# Review of risk-informed approach and challenges in its application for floating nuclear power plant

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**Abstract:** Risk-informed approach has been widely implemented in nuclear power plants (NPPs) safety design, regulation, and operation. Several regulatory agencies have issued corresponding guidelines and standards to build a specific application method, and to balance the nuclear power safety and economic. In despite of its widely application and in-depth development in nuclear power filed, the process of risk-informed design of some new nuclear reactors, such as floating nuclear power plant reactor, was challenging to develop in the absence of an acceptable risk metrics and useful guide. For instance, core damage frequency (CDF) and large release frequency (LRF) of NPPs are based on the radiation risk for public people around the NPP site, but the floating NPP located on a platform at sea usually has a small population around it. In the risk-informed System Structure Component (SSC) categorization, item's importance measures and safety significant screening metrics for NPP application could not be used in floating NPP directly. In addition, some challenging issues also will appear in determination of allowed configuration/out-of-service time, safety system availability index, and the component reliability index system. Hence, a comprehensive research of risk-informed design and decision making for these specially designed reactors should be investigated. In this paper, risk-informed approach was reviewed from regulation and application perspective, the challenges in risk-informed application for floating NPPs was introduced, and some preliminary solutions were discussed.

**Keywords:** Risk-informed, floating nuclear power plant, SSC categorization.

## 1 Introduction

Risk-informed approach first oriented from Government Performance and Results Act (GPRA) established by the U.S. Congress in 1993, and it was subsequently interpreted by U.S. NRC in the Probabilistic Safety Assessment (PSA) Implementation Plan, Risk-Informed Regulation Implementation Plan (RIRIP), and Risk-informed Performance-based Plan (RPP). Series of risk-informed guides and application standards, including risk-informed operation and risk-informed regulation, featured with the integration of PSA and deterministic engineering analysis, have been issued by U.S. NRC, i.e. Regulatory Guide 1.174~ Regulatory Guide 1.178.

Risk-informed approach plays an important role in the safety design, operation, and regulation of nuclear power plants (NPPs), and has been widely implemented in various plant designs, including the existing NPPs and some new nuclear energy systems. It has been proved to be very useful to get more economic benefits besides the approved safety level. Recent researches mainly focus on risk-informed design and design applications, risk-informed decision making, risk-informed in-service-inspection, risk-informed safety margin criteria, and risk-informed System Structure Component (SSC) categorization.

It's the best choice to carry out optimization at the conceptual design stage, as there is sufficient time to evaluate modifications for the system design before manufacture and construction. However, in despite of risk-informed approach has been used in some advanced nuclear reactors designs, such as Westinghouse IRIS, GE ESBWR, Gen-IV sodium fast reactors and helium-cooled fast reactors, the process of risk-informed design of some new nuclear reactors, such as floating nuclear power plant reactor, was challenging to develop in the absence of an acceptable risk metrics and useful guide, especially risk-informed design optimization in the conceptual design stage. First, the limitation of precise design information at a conceptual design stage results in difficulties in model development. The second limitation is the restricted time to perform analysis for several design options to get an intelligent choice.

Floating NPP designs have been developed in Russia, France, the United States, and China, which mainly used for remote island power supply. One floating NPP detail concept design has been finished in China, and the construction project has made very quick progress. The floating NPP located on a platform at sea is designed based on a PWR design which has been used for nuclear power ships. The PSA of this floating NPP has also been conducted since the initiation of its concept design. The floating NPP risk control requirements and PSA development provide feasibility of risk-informed approach in nuclear reactor design.

For the floating NPP risk-informed application, core damage frequency (CDF) and large release frequency (LRF) of general PWR NPPs are based on the radiation risk for public people around the NPP site, but the floating NPP has a small population around it. In the risk-informed SSC categorization, item's importance measures and safety significant screening metrics for NPP application could not be used in floating NPP directly. In addition, some challenging issues also will appear in determination of allowed configuration/out-of-service time, safety system availability index, and the component reliability index system.

In this paper, risk-informed approach was reviewed from regulation and application perspective, past experience and current activities/trends in promoting and implementing risk-informed regulation and application was summarized. Challenges in risk-informed application for floating NPPs were introduced, and some preliminary solutions were discussed.

## 2 Risk-informed Approach Review

### 2.1 Overview of PSA

PSA is an effective analysis tool that systematically analyses the accident sequence following a postulated initiating event, estimates the occurrence frequency, and identifies the associated dominant contributors to the defined end state of the accident sequence. PSA ultimately presents a set of scenarios, frequencies, and associated consequences, presented in such a way that forms a basis for design optimization, licensing support, determination of operational safety criteria and risk-informed decision making. The first modern PSA, the Reactor Safety Study (WASH-1400), was completed in the mid of 1970s. Its stated purpose was to quantify the risks to the general public from commercial nuclear power plant operation.

PSA has been conducted through the whole NPP life cycle. In the design, PSA could be used to optimize component designs and system configurations within given constrain, to meet safety objectives and requirements. In operation stage, PSA could be used in operating procedure risk identification and maintenance risk assessment, to minimum operation risk level, and each plant update or changes also could be evaluated by PSA. Now, aging PSA and PSA for decommissioning also have been investigated along with the increase of NPP's operation time.

### 2.2 Past Experience and Current Trends

After WASH-1400, only a few plants unilaterally decided to conduct plant specific PSAs to supplement the required deterministic safety analysis for the benefits of design and safety improvements before U.S. NRC requirement to perform the Individual Plant Examinations (IPEs) and Individual Plant Examinations for External Events (IPEEEs) in the late 1980's.

NRC's revised final policy statement in 1995 on the use of PSA in regulatory decision-making process introduced a more positive view on the role of PSA during plant operation. The key events that had a significant impact on utility decisions to make significant investments in their PSAs during this period were the issuance of maintenance rule 10 CFR 50.65 a(4), regulatory guide RG 1.174 and standard review plans.

For the first time in these regulatory guides, the NRC provided clear criteria for the review of risk-informed changes to the licensing basis including quantitative risk acceptance guidelines for judging whether a calculated change in CDF or large early release frequency (LERF) would be considered large enough to impact the regulatory decision.

In December 1998, NRC staff proposed high-level options for modifying regulations in 10 CFR Part 50 to make them risk-informed and to delineate associated policy issues for Commission consideration and identified the following three options for risk-informed modifications of 10 CFR Part 50:

- Option1: make no changes to current Part 50,
- Option2: make changes to the overall scope of systems, structures, and components (SSCs) requiring special treatment,
- Option3: make changes to specific requirements in the body of regulations, including general design criteria (GDCs).

The RIRIP specifies ongoing or planned activities to implement strategic plan that provides guidance for the agency's initiatives to support risk-informed regulation by defining strategic goals and outcomes and the strategies.

The RIRIP includes: (1) draft criteria for risk-informing a program, practice, or requirement; (2) factors to consider in risk-informing a program, practice, or requirement; (3) relevance to performance-based regulation. The challenge in developing the RIRIP was to specify staff activities that are both necessary and sufficient to implement the strategic plan strategies.

NRC's Strategic Plan defines strategic and performance goals and establishes performance measures to guide the agency's work in risk-informing its requirements in the Nuclear Reactor Safety strategic arena. Specific performance goals and strategies relate to NRC work in risk-informed regulation are: (1) STRATEGIC GOAL: Maintain safety, protection of the environment, and the common defense and security; (2) PERFORMANCE GOAL: Increase public confidence.

In February 2000, following the direction provided in NRC's Strategic Plan, NRC issued a RIRIP discussing General Process for Risk-Informing Agency Regulatory Activities and established Specific Implementation Plans to support the agency's transition to a risk-informed and performance-based regulatory environment. It provides a more detailed and specific information needed to describe the overall agency plan for deciding what, how, and when to risk-inform its regulations and regulatory processes.

Benefiting from the change toward risk-informed and performance based regulation, U.S. nuclear power plants generated nearly 812-million gross megawatt-hours (MWH) and pushed the average unit capacity factor to almost 90% in 2002, setting performance records for the fifth straight year.

At present time, NRC has been engaged in considering modifying its traditional licensing approach to develop risk-informed and performance-based approach applicable to nuclear power reactors of all types. This approach, in addition to the ongoing effort to revise some specific regulations to be risk-informed and performance-based, would establish a comprehensive set of risk-informed and performance-based requirements applicable for all nuclear power reactor technologies as an alternative (10 CFR 53) to current regulatory requirements (10 CFR 50), better focusing NRC and industry resources on the most risk-significant aspects of plant operations to better ensure public health and safety.

### 2.3 Regulatory Structure Changes toward Risk-Informed

In a risk-informed approach, risk insights (findings from PSA) are considered together with other factors to help focus licensee and regulatory attention on important issues that jeopardize public health and safety. This approach can be used to identify areas with insufficient safety and to reduce unnecessary conservatism when applied appropriately.

The change of regulatory structure in reactor regulation is mainly driven by the need of developing new reactor technology to meet the increase demand on clean, safe and economical new energy sources. The foundation of the new framework is based on the Reactor Oversight Process (ROP) cornerstones. It uses a risk-informed integrated decision making process for determining the safety importance of SSCs and the associated establishing performance criteria to ensure safe operating and public health, and meanwhile increase the regulatory effectiveness and transparency.

The new regulatory framework is performance-based. In addition, it is intended to apply in a logical and consistent manner to all types of reactors. However, the staff proposes to focus resources in the near-term on completion and subsequent implementation of the ongoing risk-informed rulemaking efforts for current operating reactors and not to initiate new efforts to risk-inform and performance-based other regulations at this time, unless specific regulations or guidance documents are identified that could enhance the efficiency and effectiveness of staff reviews of near-term applications. In a performance-based approach, decisions are made based on measurable (or calculable) target outcomes. The means of meeting those outcomes are however more flexibility to the licensees. A performance-based approach can be implemented without the use of risk insights, as it tends to emphasize on inspection or actual performance results.

## 3 Challenges in floating NPP application

Although, the Chinese regulatory agency does not require assessment of the risk of environmental contamination, a level 1 PSA for floating NPP is essential and being developed in China. The objective of PSA for floating NPP is to identify potential design flaws, to improve safety of the design, and to prepare PSA model for risk-informed applications in later times. The results of the preliminary at-power level 1 PSA show that the average CDF from internal events of this floating NPP is less than $1.0 \times 10^{-5}$ year$^{-1}$, which is mainly contributed by loss of reactor power, medium loss of coolant, loss of component circulating water, small loss of coolant and loss of main feed water internal initiating events. Through the PSA, startup control design for the passive decay heat removal system, the operator reaction time window design could obviously influence risk level and the original design might become one weak point. The floating NPP PSA will be continually updated along with the system design, construction and operation to support risk-informed applications.

### 3.1 Core Damage and Large Release Frequency Criteria

One important risk-informed application for NPP is the temporary risk increase changes and cumulative risk control over the associated plant operation time, the risk control criteria includes ΔCDF, the incremental conditional core damage probability (ICCDP), and the 'sum of each individual ICCDP' (ΣICCDP), according to the regulatory guide RG 1.174 and RG 1.177. If we have simplified level 2 PSA result, ΔLERF, the incremental conditional large early release probability (ICLERP), and the 'sum of each individual ICLRP' (ΣICLERP) also shall be considered.

The temporary risk criteria can be expressed by the following equation:

$$ICCDP = \Delta CDF * T_d$$
$$ICLERP = \Delta LERF * T_d$$

Where, $T_d$ = the time duration of the specified plant configuration.

The numerical values recommended for the parameters used for temporary risk control supported by level 1 PSA are presented as follows. They are subject to industry consensus and regulatory approval.

ICCDP: $< 5 \times 10^{-7}$
ΣICCDP: $< 10^{-6}$

$\Delta$CDF: $< 10^{-4}$ year$^{-1}$

However, all of the above numerical criteria are adopted from radiation health criteria for public people around the NPP site issued by NRC. When these criteria encounter floating NPP risk-informed application, the bases for these criteria were changed, because there are few people around floating NPP site, and the radiation health effect analysis model is different from traditional NPP. Hence, the core damage and large release frequency criteria for floating NPP could not directly adopt the above criteria released by NRC in RG series.

NRC states the safety goals for nuclear facilities as that the risk to the population resulting from nuclear operations should not exceed 0.1% of the sum of all cancer fatality risks resulting from all other causes. In the Department of Energy (DOE) safety standard for fusion facilities, the fusion radiological release requirement was inferred from this safety goal. The routine exposure limit described as follows,

$L^t \times D^p \times R^e / C^r = 0.1$ mSv/yr
Where,
$L^t$ is the numerical limitation 0.1% in NRC safety goal;
$D^p$ is radiological cancer risk coefficient, about 0.4%/0.1 Sv for long-term exposures according to BEIR-V report published by National Academy of Sciences/National Research Council;
$R^e$ is the site-boundary to average exposure ratio, conservatively assume as 2.
$C^r$ is the annual cancer fatality risk due to all causes, about 200/100,000 people • year according to statistics result in US.

If the above radiological release requirement was adopted in floating NPP safety goal requirement, one important research content still need to be investigated, the release consequence dose for public people caused by each floating NPP release category.

### 3.2 Risk-informed SSC Safety Classification

Risk-informed SSC safety classification can be used to identify items that are important to NPP safety. It is widely used to reinforce the deterministic SSC classification result. Risk-informed SSC classification assigns high safety significant (HSS) and low safety significant (LSS) on the basis of safety and non-safety classification derived from deterministic classification method. The issuance of 10 CFR 50.69, “Risk-informed categorization and treatment of structures, systems and components for nuclear power reactors”, provide clear definition for four class Risk-Informed Safety Class (RISC) SSC items, RISC-1 to RISC-4.

The importance analysis is one important step in the risk-informed SSC categorization process, which will adopt general importance measures in PSA, such as Fussell Vesely (FV), risk achievement worth (RAW), and risk reduction worth (RRW). In risk-informed SSC approach, FV of one item is generally defined as the sum of each corresponding basic events’ FV value, and RAW is generally defined as the maximum of each corresponding basic events’ RAW value. The calculation equation of theses importance measures for each basic events in PSA model are listed as follows:

$$FV = \frac{P_{(R)} - P_{(0)}}{P_{(R)}}, 0 \le FV \le 1$$
$$RAW = \frac{P_{(1)}}{P_{(R)}}, 1 \le RAW < \infty$$
$$RRW = \frac{P_{(R)}}{P_{(0)}}, 1 \le RRW < \infty$$

Where,
P(1) is the top event's failure probability with the probability of the corresponding event probability set to 1,
P(0) it the top event's failure probability with the probability of event set to 0,
P(R) is the top event's failure probability in base case.

The Nuclear Energy Institute (NEI) proposed NEI 00-04 method for risk-informed SSC safety classification, in which the FV and RAW criteria of HSS and LSS items are separately suggested as 0.005 and 2. Although these importance measure criteria could match PWR NPP's risk-informed application requirements, it shall be revised before it was used for floating NPP cases. Because the difference of system design and PSA model development state between floating NPP and general PWR NPP might incur obviously distinction in their importance analysis result.

In addition, nearly all of the risk-informed SSC safety classification methods have not considered the dynamic of plant configuration in real operation scenarios, but importance analysis result derived from the static PSA model will induce discrepancies in the accuracy aspect. One SSC item might have different importance values compared with static PSA result, and the static PSA model cannot assess importance of SSCs in out-of-service conditions, which is quite common in real operation conditions.

### 3.3 Other Challenges

Besides with the CDF/LERF criteria in safety goal challenge and safety significant criteria of importance measures in risk-informed safety classification challenge, there are also some other challenges in risk-informed application for floating NPP, such as the determination of allowed configuration /out-of-service time (AOT/ACT), safety system availability index, and the reliability requirements for these safety important component.

Criteria of AOT/ACT should be determined in basis of an appropriate ICCDP and ΔCDF in the regulatory framework. Safety system availability index, and reliability requirements for safety important components, should be deducted from CDF criteria besides a risk-informed SSC safety classification constraint.

## 4 Conclusion

Floating NPP is under construct in China, which has developed one preliminary level 1 internal PSA model. The PSA model and risk control requirements provide one opportunity for risk-informed design approach. Considering the difference in system design between floating NPP and general PWR NPP, there are several challenges in the application of risk-informed approach. Risk-informed approach was reviewed, from regulation and application perspective, including its history and current trends. The challenges in risk-informed application for floating NPPs was introduced and discussed, including core damage and large release frequency criteria, importance values criteria in risk-informed SSC safety classification. One potential method to the determination of CDF criteria was suggested and discussed. The importance values criteria and discrepancies issue caused by static PSA importance analysis was also introduced, and further study shall be investigated in these issues.

**ACKNOWLEDGMENTS**

This work was supported by the National Key Research and Development Program of China (2017YFC0307800-06).

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