Reliability Engineering and System Safety 137 (2015) 112–119

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Achieving reasonable conservatism in nuclear safety analyses

Kamiar Jamali

Office of Nuclear Safety, Associate Administrator for Safety and Health, National Nuclear Security Administration, United States Department of Energy, 19901 Germantown Road, Germantown, MD 20874, USA

ARTICLE INFO

Article history:
Received 13 August 2014
Received in revised form
22 December 2014
Accepted 14 January 2015
Available online 23 January 2015

Keywords:
Nuclear
Safety analysis
Probabilistic risk assessment (PRA)
Uncertainty analysis
Reasonable
Conservatism

ABSTRACT

In the absence of methods that explicitly account for uncertainties, seeking reasonable conservatism in nuclear safety analyses can quickly lead to extreme conservatism. The rate of divergence to extreme conservatism is often beyond the expert analysts' intuitive feeling, but can be demonstrated mathematically. Too much conservatism in addressing the safety of nuclear facilities is not beneficial to society. Using certain properties of lognormal distributions for representation of input parameter uncertainties, example calculations for the risk and consequence of a fictitious facility accident scenario are presented. Results show that there are large differences between the calculated 95th percentiles and the extreme bounding values derived from using all input variables at their upper-bound estimates. Showing the relationship of the mean values to the key parameters of the output distributions, the paper concludes that the mean is the ideal candidate for representation of the value of an uncertain parameter. The mean value is proposed as the metric that is consistent with the concept of reasonable conservatism in nuclear safety analysis, because its value increases towards higher percentiles of the underlying positively skewed distribution with increasing levels of uncertainty. Insensitivity of the results to the actual underlying distributions is briefly demonstrated.

Published by Elsevier Ltd.

1. Introduction

Safety analyses are performed to ensure that a nuclear facility's design and operational controls provide assurance that the public, workers, and the environment are protected from all nuclear hazards. Since there are many sources of uncertainties within the analyses, the assurance of "adequate protection" is provided through conservatisms applied throughout all related analyses, supporting disciplines (e.g., Quality Assurance), and the resulting design provisions (e.g., incorporation of defense-in-depth and appropriate safety margins) and operational controls. This highly desirable conservative philosophy in nuclear safety can predispose nuclear safety professionals to seek ever-increasing levels of conservatism in all areas of nuclear safety assurance. The downside of this approach is that in the absence of methodologies that explicitly account for uncertainties, including what, a priori, may appear to be reasonable conservatism can in fact lead to extreme conservatism. The divergence to extreme conservatism occurs far more rapidly than is generally recognized as shown through examples in this paper. This phenomenon is often beyond the expert analysts' intuitive feeling, but it can be demonstrated mathematically.

When complex analyses are used to derive the distributions of output variables for representation of uncertainties in analysis results, the 95th percentile is generally associated with the upper-bound [1–3]. While it is well known that the use of multiple conservative assumptions can lead to extremely conservative results, the rate and the degree of this divergence have not been widely demonstrated in the past. This paper shows that when several input parameters are taken at their bounding values, the obtained result dwarfs the derived 95th percentile of the output by orders of magnitude.

Extreme conservatism is often intentionally exercised in safety analyses because it can pay dividends in simplified analysis and review efforts. However, the search for increased conservatism cannot be pursued without consequences. Extreme conservatism can lead to safety conclusions and decisions with significantly higher safety costs, which can make nuclear facilities, even those with very low hazard and risk profiles, prohibitively expensive. This can deprive the public from the benefits derived from the operations of these facilities, from nuclear power to medical isotopes and national security needs. It can also lead to overall higher risks to the public in mission delays (e.g., waste processing), cancellation of programs resulting in continued reliance on older facilities, or unnecessary expenditure of funds and resources that might have been used in more effective projects for risk reduction.

In order to strike a balance between competing objectives of safety versus cost (including mission impacts) and to ensure a judicious use of resources, a reasonable degree of conservatism must be sought in nuclear safety analyses. However, recognizing

E-mail address: Kamiar.jamali@nnsa.doe.gov

http://dx.doi.org/10.1016/j.ress.2015.01.008
0951-8320/Published by Elsevier Ltd.

the threshold for a reasonable level of conservatism in a given application is difficult in the absence of a detailed treatment of uncertainties, including what is referred to as the "full propagation" of input parameter uncertainties.

This paper explores the impact of input parameter uncertainties on selected outputs from a nuclear safety analysis. Input parameter uncertainty is a specific but important type of uncertainty among several [4]. It has a significant impact in many areas of nuclear safety analyses and calculations including Documented Safety Analyses (DSAs) [5], Safety Analysis Reports, Integrated Safety Analyses, and Probabilistic Risk Assessments (PRAs).

The concept of reasonable conservatism in this paper is synonymous with the Nuclear Regulatory Commission (NRC) Chairman Diaz's speech on "Realistic Conservatism" given at the 2003 Nuclear Safety Research Conference [6]. In that speech, the Chairman stated that:

> Neither under-regulation nor over-regulation serves anyone's interests. Under-regulation puts the public safety at risk; over-regulation diminishes the value to society of the regulated activity. Over-regulation could also be counter-productive to safety by diverting resources from the important safety issues.
>
> … public policy should not be based on worst case scenarios and that we have to deal with probabilities and not with all possibilities. So called 'worst case scenarios' are only good as vehicles to achieve the proper bounding of realistic scenarios early in the process. Nuclear policies and regulations are necessarily conservative, but should not be driven by non-physical or unrealistic assumptions. Worst case assumptions are often considered as a first step and are used because they are simple. But, the unfortunate consequences of using worst case assumptions is that they often continue to propagate and eventually become part of the established framework. And, frankly, no one wants to appear as 'non-conservative,' or 'less conservative;' it is always easier to add to conservatism than to bring realism. But realism is what could be in the best interest of the public well-being. Rather than using worst case scenarios, we should be using realistic conservatism – based on the right science, engineering and technology – so that the end product is recognizable and useable. I believe we should avoid the 'worst case' syndrome… and seek out 'realistic conservatism.'
>
> … Sprinkling unrealistic conservatisms, even if they are small but compounding conservatisms, throughout an analysis or study can skew the results significantly. They do add up, or even multiply. How can a safety-conscious decision maker, in the broadest sense of the term, use a study that is filled with unrealistic assumptions? Who pays for unnecessary conservatism? Society does.

Some may argue that in the aftermath of the Fukushima events, no degree of conservatism in nuclear safety is too much conservatism. In this context, it should suffice to note that those location-dependent plant designs for protection against natural phenomena hazards did not meet the long-held deterministic design requirements as a minimum expected set of standards [7,8]. In other words, Fukushima reactors simply did not meet current, well-established location-specific NPH requirements for safety system designs (safety system performance goals in the range of 1E−4 to 1E−5/yr) applicable in the United States and other countries.

The NRC has long recognized the problem of over-conservatism in safety analyses and sought to establish methods for addressing it. Code Scaling, Applicability, and Uncertainty (CSAU) is one such methodology [9,10]. In the CSAU approach, the licensees can provide the best-estimate analysis results along with an estimation of uncertainty of the calculations.

This paper concludes that, in the absence of full propagation of parameter uncertainties, using mean values for nearly all input parameters (the use of bounding values may be unavoidable in a few cases) in many safety analysis disciplines is the best approach for addressing the effects of parameter uncertainties. The typical levels of conservatism when using mean values is also consistent with the concept of "reasonable conservatism" as promoted in the Department of Energy (DOE) standard DOE-NA-STD-3016-2006 [11] and elsewhere.

2. Background

Nuclear safety practitioners use different terms for the value of an input or an output variable as the desired choice among different options for parameter estimations. These include best-estimate, point-estimate, mean value, median value, upper/lower-bound, or specific percentiles of a distribution (e.g., 95th percentile) as the parameter of choice. Best-estimates and point-estimates are sometimes used interchangeably, while in certain applications the former is associated with the median- and the latter with the mean-values of the underlying distributions. Point-estimate is often a substitute for any one of the single numerical estimates that could have been chosen in the specific analysis, such as the only known value, the mean, median, the upper-bound, etc.

A key characteristic of nuclear safety analyses is that uncertainties in individual input parameters are generally large and represented by factors rather than percentages. For example, a typical input (such as the initiating event frequency) may have a factor of three, 10, or higher as the ratio between the mid-range/best-/point-/realistic-estimate and the upper- and/or lower-bound estimates. This ratio is often referred to as the uncertainty (or error) factor (UF) in PRA applications.

3. Some basics

3.1. Representation of parameter uncertainty

Any uncertain quantity, such as the probability of the occurrence of a failure, an airborne release fraction, or the height of people in a population, can be represented by a random variable. Random variables can be discrete or continuous. A random variable takes on a specific value (for a discrete distribution) or a range of values (for a continuous distribution) with an associated probability that is derived from the underlying distribution defining its variability.

3.2. Central limit theorem and lognormal distribution

The central limit theorem states that, given certain conditions, the distribution of the sum (or average) of a large number of independent, identically distributed variables will tend to the normal distribution, regardless of the underlying distribution. Therefore, if Y is the product of n random variables $X_1,\ldots,X_n$ with an arbitrary distribution, then the logarithm of Y is:

$$\log Y = \sum_{i=1}^{n} \log X_i \qquad (1)$$

And the distribution of "log Y" will tend toward a normal distribution with an increasing value of n.

In addition, given that "log Y" is normally distributed, the distribution of Y will be lognormal by definition [12,13]. Since division and exponentiation are special forms of multiplication,