DECISION MAKING METHODOLOGY OF COST-BENEFIT ANALYSIS BASED ON PROBABILISTIC SAFETY ASSESSMENT FOR ACCIDENT MITIGATION ALTERNATIVES

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ABSTRACT

Various types of safety enhancements for operating nuclear power plants have progressed since the Fukushima accident. There have been various justification principles of risk criteria for decision-making based on societal risk acceptance, cost-benefit analyses, or operating experience. The decision making from the cost-benefit analysis compares the investment required for addition or replacement with the benefit of a risk reduction for the core damage and large release accidents. The proposed decision making methodology estimates the investment costs and the benefits gained by calculating the risk reduction from a designated change. The accident mitigation alternatives including additional electrical power generators and passive safety systems were estimated. Instead of the net-benefit method, ratio assessment method presents the ratio of the results of the PSA methodology to the relative investment cost. The ratio of usefulness to the relative investment cost presents the degree of cost-benefit.

1. Introduction

A risk assessment has been used as a criterion for the licensing of new nuclear power plants, and a target for operating nuclear power plants to support the interpretation of the results and decision making on the plant modifications. As listed in Tab. 1, there are several approaches to justify the subsidiary risk criteria [1].

The USNRC defined the costs and benefits as “impacts” and “values” in their handbook [2]. “Values” as benefits include public benefits that a regulatory body is required to seek as its statutory mission. Safety improvements are included in the values. “Impacts” measure the other consequences of the proposed change. Examples include increases in the regulatory body and operating costs resulting from the action.

The cost-benefit analysis (CBA) must be justified on the basis of the decision theory framework. A decision maker can select its preferences from the quantitatively estimated risks and costs in the CBA. The decision making from the CBA compares the investment for replacement with the benefit of the risk reduction for core damage and large release accidents. Core damage frequency (CDF) and large early release frequency (LERF) are interpreted as subsidiary criteria for the risk of offsite consequences.

NEI has used a net-benefit estimation methodology as a screening tool in the applicant`s environmental report for the operating license renewal of operating NPPs [3]. The total change value is estimated based on the sum of the investment cost and benefit. The benefit was a product of the frequency change and cost from the event consequence. The monetary equivalent of the unit dose, and offsite property damage costs from a source term analysis were assumed and estimated under each accident scenario. The maximal benefit was fixed from a design modification because the absolute reductions of CDF and LERF were quantified. This net present value was used in the screening process to eliminate severe accident mitigation alternatives (SAMAs) as being not cost-beneficial without consideration regarding the degree of safety enhancement. SAMA is a feature or action including hardware modifications, procedural changes, and program improvements that can prevent or mitigate the consequences of a severe accident.

Eeckhoudt et al. used a methodology using the multiplication factor for risk aversion to estimate the benefit value [4]. It assumed that the social cost of the risk was the sum of the individual costs. The individuals were categorized depending the distance from the nuclear site. The ratio of the degree from a risk-averse individual to that from a risk neutral individual was defined as a multiplication factor for the risk aversion attitude of the public.

However, it is estimated that there are high uncertainties on specific values of the benefit. The benefit values were underestimated because some values were omitted. Sunk costs in terms of construction and maintenance were not considered in this method. In addition, direct effects out of the estimated area and indirect effects on the whole nuclear industry from accidents with core melt or the release of the radioactive materials were not included in the benefit value in the estimation methodology of the net benefit. Accordingly, the CBA has to be used as a supporting tool for decision making based on engineering judgements and design philosophies, not for a screening criterion.

The objective of this paper is to estimate the degree of safety enhancements and cost-benefits for accident mitigation alternatives through the proposed decision making methodology of a cost benefit analysis. The proposed decision making methodology estimates the usefulness-cost ratio from the invested costs and the benefits gained using a risk reduction from a designated change.

Principle	Description of the approach
Societal risk acceptance	- Interpreting overall safety goals as quantitative risk targets - Complied with other risks accepted in the society
Cost-benefit analysis	- Investment for replacement, comparing with benefits of risk reduction of large release and core damage accidents - Being able to carry out CBA to justify or reject safety improvements, given that the societal risk criteria are fulfilled
Operating experience	- Using accident and incident statistics from NPPs as references - Complied with current safety status

Tab. 1: Justification principles for subsidiary risk criteria

2. Methodology of cost benefit analysis

The target items are qualitatively evaluated in the criteria for recognizing the combined existence and the coupled design element before the CBA. In the CBA, the total net public health value of the proposed action, expressed in terms of the expected reduction in public exposure, is divided by the total costs of the action. This means how much of the safety is enhanced, considering the total costs. It simply implies the degree of the safety enhancement to the cost to be invested by applying or modifying a system in a NPP.

Because the uncertainties in converting non-monetary values into costs can be exempted in this method considering the limitations, the ratio assessment method is employed in this study. It assumes very large indirect effects of an accident under non-measurability of the utility. The value of usefulness is evaluated rather than utility from the application of the system. Instead of the total net safety value of the proposed action, which typically avoided the person-rem of the public dose, the changed CDFs estimated in the previous chapter were used as the value for the benefit. The benefit value is multiplied by the rest of the reactor lifetime when the estimated reactors are different. For the cost value, the relative engineering cost is used as the denominator in the assessment equation. That is, the usefulness-cost ratio (UCR) is presented:

$$UCR = \frac{{-\Delta CDF}/{CDF_o} \times {y}/{40}}{{\Delta COST}/{(Sunk\ Cost)}} \quad (1)$$

where y is the rest of the reactor lifetime

To estimate the degree of cost-benefit from modifications for operating nuclear power plants, two steps were performed. First, the risk reductions of the core damage accidents were calculated from the alternatives. Next, the invested costs and benefits gained were estimated for each case.

3. Assessment for accident mitigation alternatives

The estimated accident mitigation alternatives include the addition of emergency diesel generators in the safety class and alternative AC power source (AAC) in the non-safety class. In addition, passive safety systems such as a steam generator gravity injection system (SGGI) and a passive auxiliary feedwater system (PAFS) were assessed [5, 6]. They were compared with actual cases of the SAMA studied by the NEI [3]. The SAMAs, which had the potential to reduce the severe accident risk, were identified and estimated to determine if the implementation of each alternative is cost-beneficial [58].

In the case of adding an EDG, the cost of installing an additional EDG had been estimated to be greater than $20 million for the application in the Calvert Cliffs NPP for license renewal. Because this was greater than the maximum benefit, it had been screened from the CBA in the SAMA analysis [3]. However, the screening process is not applied in this analysis. The specific data from the SAMA analysis, included in the Applicant`s Environmental Report of Kewaunee PWRs (KPS), were used [7]. As the implementation costs in the KPS cases are estimated in 2008, the values are converted into the present values of implementation in 2015.

The degrees of safety enhancements from the alternatives are illustrated with the implementation costs in Fig. 1. The error bars indicate the estimated maximal and minimal values based on the cited data. The SAMAs of KPS for an operating license are included in the Fig. 1 and 2 as a shape of open interior. The data for the KPS were quite overestimated because the failure probability related with the applied system was modified as zero [7].

The usefulness with a relative value of the investment cost from each case is illustrated in Fig. 2. A slope in the graph indicates the usefulness-cost ratio because the x-axis is a dimensionless investment cost and the y-axis is usefulness from the change in the CDF. As the upper right region of the map indicates, a large invest cost is needed for the safety enhancements, and the budget has to be reviewed. A case in this region will be actually screened out in the estimation methodology of NEI due to the high cost. A case in the bottom right region will not be considered applied due to being not cost-beneficial. On the other hand, the cases in the upper left region are evaluated to be cost-beneficial and feasible for the applications. The cases of 1 SGGI and 1 AAC are included in this region. In the bottom left region, as the small portion of CDF is decreased by the application of a design and the implementation cost is quite considerable, the targeted events and the effects of the design application have to be reviewed again. As all data of SAMA are included in this region, they are needed to be considered with the existing criteria.

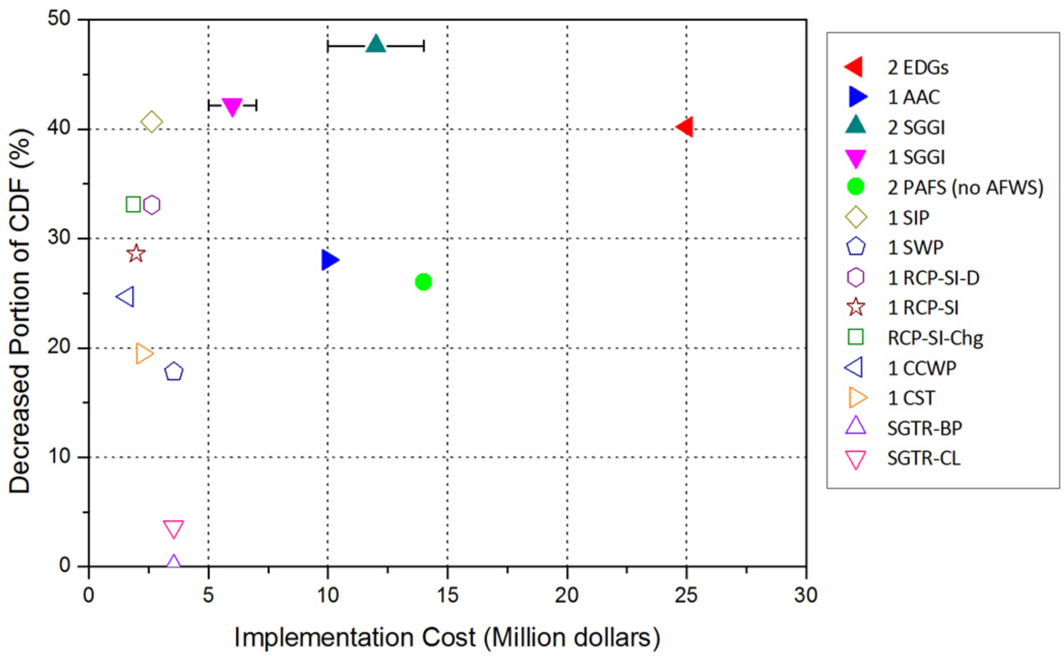

Fig. 1. Decreased portion of CDF with implementation cost for each alternative

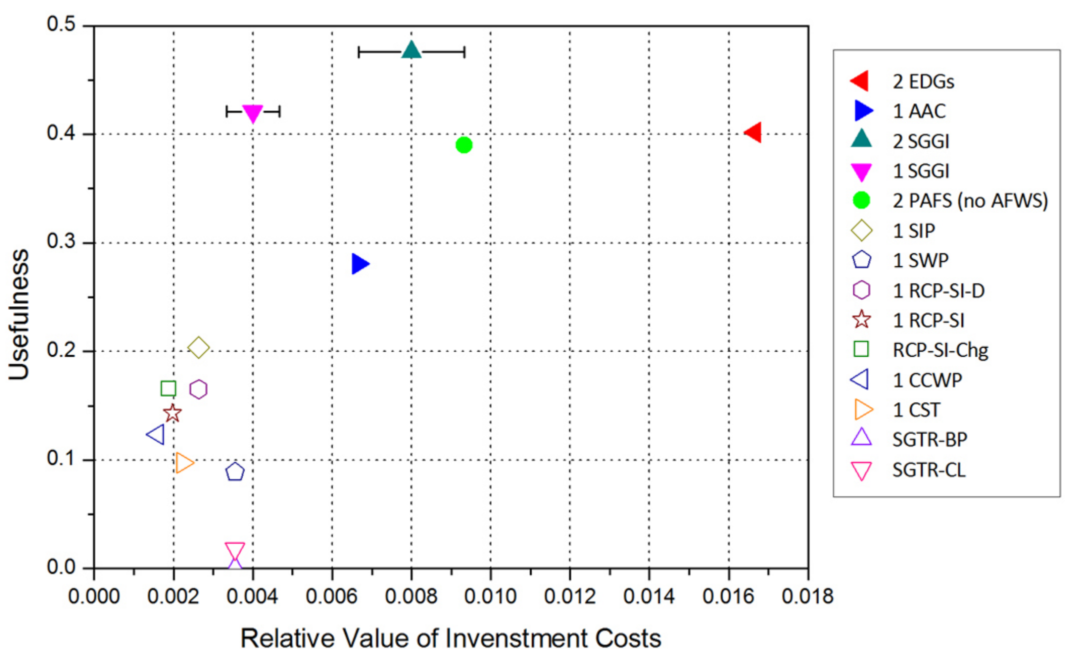

Fig. 2. Usefulness with relative investment cost coefficient for each alternative

4. Conclusion

A methodology of a CBA estimating severe accident mitigation alternatives was proposed for risk-informed decision making. The CBA was performed using the induced costs and the changed CDF from the application or modification of a component or a system to a NPP under non-measurability of the utility. The derived UCR represents the relative degree of cost-benefit compared with other alternatives. It implies the alternatives belonging to the upper left region of the UCR graph would be economically effective at decreasing the risk of core damage from the standpoint of cost-benefit.
The passive safety systems showed higher UCRs than the others. This was because the reliability of the operation initiations for the passive safety systems was higher than those of the active systems. However, the sustainability of a passive safety system still has some remaining uncertainties. It can also be considered for various thermo-hydraulic phenomena from the standpoint of a PSA.
In addition, PSA levels 2 and 3 will provide more overall and credible results for assessing the value of usefulness with the modification of the UCR in the CBA because the factors of the onsite and offsite are estimated more accurately.

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References

[1] Bengtsson, L. et al., (2010). Probabilistic Safety Goals for Nuclear Power Plants, Swedish Radiation Safety Authority, Report number: 2010:35, ISSN: 2000-0456.

[2] Heaberlin, S. W. et al., (1983). Handbook for value-impact assessment, NUREG/CR-3568; PNL-4646. Pacific Northwest Lab., Richland, WA, USA.

[3] NEI (2005). Severe Accident Mitigation Alternatives (SAMA) Analysis, Guidance Document, NEI-05-01-rev.A, Washington D.C., USA.

[4] Eeckhoudt, L., Schieber, C., and Schneider, T. (2000). "Risk aversion and external cost of a nuclear accident", Journal of Environmental Management, 58, pp. 109-117.

[5] Chang, S.H., Kim, S.H., Choi, J.Y., (2013). "Design of integrated passive safety system (IPSS) for ultimate passive safety of nuclear power plants", Nuclear Engineering Design, 260, pp.104-120.

[6] Cho, Y.J., et al. (2012). "Analytical studies of the heat removal capability of a passive auxiliary feedwater system (PAFS)", Nuclear Engineering and Design, 248, pp. 306-316.

[7] DEK (2008). Kewaunee Power Station Applicant`s Environmental Report Operating License Renewal Stage, DEK (Dominion Energy Kewaunee, Inc.), USA.