective dose equivalent (TEDE) is determined for each release category. This makes every TEDE dependent on the current EAB distance. It is recommended to create a table summarizing these results, which has columns for release category name and dose at the EAB.

A new table should be created, which has the names of each LBE sequence with their release category and ESQ determined frequency. The dose at the EAB for each event sequence is determined by mapping each event sequence to its corresponding release category dose. This is done by utilizing Excel's built-in function "VLOOKUP", with the first input being the event

sequence release category the user is looking to match in the table, the second input is the table array, and the third input is the column of the value you want to extract (following this implementation, it would be column 2). Expanding this for every event sequence will provide the appropriate dose at the EAB for each LBE.

Evaluating the risk metrics is performed by utilizing equations (1), (2), and (3), with the appropriate logic. It is recommended to have the goals of each metric under the calculated value, so it can easily be observed that the targets are satisfied are surpassed. Logic could also be added so that if a metric's target is exceeded, "Fail" is displayed, or if it is met "Success" is displayed, but this is not necessary. With this setup, changing the cell corresponding to the EAB distance changes the three risk metrics. This could be manually decreased until one of the goals is exceeded, however, to make processing easier, a VBA macro can be created for full automation. Appendix B shows a script that can be copied into the VBA editor to create a module which is capable of automatically adjusting the EAB distance until a limit is surpassed. Depending on the desired accuracy, the step size can be increased to save time or decreased to improve accuracy. At the end of the simulation, a prompt will appear providing the optimized EAB distance.

2.5. Control Room Optimization Approach Using Microsoft Excel

The process for evaluating the optimal distance of the control room is very similar to that of the EAB, just modifying the control room limit and using the appropriate χ/Q from equation (7), where σ_y and σ_z are at the control room distance. If the process in Section 2.4 has been completed, the release category doses can be adjusted by dividing by the EAB χ/Q and multiplying by the control room χ/Q. This is mathematically valid, as all terms are proportionally scaled, with the only difference between the control room dose and the EAB dose being the atmospheric dispersion factor. The same script in Appendix B can be modified for the optimal CR distance.

CHAPTER 3. MHTGR Case Study

Up to this point, everything has been hypothetical and conceptual. To prove the validity of this simplified approach and that the EAB has potential to be minimized, a case study will be conducted using data for a Modular High Temperature Gas-Cooled Reactor (MHTGR). An MHTGR is selected for this purpose because it is an advanced non-LWR with a surplus of data available to the public. A peer group has already performed an analysis to evaluate all LBEs, such that their respective event frequencies are known. The cumulative release to the environment of each radionuclide for every release category is provided in resource [14], and included in Appendix A.

Using this data and combining it with the simplified methodology discussed in CHAPTER 2, one can observe if the cumulative risk metrics for EFs and LCFs are met at the EAB. If they are easily satisfied, we can see how small we are able to shrink the EAB while still satisfying the QHOs.

3.1. Evaluation of the Cumulative Risk Metrics at 425 meters

To test the methodology presented, the standard MHTGR is evaluated at 425 meters so that the dose release categories and satisfaction of risk metrics can be verified. The data in Appendix A is used in equation (8) as the initial activity. Reference [14] also discusses fractional reduction factors ($\varsigma_{i,j;}$) in Section D.1, appropriate for each release category. The dose conversion factors for each nuclide (C_j) are taken from [11]. This leaves only χ/Q, which is evaluated at the EAB by using equations (4), (5), and (6), with the appropriate methodology discussed in 1.2.4, where σ_y and σ_z are derived from equations (9), (10), and (11). For the control room dispersion factor, equation (7) is utilized but with σ_y and σ_z at the control room distance, rather than the EAB.

Dispersion reduction factors are incorporated to solve for χ/Q more accurately, while still remaining conservative.

Table 1: Standard MHTGR Building Parameters

Reactor Building	
Volume	5203 m^3
Settling Rate	< 0.32 hr^{-1}
Plateout Rate	> 1.0 hr^{-1}
Dampers	Open when flow in > flow out
Leak Rate	1 volume/day
Site	
EAB Distance	425 m
Atmospheric Dispersion Factor at EAB	
Median	9×10^{-5} s/m^3
Breathing Rate	
0 to 8 hrs	3.47×10^{-4} m^3/s
8 to 24 hrs	1.75×10^{-4} m^3/s
1 to 30 days	2.32×10^{-4} m^3/s
Plant Rating	
Thermal Rating per Module	350 MW(th)
Number of Modules	4
Nominal Plant Rating	558 MW(e)

Calculating χ/Q at the same EAB distance of 425 m, given from Table 1, using the methodology presented, yielded a value of 1.6×10^{-4} s/m^3, while the χ/Q parameter provided in Table 1 is 9×10^{-5} s/m^3, making our χ/Q about 75% higher. This seems incredibly appropriate, as the most stable weather conditions are assumed, and every conservative position was taken. As seen in Figure 4, the reduction factor utilized was still incredibly conservative, so if higher (more accurate) reduction factors were used, we would likely get much closer to the same χ/Q value provided. However, as the intent of this methodology is to remain conservative, this proves that the equations are working exactly as designed.

To further prove that the methodology is working appropriately, the mean dose for each LBE release category is calculated. For the purpose of comparison, the χ/Q value will be the parameter provided in Table 1, rather than our calculated value. Using equation (8) and the relevant resources, Table 2 through 4 show the calculated values for mean dose of each release category compared to the values provided in resource [14].

Table 2: Mean Dose Released for DF Conditions

Dry Conditions, Forced Convection Cooldown		
Release Categories	**Calculated Mean Dose (rem)**	**Provided Mean Dose (rem)**
DF-1	9.12E-04	1.00E-03
DF-2	3.37E-04	3.00E-04
DF-3	1.33E-04	1.00E-04
DF-4	5.33E-05	4.00E-05

Table 3: Mean Dose Released for WF Conditions

Wet Conditions, Forced Convection Cooldown		
Release Categories	**Calculated Mean Dose (rem)**	**Provided Mean Dose (rem)**
WF-1	5.42E-03	5.00E-03
WF-2	4.35E-03	4.00E-03
WF-3	8.68E-04	8.00E-04
WF-4	6.39E-04	6.00E-04

Table 4: Mean Dose Released for DC Conditions

Dry Conditions, Conduction Cooldown		
Release Categories	**Calculated Mean Dose (rem)**	**Provided Mean Dose (rem)**
DC-1	9.39E-02	1.00E-01
DC-2	2.88E-02	3.00E-02
DC-3	6.86E-04	8.00E-04
DC-4	4.39E-04	4.00E-04
DC-5	1.75E-04	2.00E-04
DC-6	1.75E-04	2.00E-04
DC-7	7.11E-04	8.00E-04
DC-8	7.11E-04	8.00E-04
DC-9	2.58E-05	2.00E-05

Table 5: Mean Dose Released for WC Conditions

Wet Conditions, Conduction Cooldown		
Release Categories	**Calculated Mean Dose (rem)**	**Provided Mean Dose (rem)**
WC-1	2.04E-02	2.00E-02
WC-2	6.41E-03	4.00E-03
WC-3	7.43E-04	7.00E-04
WC-4	5.19E-04	4.00E-04
WC-5	1.82E-03	2.00E-03
WC-6	1.32E-04	1.00E-04
WC-7	8.66E-05	1.00E-04

To ensure that the calculated dose for the release categories satisfies the F-C target for LBEs, the event sequences and their respective frequencies seen in Table 7 are plotted with their appropriately mapped release category against the F-C chart of Figure 1. This is shown in Figure 6, where it can be seen that the F-C of all LBEs is well within the target, displaying room for optimization. 1.1 also discussed that any LBEs within 1% of the F-C target are considered risk significant. Figure 6 shows that prior to optimization, no LBE is remotely close to being considered risk significant. Upon minimizing the EAB, there will be higher release categories, but frequencies will remain the same. Therefore, we would expect to see the LBEs plotted in Figure 6 to shift to the right, getting closer to the F-C target, ideally staying below the risk significant and F-C targets.

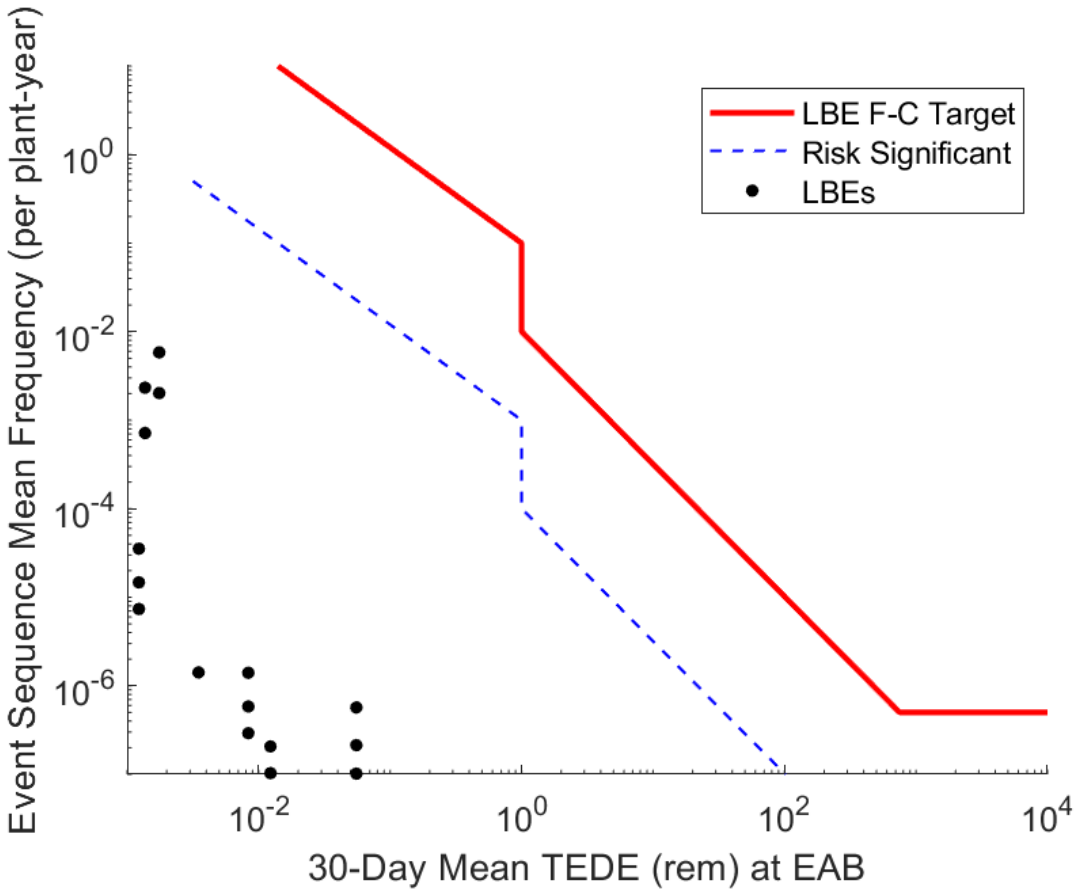

Figure 6: Initial F-C of LBEs Prior to Optimization

By comparing the results of our methodology for computing the dose of release categories to the doses provided, we can see that the results are incredibly similar. The small fraction of discrepancies may largely be due to resource [14] only providing numbers to the first decimal place, while our computations go well beyond that. Nonetheless, now that we have verified the computations for χ/Q and release category doses, and all LBEs prior to optimization are below the F-C target, we must verify that the three risk metrics are satisfied at the initial EAB. By using equations (1), (2), and (3), the following licensing targets are analyzed.

Table 6: Verifying Satisfaction of Risk Metrics

Metric	Calculated Frequency	Limit	Pass/Fail
Integrated Risk	0	< 1/p-y	Pass
EFs	0	5×10^{-7}	Pass
LCFs	2.2×10^{-8}	2×10^{-6}	Pass

Because the simplified methodology for calculating χ/Q proved to be an effective conservative result, using the value of χ/Q provided in Table 1 led to very similar doses for relevant release categories, and the licensing targets are satisfied, we have verified that the methodology is working appropriately. Now each part can be combined so that the three metrics are dependent on release categories doses, which are dependent on χ/Q, which is inherently dependent on the location of measurement (the EAB and/or control room). Therefore, by inputting these equations in Excel and decreasing the EAB in a certain step-size, we can observe how small the EAB can be before any of the three risk metrics is compromised.

3.2. Computing Minimal EAB

The atmospheric conversion factor is computed for EAB distances from 999 meters to 1 meter from the reactor building in increments of 0.01 meters. This starting point was chosen because equation 11 is valid for less than 1000 meters. Using χ/Q values, the doses are calculated for each LBE, and the risk metrics are evaluated following the methodology presented. The gathered data is plotted and compared to each respective metric, as seen below in Figure 7, Figure 8, and Figure 9.

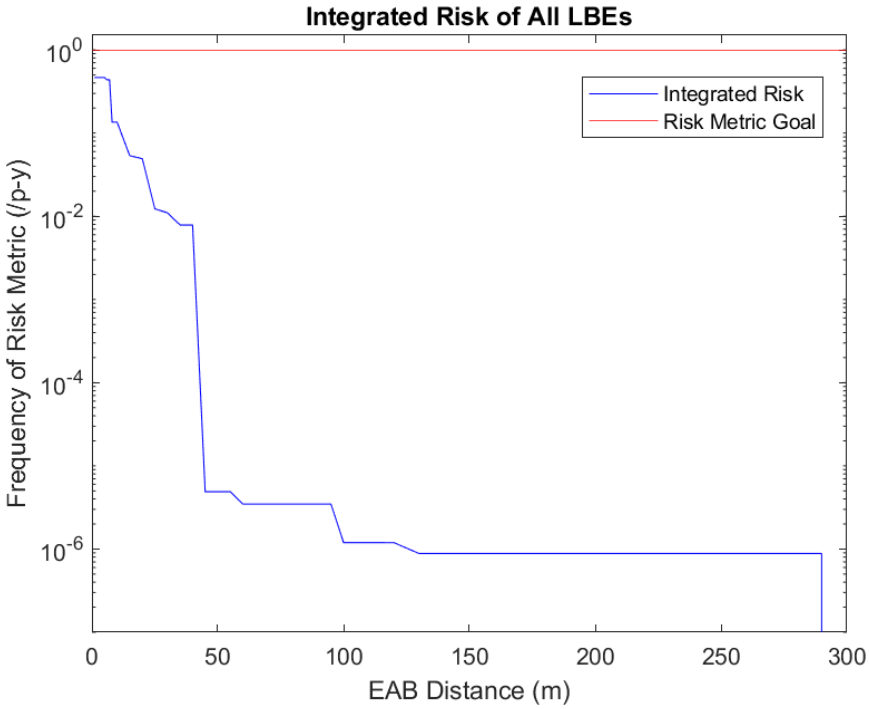

Figure 7: Evaluation of Integrated Risk vs. Risk Target

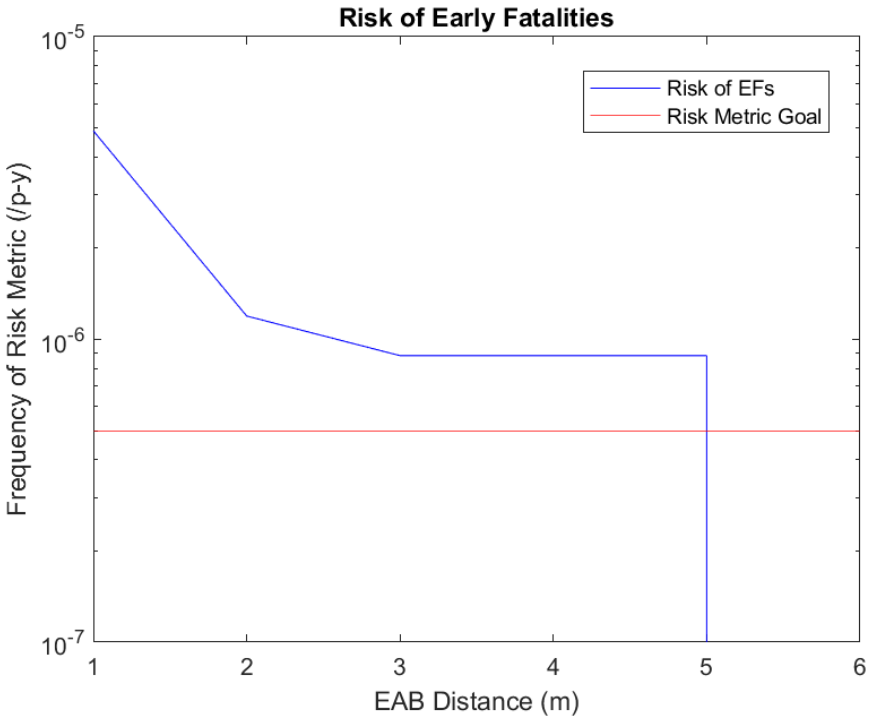

Figure 8: Evaluation of EF Risk vs. EF Target

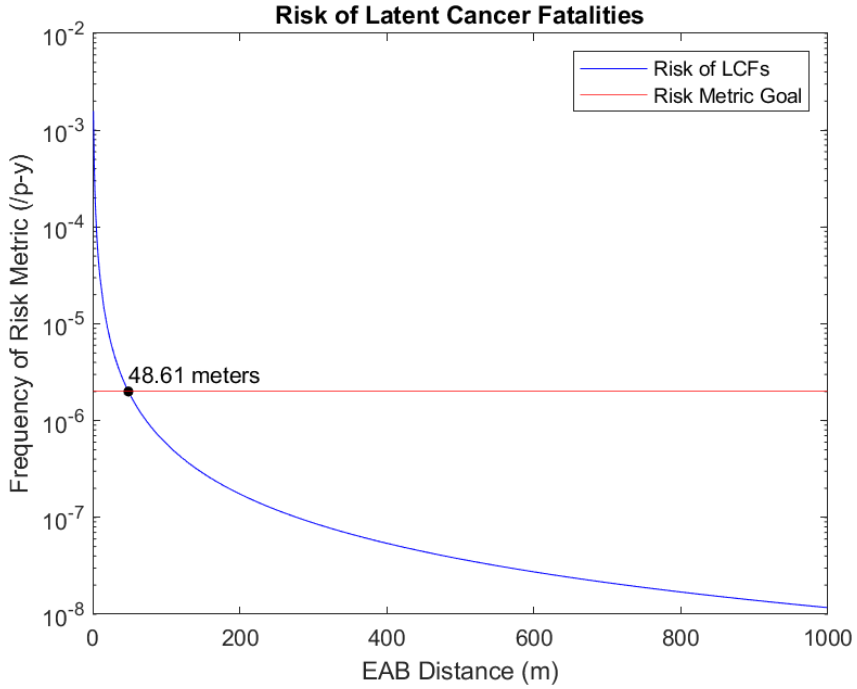

Figure 9: Evaluation of LCF Risk vs. LCF Goal

By observing the graph of Figure 7, we can see that the integrated risk of all LBEs is never a concern for the standard MHTGR. This is because summing the frequencies of all LBEs which result in radionuclide release is 0.4653, which is less than 1. Therefore, this risk metric is always satisfied. The blocky, step-like nature of this graph is due to the integrated risk being a summation of frequencies, which remain unchanged based on the EAB. As the EAB is minimized, more and more LBE frequencies are included in the summation. As there are only 24 release categories for the standard MHTGR, some of which even result in the same dose so there are in fact 22 unique doses, there will be a maximum of 22 steps in this evaluation. However, some release categories may surpass the 100 mrem mark at the same distance, resulting in even less steps.

Figure 8 shows that there is no risk of EFs until 5 meters from the reactor building, at which point the frequency of EF is 8.84×10^{-7}, surpassing the 5.0×10^{-7} threshold. This frequency is due to the release category DC-2 which is tied to three event sequences. Event sequence RS-AK alone has a dose of 5.69×10^{-7} rem at 5 meters, which results in the EF risk metric being surpassed. It is important to note, this 5-meter mark is incredibly unnecessary, as no individual of the public will be within 5 meters of the reactor building at any time. Still, up to this point the EF risk metric stands to be the limiting factor in minimizing the EAB for a standard MHTGR.

Lastly, Figure 9 displays the risk of LCFs, which shows that the risk metric is surpassed at 48.61 meters from the containment building with an LCF risk of 2.0×10^{-6} /p − y, when the χ/Q value is 6.746×10^{-3} s/m^3. This result shows that the LCF metric is the most limiting metric for EAB optimization of a standard MHTGR, resulting in the optimized EAB boundary of 48.61 meters which satisfies all three-risk metrics. The LBE consequences evaluated at the 48.61-meter EAB are shown below in Table 7.

Table 7: LBE Consequences at the Optimized EAB Boundary (48.61 meters)

Event Sequence	**Release Category**	**Frequency (/p-y)**	**EAB Dose (rem)**
PC-BT	—	6.41E-10	0
HTS-AH	DC-2	2.13E-07	2.27
RS-AK	DC-2	5.69E-07	2.27
RS-AM	DC-2	1.02E-07	2.27
PC-AU	DC-4	1.32E-03	0.0346
PC-BH	DC-5	9.05E-04	0.0138
PC-AT	DC-6	3.38E-03	0.0138

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
PC-BG	DC-7	2.33E-03	0.0560
PC-BR	DC-8	7.16E-04	0.0560
PC-AE	DC-9	2.05E-02	0.00203
PC-AF	DC-9	8.12E-03	0.00203
PC-AL	DC-9	2.15E-09	0.00203
PC-BP	DF-1	5.83E-03	0.0717
PC-BQ	DF-1	2.02E-03	0.0717
PC-BU	DF-1	2.17E-10	0.0717
PC-BC	DF-2	2.14E-02	0.0265
PC-BD	DF-2	6.28E-03	0.0265
PC-BE	DF-2	7.35E-03	0.0265
PC-BF	DF-2	1.93E-03	0.0265
PC-BJ	DF-2	2.35E-09	0.0265
PC-BL	DF-2	8.00E-10	0.0265
PC-AB	DF-3	5.27E-02	0.0104
PC-AD	DF-3	1.71E-02	0.0104
PC-AK	DF-3	1.85E-09	0.0104
PC-AQ	DF-3	9.09E-03	0.0104
PC-AS	DF-3	2.80E-03	0.0104
PC-AA	DF-4	1.94E-01	0.00419

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
PC-AC	DF-4	6.54E-02	0.00419
PC-AH	DF-4	2.14E-08	0.00419
PC-AJ	DF-4	7.34E-09	0.00419
PC-AP	DF-4	3.11E-02	0.00419
PC-AR	DF-4	1.07E-02	0.00419
PC-AW	DF-4	3.42E-09	0.00419
PC-AY	DF-4	1.16E-09	0.00419
HTS-AJ	ε	1.87E-07	0
HTS-AN	ε	2.67E-09	0
LOSP-AF	ε	5.30E-09	0
LOSP-AH	ε	1.68E-10	0
LOSP-AI	ε	4.92E-12	0
MS-AE	ε	4.25E-08	0
MS-AO	ε	4.95E-07	0
MS-AP	ε	1.91E-11	0
MS-AR	ε	1.40E-06	0
MS-AS	ε	1.25E-05	0
MS-AT	ε	3.54E-05	0
MS-BA	ε	2.39E-10	0
MS-BE	ε	1.15E-10	0

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
MS-BF	ε	9.04E-10	0
MS-BH	ε	3.02E-10	0
MS-BU	ε	4.40E-06	0
MS-CB	ε	8.37E-12	0
MS-CI	ε	3.62E-12	0
MS-CJ	ε	2.82E-11	0
MS-CK	ε	5.50E-07	0
PC-AG	ε	7.12E-08	0
PC-AI	ε	6.32E-09	0
PC-AM	ε	6.66E-10	0
PC-AO	ε	2.65E-10	0
PC-AV	ε	1.12E-08	0
PC-AX	ε	9.98E-10	0
PC-AZ	ε	2.65E-10	0
PC-BA	ε	3.41E-10	0
PC-BB	ε	4.10E-11	0
PC-BI	ε	7.68E-09	0
PC-BK	ε	6.86E-10	0
PC-BM	ε	1.77E-10	0
PC-BN	ε	2.26E-10	0

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
PC-BO	ε	2.82E-11	0
PC-BS	ε	2.01E-09	0
PC-BV	ε	5.67E-11	0
PC-BX	ε	2.60E-03	0
RS-AM	ε	4.59E-08	0
RS-AS	ε	4.33E-09	0
RW-AD	ε	2.72E-08	0
RW-AG	ε	9.03E-10	0
RW-AH	ε	1.01E-10	0
SS-AC	ε	4.25E-07	0
SS-AK	ε	3.14E-10	0
SS-AO	ε	1.42E-07	0
SS-AS	ε	2.31E-07	0
SS-AX	ε	2.31E-07	0
SS-BC	ε	2.31E-07	0
SS-BF	ε	3.60E-11	0
SS-BH	ε	2.07E-11	0
SS-BQ	ε	5.10E-05	0
SS-BS	ε	4.00E-04	0
SS-BT	ε	5.47E-06	0

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
HTS-AA	INTACT	1.82E+00	0
HTS-AB	INTACT	4.71E-01	0
HTS-AC	INTACT	7.90E-01	0
HTS-AD	INTACT	8.44E-02	0
HTS-AE	INTACT	3.91E-02	0
HTS-AF	INTACT	2.62E-01	0
HTS-AG	INTACT	3.56E-06	0
HTS-AI	INTACT	1.34E-06	0
HTS-AK	INTACT	1.92E-07	0
HTS-AL	INTACT	1.01E-07	0
LOSP-AA	INTACT	3.69E-03	0
LOSP-AB	INTACT	1.52E-03	0
LOSP-AC	INTACT	3.65E-05	0
LOSP-AD	INTACT	3.77E-05	0
LOSP-AE	INTACT	5.03E-04	0
LOSP-AG	INTACT	3.69E-10	0
MS-AA	INTACT	4.00E-02	0
MS-AB	INTACT	1.22E-02	0
RS-AD	INTACT	5.12E+00	0
RS-AE	INTACT	1.26E+00	0

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
RS-AF	INTACT	2.38E+00	0
RS-AG	INTACT	2.30E-01	0
RS-AH	INTACT	1.06E-01	0
RS-AI	INTACT	7.30E-01	0
RS-AJ	INTACT	9.51E-06	0
RS-AL	INTACT	3.64E-06	0
RS-AM	INTACT	3.56E-07	0
RS-AN	INTACT	5.17E-07	0
RS-AP	INTACT	2.71E-07	0
RS-AQ	INTACT	2.78E-08	0
RW-AB	INTACT	1.71E-02	0
RW-AC	INTACT	8.82E-03	0
RW-AF	INTACT	1.91E-09	0
SS-AA	INTACT	4.00E-01	0
SS-AB	INTACT	1.22E-01	0
SS-AI	INTACT	3.54E-04	0
SS-AJ	INTACT	1.25E-04	0
SS-AL	INTACT	7.08E-06	0
SS-AM	INTACT	2.50E-06	0
SS-AT	INTACT	7.42E-08	0

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
SS-AU	INTACT	2.59E-08	0
SS-AY	INTACT	5.44E-11	0
SS-AZ	INTACT	4.35E-12	0
SS-BD	INTACT	4.40E-05	0
SS-BE	INTACT	1.56E-05	0
SS-BJ	INTACT	3.38E-06	0
SS-BK	INTACT	1.20E-06	0
SS-BP	INTACT	1.44E-04	0
MS-BZ	WC-2	2.06E-07	0.504
MS-CG	WC-2	1.03E-07	0.504
MS-AZ	WC-4	1.05E-08	0.0408
MS-AD	WC-5	1.42E-06	0.143
MS-AN	WC-6	1.25E-05	0.0104
MS-BY	WC-6	5.22E-06	0.0104
MS-CF	WC-6	2.61E-06	0.0104
MS-AC	WC-7	5.66E-05	0.00681
MS-AX	WF-1	1.20E-09	0.426
MS-AL	WF-2	1.40E-06	0.3418
MS-BW	WF-2	5.84E-07	0.3418
MS-CD	WF-2	2.92E-07	0.3418

Table 7 (continued)

Event Sequence	Release Category	Frequency	EAB Dose
MS-AW	WF-3	3.05E-08	0.0682
MS-BD	WF-3	3.05E-09	0.0682
MS-AK	WF-4	3.54E-05	0.0503
MS-AQ	WF-4	3.54E-05	0.0503
MS-BI	WF-4	2.59E-12	0.0503
MS-BV	WF-4	1.47E-05	0.0503
MS-CC	WF-4	7.37E-06	0.0503

Release categories denoted by ε in Table 7 represent a very small frequency and corresponding dose, while "intact" resembles there is no radionuclide release to the environment and hence no release category. Using the frequencies and consequences of the optimized boundary, the LBEs are replotted in the F-C chart to observe if any of the LBEs exceed the F-C target and if any are considered risk significant. This is shown below in Figure 10: F-C of LBEs at the Optimized EAB. By comparing Figure 10: F-C of LBEs at the Optimized EAB to Figure 6, it can be seen that there is a significant increase in the mean dose of LBEs at the EAB, however, all LBEs appear to remain well below the F-C target. More than that, at the optimized EAB it appears that each of the LBEs remain below the risk significant metric. These results paired with Figure 7, Figure 8, and Figure 9, show that the LCF metric is the limiting factor in optimizing the EAB, and that at the optimized boundary of 48.61 meters all risk metrics are satisfied and all LBEs are below the F-C target and are not risk significant.

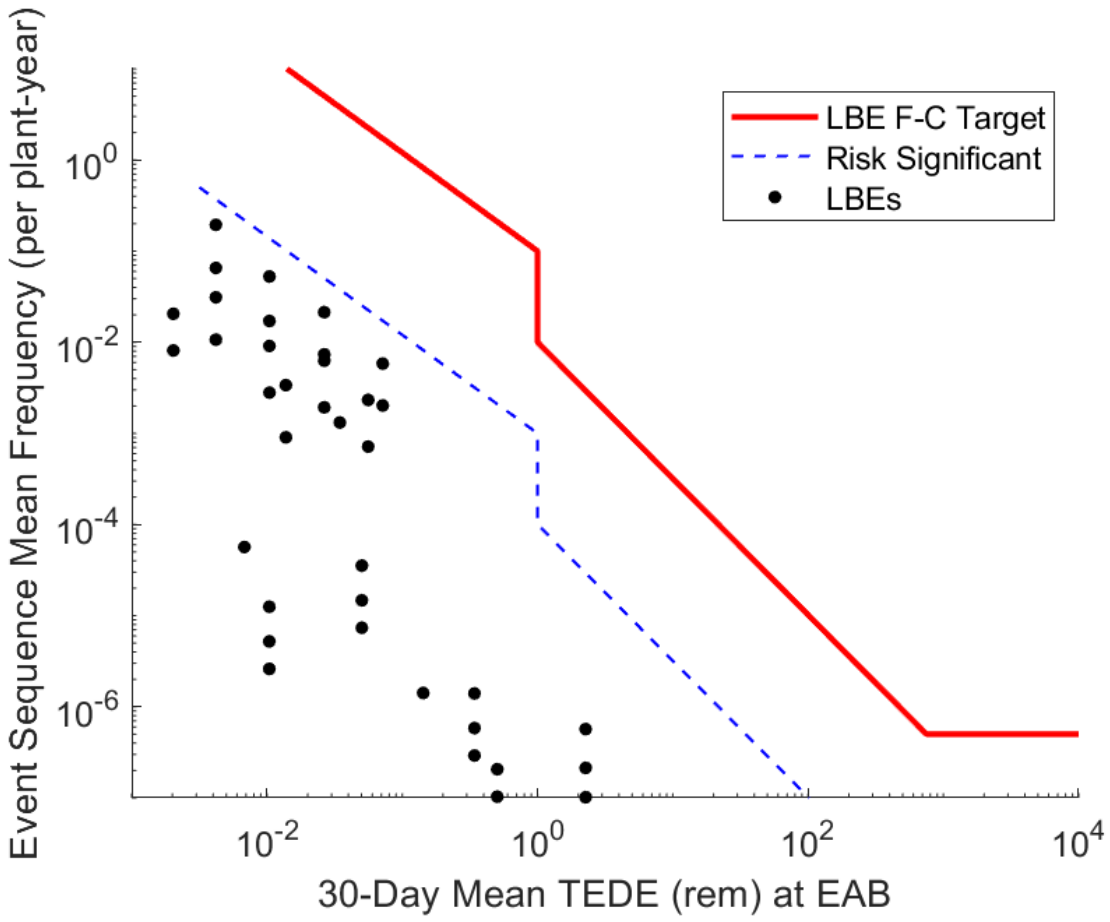

Figure 10: F-C of LBEs at the Optimized EAB

Because this result uses conservative methodology, realistically the EAB could be even closer, highlighting the inherent safety features, both passive and active, of the standard MHTGR and many advanced non-LWRs. As similar technology becomes more and more prevalent, such as SMRs, smaller EABs will be incredibly useful. If an NPP owner were to place an SMR near New York City, an urban area where land is difficult to come by, a smaller EAB will save the reactor owner money on land, while simultaneously putting less members of the public at risk.

3.3. Computing Control Room Dose

The control room dose is slightly less dynamic than the EAB dose, due to the control room being located at a much smaller distance. Equation (7) is utilized to determine the control room dispersion factor, which is dependent on the width of the building and the distance to the control room. Table 1 only provides the building cross section and does not provide the specific reactor building dimensions or location of the control room. Based on the equation for *K* in Equation (7), a smaller building width results in a lower χ/Q. To remain conservative, we will assume that the building is rectangular, rather than square, so that the building width is larger and hence χ/Q is larger. The reactor building cross section is provided to be 732 m^2, so we will assume the building is 32 x 22.9 m, making the building width 32 m.

Using these realistically assumed dimensions, χ/Q for the control room is evaluated over various distances, similar to the evaluation of doses at the EAB in 3.2, so that the location of the control room can be optimized and confirmed to be within the EAB boundary established. As stated in 1.1, the control room limit for occupants is 5 rem per accident, which is independent of accident frequency. Therefore, only the release category with the highest dose will need to be observed to evaluate the control room distance. By observing Table 2, the release categories with the highest doses are DC-1 and DC-2. However, resource [14] does not attribute any LBEs to DC-1, therefore DC-2 is the release category with the maximum dose released and will be the limiting factor for control room distance.

The results of these computations are displayed in Figure 11 below. It can be seen that at the EAB established in 3.2 (> 48.61 meters), the maximum dosage from a single accident for the control room is well below the limit. The 5 rem limit is surpassed at a distance of 14.74 meters from the reactor building.

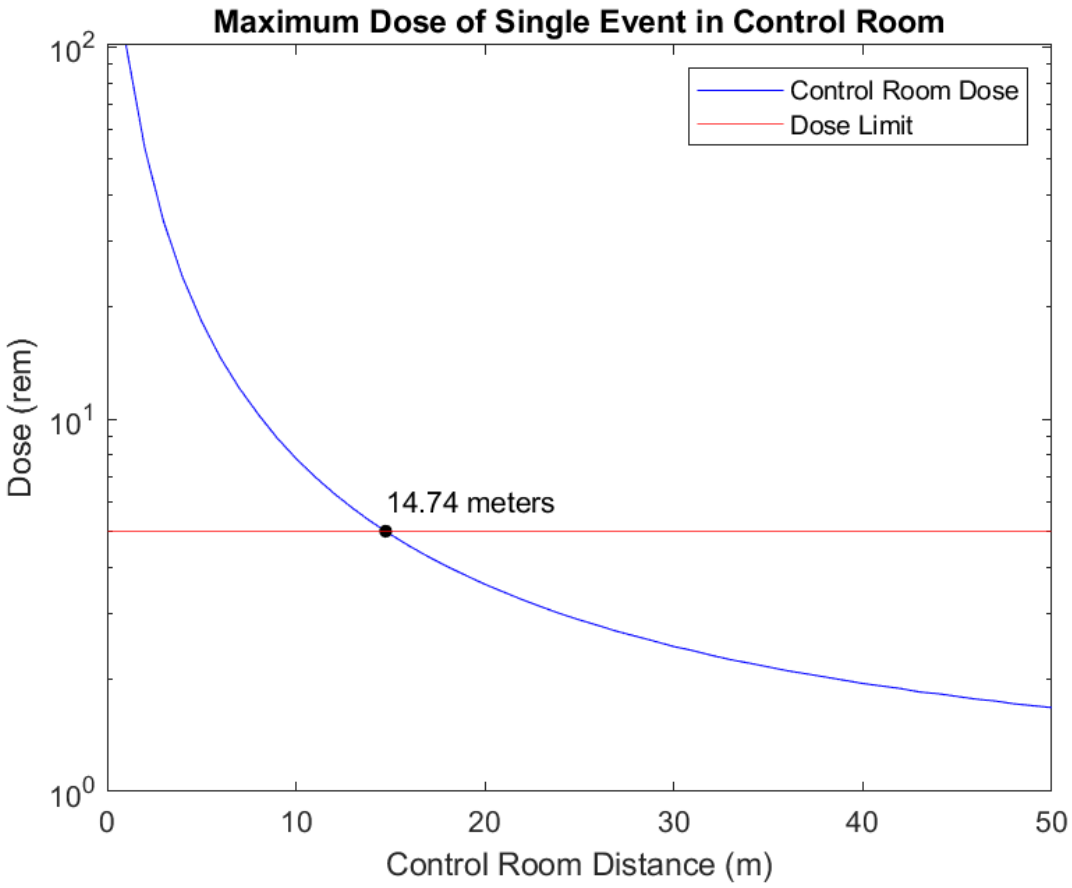

Figure 11: Evaluation of Control Room Dose vs. Control Room Limit

3.4. Summary of Case Study Results

Table 8 below summarizes the results from the MHTGR case study.

Table 8: Summary of Case Study Results

Metric	Limit	Distance at Limit
Integrated Risk	< 1 /p-y	N/A
EFs	5×10^{-7} /p-y	5 meters
LCFs	2×10^{-6} /p-y	48.61 meters
Control Room	5 rem /accident	14.74 meters

By observing Table 8, it is seen that the limiting metric for the standard MHTGR is the frequency of LCFs at the EAB. Rounding up, at an EAB distance of about 50 meters from the reactor building the integrated risk, EF, and LCF metrics are all satisfied while no LBEs pass the F-C target (Figure 10). Furthermore, the control room must be located within the EAB, and the calculations show that the control room can be located at a distance 15 meters from the reactor building while satisfying the dose limits for all LBEs. This distance falls well within the EAB, proving the solution to be feasible. The EAB of a standard MHTGR provided in Table 1 is 425 meters, which this case study has proven can be decreased by about 80%, while still satisfying the risk metrics.

CHAPTER 4. Conclusions

This research paves the wave for optimizing the EAB for advanced non-LWRs. By utilizing results from ESQ and MST analysis, one can conservatively compute the atmospheric dispersion factor over various EAB distances and use those factors in conjunction with accident frequencies and release categories to evaluate the integrated risk, EF, and LCF metrics at the EAB. As proven in the MHTGR case study, these metrics can very well be met at the EAB, rather than at the 1-mile and 10-mile mark referenced in NEI 18-04 [4], saving time and resources on intense computations, as well as further protecting the public. These methods can hasten the pace of reactor licensing, as well as enable nuclear power plants to take up less land, greatly benefiting NPP owners.

By performing a case study on a standard MHTGR, it was shown that the three risk metrics of NEI 18-04 [4] can be evaluated and satisfied at an EAB of about 50 meters, with the control room being as close as 15 meters from the reactor building. Typical MHTGR EABs range from about 400 to 800 meters, while the control room is about 100 meters away. These results show that a standard MHTGR NPP site can be diminished by about 80% while satisfying the safety goals.

These methods can be expounded upon in future research to obtain more realistic, less conservative results, if desired. Incorporating events like cyber-attacks or security breaches into the risk assessment, rather than only having SSC failures and human error, would provide a more realistic risk assessment which could be used in conjunction with this work. Also, using site specific meteorological data rather than conservatively assumed conditions would lead to more accurate results.

From an optimization standpoint, a cost-benefit analysis could be performed to further justify the EAB distance. For example, perhaps the EAB can be 50 meters but the cost of safety

features to ensure this distance is $1 billion, while an EAB at 100 meters may cost $100 million (these numbers are made-up). Combining the methods of this report with a cost analysis would provide NPP owners with a better idea of how they can optimize their plant.

APPENDICES

Appendix A

The following are the radioactive nuclide releases to the environment for each release category, which is utilized for evaluation of EFs and LCFs at the EAB for the MHTGR case study.

Cumulative Release to environment (Ci)				
Nuclide	**DF-1**	**DF-2**	**DF-3**	**DF-4**
Kr-87	6.90E-01	1.80E-01	1.30E-02	1.10E-02
Kr-88	1.60E+00	6.80E-01	9.20E-02	7.20E-02
Rb-88	1.10E+00	6.50E-01	8.90E-02	7.00E-02
Sr-89	6.40E-05	3.10E-05	2.30E-05	6.00E-06
Sr-90	1.00E-05	4.10E-06	3.20E-06	8.40E-07
Ag-110m	4.40E-05	2.30E-05	1.40E-05	3.80E-06
I-131	3.20E-03	1.20E-03	6.40E-04	1.80E-04
I-132	3.50E-02	7.70E-03	7.40E-04	5.90E-04
I-133	2.10E-02	7.10E-03	2.30E-03	9.60E-04
Cs-134	4.00E-05	2.00E-05	7.20E-05	1.90E-05
I-135	3.30E-02	9.70E-03	1.70E-03	1.00E-03
Xe-135	1.80E+00	1.20E+00	4.20E-01	2.30E-01
Cs-137	1.80E-04	9.30E-05	3.40E-04	8.90E-05

Cumulative Release to environment (Ci)		
Nuclide	**WF-1**	**WF-2**
Kr-88	3.30E+00	2.70E+00
Sr-89	4.80E-01	4.60E-01
Sr-90	8.50E-02	8.40E-02
Ag-110m	2.10E+00	2.10E+00
I-131	3.90E+00	3.40E+00
I-132	4.40E+00	3.60E+00
Te-133m	1.40E+00	6.30E-01
I-133	4.00E+00	2.90E+00
I-134	2.70E+00	1.50E+00
Cs-134	3.70E+00	3.70E+00
I-135	2.60E+00	1.50E+00
Cs-137	1.70E+01	1.70E+01
Ba-137m	1.60E+01	1.60E+01
Xe-138	1.70E+00	9.10E-01
Cs-138	5.90E-01	9.10E-01
Ce-144	8.20E-02	5.60E-02

Cumulative Release to environment (Ci)							
Nuclide	**DC-1**	**DC-2**	**DC-3**	**DC-4**	**DC-5**	**DC-7**	**DC-9**
Kr-88	1.70E+02	4.30E+01	1.60E+00	1.10E-01	4.00E-01	1.20E+00	5.60E-03
Rb-88	1.60E+02	4.00E+01	1.50E+00	1.10E-01	3.80E-01	3.80E+00	5.40E-03
Sr-90	6.40E-03	1.60E-03	2.80E-05	1.20E-05	7.00E-06	9.50E-06	1.60E-06
Ru-103	3.00E+02	7.40E+01	3.60E-02	5.10E-02	8.90E-03	9.10E-02	3.00E-02
Sb-125	5.20E+02	1.30E+02	5.00E-03	2.30E-03	1.20E-03	4.80E-04	3.30E-03
Te-129m	5.20E-04	1.30E-04	9.20E-06	3.60E-06	2.30E-06	7.80E-06	8.50E-03
I-131	6.40E+04	1.60E+04	8.80E+00	4.20E+00	2.20E+00	1.00E+00	3.10E-01
Te-132	2.60E+03	6.60E+02	6.50E+00	2.20E+00	1.60E+00	4.90E-01	8.90E-02
I-132	3.00E+03	7.60E+02	4.00E+00	1.50E+00	1.00E+00	5.00E-01	5.20E-02
I-133	1.40E+03	3.60E+02	6.20E+00	1.50E+00	1.60E+00	8.00E-01	7.10E-02
Xe-133	2.00E+04	5.10E+03	4.70E+02	2.10E+02	1.20E+02	5.60E+01	1.45E+01
Cs-134	3.70E+02	9.30E+01	5.60E-05	2.40E-05	1.40E-05	2.80E-05	3.40E-06
Xe-135	4.80E+02	1.20E+02	3.30E+01	4.60E+00	8.30E+00	4.90E+00	2.40E-01
Cs-137	3.10E+02	7.80E+01	1.50E-04	6.00E-05	3.70E-05	1.10E-04	9.80E-06

Cumulative Release to environment (Ci)						
Nuclide	**WC-1**	**WC-2**	**WC-3**	**WC-4**	**WC-6**	**WC-7**
Kr-88	2.50E+00	9.80E+00	1.20E-01	1.40E+00	6.30E-01	7.50E-02
Sr-89	1.40E+00	8.00E-01	8.60E-03	1.20E-02	6.10E-03	2.40E-02
Sr-90	8.80E-02	3.00E-02	5.30E-04	1.90E-03	9.70E-04	4.00E-03
Y-91	4.10E-01	4.80E-01	2.50E-03	6.50E-03	3.00E-03	9.80E-03
Ag-110m	3.90E-01	2.50E+00	2.40E-03	4.20E-02	2.30E-02	9.60E-02
I-131	2.60E+01	4.60E+00	1.00E+00	8.00E-01	3.30E-01	2.90E-01
Te-132	6.10E+01	1.80E+01	3.60E-01	2.00E-01	9.60E-02	7.30E-01
I-132	3.10E+01	7.80E+00	1.00E+00	8.70E-01	3.30E-01	4.20E-01
I-133	3.70E+01	8.80E+00	1.50E+00	1.10E+00	4.30E-01	3.70E-01
Xe-133	3.70E+02	1.10E+02	4.60E+01	1.30E+01	6.40E+00	9.20E+00
I-134	5.00E-03	6.40E+00	1.50E-04	7.90E-01	2.70E-01	2.20E-03
Cs-134	6.20E-01	4.40E+00	3.70E-03	7.40E-02	3.90E-02	1.70E-01
I-135	1.20E+01	6.20E+00	4.70E-01	7.90E-01	2.90E-01	1.50E-01
Xe-135	8.10E+01	1.70E+01	8.10E+00	4.10E+00	2.00E+00	2.00E+00
Cs-137	2.50E+00	3.30E+00	1.50E-02	3.50E-01	1.80E-01	7.90E-01
Ba-137m	2.30E+00	1.90E+01	1.40E-02	3.20E-01	1.70E-01	7.40E-01
Ce-144	1.30E+00	3.00E-01	7.70E-03	3.80E-03	1.60E-03	4.80E-03

Appendix B

Below is the VBA script used in Excel to automate the EAB distance optimization calculations, followed by the corresponding pseudocode. The script is a general framework which requires only minor modifications to be adjusted to the user's personal Excel setup. This code can be copied into the users VBA editor, and by changing the sheet name, cell locations of EAB distance and risk metrics, and adjusting the step size and risk limits (if needed), this script can be run through excel to output the minimal EAB distance at which the risk metrics are satisfied. This same method is used for the evaluation of the minimal control room distance as well but is adjusted accordingly.

```
Sub Find_Minimum_EAB()
    Dim ws As Worksheet
    Set ws = ThisWorkbook.Sheets("Sheet1") ' Change "Sheet1" to actual sheet name
     ' Define key cell locations
    Dim EAB_Distance_Cell As Range
    Set EAB_Distance_Cell = ws.Range("EABcell") ' Change to your EAB distance cell
    Dim Risk_Metric_Cells As Range
    Set Risk_Metric_Cells = ws.Range("RM1:RM3") ' Change to actual risk metric cells
    Dim Risk_Limits(1 To 3) As Double
    Risk_Limits(1) = 1 ' Set limit for Integrated Risk
    Risk_Limits(2) = 0.0000005 ' Set limit for early fatalities
    Risk_Limits(3) = 0.000002 ' Set limit for latent cancer fatalities
    ' Define step size and initial distance
    Dim EAB_Distance As Double
    Dim Step_Size As Double
    Dim Min_EAB As Double
    EAB_Distance = 425 ' Set initial guess (meters)
    Step_Size = 0.01 ' Step size (adjustable)
```

```
    Min_EAB = EAB_Distance
    ' Set initial EAB distance
    EAB_Distance_Cell.Value = EAB_Distance
    ' Loop to decrease EAB until a constraint is exceeded
    Do While EAB_Distance > 10 ' Minimum reasonable distance (adjustable)
        ' Update the EAB distance
        EAB_Distance_Cell.Value = EAB_Distance
        Application.Calculate ' Recalculate sheet
        ' Check risk metrics
        Dim i As Integer, Risk_Failed As Boolean
        Risk_Failed = False
        For i = 1 To 3
            If Risk_Metric_Cells.Cells(1, i).Value > Risk_Limits(i) Then
                Risk_Failed = True
                Exit For
            End If
        Next i
        ' Stop if a risk metric fails
        If Risk_Failed Then Exit Do
        ' Update minimum EAB
        Min_EAB = EAB_Distance
        ' Decrease distance
        EAB_Distance = EAB_Distance - Step_Size
    Loop
    ' Output the last valid EAB
    MsgBox "Minimum EAB distance: " & Min_EAB & " meters", vbInformation,
"Calculation Complete"
    EAB_Distance_Cell.Value = Min_EAB
End Sub
```

The pseudocode for optimization is as follows:

```
START
  Set initial EAB_distance to a large value
  Set step_size to a small decrement value
  Set risk_limits for early fatalities, latent cancer fatalities, and cumulative risk

  WHILE EAB_distance is greater than a minimum threshold
    Update Excel cell with current EAB_distance
    Recalculate doses and risk metrics

    IF all three risk metrics satisfy their limits THEN
      Store the current EAB_distance as a valid solution
    ELSE
      Break loop (since going lower fails constraints)
    END IF

    Decrease EAB_distance by step_size
  END WHILE

  Display the minimum valid EAB_distance
END
```

Appendix C

Definition of dose release categories for the standard MHTGR. [15]

Table C-1: Dry Conditions, Forced Convection Cooldown Category Descriptions

Release Category	**Descriptions**
DF-1	Primary coolant leak occurs where 6.5 cm^2 < Area < 84 cm^2. Reactor is tripped. HTS or SCS maintains forced convection cooling. HPS pumpdown is ineffective. Radionuclides are released through the reactor building dampers.
DF-2	Primary coolant leak occurs where 0.2 cm^2 < Area < 6.5 cm^2. Reactor is tripped. HTS or SCS maintains forced convection cooling. HPS pumpdown is ineffective. Radionuclides release leaks to the environment after some retention in the reactor building.
DF-3	Primary coolant leak occurs where 2×10^{-4} cm^2 < Area < 0.2 cm^2. Reactor is tripped. HTS or SCS maintains forced convection cooling. HPS pumpdown fails. Radionuclides release leaks to the environment after some retention in the reactor building.
DF-4	Primary coolant leak occurs where 2×10^{-4} cm^2 < Area < 0.2 cm^2. Reactor is tripped. HTS or SCS maintains forced convection cooling. HPS pumpdown occurs. Radionuclides release leaks to the environment after some retention in the reactor building.

Table C-2: Wet Conditions, Forced Convection Cooldown Category Descriptions

Release Category	Descriptions
WF-1	Moderate steam generator leak occurs. Reactor trip occurs. Steam generator isolation from steam heater is delayed. Isolation and dump of the steam generator occurs within 20 min. SCS maintains forced convection cooling. Primary relief valve opens and fails to reclose. Radionuclides are released through the reactor building dampers.
WF-2	Moderate steam generator leak occurs. Reactor trip occurs. Steam generator isolation and dump is delayed up to 30 min. SCS maintains forced convection cooling. Primary relief valve opens and fails to reclose. Radionuclides are released through the reactor building dampers.
WF-3	Moderate steam generator leak occurs. Moisture monitors detect leak. Steam generator isolation is delayed. Isolation and dump of the steam generator occurs within 30 min. SCS maintains forced convection cooling. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.
WF-4	Moderate steam generator leak occurs. Reactor trip occurs. Steam generator isolation and dump is delayed up to 30 min. SCS maintains forced convection cooling. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.

Table C-3: Dry Conditions, Conduction Cooldown Category Descriptions

Release Category	Descriptions
DC-1	Earthquake with ground accelerations greater than 0.8 g causes instrument line failure in all four modules. Reactor is tripped. HTS, SCS, and RCCS fail in all four modules due to high ground accelerations. HPS pumpdown is also not available. Reactor vessel is depressurized. Radionuc1ides are released to the atmosphere after some retention in the reactor building.
DC-2	Loss of main loop cooling occurs. Reactor is tripped. SCS fails to maintain forced convection cooling. RCCS cooling fails. Primary system is depressurized using HPS pumpdown within 2 days. Radionuclides release leaks to the environment after some retention in the reactor building. Reactor building silo is sealed some time after 100 h.
DC-3	Primary coolant leak occurs in all four modules due to earthquake where Area $\geq 0.19\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown fails. Radionuclides release leaks to the environment after some retention in the reactor building.
DC-4	Primary coolant leak occurs where $0.013\ \text{cm}^2 \leq \text{Area} \leq 0.19\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown fails. Radionuclides release leaks to the environment after some retention in the reactor building.
DC-5	Primary coolant leak occurs where $0.19\ \text{cm}^2 \leq \text{Area} \leq 6.5\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown fails. Radionuclides release leaks to the environment after some retention in the reactor building.

Table C-3 (continued)

DC-6	Primary coolant leak occurs where $0.013\ \text{cm}^2 \leq \text{Area} \leq 0.19\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown is successful. Radionuclides release leaks to the environment after some retention in the reactor building.
DC-7	Primary coolant leak occurs where $0.19\ \text{cm}^2 \leq \text{Area} \leq 6.5\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown is successful. Radionuclides release leaks to the environment after some retention in the reactor building.
DC-8	Primary coolant leak occurs where $\text{Area} \geq 6.5\ \text{cm}^2$. Reactor is tripped. HTS and SCS fail to maintain forced convection cooling. Passive cooling by RCCS continues. HPS pumpdown is ineffective for this leak size. Radionuclides are released through the reactor building dampers.
DC-9	Primary coolant leak where $1.9 \times 10^{-4}\ \text{cm}^2 \leq \text{Area} < 0.013\ \text{cm}^2$. HTS and SCS fail to maintain forced convection cooling. Passive cooling by the RCCS continues. HPS pumpdown is ineffective. Radionuclide release leaks to the environment after some retention in the reactor building.

Table C-4: Wet Conditions, Conduction Cooldown Category Descriptions

Release Category	Descriptions
WC-1	Small steam generator leak occurs. Moisture monitors detect leak. Reactor is tripped. Automatic isolation of the steam generator occurs. Steam generator dump valves fail to open. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and fails to reclose. Radionuclides are released through the reactor building dampers.
WC-2	Moderate steam generator leak occurs. Reactor is tripped. Steam generator is isolated within at most 6 min. Steam generator dump is delayed or malfunctions. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and fails to reclose. Radionuclides are released through the reactor building dampers.
WC-3	Small steam generator leak occurs. Moisture monitors detect leak. Reactor is tripped. Automatic isolation of the steam generator occurs. Steam generator dump valves fail to open. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.
WC-4	Moderate steam generator leak occurs. Reactor is tripped. Moisture monitors detect leak. Steam generator isolation is delayed when steam valves fail open. Manual isolation and dump of the steam generator occurs within 20 min. SCS fails to maintain forced cooling. Passive cooling by RCCS continues. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.

Table C-4 (continued)

WC-5	Moderate steam generator leak occurs. Reactor is tripped. Moisture monitors detect leak. Automatic isolation of the steam generator occurs. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and fails to reclose. Radionuclides are released through the reactor building dampers.
WC-6	Moderate steam generator leak occurs. Reactor is tripped. Steam generator is isolated with at least 6 min (either by moisture monitor detection or high pressure signal). Steam generator dump is delayed or malfunctions. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.
WC-7	Moderate steam generator leak occurs. Reactor is tripped. Moisture monitors fail to detect leak. Automatic isolation and dump of the steam generator occurs. SCS fails to maintain forced convection cooling. Passive cooling by the RCCS continues. Primary relief valve opens and successfully recloses. Radionuclides are released through the reactor building dampers.

REFERENCES

[1] "10 CFR 20." Accessed: Jan. 18, 2025. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2024-title10-vol1/pdf/CFR-2024-title10-vol1-part20.pdf

[2] "Appendix C - Quantitative Guidelines from the Framework for Risk-Informing 10 CFR Part 50.," 2002.

[3] "CFR-2024-title10-vol1-part50.pdf." Accessed: Feb. 19, 2025. [Online]. Available: https://www.govinfo.gov/content/pkg/CFR-2024-title10-vol1/pdf/CFR-2024-title10-vol1-part50.pdf

[4] "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development.pdf." Accessed: Jan. 18, 2025. [Online]. Available: https://www.nrc.gov/docs/ML1924/ML19241A472.pdf

[5] "Medical Management of Radiological Casualties." Accessed: Jan. 22, 2025. [Online]. Available: https://afrri.usuhs.edu/sites/default/files/2020-07/4edmmrchandbook.pdf

[6] "Beir VII: Health Risks from Exposure to Low Levels of Ionizing Radiation." Accessed: Jan. 22, 2025. [Online]. Available: https://nap.nationalacademies.org/resource/11340/beir_vii_final.pdf

[7] "RG 1.145." Accessed: Feb. 23, 2025. [Online]. Available: https://www.nrc.gov/docs/ml0037/ML003740205.pdf

[8] "RG 1.194." Accessed: Feb. 24, 2025. [Online]. Available: https://www.nrc.gov/docs/ML0315/ML031530505.pdf

[9] J. V. R. Jr and C. J. Fosmire, "ESTIMATING CONCENTRATIONS IN PLUMES RELEASED IN THE VICINITY OF BUILDINGS: MODEL DEVELOPMENT".

[10] J. V. Ramsdell and C. J. Fosmire, "ESTIMATING CONCENTRATIONS IN PLUMES RELEASED IN THE VICINITY OF BUILDINGS: MODEL EVALUATION".

[11] "Limiting Values of Radionuclide Intake And Air Concentration and Dose Conversion Factors For Inhalation, Submersion, And Ingestion." Accessed: Feb. 28, 2025. [Online]. Available: https://rais.ornl.gov/documents/FGR11.pdf

[12] D. Chanin, "NUREG/CR-6613, Vol. 1".

[13] E. C. Eimutis and M. G. Konicek, "Derivations of continuous functions for the lateral and vertical atmospheric dispersion coefficients," *Atmospheric Environment (1967)*, vol. 6, no. 11, pp. 859–863, Nov. 1972, doi: 10.1016/0004-6981(72)90057-1.

[14] E. A. Bellis and J. Vasquez, "Probabilistic Risk Assessment for the Standard Modular High Temperature Gas-Cooled Reactor Vol. 2," GA Technologies, Inc., San Diego, CA (United States), Report DOE/HTGR--86-011-Rev.1, Jun. 1986. doi: 10.2172/455545.

[15] E. A. Bellis and J. Vasquez, "Probabilistic Risk Assessment for the Standard Modular High Temperature Gas-Cooled Reactor Vol. 1," GA Technologies, Inc., San Diego, CA (United States), Report DOE/HTGR--86-011-Rev.1, Jun. 1986. doi: 10.2172/455545.