High-Temperature Gas-Cooled Reactor (HTGR) Workshop
March 18-20, 2024

Application of PSA in high-temperature reactors

PSA在高温堆中的应用

NNSA/NSC

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1. Nuclear safety regulatory requirements regarding PSA

- The PSA topic is in Chapter 19 of the Safety Analysis Report and is a nuclear power plant license document. The National Nuclear Safety Administration has clear requirements for the format and content of the PSA report.
- PSA专题在安全分析报告第十九章，是核电厂执照文件。国家核安全局对PSA报告的格式和内容有明确要求。
- At present, a comprehensive system of PSA-related regulations and standards has been formed in China, including nuclear safety regulations, guidelines, technical policies and industry standards.
- 目前国内已经形成比较全面的PSA相关法规标准体系，包括核安全法规、导则、技术政策和行业标准。

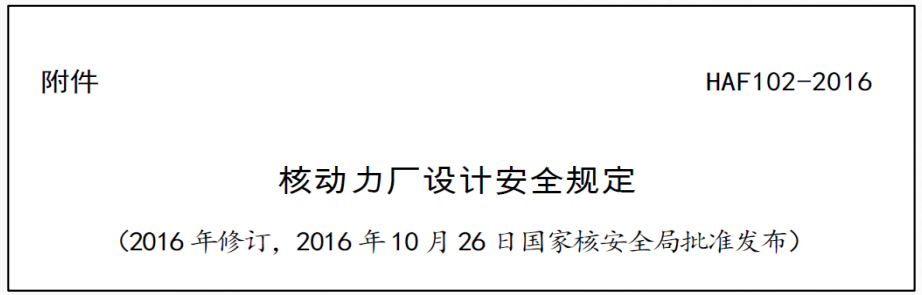
Format and Content of PSA

1. Nuclear safety regulatory requirements regarding PSA

- **Safety regulations for the design of nuclear power plants**
- **核动力厂设计安全规定**

4.7.1 A comprehensive deterministic safety evaluation and probabilistic safety evaluation must be carried out throughout the design process of the nuclear power plant to ensure that all design safety requirements are met at all stages of the nuclear power plant life cycle and to confirm that the design delivered at completion, operation and modification meets the requirements of manufacture and construction.

4.7.1 必须在核动力厂的整个设计过程中进行全面的确定论安全评价和概率论安全评价，以保证在核动力厂寿期内的各个阶段满足全部设计安全要求，并确认在竣工、运行和修改时交付的设计满足制造和建造的要求。



附件 HAF102-2016

核动力厂设计安全规定

（2016 年修订，2016 年 10 月 26 日国家核安全局批准发布）

Safety regulations for the design of nuclear power plants

1. Nuclear safety regulatory requirements regarding PSA

- **Safety regulations for the design of nuclear power plants**
- **核动力厂设计安全规定**

5.8.3 The design must take into account probabilistic safety analysis for all operating modes and all states (including shutdown conditions) of the nuclear power plant:

5.8.3 设计必须适当考虑核动力厂所有运行模式和所有状态（包括停堆工况）下的概率安全分析：

1 Demonstrate that the overall design is balanced, that no single facility or assumed initial event would make an excessive or significantly uncertain contribution to the overall risk, and that the levels of defence in depth should be as independent as practicable;

1 论证整个设计是平衡的，没有任何一个设施或假设始发事件对于总的风险会有过大的或明显不确定的贡献，且纵深防御的各层次应尽实际可能独立；

1. Nuclear safety regulatory requirements regarding PSA

- **Safety regulations for the design of nuclear power plants**
- **核动力厂设计安全规定**

2 Providing assurance that cliff edge effects will be prevented in the nuclear power plant;

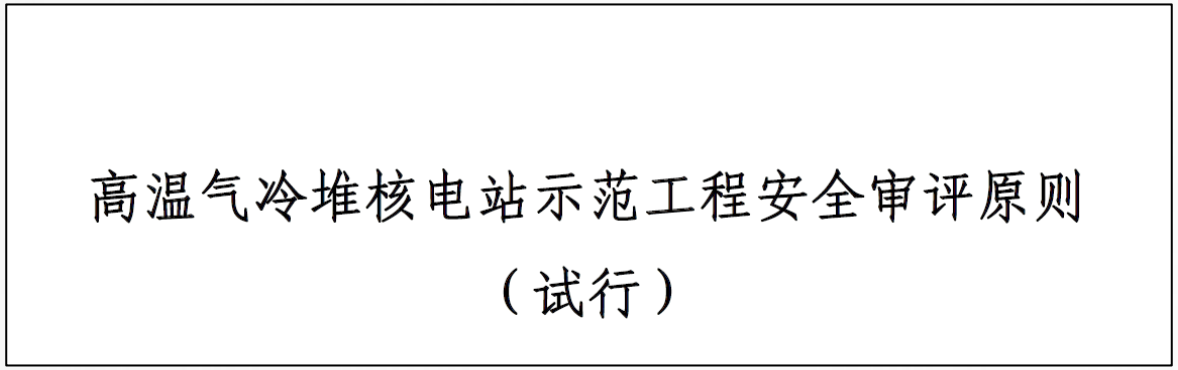
2 确认核动力厂不存在陡边效应；

3 Compare the results of the analysis with the acceptance criteria for risk where these have been specified.

3 将分析结果和已规定的风险准则进行比较。

1. Nuclear safety regulatory requirements regarding PSA

- In the HTR-PM safety review, in addition to complying with China's current effective nuclear safety regulations and standards, the principles of high-temperature reactor review are formulated to clarify the position of the National Nuclear Safety Administration on some important issues in the HTR-PM safety review.
- 在HTR-PM安全审评中，除遵守我国现行有效的核安全法规和标准外，通过制定高温堆审评原则，以明确国家核安全局对HTR-PM安全审评中一些重要问题的立场。



Principles for the review of high-temperature reactors

1. Nuclear safety regulatory requirements regarding PSA

- **Principles for the review of high-temperature reactors**
- **高温堆审评原则**

- **Nuclear Safety Guideline HAD102/17 "Safety Evaluation and Verification of Nuclear Power Plants" recommends probabilistic safety objectives for new nuclear power plants: the frequency of core damage is less than 10^{-5} per reactor year, and the frequency of large amounts of radioactive material release is less than 10^{-6} per reactor year.**
- **核安全导则HAD102/17《核动力厂安全评价与验证》中推荐了对新的核动力厂的概率安全目标：堆芯损坏频率小于10^{-5}/堆•年，放射性物质大量释放频率小于10^{-6}/堆•年。**

1. Nuclear safety regulatory requirements regarding PSA

- **Principles for the review of high-temperature reactors**
- **高温堆审评原则**

- **According to the characteristics of HTR-PM, the recommended probabilistic safety objective is as follows: using probabilistic safety analysis, the cumulative frequency of all beyond design-basis accident sequences that lead to an individual effective dose exceeding 50mSv off-site (including at the site boundary) should be less than 10^{-6}/reactor year.**
- **针对HTR-PM的特点，为其推荐的概率安全目标是：采用概率安全分析，所有导致场外（包括厂址边界处）个人有效剂量超过50mSv的超设计基准事故序列累计频率应小于10^{-6}/堆•年。**

1. Nuclear safety regulatory requirements regarding PSA

- **Principles for the review of high-temperature reactors**
- **高温堆审评原则**

- **The important role of deterministic safety methods in ensuring the safety of nuclear power plants has been proved by a large number of practices. However, the development of deterministic methods for traditional pressurized water reactor nuclear power plants and boiling water reactor nuclear power plants has been relatively complete, while for other types of reactors and some reactors of innovative design, relatively complete deterministic safety requirements have not been established.**
- **确定论在保证核电厂安全方面的重要作用已为大量实践所证明，目前对于传统的压水堆核电厂、沸水堆核电厂等确定论方法的发展已比较完备，而对于其它反应堆和革新型反应堆，尚未建立完备的安全要求。**

1. Nuclear safety regulatory requirements regarding PSA

- **Principles for the review of high-temperature reactors**
- **高温堆审评原则**

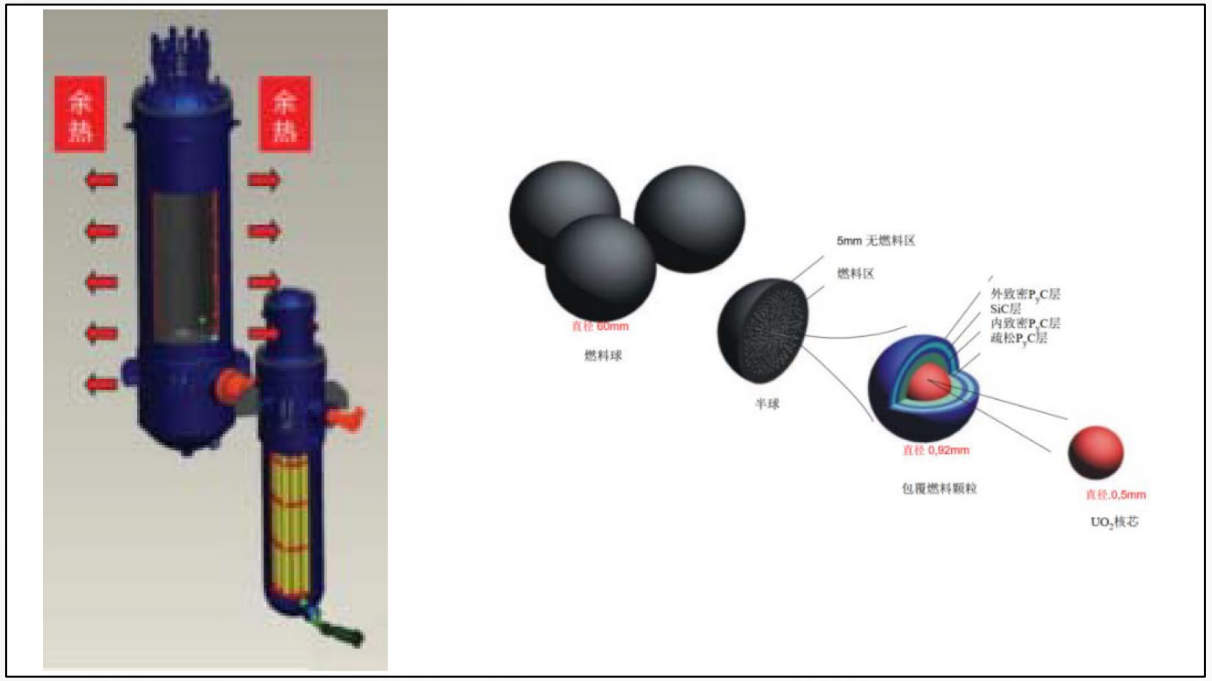
For HTR-PM, probabilistic safety analysis can be used to support the following tasks:

对于HTR-PM，概率安全分析可以支持如下的工作：

1. **Confirm that the safety objectives of the HTR-PM are met, including the probabilistic safety objectives;确认满足了HTR-PM的安全目标，包括概率安全目标；**
2. **Support the division of plant states of HTR-PM;支持HTR-PM电厂状态的划分；**
3. **Support the selection of the important beyond design-basis accident sequence to be considered in the design of HTR-PM; 支持对HTR-PM设计中所要考虑的超设计基准事故重要事件序列的选取；**
4. **Support the selection and determination of accident source items; 支持事故源项的选取和确定；**
5. **Support the establishment of HTR-PM defense-in-depth level; 支持HTR-PM纵深防御层次的设置；**
6. **Support the formulation of HTR-PM technical specifications; 支持HTR-PM运行技术规格书的制定；**
7. **Support the establishment or adjustment of certain specific safety requirements. 支持某些具体安全要求的建立或调整。**

2. Review of PSA for HTR-PM

- HTR-PM performs probabilistic safety analysis (PSA) during the design phase to evaluate the overall risk level of the plant and identify weaknesses to support HTR-PM's demonstration of compliance with safety objectives.
- HTR-PM在设计阶段开展了概率安全分析（PSA）工作，用于评价电厂整体风险水平并发现薄弱环节，支持HTR-PM对于安全目标符合性的论证等。



2. Review of PSA for HTR-PM

- **1. Internal event PSA内部事件PSA**

Combined with the construction design of HTR-PM, the PSA of internal events under power operation and low power shutdown conditions was completed. The integrated analysis framework of level 1 and 2 PSA was adopted, that is, the possible types of radioactive release were considered when analyzing the state of the accident sequence.

结合HTR-PM施工设计的情况，完成了功率运行和低功率停堆工况内部事件PSA，采用1、2级PSA集成式的分析架构，即在分析事故序列的状态时考虑可能的放射性释放类。

- **2. Internal fire PSA内部火灾PSA**

With reference to the fire PSA development method of NUREG/CR-6850 pressurized water reactor nuclear power plant, the fire PSA work of high temperature gas cooled reactor is explored and carried out. According to the actual situation of HTR-PM, the fire risk assessment method of HTR-PM is studied by taking a typical plant as an example.

参考NUREG/CR-6850压水堆核电厂火灾PSA 开发方法，探索并开展了高温气冷堆的火灾PSA工作。根据HTR-PM的实际情况，以典型厂房为例进行了高温气冷堆火灾风险评价方法的研究。

2. Review of PSA for HTR-PM

- **3. Internal flooding of PSA 内部水淹PSA**

  A simplified but conservative approach was used to assess flooding risk.

  采用了简化但保守的方式对水淹风险进行评价。

- **4. Seismic risk assessment 地震风险评价**

  The PRA-Based seismic margin assessment method was used to demonstrate that the HTR-PM has sufficient margin beyond the design basis ground motion level to ensure the safety of the nuclear power plant.

  采用PRA-Based抗震裕度评价方法，论证在设计基准地震动水平之上，HTR-PM仍有足够的裕度，可以保证核电厂的安全。

2. Review of PSA for HTR-PM

- Applications of PSA technology in HTR-PM include:
- PSA技术在HTR-PM中的应用情况包括：

1 Demonstration of safety objectives 安全目标论证

According to the results of the PSA of HTR-PM, the individual effective dose consequence of the other release categories is less than 50 mSv, except for the release category LARGE. Conservatively assuming that all accident sequences attributed LARGE category will result in large release consequences with dose exceeding 50 mSv, the cumulative frequency of accident sequences resulting in a large number of release consequences can be expected to be on the order of 10^{-8} per reactor year.

根据HTR-PM的概率安全分析结果，除释放类LARGE外，其它释放类的个人有效剂量后果都小于50mSv。保守假设导致释放类LARGE的所有事故序列都将造成剂量超过50mSv的大释放后果，造成大量释放后果的事故序列累计频率预计在10^{-8} 每堆年。

2. Review of PSA for HTR-PM

□ 2 plant states division电厂状态划分

The plant operation state of HTR-PM is divided into four categories, which include anticipated operating event, design basis accident, and beyond design basic accident in addition to normal operation state. The frequency range of anticipated operating event, design basis accident is based on the frequency of postulated initiating events, while the identification of beyond design basic accident is based on the frequency of the accident sequence, combined with deterministic method and engineering judgment. The determination of the principal above has gone through many discussions and consultations, in which the views and information from PSA play an important role.

HTR-PM 的电厂状态除正常运行工况外，还包括预计运行事件、设计基准事故和超设计基准事故。预计运行事件、设计基准事故频率范围划分以假设始发事件的发生频率为依据；超设计基准事故 包括预计运行事件、设计基准事故之外的所有事故序列，划分以事故序列的频率为基础，并结合确定论和工程判断。上述划分准则的确定，历经了多次讨论和协商，其中来自概率安全分析的观点和信息在其中扮演了重要的作用。

2. Review of PSA for HTR-PM

□ 3 Selection of important beyond design basic accident sequences 超设计基准事故重要序列选取

HTR-PM tries to propose a set of principles that are suitable for the characteristics of the risk spectrum of HTR, and combines probabilistic，deterministic and engineering judgments, conducts an study of the beyond design basic accident sequence, and proposes the important beyond design basis accident sequences that need to be considered in the design of HTR-PM.

HTR-PM尝试提出适用于高温堆风险特点的、概率论、确定论和工程判断相结合的原则，对超设计基准事故序列进行研究，提出HTR-PM设计中需要加以考虑的超设计基准事故的重要事件序列。

2. Review of PSA for HTR-PM

□ 4 Demonstration of design alternatives设计方案论证

In the process of important design adjustments or solidification, HTR-PM adopts a comprehensive decision-making approach, and the information or viewpoints of probabilistic safety analysis have always been important input information to be considered in comprehensive decision-making. It should be pointed out that the participation and support of probabilistic safety analysis in design does not necessarily mean that specific improvement plans must be proposed by probabilistic safety analysts. In the process of design scheme argumentation, probabilistic safety analysis plays an important role in understanding the impact of safety, the balance between safety and availability, and other aspects.

HTR-PM在重要的设计方案调整或固化过程中，概率安全分析的信息或观点一直是综合决策要考虑的重要输入信息。PSA参与设计并支持设计，并不意味着必须由PSA人员来提出具体的改进设计的方案。在设计方案论证过程中，PSA关于安全性影响、安全性与可用性的平衡等方面的见解发挥了重要作用。

3. Future applications of PSA

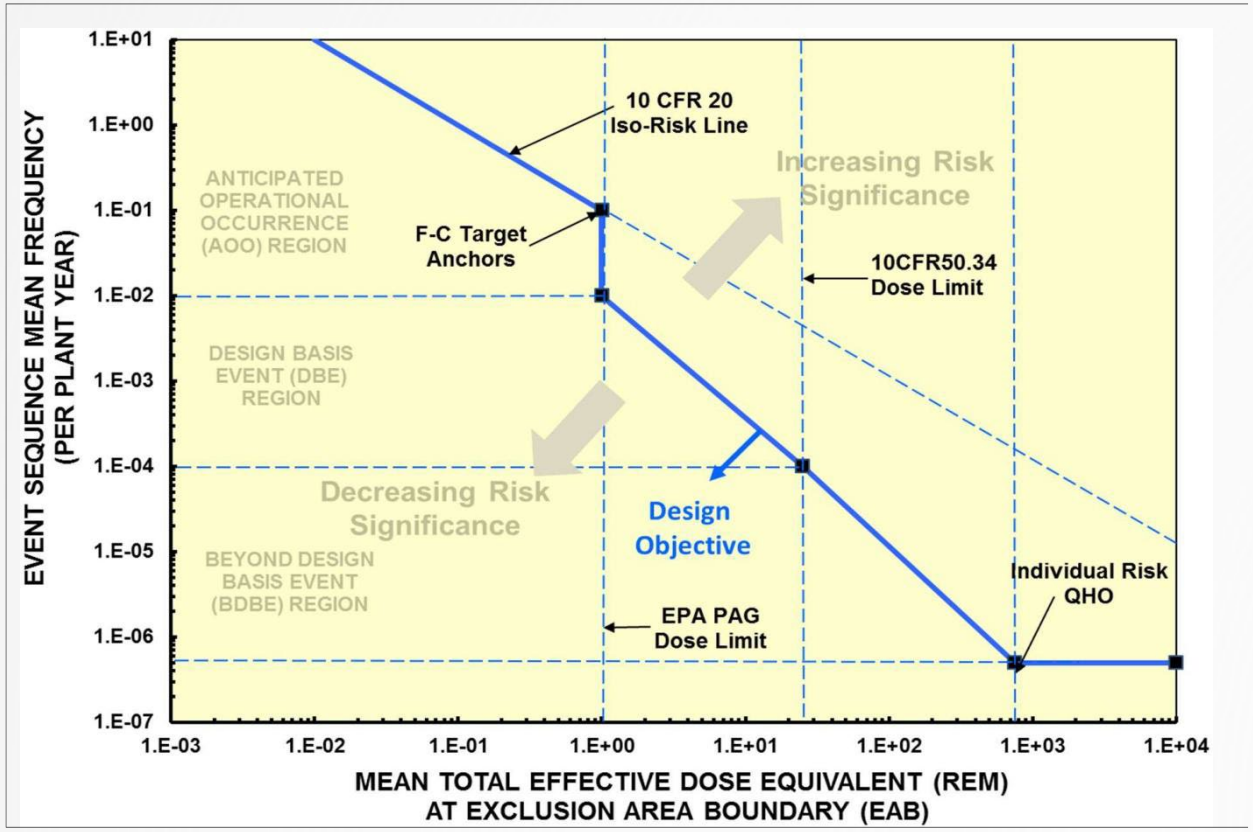
In 2019, NEI published the Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development (NEI 18-04) for the Advanced Non-Light Water Reactor Licensing Modernization Project. This document presents a technology-inclusive, risk-informed, and performance-based (TI-RIPB) process for selection of Licensing Basis Events (LBEs); safety classification of structures, systems, and components (SSCs) and associated risk-informed special treatments; and determination of defense-in-depth (DID) adequacy for non-light water reactors (non-LWRs) including, but not limited to, molten salt reactors, high-temperature gas cooled reactors. This guidance provides applicants one acceptable method for establishing the aforementioned topics as part of demonstrating a specific design provides reasonable assurance of adequate radiological protection.

2019年，针对先进非轻水反应堆执照许可现代化项目，NEI发布了NEI 18-04,介绍了技术包容、风险指引和基于性能（TI-RIPB）的过程，用于非轻水堆选择执照基准事件（LBE）、构筑物、系统和设备（SSC）的安全分级和相关风险指引的特殊处理以及确定非轻水反应堆纵深防御（DID）充分性。本导则为申请者提供了一种可接受的方法，用于确定上述议题，为特定设计的辐射防护充分性提供了合理保证

3. Future applications of PSA

Step 1: Selection of licensing basis events Establish a frequency-consequence curve and select licensing basis events

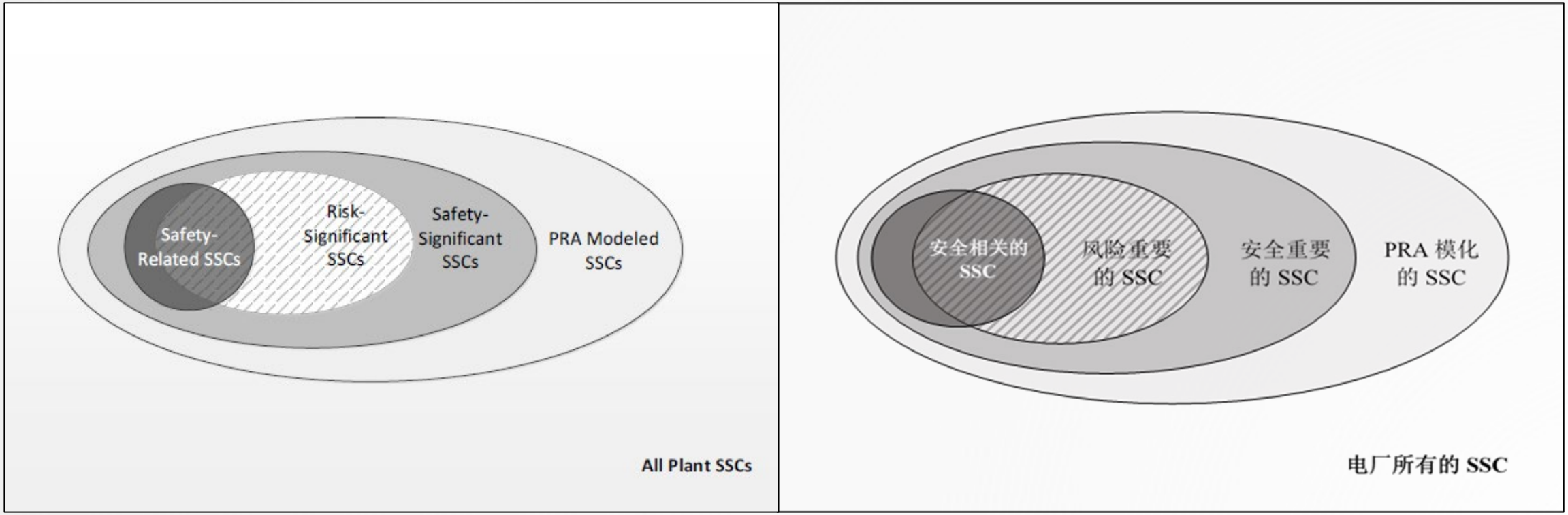
第一步：执照基准事件的选择,建立频率-后果曲线，选择执照基准事件



3. Future applications of PSA

Step 2: safety classification of structures, systems, and equipment

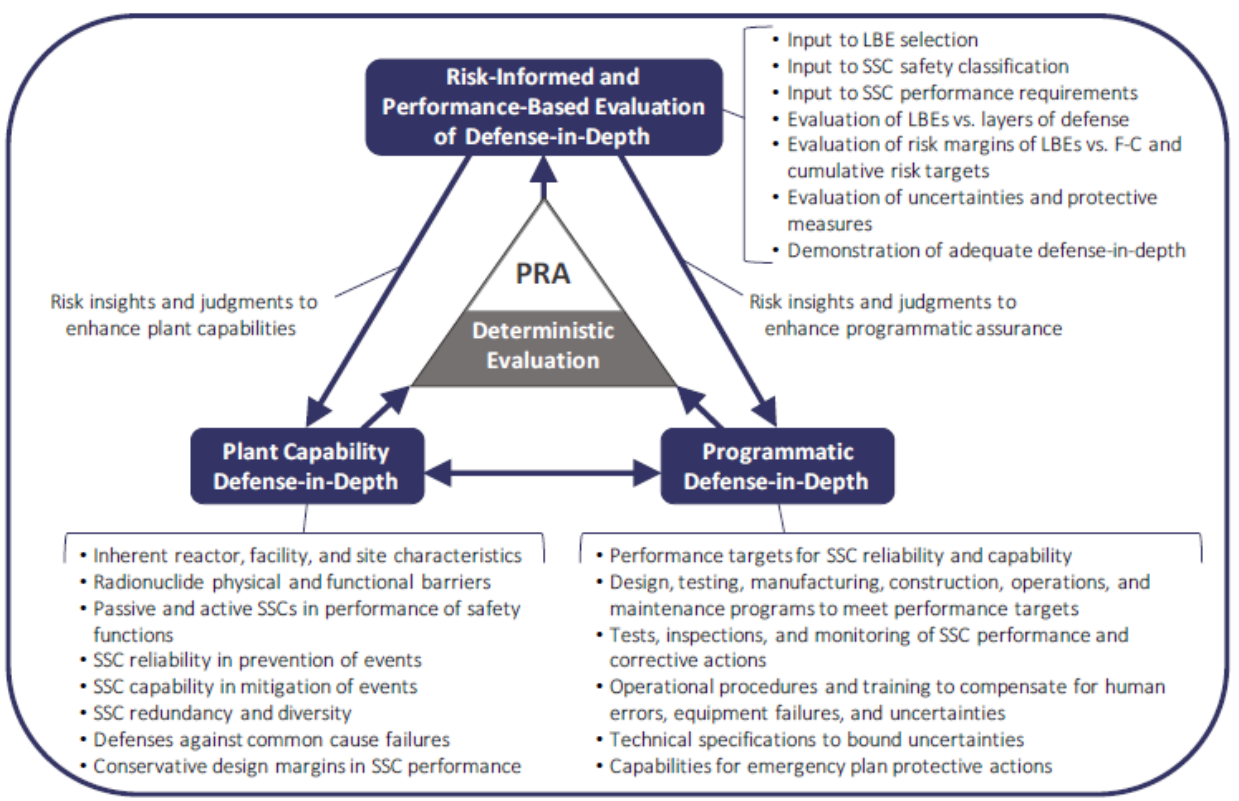
第二步：对构筑物、系统、设备开展安全分级

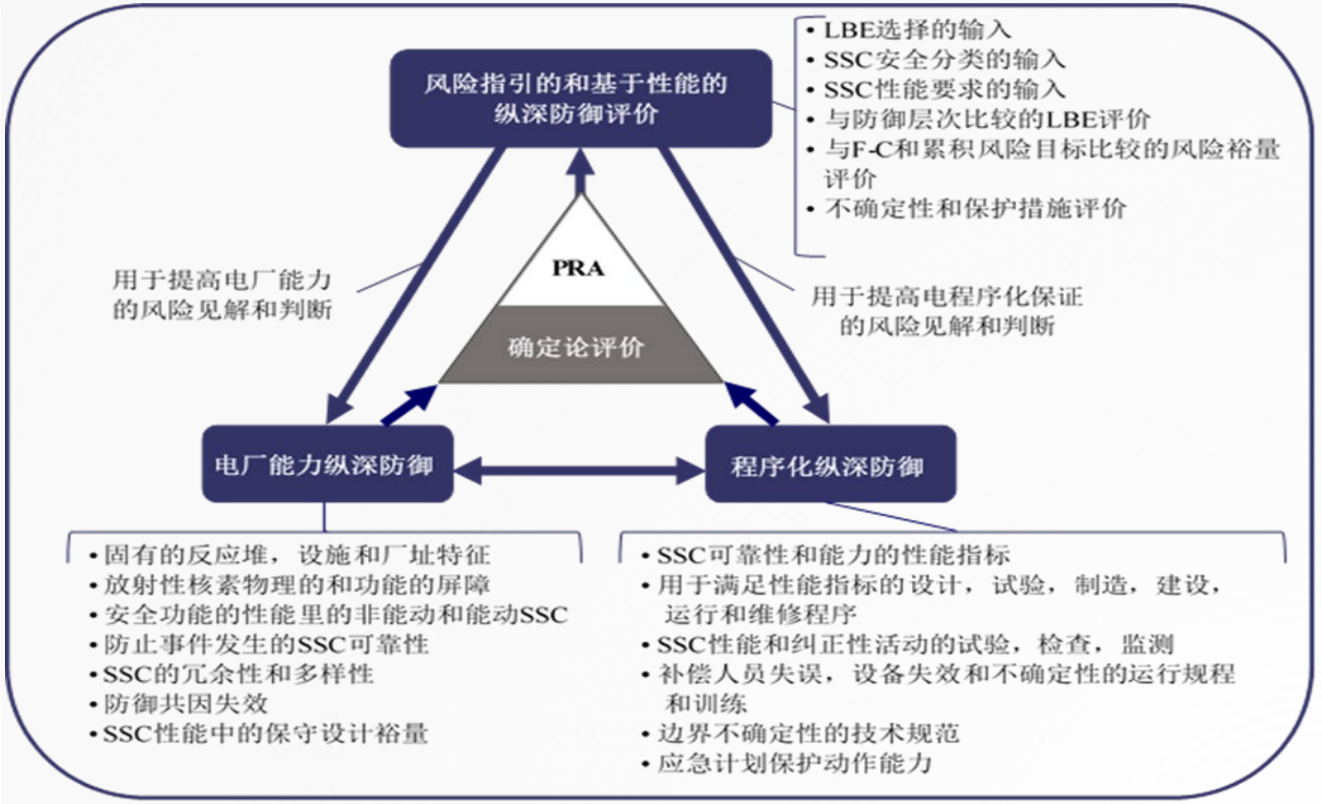


3. Future applications of PSA

Step 3: evaluation of defense-in-depth (DID) adequacy

第三步：纵深防御的充分性评估





3. Future applications of PSA

The National Nuclear Safety Administration established a special working group for the evaluation and supervision of the demonstration project of high-temperature gas cooled reactor nuclear power plants in 2023, urging design and operation units to strengthen in-depth research on high-temperature gas cooled reactor technology, effectively carry out subsequent design optimization, and continuously improve the safety and stability of high-temperature gas cooled reactor operation.Based on the safety characteristics of high-temperature reactors, a safety supervision methodology, implementation path, and specific regulatory requirements for high-temperature gas cooled reactors will be constructed in conjunction with NEI 18-04 in the future.

国家核安全局于2023年成立高温气冷堆核电站示范工程审评监督专项工作组，督促设计方和营运单位加强对高温气冷堆技术开展深入研究，切实有效做好后续的设计优化，不断提升高温气冷堆运行的安全性和稳定性。基于高温堆的安全特性，后续将结合NEI 18-04构建高温气冷堆的安全监管方法论、实现路径和具体的监管要求。

Thank you for your attention!
谢 谢!