Determination of Large Early Release Frequency Used in PSA

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Abstract

The correlations between Large Early Release Frequency (LERF) and Early Fatality need to be investigated for risk-informed application and regulation. In RG-1.174, there are decision-making criteria using the measures of CDF and LERF, while there are no specific criteria on LERF. Since there are both huge uncertainty and large cost need in off-site consequence calculation, a LERF assessment methodology need to be developed and its correlation factor needs to be identified for risk-informed decision-making. This regards, the robust method for estimating off-site consequence has been performed for assessing health effects caused by radioisotopes released from severe accidents of nuclear power plants. And also, MACCS2 code are used for validating source term quantitatively regarding health effects depending on release characteristics of radioisotopes during severe accidents has been performed. This study developed a method for identifying correlations between LERF and Early Fatality and validates the results of the model using MACCS2 code. The results of this study may contribute to defining LERF and finding a measure for risk-informed regulations and risk-informed decision-making.

1.Introduction

The outcome of a probabilistic safety assessment (PSA) for a nuclear power plant is a combination of qualitative and quantitative results. Quantitative results are shown as Core Damage Frequency (CDF) and frequency of radioactive release, e.g., as Large Early Release Frequency (LERF). In some countries, the safety authorities define these values or higher level safety goals. In other countries, they have been defined by the nuclear utilities. Ultimately, the goals are intended to define an acceptable level of risk from the operation of a nuclear facility. It provides a tool for identifying and ranking issues with safety impact, and it includes both procedural and design related issues. Thus, CDF and LERF (safety goals) not only define an acceptable safety level, but they also have a wider and more general use as decision criteria.

The objective of using CDF and the LERF is to assess, from a risk perspective, the impact on the current licensing basis of any changes that may be proposed by various licensees. The use of CDF and LERF has been judged appropriate since the regulatory utilities have performed level-1 and level-2 PSA. Therefore, information on core damage frequency, containment failure likelihood, containment failure mode, and radiological releases, are readily available from these studies. Difficulties exist in defining “large early” release frequencies, since there are spectrums of fission product releases that are estimated as likely to occur following severe accidents, with their expected release quantities ranging over several orders of magnitude and occurring at various times following accident initiation.

The concept of CDF and LERF has been considered as a suitable metrics for making risk-informed regulatory decisions. However, the definition of "large early release" and the associated time needs to be evaluated from the regulatory perspective and the potential implication of severe accidents. The definition of what constitutes a large early release differs a lot, and there are many parameters involved in the definition, the most important ones being the time, the amount, and the composition of the release. The underlying reason for the complexity of the release definition is largely the fact that the release definition constitutes the link between the level-2 PSA results and an indirect attempt to assess health effects from the release. However, such consequence issues are basically addressed in level-3 PSA, and can only be fully covered in level-3 analysis. In order to judge on the acceptability of results, various criteria for interpretation of results and assessment of their acceptability need to be defined. In this study MACCS2 code are used for evaluating the source terms quantitatively regarding health effects depending on release characteristics of radioisotopes during severe accidents [1].

2. LERF (LARGE EARLY RELEASE FREQUENCY) Alternatives

The result of a literature survey of the available alternatives for the definition of large early release for estimation of the large release frequency following postulated severe accidents has resulted in the evaluation of the following alternatives:

- Alternatives 1: Any release that occur because of severe accidents that would entail early containment failure (including containment isolation failure) and containment bypass conditions
- Alternatives 2: Any release that would exceed specific thresholds in terms of fractional releases and timing of release
- Alternatives 3: Any release that occur because of severe accidents that would entail 10% or more of the initial core inventory of iodine.
- Alternatives 4: A collection of all releases that would result in one or more early fatalities offsite

The first three alternatives are solely based on the release thresholds, and can be readily calculated using the results of the level-2 PSAs. For Alternatives 1, the bypass and early containment failure frequencies reports in the Level-2 PSAs were summed to provide an estimate of the LERF. This approach simply considers early failure and bypass events without considering the magnitude of the environmental source terms. However, not all early containment failures result in large source terms and there is a threshold below which early fatalities will not occur. The threshold for early fatalities depends on several factors. In many calculations were performed to determine the conditions under which an off-site early fatality could occur as a function of the fraction of the core inventory released of different radionuclide groups. A threshold of I, Cs, Te ≥ 0.03 was determined based on a spectrum of these calculations. This threshold is used as the basis for Alternatives 2 below. For Alternatives 2, the frequencies of release categories reported in the IPEs that resulted in at least 3 percent release of I, Cs, and/or Te were summed to provide an alternate estimate of LERF based on the calculations reported in above. The Alternatives 3 approach is similar to Alternatives 2 above but uses larger release fractions to define LERF. The frequencies of release categories reported in the IPEs that resulted in at least 10 percent release of I and Cs were summed to provide another estimate of LERF. The 10 percent release fractions were used because several utilities used this threshold to define a large release in their IPE submittals. Estimation of release frequency using Alternatives 4 requires either a level-3 PSA (i.e., offsite consequence calculations) or other approximations for calculation of early fatalities in the immediate vicinity of the power plants (i.e., in the area outside the exclusion zone extending to about 2 km from the plant)

3.Modeling Methods

3.1 Risk-Based Regulatory Acceptance Criteria for Site Specific Application of Safety Goals

The purpose of this section is to explore the concept of using the Safety Goal quantitative health effects (QHO) on early fatalities to derive lower tier risk acceptance criteria for application on a plant-specific basis. A starting point for expressing the early fatality QHO in a form that can be used to derive different tier criteria is the following working definition for the risk of early fatalities for any specific plant in terms of the normal determinations of probabilistic risk assessments (PRAs) [5].

$$\text{Mean number of early fatalities} \equiv \sum_i (\text{STCF})_i\,(\text{C}_{\text{ef}})_i \tag{1}$$

where i refers to the spectrum of accident sequences

$(\text{STCF})_i$ is the source term release category frequency for sequence i,

$(C_{ef})_i$ Is the early fatality consequences given the sequence i which has associated with it a source term, that may be defined in terms of the equivalent release of iodine to the outside environment.

The QHO objective for early fatalities is expressed in terms of individual risk. The Safety Goal Policy Statement specifically states that the early fatality QHO is to be determined by calculating the cumulative individual fatalities within one mile of the site boundary, C_{ef}, and dividing that by the population within that same one mile region, P_1. Therefore, Equation 1, for purposes of comparing with the early fatality QHO, should be rewritten as

$$\text{Individual risk(IR)} \equiv \sum_i (\text{STCF})_i\,(\text{C}_{\text{ef}})_i/\text{P}_1 \tag{2}$$

In order to proceed further, we first note that, in general, the individual early fatality (IEF) within one mile of the site boundary can be related to the total effective dose expressed in terms of the equivalent release of iodine by the relationship

$$IEF_{ef1} \equiv \frac{(C_{ef})_i}{P_i} = 1 - \exp[-K] \tag{3}$$

$$K \equiv 0.693\left(\frac{H}{D_{50}}\right)^{\beta} \tag{4}$$

where H total effective acute dose to the target organ
D_{50} dose required for producing an effect in 50 percent of the exposed individuals
β beta or exponential parameter in the hazard function that defines the steepness of the dose response function.

Consequently, if a calculation were available that gave the individual early fatality risk within one mile of the site boundary, for any effective acute dose, Dose, then Equation 2 would be rewritten as

$$\text{Individual risk} \equiv \sum_i (\text{STCF})_i\,(\text{IEF})_i \tag{5}$$

For our present purposes, Equation 3 can be rewritten as

$$\sum_i (\text{STCF})_i \left\{1 - e^{\left[-0.693(H/D_{50})^{\beta}\right]}\right\}_i \equiv \text{Individual risk} \tag{6}$$

The items on the left of Equation 6 are those that are determined by a full-scope Level 2 PRA with source term capability and a site characterization parameter. The items on the right contain the result of a Level 3 consequence analysis for individual risk. This parameter can easily be determined using an appropriate computed output. The ULJIN FSAR and PSA report was used to determine site-specific early fatality consequences for a standard plant (for inventory), summary evacuation assumptions, actual site population and wind rose, best-estimate meteorology, and a variety of source terms.

Although the values for C_{ef} out to the one mile boundary were not specifically reported in the ULJIN 3&4 FSAR and PSA, the information may still exist in the archival print-outs of the computed output. In case these data are not currently available, Section 3.2 presents a convenient and robust method for estimating the radiation doses from nuclear plants for any reference source term.

3.2 Factors Affecting Early Fatality

Although the unique accidents sequence and source term release rate are considered in the consequence analysis, the resulting offsite health effects may be different if the source term release parameters and weather conditions are different. Therefore, we have made basic spectra base on the relative importance of source term release parameters on offsite health effects. We then investigated the variation of health effects resulting from the severe accidents of the ULJIN 3&4 nuclear power plants from spectrum to spectrum by using MACCS2 code.

The notion of a "large release" implies the existence of a threshold in release space; that is, given a spectrum of possible releases there exists a boundary which distinguishes "large" from "not large". Attempts have been made to define a large release magnitude based on off-site health effects. There is an inherent arbitrariness in their definition since off-site health effects depend not only on release magnitude but also on site-specific parameters, such as population. Thus what would be a large release at one site (or scenario), would not necessarily be one at some other site (or scenario). Weather variability and wind rose are other site-specific factors. In a hypothetical calculation, the population was fixed by assuming one person located at the site boundary in each of the 16 angular sectors around the site and the population weighted risk of early fatalities was calculated for large releases. The individual early fatality risk is the number of early fatalities (which is one in this case since for a particular release the wind only blows into one angular sector) divided by the total population "at risk" which is 16 in this particular case. This report explores the implications of some potential definitions.

The source term profiles which were derived from the Individual Plant Examination (IPE) of the UJN 3&4 nuclear power plants were used to evaluate health consequences. According to the IPE results, 19 source term categories (STC) are defined by categorizing similar containment failure modes. The MACCS2 code is used to evaluate the health effects resulting from the source terms of the UJN 3&4 nuclear power plants. In MACCS, the dispersion and deposition of radionuclides released from the reactor containment to the atmosphere were modeled with a Gaussian plume model. The site was selected as the center of a polar grid and the grid was divided into 16 equally spaced sectors. Evacuations are considered as 1150 emergency response actions. These actions are to mitigate the effects of a release of radioactivity during a severe accident and are designed to reduce radiation exposures, public health effects.

For site-specific analyses, it has been our practice to consider the individual early fatality as a scenario and site-specific constant. In this analysis, the individual early fatality is treated as a random variable, which represents the variability (across the spectrum of sites) of the scenario and site-related parameters important to early fatality risk. The individual early fatality can be represented as:

$$IEF = f(\lambda_l, C_0, t_0, \sigma_y, \sigma_z) \tag{7}$$

where σ_y, σ_z horizontal and vertical dispersion coefficients

λ_l the rate at which the fission product is released(release fraction)

C_0 power level

t_0, exposure duration (release time)

This section discusses those parameters that are important to early fatality risk. This includes those parameters that are determined by plant design/plant operations and that should be captured in a proper definition of the LERF. The second category includes those parameters that are determined by site characteristics. The plant design/plant operations related parameters potentially important to early fatality risk:

1) Source Term Characteristics
   A. magnitude of the fission product release from containment (particularly the volatile I and Te groups)

B. release thermal energy and release height,

2) Timing Characteristics

A. timing of release (relative to the start of protective actions) – effective evacuation begins before the start of radionuclide release.

B. absolute time of release relative to reactor shutdown (for radionuclide decay considerations)

Figure 1 shows three primary factors: release magnitude, release timing, and emergency response, along three axes. With site demographics, meteorology, etc. fixed, various combinations of values of the depicted variables, for example, low magnitude/early timing/conservative (slow) emergency response, or, alternatively, large magnitude/late timing/NUREG-1150 type (prompt) response, could give rise to one early fatality. This schematic depiction is simply meant to show that there is no unique answer (a single point in the parameter space) to the question of what source term leads to one early fatality. There are, instead, a number of possible answers, or sets of points whose locus would define a hypothetical early fatality surface in the schematic parameter space of Fig. 1 [7].

The source term, as traditionally specified by a set of fractional releases of the initial core inventory, and the time of release to the environment, defines the magnitude of the release to the environment. The timing is significant in that physical removal processes occurring in containment can lower the fractional releases and radioactive decay can significantly lower the amounts of short lived isotopes which reach the environment and which are known to contribute significantly to the early dose and therefore early fatalities. On the other hand, timely and effective evacuation can in many instances mitigate early consequences which in the absence of such emergency actions would be quite serious. Hence, it is to be expected that a spectrum of source terms exists, given their magnitude and timing, and given the type and effectiveness of emergency responses that could occur, which will result in the potential to lead to one mean early fatality and could be candidates for a large release source term definition. The MELCOR Accident Consequences Code System (MACCS) was used to validate off-site early fatalities. The protective actions are modeled in MACCS. The emergency responses modeled in the EARLY module of the MACCS code are of importance. In this study, three release category timing subgroups were defined for each release category. For subgroup 1, it was assumed that evacuation commenced at least 30 minutes prior to the start of radionuclide release. For subgroup 3, the start of evacuation was delayed until one hour or more after radionuclide release had begun. For subgroup 2, the start of evacuation was assumed to occur within a time window from 30 minutes before, to one hour after, the start of release [8].

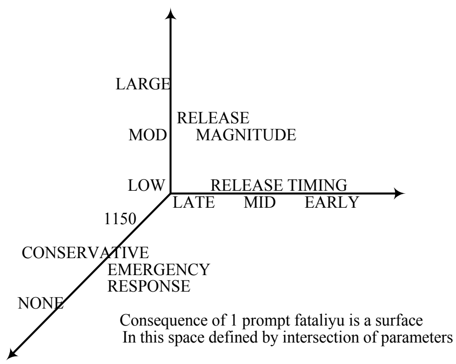

Figure 1. Release magnitude, release timing, and emergency response.

4. Results

The set of calculations, displayed in Figure 2, were designed to evaluate the site boundary dose as a function of the 1-131 released inventories for the cases, 1 and 2. Assuming one person located at the site boundary in each of the 16 angular sectors, the population weighted risk of early fatality was calculated (this is the number of early fatalities divided by the total population "at risk" which is equal to 16 in this particular case). For most weather conditions, the plume at the site boundary spreads over only a fraction of a sector, and since there is only one person in each sector, the code calculates a fractional fatality in most cases. (If one early fatality occurred in each case, the population weighted risk would be identical to 1/16 or 0.0625). That is why Tables 1 show mean values of the population weighted risk below 0.06 in all cases.

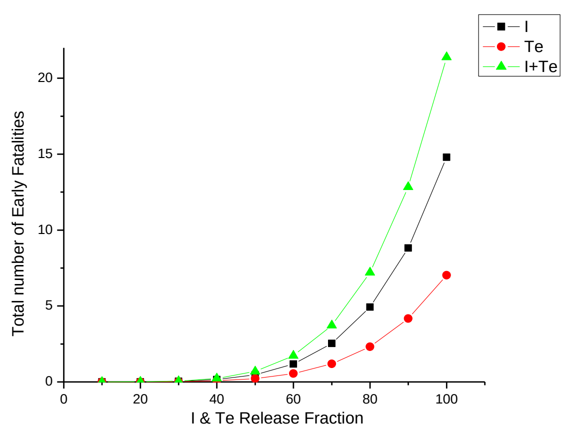

Figure 2. Total number of early fatalities as a function of I-131 & Te-132 release.

Regardless of the magnitude of the source term, if evacuation commences sufficiently prior to the time when the release of radio-nuclides begins then the probability of early fatalities is dramatically reduced. In the NUREG-1 150 study, three release category timing subgroups were defined for each release category. For subgroup 1, it was assumed that evacuation commenced at least 30 minutes prior to the start of radionuclide release. For subgroup 3, the start of evacuation was delayed until one hour or more after radionuclide release had begun. For subgroup 2, the start of evacuation was assumed to occur within a time window from 30 minutes before, to one hour after, the start of release.

Figure 3 illustrates the impact of these various evacuation assumptions on the early fatality risk. This figure plots the early fatality risk against the iodine release fraction. Individual data points for the three release category subgroups are shown with different symbols. This figure illustrates the effectiveness of early evacuation in reducing the Individual Early Fatality Risk. The diamond shaped symbols represent sequences for which evacuation was delayed until one hour or later after the start of radionuclide release (subgroup 3). These results are dominated by the fraction of the affected population who are assumed not to evacuate. For sequences characterized by evacuation commencing at about the same time as the start of radionuclide release (subgroup 2), the results (shown as circles) generally fall between the results for subgroups 1 and 3.

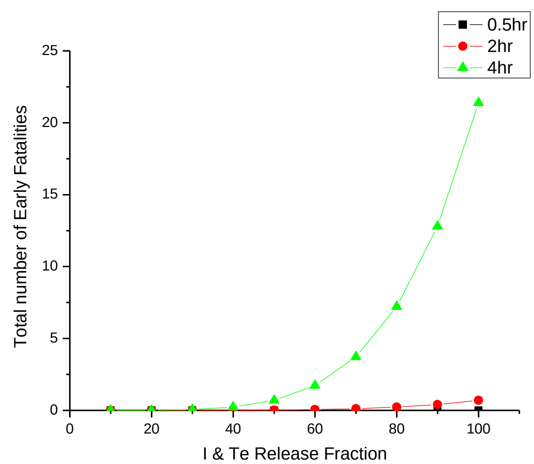

Figure 3. Early Fatalities as a function of 1-131 Release and evacuation assumptions.

5. Conclusion

This paper defines a simple relationship between the Safety Goal QHO for Individual Early Fatality and a Large Early Release Frequency (LERF) that can be used to estimate the Safety Goal QHO for a specific plant. This paper also provides a quantitative definition of the LERF. The relationship utilizes simple site-specific characteristics and results from a Level 2 plant-specific probabilistic risk assessment (PRA) (release category frequencies and source term characteristics). And also, this produces the correlation factor between early fatality and LERF and has calculated the early fatality to validate the results, according to the residential distance using MACCS code. This methodology may provide a simple and easy to use approach for providing reasonably robust estimates for the individual early fatality frequency for PRA analyses lacking a detailed Level 3 offsite consequence. This methodology has been applied to a broad spectrum of PRA sequence classes and in all cases the comparison with the PRA result have been favorable. And he results of this study may contribute to defining LERF and finding a measure for Risk-informed Regulations and Risk-informed decision-making.

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