Flaws with the Alternative Evaluation of Risk Insights (AERI)

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Key points:

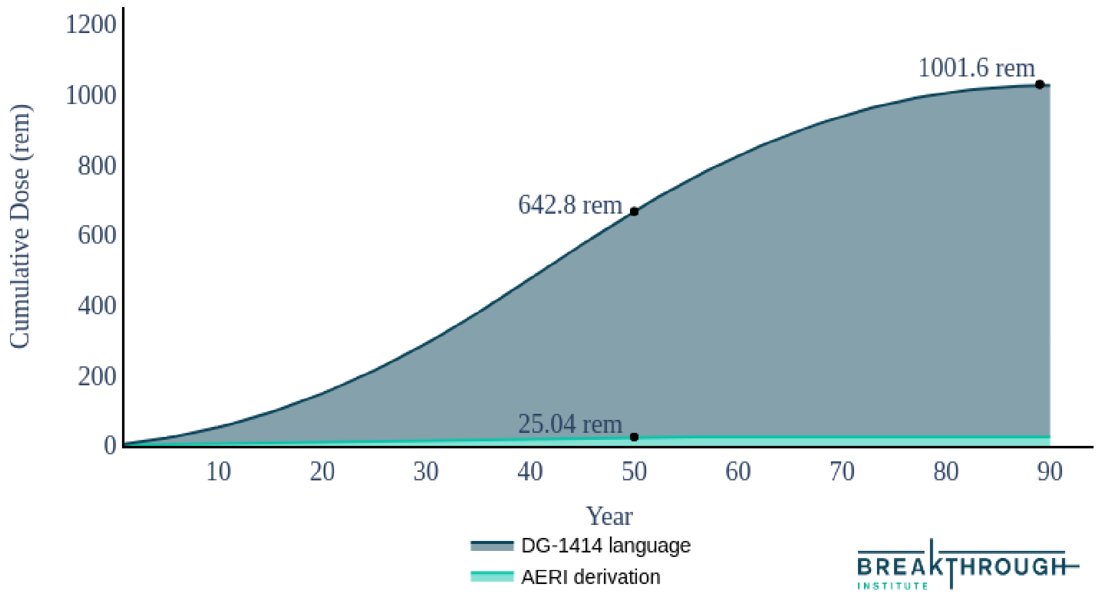
- NRC staff has proposed an alternative risk evaluation approach in the draft Part 53 rule, the alternative evaluation of risk insights (AERI), that results in mathematically impossible conditions.
- The NRC staff proposed the AERI approach as an alternative to the conventional time- and cost-intensive probabilistic risk assessment. But as defined in the regulatory draft guide, the AERI approach is unusable and does not represent a feasible alternative method of risk assessment.
- The AERI draft regulatory guide assumes a catastrophic nuclear accident to occur every year of the reactor licensing period.
- This analysis demonstrates that it is physically impossible, given NRC rules and practice, for a reactor to be operational within a year following a catastrophic accident.
- A catastrophic nuclear accident frequency of once per year would result in unrealistic lifetime radiation dose to exposed populations, based on the NRC dose derivation.
- The NRC staff should revert to the approach used in the radiation dose derivation in the AERI regulatory draft guide and base AERI calculations on a plausible assumption of one catastrophic nuclear accident during the licensing period.
- By revising the frequency of catastrophic events outlined in the regulatory draft guide to accurately reflect both the intent of the AERI approach and functional possibility, NRC staff can offer an alternative risk assessment approach for reactor designs that meet the qualification requirements.

Abstract: The alternative evaluation of risks insight (AERI) defined in the draft regulatory guide DG-1414 is a demonstrably conservative approach that was developed to eliminate the need to use a probabilistic risk assessment (PRA) to estimate individual event sequence frequencies. DG-1414(C)(3)(d) states *"In the absence of using a PRA to develop a realistic estimate of that annual frequency, another approach or method is needed."* Based on LWR history, the foundation of the AERI approach approximates the sum of initiating event frequencies to one/plant-year. The 'conditional' risk is then defined by assuming a maximum bounding event. The AERI approach is mathematically derived based on a single bounding event, presumably through the reactor licensing period.[1] However, there is a disconnect in the

[1] 40-year reactor licensing period see: Nuclear Regulatory Commission (January 3, 2022) *Introduction*. Retrieved from: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/fs-reactor-license-renewal.html

translation of the AERI conditions from the mathematical derivation to the language presented in the DG-1414. The language in DG-1414 is based on multiple bounding events with a frequency of one maximum bounding event per year, presumably over the course of the reactor licensing period. In the former case, the dose limit of 25 rem would be met by the 50th year, while in the latter case, the limit would be met between the 6th and 7th year. The graphical abstract summarizes the dose consequence interpreted from the AERI deviation compared to the language contained in DG-1414. This disconnect must be corrected for the AERI methodology to have a regulatory basis within the constraints of possible outcomes.

Graphical Abstract



1. Introduction

In compliance with Section 103 of the Nuclear Energy Innovation and Modernization Act (NEIMA) of 2019, Part 53 is a risk-informed, technology-inclusive regulatory framework being developed by the NRC for licensing new reactors. The AERI approach is an alternative methodology for risk evaluation under Part 53, Framework B, Subpart R[2] that can be used by advanced reactor applicants in lieu of a Probabilistic Risk Assessment (PRA). The draft regulatory guide 1414 (DG-1414)[3], published in

[2] See ADAMS Accession Number: ML22272A040 Section 53.4730(a)(34)(ii)

[3] See ADAMS Accession Number: ML22272A045

September 2022, provides guidance on the use of the AERI methodology to inform the content of applications and licensing basis for light water reactors (LWRs) and non-LWRs.

The initial AERI approach stipulates that the dose consequence estimate from a postulated bounding event at a location 100 meters (328 feet) away from the commercial nuclear plant should not exceed 10 mSv (1 rem) TEDE[4] over the first four days following a release, an additional 20 mSv (2 rem) TEDE in the first year, and 5 mSv (0.5 rem) TEDE per year in the second and subsequent years. However, multiple stakeholders submitted comments arguing that these AERI entry conditions are overly conservative. Moreover, the scoping calculations from the MELCOR Accident Consequence Calculation System (MACCS) indicated that the dose at 100 meters is an inadequate predictor of conditional risk.

As a result, the AERI conditions were revised after the ACRS Part 53 subcommittee meeting in October 2022, to address stakeholder comments and reflect insights from the MELCOR Accident Consequence Calculation System (MACCS) calculations. The AERI revision[5] stipulates that the dose consequence estimated from a postulated bounding event within the area between the commercial nuclear plant's exclusion area boundary (EAB) and 16.1 kilometers (10 miles) from the EAB is less than 25mSv (2.5 rem) TEDE in the first year. The MACCS scoping calculations infer that the 2.5 rem criterion is consistent with a 25 rem lifetime (50-year) dose.

The revision, however, does not make mention of the dose consequence in the second and subsequent years. *If we assume the 25 rem following a bounding event over the course of a 40-year reactor licensing period, then the dose consequence in the first year is 2.5 rem and residual dose is 0.46 rem in the second and subsequent years.* Despite the revisions to the AERI entry conditions at the subcommittee meeting in October 2022, the AERI approach still possesses unreasonably conservative restrictions that have been highlighted on several occasions by the Breakthrough Institute (BTI).

On two occasions, BTI expressed concerns regarding the AERI approach via presentations to staff.[6] Additionally, BTI submitted multiple public comments to the NRC reiterating concerns about the AERI entry conditions.[7] Despite attempts to emphasize the complications of the entry conditions outlined in the AERI approach, an effort has not been made by the NRC staff to address or engage on these concerns. The NRC staff acknowledged public comments regarding the overly conservative nature of the AERI conditions[8]; however, efforts to address said comments have been non-existent. The NRC staff, incorrectly, stated that stakeholders have not provided safety reasons why the AERI conditions should be less restrictive[9].

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4 Total effective dose equivalent

5 See ADAMS Accession Number ML22301A107 Slide 16

6 See ADAMS Accession Numbers: ML22180A296 and ML22209A004

7 See ADAMS Accession Numbers: ML22222A023, ML22244A053, and ML23006A081

8 See NRC Accession Number: ML22299A184 Page 172 lines 17 - 21

9 See NRC Accession Number: ML22299A184 Page 172 lines 22 - 25 and Page 173 lines 1 - 5

The goal of this whitepaper is to provide a mathematical argument against the restrictive proposed AERI entry conditions, further reiterating concerns previously expressed by the BTI. This study highlights the mistranslation of the AERI derivation in DG-1414 and the AERI dose consequence. Other recommendations have been made for improving the AERI methodology, but are outside the scope of this whitepaper.

2. Disconnect between AERI derivation and the draft regulatory guide language

AERI's mathematical derivation is based on a risk assessment of a "maximum bounding event". The maximum bounding event is the maximum consequence event, defined in the AERI derivation as follows:

$$c_{max} = max(c_1, c_2, \ldots c_n),$$

where c_i is a consequence and c_{max} is the maximum bounding consequence. Therefore, the risk is defined as

$R \leq (\Sigma f_i)c_{max}$, where Σf_i is the sum of initiating event frequencies; $\Sigma f_i \asymp$ 1/plant-year

The same event is not explicitly defined in the draft regulatory guide (DG)-1414(C)(1), instead referring to a '*postulated bounding event*' as an event sequence in the '*probabilistic risk assessment (PRA) sense*'. Events in the PRA sense would describe the risk of a nuclear catastrophe, in which case, we can assume a maximum bounding event. However, clear and consistent language between the derivation and DG-1414 is not well translated. For the remainder of this work, a bounding event describes a maximum consequence event as per the AERI derivation or a catastrophic event in the 'PRA sense' as per DG-1414.

The sum of initiating event frequencies (Σf_i) assumes that there is some non-bounding event, c_i, per year, which is a reasonably conservative assumption; however, when multiplied by c_{max}, the risk then assumes a maximum bounding event per year. The mathematical derivation of AERI only models one maximum bounding event in its assessment of the 'expected number of latent cancer fatalities in the 10-mile radius over 50 years following the occurrence of the bounding event' - *which implies a singular bounding event*.

On the other hand, DG-1414(C)(3)(d) assumes one postulated bounding event per year, per reactor lifetime: *"Based on LWR statistics, this frequency can be taken to be once per year (1/year)",* which presumes a maximum bounding event per year, as per the definitions previously discussed. It should be noted that the origin of the frequency basis based on LWR statistics is not cited in DG-1414. It is also noteworthy that the LWR statistics referred to in DG-1414(C)(3)(d), are not based on a bounding event,

c_{max}, which the NRC uses in the mathematical derivation. Instead, it is based on some initiating non-bounding event, c_i.

Contrary to AERI's mathematical derivation, which takes into account a single bounding/catastrophic event, presumably per reactor licensing period, DG-1414 introduces the presumption that one bounding/catastrophic event will occur per year, per reactor licensing period. In other words, to occur on the frequency presumed in DG-1414, if a reactor experiences one bounding event within its reactor lifetime, then the process of event investigation, recovery, damage repair, and return to operation-ready status will occur within one year of the bounding event. However, this assumption is ambitious and unrealistic in reference to the historical occurrence of, and response to, reactor bounding events in the United States.

For example, the bounding event at the Three Mile Island Unit 2 (TMI-2) in 1976 was rated Level 5 on the International Nuclear Event Scale (INES) and was indefinitely shut down following the bounding event. This is contrary to the assumption stated in AERI, which implies that the reactor should be operational within one year of the bounding event. In the case of TMI-2, the investigation process alone following the bounding event spanned nine months. On the other hand, Three Mile Island Unit 1 (TMI-1), the undamaged reactor that did not experience any event, was held indefinitely non-operational following the TMI-2 bounding event. TMI-1 was non-operational for 6 years prior to the issuance of operation-ready status. Figure 1 contextualizes the assumption presented in the AERI entry condition by comparing the assumption to historical events in the US.

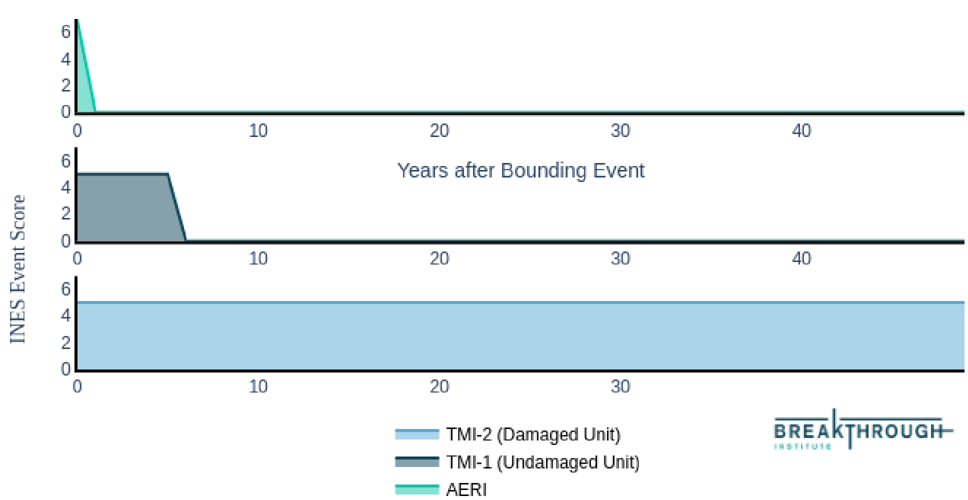

Figure 1. Comparison of AERI frequency assumption of reactor operational readiness following one bounding event and the historic operational readiness of reactor units following the TMI accident.

It is also critical to highlight the dose consequence as a result of the most serious accident in U.S. commercial nuclear power plant operating history. The revised AERI approach specifies a dose consequence of 2.5 rem within the first year of the bounding event and 0.46 rem residual dose in the second and subsequent years. However, the revised AERI dose consequence remains overly conservative given historic reference. The TMI bounding event led to small radioactive releases; however, these releases had no detectable health effects on plant workers or to the public. In fact, the population of 2 million people around TMI during the accident received an estimated radiation dose of only 0.001 rem (1 millirem) above typical background radiation[10].

3. AERI Dose Argument:

The presented arguments are based on the revisions to the AERI entry conditions which limit the cumulative dose received during reactor licensing period and residual dose period to 25 rem. However, the revision does not address any change in the language contained in DG-1414. AERI's mathematical derivation concluded with a net offsite dose limit of 25 rem presumably over the course of the licensing period - 40 years, following one bounding event. This work evaluates the difference in cases presented by the AERI derivation and the language in DG-1414.

3.1. Case 1: Single bounding event per licensing period

In this section, we discuss the fraction of the population that receives the net offsite dose from a single maximum bounding event during the reactor licensing period and reactor licensing period accounting for residual dose[11]. This study also assesses the population's age distribution with respect to the net offsite dose exposure. This evaluation assumes that the population present during the single bounding event within the first year did not relocate for the entire period including the reactor licensing period and an additional 50 years of residual dose.

a. Licensing period alone

Figure 2 shows the change in population receiving partial dose versus total dose following the single bounding event. Complimentarily, Figure 3 demonstrates the cumulative offsite dose exposure to the population overtime following the single bounding event. Based on the criteria posed in the AERI derivation, if we assume that the reactor is allowed to operate following a single maximum bounding event within the first year, then by the end of the 40-year licensing period, ~50% of the population (see Figure 3) would have received a dose of 20.44 rem from the bounding event. Realistic age distribution considerations provided in subsection (c) elucidates

[10] Backgrounder on Three Mile Island Accident see: Nuclear Regulatory Commission (November 15, 2022). Retrieved from: https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/3mile-isle.html

[11] The NRC dose derivation assumed a residual dose for 49 years, beginning one year after the event

the statistical importance of considering deaths from causes unrelated to plant operation in the dose consequence assessment.

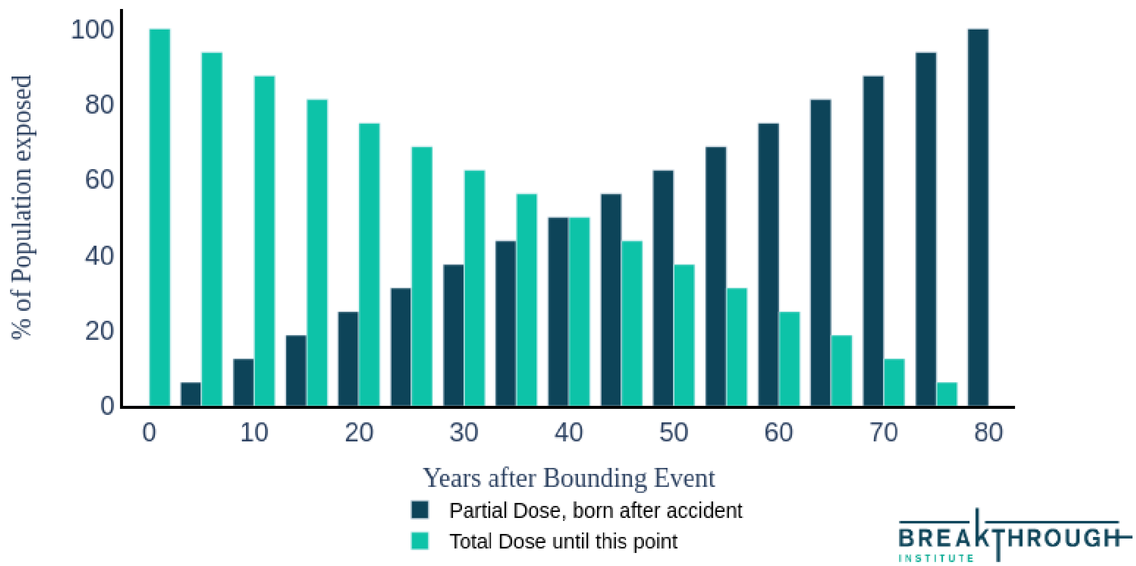

Figure 2. Change in population following a single bonding event over the course of the reactor licensing period and the residual dose period.

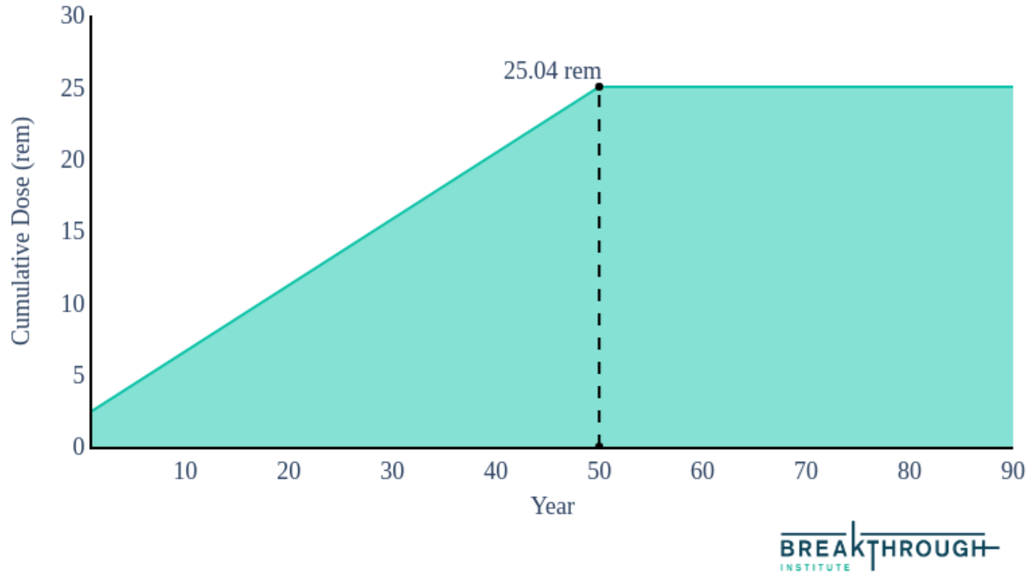

Figure 3. Cumulative offsite dose exposure to population following one bounding event in the first year of reactor operation.

b. Licensing and residual dose period

As per the intent of the AERI derivation, we assume a single postulated bounding event over the course of the 40-year licensing period. This single postulated bounding event will expose a population to a dose of 2.5 rem in the first year and 0.46 rem per year in the second and subsequent years. Using a population model, which assumes a birth rate of 12.5 per 1000 people[12], a static population (death rate = birth rate), and a life expectancy of 80 years, we can investigate the population deceased before receiving the full dose consequence. Figure 4 shows the percentage of the population that are deceased (due to causes unrelated to plant operation) before receiving full dose from a single bounding event over the course of the licensing period and the residual dose period. The bar graph denoting the deceased population is replaced by the population born after the accident that also receives partial dose in Figure 2.

Under these assumptions that approximate actual US values, the fraction of the population that would have received the net dose during the reactor lifetime plus 50 additional years of residual dose, would be zero. If no individual, on average, experiences the entire period in this example, similarly, no one would experience the full timeline in the more complex scenario of annual events described in DG-1414. Further, no individual could receive the dose the NRC staff derived as a basis for AERI.

[12] Birth rate of 12.5% taken as median of rates reported in 2009 and 2019 see: Center for Disease Control (August 12, 2022) *Births*. Retrieved from https://www.cdc.gov/nchs/hus/topics/births.htm

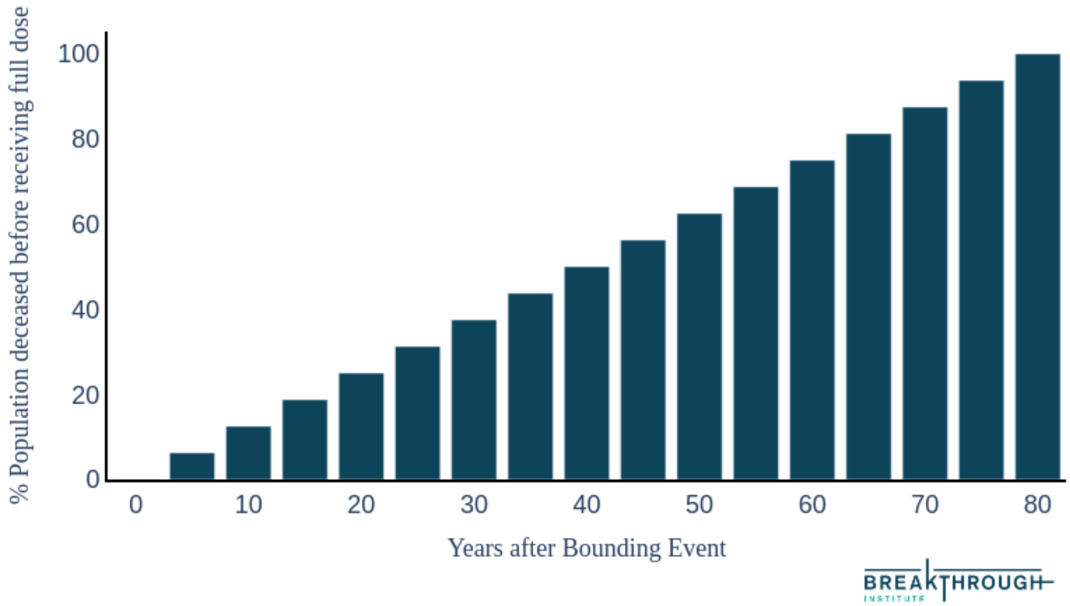

Figure 4. Deceased population that received partial dose over the course of the reactor licensing period and the residual dose period.

c. Age distribution and dose

The revised AERI entry condition assumes a population-weighted risk. In this section, we consider age distribution in the dose consequence based on the occurrence of a single bounding event as prescribed by the AERI derivation. Using a life expectancy of 80 years, people ≥ 40 years at the time of the single bounding event would be deceased by the end of the reactor license period - 40 years from causes unrelated to plant operation. Table 1 summarizes the population age ranges and their corresponding percentages. In this case, the range of interest is 35 - 49 years, which constitutes 19% of the population. If we assume that the population is spread uniformly across the 30- 34 year range, then the population between 40 and 49 years old represents 12.66% of the total population. By way of simple addition of the population 40 years or older, it is expected that 48.66% of the population will be deceased from causes unrelated to reactor plant operation by the 40th year. If we extended a similar logic to the additional 50-year residual dose period, then the population receiving the full dose would be zero. Although this evaluation uses a valid life expectancy of 80 years, it should be noted that only 4.7%[13] of the population exceeds the average expectancy.

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[13] 90-and-up population, , Census Bureau (May 19, 2022) Retrieved from: https://www.census.gov/newsroom/releases/archives/aging_population/cb11-194.html

Table 1: Age distribution of the US population by percentage [14]

Age range	Percentage, %
0 - 4	5.7
5 - 19	19.1
20 - 34	20.2
35 - 49	19
50 - 64	19.2
65+	16.8
0 - 65+	100

3.2. Case 2: Multiple bounding events, one per year, per licensing period

Examination of a simplified case that considers an event in the first year of operation which includes the residual dose timeline if a bounding event occurred once-annually as defined in DG-1414, is informative. In this section, we discuss the fraction of the population that receives the net offsite dose from multiple bounding events during the reactor licensing period and reactor licensing period with residual dose. This assessment assumes that the population present during the single maximum bounding event within the first year did not relocate for the entire period, including the reactor licensing period and 50 additional years of residual dose.

a. Licensing period alone

Taking into account AERI's frequency criteria in DG-1414, we will now assume one bounding event per year. Intuitively, instead of decreasing over time, the dose exposure compounds with the occurrence of a bounding event every year over the course of the reactor licensing period. *It is highly unlikely that a licensed reactor would be allowed to operate following a maximum bounding event every year, let alone be given a license renewal.* Nevertheless, for argument's sake, if we assume one bounding event per year using the dose consequence outlined in DG-

[14]Age distribution of the US population see: USA facts (2021), Census Bureau. Retrieved from: https://usafacts.org/data/topics/people-society/population-and-demographics/our-changing-population

1414(B)[15], then by the end of the 40-year reactor license period, the offsite dose to population would be 510 rem as shown in Figure 4. Furthermore, using the same model, the offsite dose limit of 25 rem would be achieved between the 6th and 7th year of consecutive bounding events.

b. Licensing and residual dose period

To further exacerbate the irrational basis for the AERI entry conditions, we have expanded the model to include the additional 50-year residual dose. In this regard, the total dose received by the offsite population from the 40-year reactor operation and the 50-year residual dose would be 1001.60 rem. Figure 5 shows the cumulative increase in dose exposure as a result of bounding events occurring at a frequency of 1/year. The criteria posed in AERI very easily exhibit improbable/unrealistic conservative risk estimates. A direct contradiction to the DG-1414(C)(2)(d) intent to require *"A realistic dose consequence estimate with a realistic description of the uncertainties is preferred".*

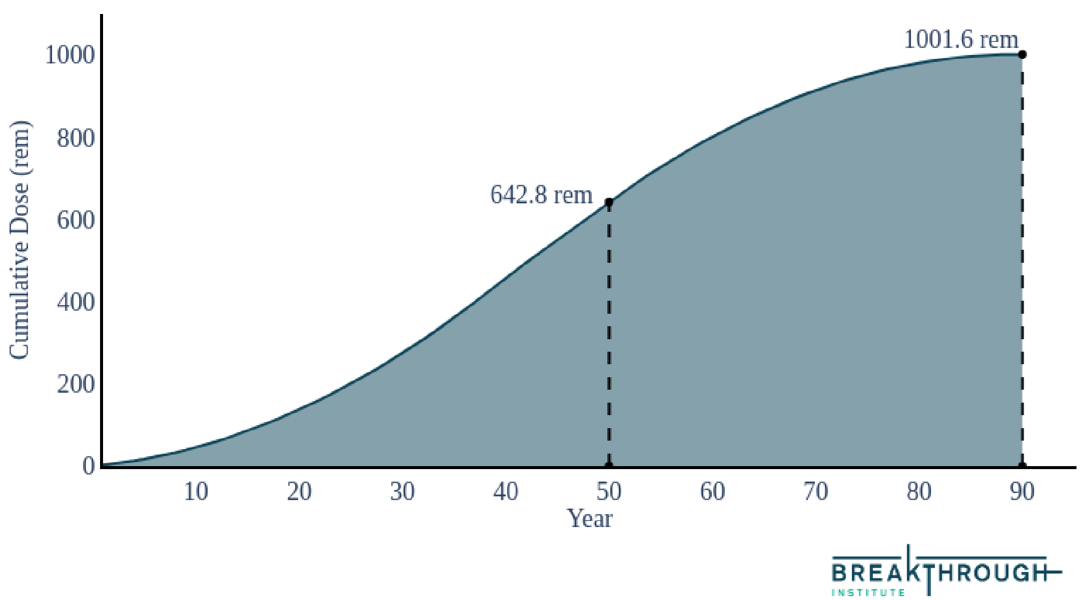

Figure 5. Cumulative offsite dose exposure to population following annual bounding events over the course of the reactor licensing period and the residual dose period.

[15] The dose consequence estimate from a postulated bounding event at a location 100 meters (328 feet) away from the commercial nuclear plant should not exceed 10 mSv (1 rem) TEDE over the first four days following a release, an additional 20 mSv (2 rem) TEDE in the first year, and 5 mSv (0.5 rem) TEDE per year in the second and subsequent years

4. Brief reverse AERI dose case

Following the outline of a number of cases highlighting the unreasonably impossible restrictions provided in the AERI entry conditions, this section provides a reverse assessment of the dose limit referenced in AERI. To reiterate, as defined in AERI, the cumulative offsite dose limit from the occurrence of one bounding event per year per licensing period, i.e. 40 years, is 25 rem. If we divide the 25 rem by 40 years, then the dose per year, per bounding event would be approximately 0.625 rem, which is equivalent to natural background radiation.[16] It becomes clear that a 25 rem exposure basis for a bounding event per year for the 40-year operating period is counterintuitive to the intent of AERI .

5. Proposed solution

The BTI recommends that the language outlined in DG-1414 accurately and consistently reflects the mathematical deviation of the AERI approach. In its current state, the DG-1414 assumes one bounding event per year during the reactor licensing period; however, the derivation upon which the AERI approach is based is not accurately represented in DG-1414. The current whitepaper investigates the viability of the AERI approach based on the language presented in DG-1414 compared to the intention of mathematical derivation. The cases outlined herein draw attention to the physically impossible conservative bounding event frequency and compounding dose consequence in DG-1414. Guidance on the use of the AERI methodology needs to be revised to reflect the intent of the mathematical deviation: one bounding event per licensing period.

To reconcile the discrepancies between the dose derivation and DG-1414, Section 3(d) of DG-1414 should be revised to read:

> *An annual frequency is needed to support a comparison with the QHOs, which are frequency based. In the absence of using a PRA to develop a realistic estimate of that annual frequency, another approach or method is needed. One acceptable approach is to assume a frequency which represents the sum of the event sequence frequencies and is equal to the sum of the initiating event frequencies. ~~Based on LWR statistics, this~~ The* ***minimum feasible*** *frequency can be taken to be once per ~~year (1/year)~~* ***licensing period (1/40 years)****. This frequency, while conservative, can be used along with the postulated bounding event's consequences to compare to the QHOs.*

[16] Background radiation is 0.62 rem see: Environmental Protection Agency (October 24, 2022) *Average US Doses and Sources.* Retrieved from: https://www.epa.gov/radiation/radiation-sources-and-doses

> *For example, if the QHO comparison is favorable even when assuming that the postulated bounding event were to occur once ~~annually~~ **during the license of the plant**, then this is a sufficient demonstration that the QHOs are met, if supported by an explanation that the ~~once-annually~~ **frequency** assumption is clearly very conservative.*
>
> *The use of a different frequency may be acceptable but will be reviewed on a case-by-case basis and justification for that frequency should be provided*

The changes represent the minimum required to be realistically viable and represent the most conservative option possible. A less conservative and more risk-informed frequency is recommended.

6. Conclusion

The AERI approach is proposed in the Part 53 rule as a method to eliminate the requirement of a PRA for estimating individual event frequencies. It presents a promising risk evaluation alternative for new and advanced reactors. The mathematically derived conditions of the AERI approach were used to provide guidance on the use of AERI in DG-1414. However, there is a disconnect in translation between the guidance in DG-1414 and the mathematical preface from which AERI was derived. The AERI derivation reasonably assumes the occurrence of one bounding event, while the DG-1414 assumes the occurrence of one bounding event per year, assumed to occur the entire reactor licensing period. Furthermore, there are several concerns about the unreasonably restrictive conditions outlined in the AERI approach, particularly relating to the bounding event frequency and dose consequence. AERI as outlined in DG-1414, assumes an annual occurrence of a bounding event per reactor licensing period. The revised AERI further assumes that a population will receive an offsite dose of 2.5 rem in the first year of a bounding event and 0.46 rem per year in the second and subsequent years. However, this dose consequence compounds to 458.8 rem by the 40th year of reactor operation and a total of 1001.6 rem by the 90th year, which presents an unreasonably conservative approach.

BTI requests that NRC staff recognize these concerns and consider adjusting the AERI approach to be more realistic. The requirements should be adjusted as defined in Section 5 to achieve the stated intention of AERI.