Using bootstrap method to establish surrogate safety goals for a society with operating NPPs

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Abstract: Quantitative risk values for nuclear power plants can be obtained by conducting Probabilistic Safety Assessment (PSA). However, people cannot judge the risk level without comparing the risk values from PSA with the standards of acceptable risk in society. Acceptable risk standards are affected by many factors, and those factors are preferentially considered in specified applications. In the U.S.A., both qualitative safety goals and quantitative health objectives (QHOs) for the current generation of light water reactors have been established by the comparative methods which are described in the Safety Goals Policy Statement Published by the U.S. Nuclear Regulatory Commission. In U.S.A. most of the existing nuclear power plants (NPPs) have conducted Level 1 PSA or simplified Level 2 PSA models, wherein surrogate safety goals are needed to evaluate whether or not the risks of those NPPs satisfy the QHOs. The existing surrogate safety goals had been established based on the QHOs. However, there are some problems in the derivation process, for example, unreasonable assumptions and logic. Apart from the U.S.A., most other countries with operating NPPs simply adopt the surrogate safety goals recommended by International Atomic Energy Agency without considering the society-specific risk and the development status of nuclear power. In this paper, the process of how to derive QHOs from qualitative safety goals and a model of quantitative health risk are first introduced, and then the models using Core Damage Frequency and Large Early Release Frequency based on QHOs are introduced. Generally speaking, there are multiple types of NPPs utilized in an individual society, and the environmental conditions of the plants are different from each other. So the specified society has the CDF and LERF samples satisfying the QHOs. The Bootstrap method is a resampling method and is suitable to the problems of small sample size. The upper limits of the confidence interval of CDF and LERF samples are obtained as surrogate safety goals by Bootstrap method. Lastly the QHOs of Chinese NPPs regarding individual early fatality and individual latent cancer fatality are estimated from the statistical data published by the government, and the CDF sample collected from the reference is applied to determine the surrogate safety goal CDF from the Bootstrap method.

Keywords: safety goals; surrogate safety goals; bootstrap method

1. Introduction

Quantitative risk values of nuclear power plants (NPPs) can be obtained by conducting Probabilistic Safety Assessment (PSA). However, whether the risk level is acceptable or not depends on the standards of acceptable risk. If the estimated risk value is larger than the risk thresholds in the acceptable risk standards, then it is concluded that the risk of NPPs is high. Therefore, establishing acceptable risk standards has become an important part of NPPs risk management [1][2].

The acceptable risk standards are affected by many factors, for example: current social risk, ethics, morality, law, society, psychology, culture, values, political and economic factors and so on. The determination of acceptable risk is a complex integrated decision process. For example, Fischhoff introduces five generic complexities in establishing acceptable risk standards: (a) uncertainty about how to define the decision problem, (b) difficulties in assessing the facts of the matter, (c) difficulties in assessing the relevant values, (d) uncertainties about

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the human element in the decision-making process, and (e) difficulties in assessing the quality of the decisions that are produced [3].

When compared with the consequence of other industrial accidents, nuclear accident consequence has some unique features. When reactor core damage events occur and the accident mitigating systems fail, various kinds of radioactive nuclides will be released to the environment and will cause acute, long-term hazards for the public and environment around the plant. Nuclear power risk has the following characteristics: sense of uncontrollability by the public, incurred involuntarily, acute death, long term consequences, many alternative accident paths, large uncertainty and so on [4]. These characteristics are not favorable to the acceptance of nuclear power risk.

The purpose of this study is examining how to deal with the difficult problems of the establishment of safety goals and surrogate safety goals of NPPs by employing the PSA methodology. In the following, the authors will present the historical review on setting safety goals for operating NPPs in section 2. The relationship between, and models for, PSA and quantitative health objectives (QHOs) of safety goals is introduced in section 3. The models for calculating the figures for Core Damage Frequency (CDF) and, Large Early Release Frequency (LERF) based on the QHOs are introduced in section 4. The bootstrap method is used for statistical analysis of CDF and LERF samples satisfying the QHOs. The steps for selection of the upper limits of the confidence interval as the surrogate safety goals for NPPs are introduced in section 5. The example study for Chinese individual fatality risk and establishment of the surrogate safety goal from 21 CDF examples are given in section 6, and the conclusion is in section 7.

2. Historical review on setting safety goals and surrogate safety goals in NPPs

From 1970s to 1980s, many papers studying the establishment of risk criteria for nuclear power plants were published [5]. After the Three Mile Island accident, the U.S. Nuclear Regulatory Commission (NRC) began to establish safety goals for operating NPPs, responding to the recommendations of the President’s Commission on the Accident at Three Mile Island. Firstly, NRC developed a guidance document and the Advisory Committee on Reactor Safety (ACRS) gave preliminary quantitative safety goals as reference values from expert group decision [6][7]. Both documents were used as a principal basis of discussion at the workshop held by the NRC in 1981. Although the discussion was not limited to the content of the documents, the results of workshop did not deviate from the value of the quantitative analysis. NRC used a stakeholder consultation method and called-on many scholars from technical, social, human and other disciplines to attend this seminar, at which economic, ethical and sociopolitical factors related to the safety goals were discussed, following the discussion guidelines and agenda given by NRC [8]. A safety goals policy statement was published after another four public meetings during 1982 [9]. The comparative method was used to establish safety goals for the current generation NPPs. From 1983 to 1985, NRC collected comments and views from the public and experts of ACRS and then published a revised safety goals policy statement [10]. In this way, both experts and the public contributed to the process of establishing acceptable risk. In 1986, NRC published the final version of its safety goals policy statement which included Qualitative Safety Goals, Quantitative Safety Goals (also called Quantitative Health Objectives, QHOs), and guidance [11]. It can be seen that establishing nuclear safety goals is a complex, integrated group decision-making process.

The legal regulations of nuclear safety stipulate that stakeholders of plants should submit Level 1 PSA results to the regulator when they apply for a plant license [12]. Establishing surrogate safety goals based on the QHOs is a necessary task in order to judge the risk level of plants which don’t have a Level 3 PSA. Core Damage Frequency (CDF) less than 1E-04 per reactor year was once used as a safety goal in the draft policy statement during the process of establishing safety goals. However the experts of ACRS considered this numerical core damage limit to be arbitrary and rejected this number [13]. In the policy statement, a large release guideline was given, but there was no detailed quantitative evidence to prove that this risk threshold was reasonable at that time.

The introduction and number of large release guidelines is therefore arbitrary.

In 1989, in order to implement the safety goals, the task of establishing acceptable surrogates for the early and latent QHOs for the current generation of light water reactors was conducted by NRC. These are called surrogate goals because they are used as alternatives to QHOs. They are also called subsidiary objectives because they support the QHOs [14]. NRC staff explained that surrogate safety goal for CDF and containment performance objective are established through the large release guidelines [15]. But the results of the large release definition study showed that given a large release at 1E-06 per reactor year, any large release definition would result in a degree of conservatism several orders of magnitude more conservative than the QHOs [16]. This guideline is more conservative than previous subjective estimation in the safety goals policy statement. So surrogate safety goal for CDF and containment performance objective based on the large release guideline are also conservative. They are not consistent with the guidelines of the ACRS, which stipulate that surrogate safety goals should not be so conservative as to create a de facto new policy and are based on the QHOs.

NRC introduced the LERF goal of 1E-05 per reactor year as an acceptable surrogate for the early fatality QHO and the CDF goal of 1E-04 per reactor year as an acceptable surrogate for the cancer fatality QHO [17]. But there are some problems in the derivation. The selected numerical values of nuclear accident consequence are not consistent with the hypothesis condition; Assumptions that the accident occurs in an open containment is not reasonable and is too conservative. The process gives a proof of whether the CDF and LERF of the Surry plant specifically satisfies the QHOs or not, rather than establishing surrogate safety goals for all operating NPPs in a society.

Scholars also have some misunderstandings of the surrogate safety goals. Arndt considers that the numerical value of 1E-04 for CDF multi by one-tenth for conditional containment failure probability (CCFP) equal to 1E-05 for LERF, so the acceptable criteria LERF=1E-05 per reactor year is derived from the product of CDF and CCFP [18]. Kumamoto explains that severe core damage accidents are not expected to occur more than once in 100 years, based on the assumption that 100 plants are operating in the US. This is the interpretation of 1E-04 per reactor year for the CDF safety goal [14]. The explanation and understanding of surrogate safety goals from the point of numerical values are not based on the QHOs. On the other hand, other countries with operating nuclear power plants simply adopt the surrogate safety goals recommended by the International Atomic Energy Agency (IAEA) which are the same CDF and LERF of NRC without considering the society-specific risk and the development status of nuclear power.

The processes of establishing the surrogate safety goals are unclear, which leads the public to have low confidence in the risk level. The mathematical models and methods to establish surrogate safety goals for a society which has multiple types of reactors and different offsite environments for its NPPs is provided in this paper as a response to this current situation.

3. Relation between PSA and nuclear power plant safety goals

3.1 Explanation of PSA and its procedure

According to the steps of analysis, full scope PSA is divided into three levels, including level 1 PSA, Level 2 PSA, and level 3 PSA, which are accident frequency analysis, radionuclide transport analysis, and offsite consequence analysis respectively. There are four steps in the full scope PSA, including the accident frequency, accident progression, source term, and consequence analyses.

In the accident frequency analyses, after internal or external initiating events occur, various safety systems and auxiliary systems are used to mitigate the accident in order to prevent core damage. Some systems cannot response to the accident and should be manually initiated by operators according to the requirements of accident procedures. Human error is also a significant part of the process of the accident, because operators may make mistakes in the accident mitigation process.

The accident frequency analysis uses event tree and fault tree techniques to model and compute the various accident sequences causing core damage, and then the CDF of plant is obtained. The accident sequences that have a similar set of initial conditions for the subsequent accident progression analysis are grouped into plant damage states (PDS).

Core damage means that the first barrier of defense in depth (DID) is destroyed. In the accident progression analyses, the operators, following severe accident management procedures, employ containment spray, the depressurization of the primary loop and other measures to maintain the integrity of the second and third barriers of DID. If the integrity of these barriers cannot be ensured, operators will minimize the release of radionuclides from the molten core to the atmosphere. This process is modeled by accident progression event tree (APET) method. Then the paths of accident progression that have a similar set of conditions for source term analysis are grouped into accident progression bins (APBs).

During the accident progression, the radionuclides contained within the fuel rods leak into the atmosphere from the damaged fuel cladding, pressure boundary of the primary loop and containment. In each APB, some factors, such as the core inventory, primary coolant system retention capacity, pressure vessel failure mode, containment and related systems retention and decontamination capacity and containment failure mode, are the inputs of source term calculations which vary with the design of NPPs. Then the source terms that have a similar set of conditions for consequence analysis are grouped into source term groups (STGs). The calculations of public individual early fatality risk and individual latent cancer fatality risk require further inputs, such as buildings, topography, population, production activities, weather conditions around the plant, emergency response plan and STGs.

3.2 Formulations of safety goals

A full scope PSA of a specified plant is a complex calculation. The Equation (1) shows the simplified calculation of the public health risk.

Where $\mathbf{R}(C)$ is the vector of the public health risk; $\mathbf{f}(IE)$ is the vector of frequencies for the initiating events; $\mathbf{P}(AS|IE)$ is the matrix of conditional probabilities of transition from initiating events to accident sequences; $\mathbf{P}(PDS|AS)$ is the matrix of conditional probabilities of transition from accident sequences to plant damage states; $\mathbf{P}(APB|PDS)$ is the matrix of conditional probabilities of transition from plant damage states to accident progression bins; $\mathbf{P}(STG|APB)$ is the matrix of conditional probabilities of transition from accident progression bins to source term groups; $\mathbf{P}(WT|STG)$ is the matrix of vectors which contain the frequencies at which accidents involving specific weather types occur in conjunction with a particular source term group; and, $\mathbf{C}(STG \cap WT)$ is the vectors of public health consequences under the accidents involving specific weather types occurring in conjunction with a particular source term group.

The judgment on whether the NPP's risk is accepted by the public depends on the safety goals of the NPPs. The qualitative safety goals are the top level in the safety goals policy statement published by NRC, as follows:

- Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health.
- Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks.

$$\begin{aligned}\mathbf{R}(C) &= \mathbf{f}(STG)\times\mathbf{C}(STG\cap WT)\\ &= \mathbf{f}(APB)\times\mathbf{P}(STG|APB)\times\mathbf{C}(STG\cap WT)\\ &= \mathbf{f}(PDS)\times\mathbf{P}(APB|PDS)\times\mathbf{P}(STG|APB)\times\mathbf{C}(STG\cap WT)\\ &= \mathbf{f}(IE)\times\mathbf{P}(AS|IE)\times\mathbf{P}(PDS|AS)\times\mathbf{P}(APB|PDS)\times\mathbf{P}(STG|APB)\times\mathbf{P}(WT|STG)\times\mathbf{C}(STG\cap WT)\end{aligned} \tag{1}$$

In the qualitative safety goals, the risks from operating plants are compared with the risks from all other accidents. The regulator uses "not significant" to tell the public that the use of nuclear power in U.S. society is safe if the plants meet the safety goals. But the qualitative safety goals are hard to implement for the stakeholders of plants and regulators. In order to implement the safety goals, the QHOs are proposed based on the first qualitative safety goal. The QHOs are as follows:

- "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents should not exceed one-tenth of one percent (0.1%) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed."
- "The risk to the population in the area of a nuclear power plant of cancer fatalities that might result from nuclear power plant operation should not exceed one-tenth of one percent (0.1%) of the sum of cancer fatality risks resulting from all other causes."

Individual social health risks multiplied by a proportional coefficient are the numerical values of QHOs. This proportional coefficient, one-tenth of one percent, is a quantitative value for no significant additional risk [11].

The average individual in the prompt fatality QHO is defined as the average individual biologically (in terms of age and other risk factors) and locationally who resides within a mile from the plant site boundary, because individuals within this distance would generally be subject to the greatest risk of prompt death attributable to radioactive causes from the consequences of major reactor accidents [19]. The cumulative estimated individual risks divided by the number of individual who reside within one mile equals the numerical value of the individual early fatality QHO. The regulator defines the population in the cancer fatality QHO as the persons who reside within ten miles of the plant site boundary, because the bulk of significant exposure of the population to radiation would be concentrated within this distance [19]. Although the risk of cancer fatality QHO is a social risk for a group of persons, the calculation method of cancer fatality QHO is similar with the individual early fatality QHO. The cumulative the estimated individual risks divided by the number of individuals who reside within ten miles is equal to the numerical value of individual cancer fatality QHO. So the figures of merit of QHOs used to evaluate risk level are individual early fatality risk (IEFR) and individual latent cancer fatality risk (ILCFR).

The equations of QHOs are as follows:

$$R_{N-IEF} \le 0.1\% \times R_{S-IEF} \quad (2)$$

$$R_{N-ILCF} \le 0.1\% \times R_{S-ILCF} \quad (3)$$

Where: R_{N-IEF} is the individual early fatality risk from the current operating NPPs; R_{S-IEF} is the individual early fatality risk from other social accidents; R_{N-ILCF} is the individual latent cancer fatality risk from the current operating NPPs; and, R_{S-ILCF} is the individual latent cancer fatality risk from other social accidents.

4. Surrogate safety goals

4.1 Large early release frequency

Early health effects caused by radioactive irradiation are non-stochastic effects, and threshold effects which mean the effect will not be experienced unless a threshold dose is exceed for an individual. After a serious accident occurs in NPP, the residents nearby are directly exposed to a high dose from the radioactive plume and radioactive materials deposited on the ground. They have two kinds of early health effects, early fatality and injury, within the first few days or weeks after exposure. Early Fatalities include the potentially lethal hematopoietic death, pulmonary death and gastrointestinal syndromes.

The relationship between early health risk and hazard is as follows [20]:

$$R = 1 - \exp(-H) \quad (4)$$

Where R is the probability that a person will, in the absence of competing risks, exhibit the effect of interest; H is a two-parameter cumulative Weibull hazard function of both the dose received by the person and the dose rate. The function is as follows:

$$H = \ln 2 \times \left(\frac{D}{D_{50}} \right)^{V}, D > T \quad (5)$$

Where: D is the mean absorbed dose to the relevant organ; D_{50} is the dose at which half of the population experiences the effect, V is the shape parameter and T is the population threshold dose.

The main factor in the early health risk functions (4) and (5) is the individual exposed dose. When the absorbed dose exceeds the threshold for a specified organ, the individual early fatality risk will increase with the increase of the exposure dose.

Large releases of radionuclides are related to the failure modes of containment, which are roughly divided into early-containment failure (including containment bypass) and late-containment failure. Both failure modes may result in a large release. According to the results of NUREG-1150, the APBs for early-containment failure and containment bypass after the vessel failure are the main contributors for the early fatality caused by internal IEs, fire and earthquake. The contribution of APBs to late-containment failure is relative small, nearly zero for PWR in particular [21]. The main reason why the residents may experience the early fatality is a large release of radionuclides caused by early-containment failure. So the risk metric LERF is used to measure the surrogate safety goal of the early fatality QHO.

The relationship between early health risk and LERF is as follows:

$$
\begin{aligned}
IEFR &= \sum\nolimits_1^N \left[\left(EF_n \times LERF_n \times P\left(WT \middle| STG_n\right) \right) \big/ TP(1) \right] \\
&= \sum\nolimits_1^N \left[\frac{EF_n}{TP(1)} \times LERF_n \times P\left(WT \middle| STG_n\right) \right] \qquad (6) \\
&= \sum\nolimits_1^N \left[IEF_n \times LERF_n \times P\left(WT \middle| STG_n\right) \right]
\end{aligned}
$$

Where IEFR is the individual early fatality risk within 1 mile; EF_n is the number of early fatalities within 1 mile conditional on the occurrence of accident sequence “n”; $LERF_n$ is the frequency of large early release capable of causing early fatalities for accident sequence “n”; $P\left(WT \middle| STG_n\right)$ is the conditional probability that accident sequence “n” involving weather type will occur given that the accident in source term group “n” has occurred; $TP(1)$ is the total population to 1 mile; IEF_n is the consequence of individual early fatality within 1 mile conditional on the occurrence of accident sequence “n”; and, N is the number of dominant accident sequences that contribute to the early fatality and LERF.

The definition of large early release is as follows [22]:

- unscrubbed containment failure pathway of sufficient size to release the contents of the containment (*i.e.*, one volume change) within 1 hour, which occurs before or within 4 hours of vessel breach; or
- unscrubbed containment bypass pathway occurring with core damage.

The above definition shows the modes and times of containment failure that cause large early release of radionuclides. We can select the APBs conforming to the definition of large early release from the results of accident progression analysis. EF_n and $LERF_n$ depend on the accident sequence “n” of the selected APBs. The inputs, $P\left(WT \middle| STG_n\right)$ and $TP(1)$, are determined from the static data about weather and population.

4.2 Core damage frequency

After core damage, some accident progress may be mitigated by the containment and related safety systems, so that there are no radionuclides released into the environment. Under the condition that the containment rupture and bypass occur in the accident progress, a large number of radionuclides are released into the environment. In the early containment failure, people will receive early exposure with high dose rates and high dose from early pathways, such as: cloud shine, ground shine, inhalation and resuspension inhalation. In the late containment failure progresses, people will receive long-term exposure with low dose rates and low doses from long-term pathways that include ground shine, resuspension inhalation, and ingestion from contaminated food and water. The people who are not killed by acute radiation or receive long-term low-dose external exposure may have potential cancer fatalities.

Cancer fatality caused by radiation is a random effect, assuming the overall risk as a linear non-threshold function of the dose. The risk of cancer is zero for a period of time after exposure, called the incubation period. After the incubation period, the risk of cancer will continue for a period of time, which is related to the kinds of cancer, called the risk period. The length of the risk period is affected by many factors; some persons have a limited time, but some persons will be in constant risk until their death.

The function of the dose-response relationship for radiation-induced cancer is as follows [23]:

$$R=\begin{cases} aD\cdot\left(b+cD\right) & D<1.5Gy \\ aD & D\geq 1.5Gy \end{cases} \tag{7}$$

Where: R is the risk of specified cancer after receiving D dose; D is the organ-specific average absorbed dose; a is the lifetime risk factor of specified cancer effect; and, (b+cD) is the correction factor related to the kinds of cancer.

In the cancer fatality risk model, when the public experience early or late, external or internal irradiation, all of them have potential cancer fatalities. All the source term groups are the inputs of the calculation of potential cancer fatality risk. So, CDF is selected as the risk metric of the surrogate safety goal for the latent cancer fatality QHO. According to the results about contributions of accident progression bins to mean latent cancer fatalities risks for five plants in the NUREG-1150 report, the APBs with early containment failure and bypass after core damage are the major contributors of latent cancer fatality risk..

The function between CDF and individual latent cancer fatality risk is as follows

$$\begin{aligned} ILCR &= \sum\nolimits_1^M\left[\left(LCF_m\times RF_m\times P\left(WT\left|STG_m\right.\right)\right)\big/TP\left(10\right)\right] \\ &= \sum\nolimits_1^M\left[\frac{LCF_m}{TP\left(10\right)}\times CDF_m\times CCFP_m\times P\left(WT\left|STG_m\right.\right)\right] \\ &= \sum\nolimits_1^M\left[ILCF_m\times CDF_m\times CCFP_m\times P\left(WT\left|STG_m\right.\right)\right] \end{aligned} \tag{8}$$

Where: ILCR is the individual latent cancer fatality risk within 10 miles; LCF_m is the number of cancer fatalities within 10 miles conditional on the occurrence of accident sequence “m”; RF_m is the release frequency of source term group “m” causing cancer fatalities for accident sequence “m”; $P\left(WT\left|STG_m\right.\right)$ is the conditional probability that accident sequence “m” involving weather type will occur given that the accident in source term group “m” has occurred; $TP\left(10\right)$ is the total population to 10 miles; $ILCF_n$ is the consequence of individual latent cancer fatality within 10 miles conditional on the occurrence of accident sequence “m”; $CCFP_m$ is the conditional frequency of containment failure in the accident sequence “m”; CDF_m is the core damage frequency in the accident sequence “m”; and, M is the number of dominant accident sequences that contribute to the latent cancer fatality and source term group.

According to the equation (2), (3), (6) and (8), the equations for LERF and CDF surrogate safety goals are as follows:

$$R_{N-IEF}=\sum\nolimits_1^N\left[IEF_n\times LERF_n\times P\left(WT\left|STG_n\right.\right)\right] \tag{9}$$

$$R_{N-ILCF}=\sum\nolimits_1^M\left[ILCF_m\times CDF_m\times CCFP_m\times P\left(WT\left|STG_m\right.\right)\right] \tag{10}$$

In Eqs. (9) and (10), the inputs for determining the LERF surrogate safety goal are individual early fatality risk threshold, accident sequence, individual early fatality consequence in specified accident sequence, and the frequency of weather type. The inputs for determining the CDF surrogate safety goal are individual latent cancer fatality risk threshold, accident sequence, individual latent cancer fatality consequence, the conditional frequency of containment failure in specified accident sequence, and the frequency of weather type.

5. Using bootstrap methods to calculate the confidence interval of samples

5.1 Samples of CDF and LERF satisfying QHOs

Based on the Eqs. (9) and (10), society-specific number of QHOs, the types of reactor, offsite environment and population distribution are the inputs for establishing the surrogate safety goals CDF and LERF when a society has only one NPP. But a society may have multiple types of reactor and the plants’ weather conditions, population distribution and emergency response plan are different from each other. For example, the types of generation Ⅱ reactor in China include CNP300、CNP650、M310、CPR1000、CNP1000、CANDU-6 and WWER-1000/B. The Chinese NPP site distribution is very wide, from south to north along the coastline. Daya Bay plant is located at 22 degrees North latitude and Hongyan River plant is located at the 40 degrees North latitude. The sites vary very much in meteorological conditions and population distribution. These sites are selected under the requirements of population distribution, hydrogeology, atmospheric dispersion, and weather conditions in site regulations issued by Chinese nuclear safety agency [24]. So the numbers of CDF and LERF satisfying QHOs obey a certain distribution for specified generation of NPPs in a society. The statistical method is suitable to establish the surrogate safety goals.

In this case, the prerequisite of establishing surrogate safety goals is collecting the samples of CDF and LERF satisfying the QHOs according to Eqs. (9) and (10). Comparing the results of Level 3 PSA of all the operating plants in the specified society with QHOs, we can confirm whether the CDF and LERF satisfy the QHOs or not. But one of the reasons for establishing a surrogate safety goal is that most of plants don't have a Level 3 PSA model. Some representative nuclear power plants can be selected to carry out full scope PSA by regulators, which is similar with the program of NUREG-1150 carried-out by U. S. NRC. The main contributors to APBs and PDS for the health effect caused by nuclear accident are identified. Then other plants with the same type of reactors and containment in the full scope PSA can perform a simple Level 3 PSA about the main risk contributors. Through comparing the health risk from the simple Level 3 PSA with QHOs, we get the CDF and LERF sample satisfying the QHOs.

5.2 The process for using bootstrap method to determine the upper limit of confidence interval

For generation-specific NPPs, the CDF and LERF samples satisfying QHOs obey a certain distribution which is unknown. In this case, we only use non-parametric statistical methods to establishing the surrogate safety goals based on the samples, avoiding the subjective uncertainty introduced by the distribution hypothesis. Meanwhile, the number of NPPs in a society is limited because of the inherent high cost of investment and construction, and the long construction periods of NPPs.

Under the restrictive conditions of non-parametric statistical method and small samples, Bootstrap method is suitable to estimate confidence intervals of the average based on CDF and LERF samples satisfying QHOs. If the CDF and LERF of other NPPs falling in the intervals, we think these plants satisfy the QHOs. The upper limits of the confidence intervals are as the surrogate safety goals for CDF and LERF respectively.

In 1979, Efrom proposed the Bootstrap method and its Monte Carlo approximate form, which was a kind of resampling method [25]. In statistics, "Bootstrap" means that the new samples and statistics are sampled from the original samples with replacement, and represent a copy of the original observation information [26]. The Bootstrap method only depends on the collected sample information and does not need other assumptions and additional sample data. Because of these advantages, Bootstrap method is used in the evaluation of confidence intervals of incremental cost-effectiveness in pharmacoeconomics [27], and the prediction of the reliability of satellite systems based on the small samples of incomplete failure data [28], which are random sampling with replacement and massive expansion of original samples.

The physical meaning of resampling in the Bootstrap method for NPPs is to assume that a large number of plants with the same types of reactor and containment of the sample plant are constructed under the site regulations without considering the economic factors. Two parts of the data are contained in the Bootstrap sample. The first part of the data is the CDF or LERF of existing NPPs satisfying QHOs; the second part of data is the CDF or LERF of hypothetic NPPs. Because the plant sites meet the requirements of regulation, the health risk of hypothetical NPPs also meets the QHOs.

CDF data is used as an example to illustrate the process which determines the surrogate safety goal CDF_{SG} by the Bootstrap method:

Step I: The n CDF samples that satisfy the latent cancer fatality QHO are independent of each other and form an empirical distribution. These samples obey an unknown distribution F.

$$X_1, X_2, \cdots, X_n \qquad X_i \sim i.i.d.F$$

The CDF sample is as follows:

$$X_1 = CDF_1, X_2 = CDF_2, \cdots, X_n = CDF_n$$

Step II: A subset of m samples, called the Bootstrap sample, is sampled from CDF samples with replacement. The number of samples m is related to the original sample number n and the degree of accuracy of the confidence interval by the Bootstrap estimate. If the original sample number n is more than 5 and less than 30, the number of samples m is equal to n-3; if the original sample number n is more than 30, m is equal to n and cannot be greater than n. The Bootstrap sample is as follows:

$$X_i^* = CDF_i^* \qquad X_i \sim i.i.d.F \qquad i = 1, 2, \cdots, m$$

Step III: Repeat Step II k times, and k independent Bootstrap samples X^{*1}, X^{*2}, $\cdots$ X^{*k} are obtained. The averages of each Bootstrap samples are calculated and form the empirical distribution of the Bootstrap sample mean $\theta^* = S\left(X^*\right)$. This empirical distribution is used to approximate the population mean $\theta = S\left(X\right)$.

Step IV: Calculate the upper limit of a one-sided confidence interval for the empirical distribution $\theta^* = S\left(X^*\right)$.

The choice of confidence level depends on subjective judgment. When the confidence level is determined by the decision of an expert panel, the surrogate safety goals are determined through these four steps.

6. Examples

6.1 QHOs of Chinese society

In order to determine the surrogate safety goals, the IEF and ILCF based on other social accidents are first obtained from statistical data. Data about Chinese total population, population mortality rate, the numbers of early fatalities and malignant tumors referred to the types of various causes of U.S. fatality in WASH-1400 are collected from National Bureau of Statistics of the People's Republic of China [29] and Chinese Health Statistics Yearbook [30] from 2004 to 2014. Figure 1 shows the individual fatality risk of Chinese society.

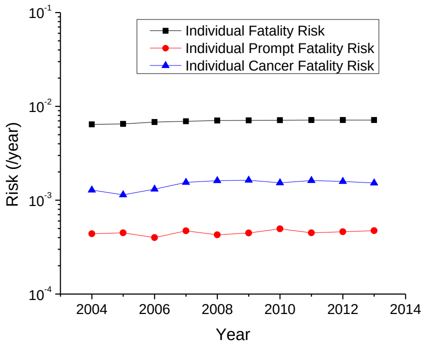

Fig.1 Individual risk in Chinese society.

$$R_{S-IEF} = 4.52 \times 10^{-4} \text{ / year} \qquad (11)$$

$$R_{S-ILCF} = 1.58 \times 10^{-3} \text{ / year} \qquad (12)$$

Individual fatality risk increase very slowly during these 10 years. Individual cancer fatality risk has obvious volatility in the first 5 years, but the volatility from 2008 to 2013 is very small. Individual early fatality risk shows little volatility during the 10 years. So, individual early fatality risk is taken as the average number across the ten years and individual cancer fatality risk is the average number of the five years from 2008 to 2013. The two numbers represent the recent individual risk with two causes of death in Chinese society.

According to Eqs. (2) and (3), the individual early fatality risk and individual cancer fatality from nuclear accidents in Chinese society are as follows:

$$R_{N-IEF} \leq 0.1\% \times R_{S-IEF} = 4.52 \times 10^{-7} \text{ / year} \qquad (13)$$

$$R_{S-ILCF} \leq 0.1\% \times R_{S-ILCF} = 1.58 \times 10^{-6} \text{ / year} \qquad (14)$$

The Chinese QHOs have the same magnitude with the American QHOs where the prompt fatality QHO is 5 $\times 10^{-7}$ per year and the cancer fatality QHO is 2 $\times 10^{-6}$ per year [16].

6.2 The CDF surrogate safety goal for a specific society

This section describes examples that use published data to show the application of Bootstrap methods. The 21 CDF statistics of American nuclear power plants are obtained from the literature [31]. These data for plants are updated CDF after the plants have made some changes, including hardware and procedural improvements, modeling and data changes and so on. Meanwhile, the results of risk analyses have been compared with the American QHOs. So they have satisfied the QHOs.

The original sample number n is equal to 21, and the Bootstrap sample number m is equal to 18. The number of samples k is set to 1000. R language is used to calculate the surrogate safety goal CDF_{SG} at confidence levels 95% and 99% in Table 1.

Table 1 Establishing surrogate safety goal CDF using bootstrap method

Confidence Level	CDF_{SG}
95%	1.65E-04
99%	2.02E-04

The results in Table 1 for different confidence levels are close to the existing surrogate safety goal CDF=1E-04 per reactor year. So the Bootstrap method may be considered useful to establish surrogate safety goals based on the collected CDF and LERF samples satisfying the QHOs.

6.3 Discussion

Now, the number of operating Generation II NPPs is nearly 27 in China, and the Chinese QHOs have the same magnitude with the American QHOs. From the results in section 6.2, it is reasonable that the Chinese nuclear safety regulatory use CDF=1E-04 per reactor year as the surrogate safety goal for the existing NPPs [12].

7. Conclusion

In this paper, we provide a brief overview of the development of NPP safety goals. The process that NRC uses, involving stakeholder consultation methods and reference documents to determine the safety goals for operation of nuclear power plants, is introduced. The qualitative safety goals compare the health risk of nuclear accidents with that of social causes, and one-tenth of one percent is the ratio of no significant additional early fatality and latent cancer fatality risk for the public. Considering the current situation of risk analysis, implementation of the safety goals may require development and use of surrogate safety goals. The development process of surrogate safety goals given by NRC from the literature review is not clearly deducible, and researchers have misunderstandings of the process. The regulators of other countries directly use these surrogate safety goals and don’t determine the surrogate safety goals according to the current situation of nuclear power in their country specifically.

Methodologically, we investigate the process of surrogate safety goals based on the QHOs. The functions of relationship between surrogate safety goals and the latent cancer fatality risk and early fatality risk by social causes are given respectively. The inputs of the functions are related to the development of society specific nuclear power. When a society has multiple types of reactors and containment for current operating plants, which vary in meteorological conditions and population distribution around the plant sites, the CDF and LERF of plants satisfying the QHOs are used as samples. Then the upper limit of a one-sided confidence interval from Bootstrap method is proposed as the surrogate safety goal.

The data on individual early fatality and cancer fatality risk by social causes in China from 2004 to 2013 are collected and analyzed. The Chinese early fatality QHO is stricter than the latent cancer fatality QHO, so the early fatality QHO is the controlling objective. Supposing that a society has 21 plants, which represent the multiple types of reactors and containment, the Bootstrap method is used to determine the surrogate safety goal CDF for this society. Comparing the results with the current surrogate safety goal CDF=1.00E-04 per reactor year, Bootstrap method is useful to determine the surrogate safety goals based on the samples.

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