리스크정보활용 체계 연구 및 해외대비 국내 수준

2023.10.25

양준언

한국원자력연구원,
(전)KNS 고급정책연구소장, 원자력리스크연구회장

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KNS(R)-001-2023

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– 리스크정보활용·성능기반방식을 중심으로 –

2023. 08

한국원자력학회
Korean Nuclear Society

국내 원자력 시설 리스크 평가와 관리 분야 발전 방안

(White Paper on the Improvement of Risk Assessment and Management Framework for Nuclear Facilities in Korea)

2016. 7

력 및 안전분회

과제 자문단

(1) 국내 자문단
- 김도형(한국원자력안전기술원)
- 김동산(한국원자력연구원)
- 김만철(중앙대학교)
- 김인구(한국원자력안전기술원)
- 나장환(한국수력원자력)
- 박진희(한국원자력연구원)
- 석호(한국전력기술주식회사)
- 이승준(UNIST)
- 이창주(한국원자력안전기술원)
- 장희승(한국수력원자력)
- 최선영(한국원자력연구원)
- 허균영(경희대학교)
- 황석원(한국수력원자력 중앙연구원)
- 황태석(한국원자력안전기술원)

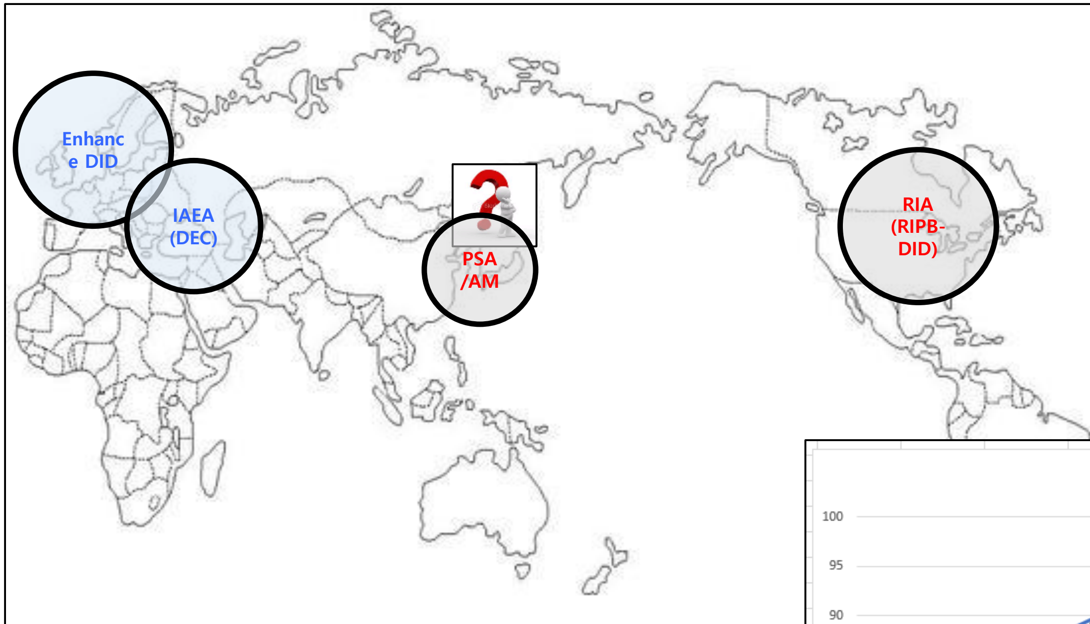
(2) 해외 자문단
- 강현국(미국 RPI)
- 인용호(ENERCON)

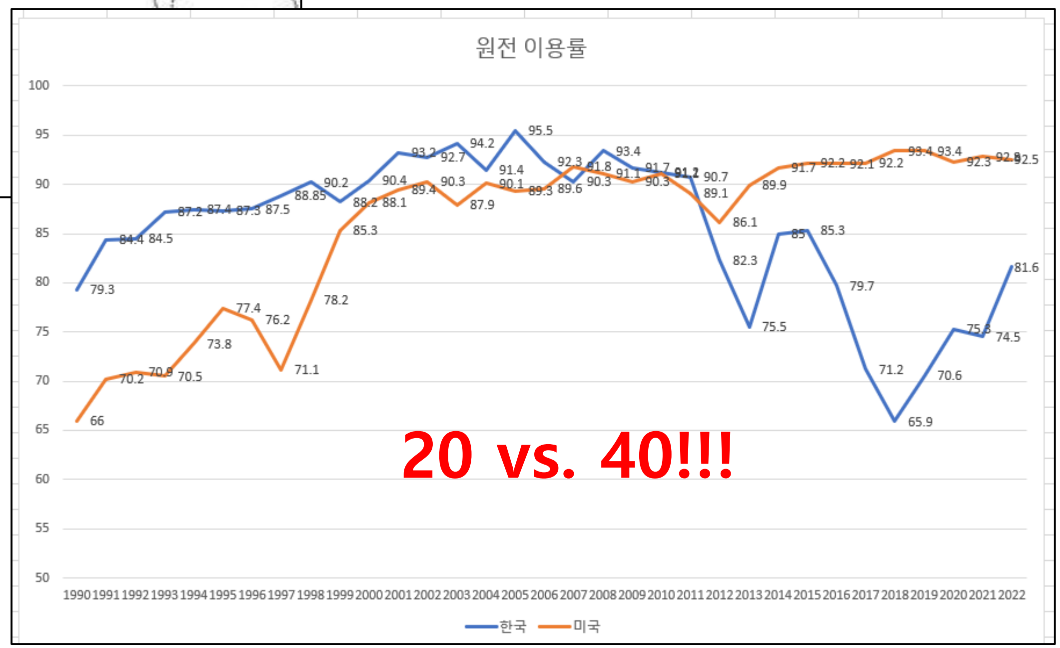
목차

KANRR
원자력리스크연구회

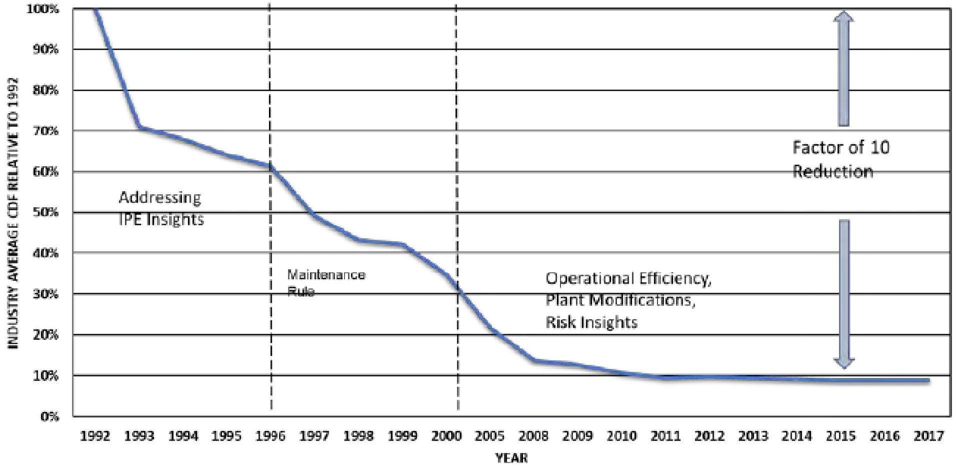
한국원자력연구원
KAERI Korea Atomic Energy Research Institute

What is the most appropriate regulation framework after the Fukushima accident?





미국 RIPBA 현황 (1/2)



Source: Multiple Sources including IPE submittals and ROP data for Mitigating System Performance Index

Figure 12 - Industry Average CDF Trend

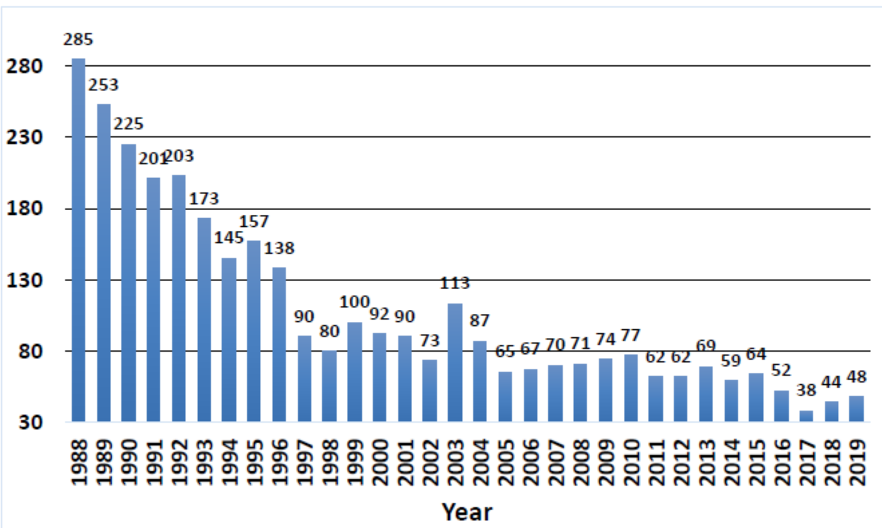
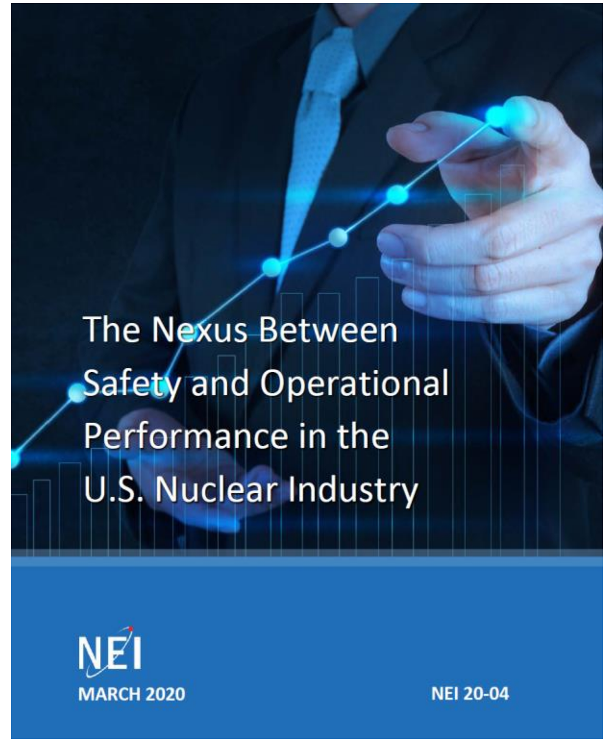


Figure 8 - U.S. Nuclear Plant Unplanned Reactor Trips (1988-2019)



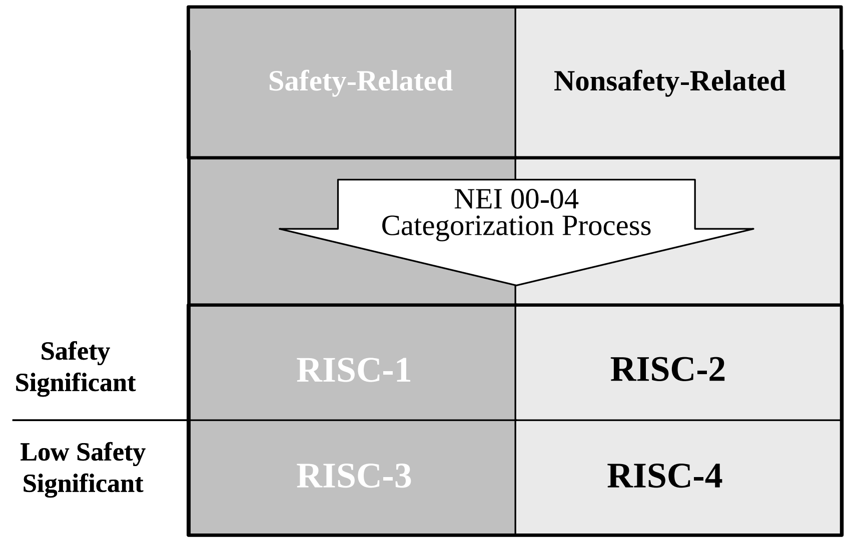
The breadth of improved industry performance has directly led to improved safety and has reduced risk.

미국 RIPBA 현황 (2/2)

❑ RITS

- RITS-1: Improve Technical Specifications (TS) required action end states
- RITS-2: Revise requirement for missed surveillances, Surveillance Requirement (SR) 3.0.3
- RITS-3: Relax mode-change requirements, Limiting Condition for Operation (LCO) 3.0.4
- RITS-4: Improve individual risk-informed (RI) completion times (4a) and risk-managed TS completion times (4b)
- RITS-5: Relocate surveillance frequencies to licensee control (RITS-5b)
- RITS-6: Revise required actions and completion times, LCO 3.0.3
- RITS-7: Address non-TS support system impact on TS systems
- RITS-8: Relocate LCOs that do not satisfy Criterion 4 of Code of Federal Regulations (CFR) 10CFR50.36(c)(2)(ii)

❑ RI-SSCC



Influencing Factors

- The cultivation of a strong **safety and reliability culture** by utilities,
- A **strong independent nuclear regulator** in the U.S. Nuclear Regulatory Commission (NRC),
- An independent industry excellence organization in the Institute of Nuclear Power Operators (INPO), and
- **The NRC's adoption of a risk-informed safety focus.**

- Over the past 20 years, improving plant performance has been coupled with the enhanced safety focus provided by **a risk-informed approach that focuses resources on the most safety significant issues.**

[NEI (2020), The Nexus between Safety and Operational Performance, Nuclear News, May, 2020]

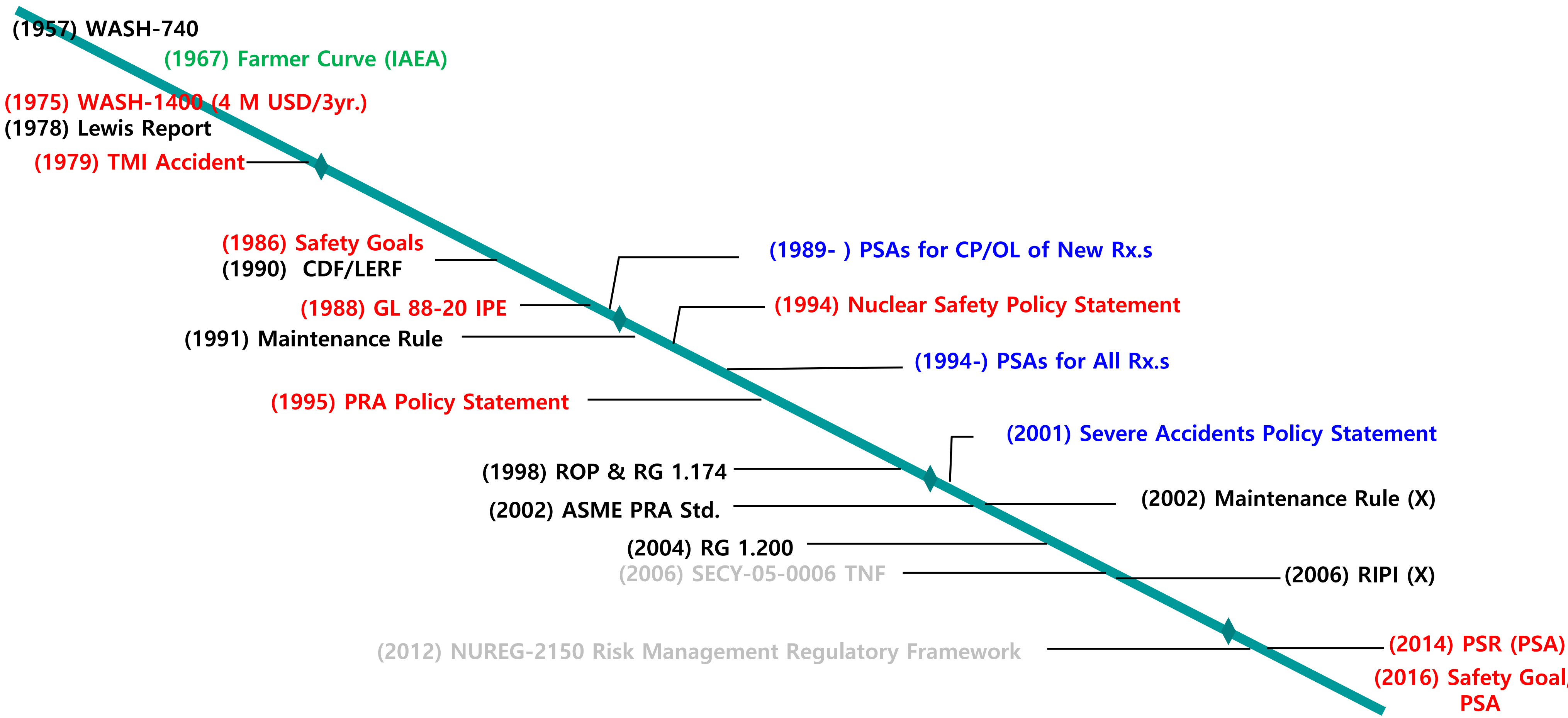
NRC's RIPBA Activities

- **Operating Reactors**
  - Risk-Informed Reviews of Instrumentation and Control (I&C) Systems and Components: Integrating Risk Insights into the Digital I&C Regulatory Framework
  - Use of Systems-Theoretic Accident Model and Processes (STAMP)-based Methods for Digital Nuclear Safety System Evaluation
  - Technical Assistance for Integration of Risk-Informed Performance Based Approach to Seismic Safety of Nuclear Facilities
  - Revisions to NUREG-0654, Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness for NPP
  - Revision to NUREG/CR-7002, "Criteria for Development of Evacuation Time Estimate Studies"
  - Power Reactor Cyber Security Program Improvements
  - Ensure Force-on-Force (FoF) Scenarios Are Realistic and Reasonable
  - Consequence-based Security for Advanced Reactors
  - Revision of the Emergency Preparedness Significance Determination Process
  - Baseline Security Program Revision
  - State-of-the-Art Reactor Consequence Analyses
  - Probabilistic Methodologies for Component Integrity Assessment
  - Implementing Lessons Learned from Fukushima
  - Accident Sequence Precursor (ASP) Program
  - Probabilistic Flood Hazard Assessment (PFHA)
  - Risk Assessment of Operation Events (RASP Handbook)
  - Maintenance and Development of the Systems Analysis Programs for Hands-on Analysis Integrated Reliability Evaluations (SAPHIRE) Code
  - Standardized Plant Analysis Risk Models (SPAR)
  - Full-Scope Site Level 3 PRA
  - Data Collection for Human Reliability Analysis (HRA)
  - Human Reliability Analysis (HRA) Methods and Practices
  - National Fire Protection Association (NFPA) Standard 805
  - Assess Debris Accumulation on Pressurized Water Reactor (PWR) Sump Performance, Generic Safety Issue (GSI)-191
  - Develop Risk-Informed Improvements to Standard Technical Specifications (STS)
  - Implement 10 CFR 50.69: Risk-Informed Categorization and Treatment of Structures, Systems and Components for Nuclear Power Reactors
  - Graded Approach to the Use of Safety Significance in the Low Safety Significance Issue Resolution Process
  - Guidance for Unattended Opening Evaluations
  - Risk-Informed Adversary Timeline Calculations
  - Transition from Physical Security Plan to Safeguards Contingency Plan
  - Emergency Preparedness (EP) Program Review 24-Month Frequency Performance Indicators Development to Satisfy 10 CFR 50.54(t) Requirements

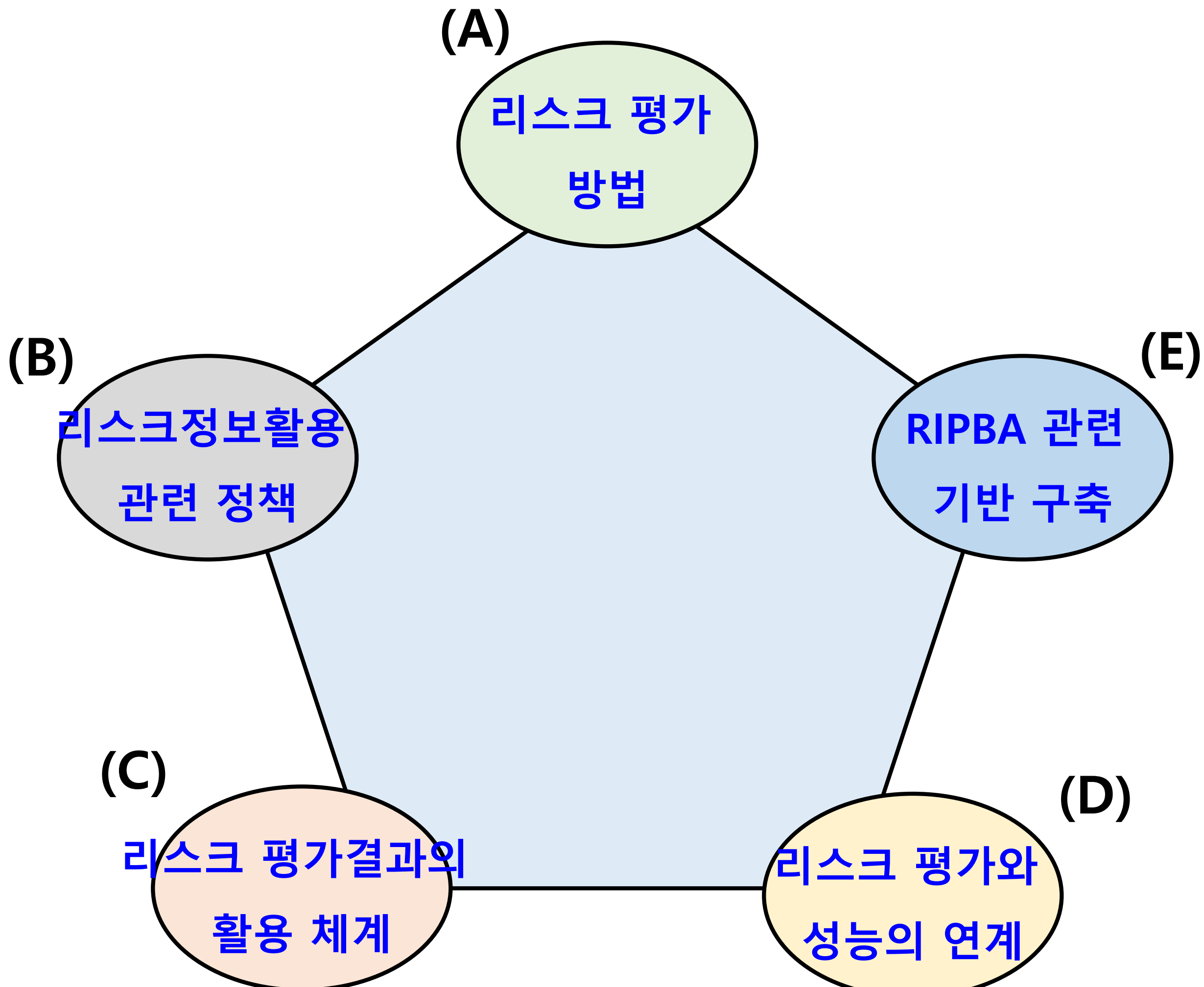
- **Advanced Reactors**
  - Technical Assistance for Research on Innovative Methods and Technologies to Enhance Seismic Safety for Design and Construction of Commercial Reactors
  - Risk-Informed Review of Small Modular Reactor (SMR) Designs
  - Non-Light Water Reactor Licensing Modernization
  - Risk-informed Emergency Planning Zone Size Evaluation
  - Advanced Reactor Regulatory Framework
  - Physical Security for Advanced Reactors

Milestones of PSA/RIPBR in U.S.A. & Korea

Preliminary results indicated that the most important transients involved the loss of offsite power and the loss of plant heat removal systems. (WASH-1400)



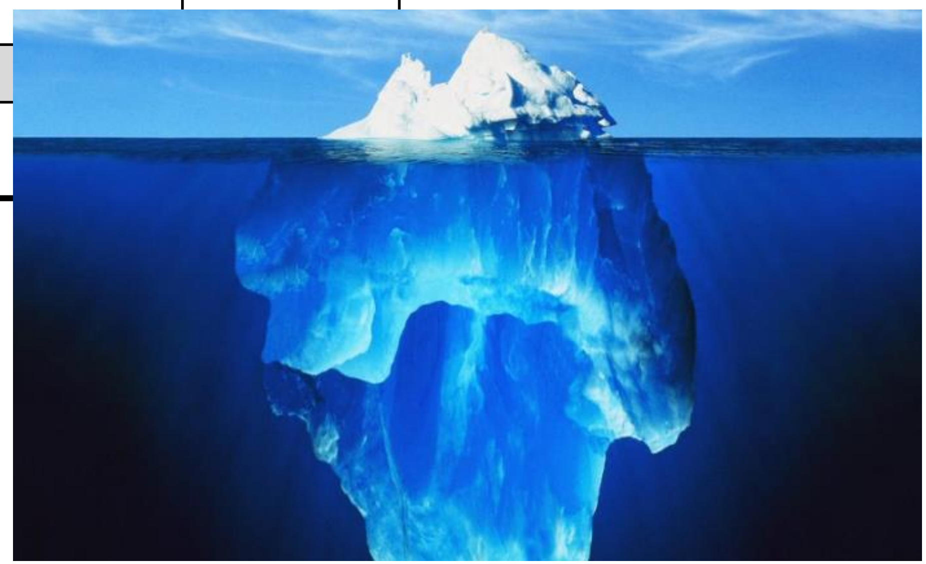
RIPBA의 5가지 측면



한국원자력연구원 KAERI Korea Atomic Energy Research Institute

(A) 리스크 평가 방법: Scope of PSA

Operation Mode	Hazards		Level 1	Level 2	Level 3
At-Power Operation	Internal Hazards	Internal Events (LOCAs, transients)			
		Internal Floods			
		Internal Fires			
	External Hazards	Seismic Events			
		Others (external floods, high winds, etc.)			
Low Power /Shutdown Operation	Internal Hazards	Internal Events			
		Internal Floods			
		Internal Fires			
	External Hazards	Seismic Events			
		Others (external floods, high winds, etc.)			



* For each hazard, "**single-unit PSA**" and "**multi-unit PSA**" can be performed.

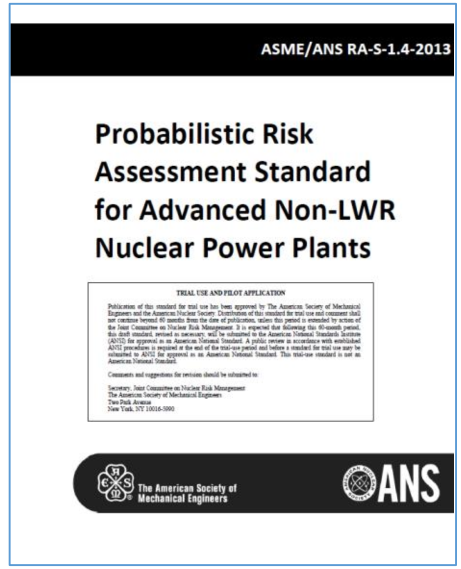
(A) 리스크 평가 방법: PRA Standard (1/2)

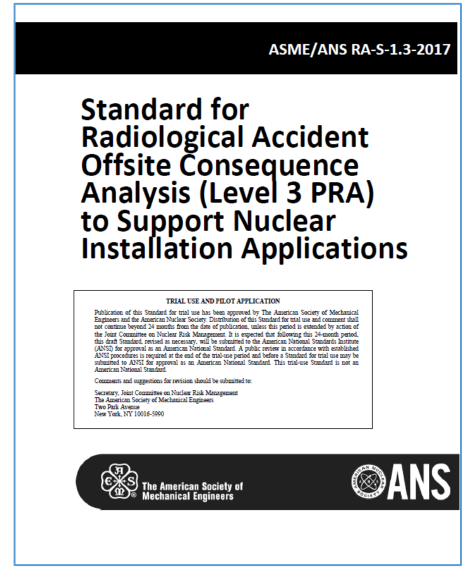
ANS/ASME Joint Committee on Nuclear Risk Management (3/5/2020)

Co-chair: Robert J. Budnitz — Co-chair: C. Rick Grantom

Vice co-chair: Dennis W. Henneke — Vice co-chair: Pamela F. Nelson

Subcommittee on Risk Applications (SCoRA) Gerry Kindred (Chair) Gary Demoss (Vice Chair) Diane Jones (Vice Chair)	**Subcommittee on Standards Development (SC-SD)** Matthew Denman (Chair) N. Reed Labarge (Vice Chair)	**Subcommittee on Standards Maintenance (SC-SM)** Paul Amico (Chair) Andrea Maioli (Vice Chair)
Physical/Cyber R-I Security Guidance Document	ANS/ASME-58.22, Low Power Shut Down PRA (will become RA-S-1.6)	ASME/ANS RA-S, Level 1 PRA Including LERF (Part 1)
	ASME/ANS RA-S-1.2, Level 2 PRA (previously ANS-58.24)	ASME/ANS RA-S, Internal Events At-Power PRA (Part 2)
	ASME/ANS RA-S-1.3, Level 3 PRA (previously ANS-58.25)	ASME/ANS RA-S, Internal Flood At-Power PRA (Part 3)
	ASME/ANS RA-S-1.4, Non LWR PRA	ASME/ANS RA-S, Fires At-Power PRA (Part 4)
	ASME/ANS RA-S-1.5, Advanced LWR PRA	ASME/ANS RA-S, External Hazards At-Power (Parts 5-10)
	ASME/ANS RA-S-1.7, Multi-Unit PRA	





- **Different Tech. Env.**
  - Lack of Data (Ex. CCF, GMRS)
  - Lack of Experts
    - It is not easy to organize the peer review team independent from the target project.
  - CANDU PSA
- **Different Regulation Framework**
  - Safety Goal (Cs-137 related)
    - Full Scope Level 2 PSA
  - Level 3 PSA for New NPPs
  - RIA is not active
- **Korean PSA codes**
  - AIMS-PSA, SAREX, FTREX
  - CINEMA, RCAP, etc.

(A) 리스크 평가 방법: PSA Standard (2/2)

Attributes of PRA	Capability Category I	Capability Category II	Capability Category III
1. Scope and level of detail:	Resolution and specificity sufficient to identify the **relative importance** of the contributors …	Resolution and specificity sufficient to identify the relative importance of the **significant contributors** …	Resolution and specificity sufficient to identify the relative importance of **the contributors** …
2. Plant specificity:	Use of **generic data/models** acceptable except for the need to account for the unique design and operational features of the plant.	Use of **plant-specific data/models** for the **significant** contributors.	Use of **plant-specific data/models** for **all** contributors, where available.
3. Realism:	Departures from realism will have **moderate impact** on the conclusions and risk insights as supported by good practices.	Departures from realism will have **small impact** on the conclusion and risk insights supported by good practices.	Departures from realism will have **negligible impact** on the conclusion and risk insights supported by good practices.

Attributes of PRA	Capability Category I	Capability Category II
1. Scope and Level of Detail: The degree to which the scope and level of detail of the plant design, operation, and maintenance are modeled	Resolution and specificity are sufficient to identify the relative importance of **the contributors** at the hazard group, initiating event group, and functional or systemic **accident sequence level**, including associated HFEs [Notes (1) and (2)].	Resolution and specificity are sufficient to identify the relative importance of **the risk-significant contributors** at the hazard group, initiating event group, functional and systemic accident sequence, and **basic event level**, including associated HFEs, and for hazards other than internal events, at **the hazard scenario level** [Notes (1) and (2)].
2. Plant Specificity: The degree to which plant-specific information is incorporated in modeling the as-built, as-operated plant	Use of **generic data/models** is acceptable except for the need to account for unique design and operational features of the plant that have bearing on the assessment of CDF/LERF.	**Plant-specific data/models** are used for the risk-significant contributors to the extent feasible
3. Realism: The degree to which realism is incorporated in modeling the expected response of the plant	Departures from realism may have **a moderate impact** on the conclusions and risk insights as supported by state of the practice [Note (3)].	Departures from realism will have **a small impact** on the conclusions and risk insights as supported by state of the practice [Note (3)].

(B) 리스크정보활용 관련 정책: 정책 선언

PRA Policy Statement (1995)

- The use of PRA technology should be increased in all regulatory matters to the extent supported by the state-of the-art in PRA methods and data and in a manner that complements the NRC's deterministic approach and supports the NRC's traditional defense-in-depth philosophy.
- PRA and associated analyses (e.g., sensitivity studies, uncertainty analyses, and importance measures) should be used in regulatory matters, where practical within the bounds of the state-of-the-art, to reduce unnecessary conservatism associated with current regulatory requirements, regulatory guides, license commitments, and staff practices.
- PRA evaluations in support of regulatory decisions should be as realistic as practicable and appropriate supporting data should be publicly available for review.

Nuclear Safety Policy Statement (1994)

- The regulatory organization reviews the introduction of "Optimum Assessment & Probabilistic Assessment" for safety analyses, and encourages the licensee to introduce new technologies when and if they are considered to be reasonable safety assurance measures, as proven by their application.
- An "Overall Safety Assessment" is performed using probabilistic safety assessment and "Nuclear Regulation based on Risk" is done through sound safety regulations in consideration of cost-benefit factors.
- Quantitative safety goals and regulatory guidelines for the examination, prevention and mitigation of severe accidents are established and improved to be gradually applied to advanced nuclear power plants as well as to existing ones. In addition, design and operational safety of nuclear power plants are achieved through the measures in order to minimize human errors.

(B) 리스크정보활용 관련 정책: 안전 목표

❑ Safety Goal Policy Statement (1986)

- 0.1 % Rule
  - 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 near 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.
- QHO (Quantitative Health Objective)
  - **Early Fatality: 5×10^{-7} /yr.**
  - **Cancer Fatality: 2×10^{-6} /yr.**
- Subsidiary Goal
  - **CDF: 1×10^{-4} /yr.**
  - **LERF: 1×10^{-5} /yr.**

❑ 국내 안전 목표 (2016)

제9조(위험도(risk) 평가)

① 확률론적 안전성평가의 기술적 적합성, 상세성 및 분석범위는 발전용원자로시설의 사고로 인한 위험도(risk)를 종합적으로 평가하기에 적합하여야 한다.

② 제1항의 확률론적 안전성평가에 적용하여야 할 목표치는 다음 각 호와 같다.

1. 부지 인근 주민의 발전용원자로시설 사고로 인한 초기사망 위험도 및 암사망 위험도가 각각의 전체 위험도의 0.1% 이하이거나 또는 그에 상응하는 성능목표치를 만족할 것

2. 방사성핵종 Cs-137의 방출량이 100TBq을 초과하는 사고 발생 빈도의 합이 1.0x10-6/년 미만일 것

③ 제1항의 확률론적 안전성평가의 결과는 발전용원자로시설의 중대사고 예방 및 완화 능력을 향상시키기 위하여 활용되어야 한다.

(C) 리스크 평가결과의 활용 체계

- ❑ **Reg. Guide 1.174:**
  - An Approach for Using PRA in Risk-informed Decisions on Plant Specific Changes to the Licensing Basis
  - Issued July 1998
  - Five fundamental safety principles
    - Meet the current regulation
    - Maintain defense-in-depth
    - Maintain sufficient safety margins
    - Risk increases are small, including cumulative risk
    - **Develop performance-based monitoring strategies**

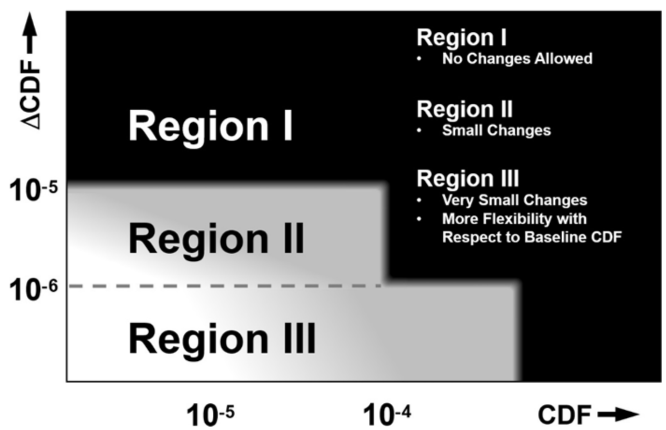


Figure 4. Acceptance guidelines* for core damage frequency

- ❑ **(RG 1.175) In-Service Testing**
- ❑ **(RG 1.177) Technical Specifications**
- ❑ **(RG 1.178) In-Service Inspection**
- ❑ **(RG 1.176) Graded Quality Assurance**
  - 10 CFR 50.69 "Scope of SSCs, Governed by Special Treatment Requirements"
    - March 2003 Commission approved

- ❑ **(2020/2007) 규제지침 16.9 '변경허가신청에서의 리스크정보활용 일반사항**
- ❑ **(2008) RI-ISI에 대한 특정기술주제보고서**
- ❑ **원자력안전위원회고시 제2018-5호(원자로격납건물 기밀시험에 관한 기준)**

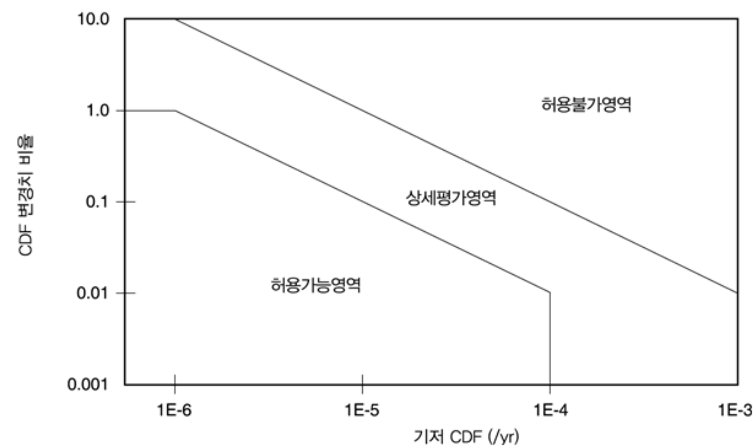


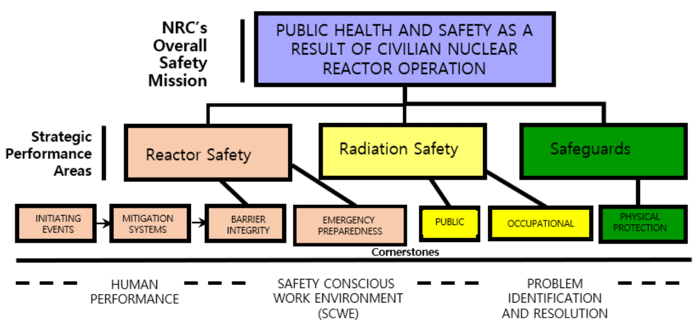
그림 1. 변경허가신청 사안에 따른 노심손상빈도 변경에 대한 허용기준

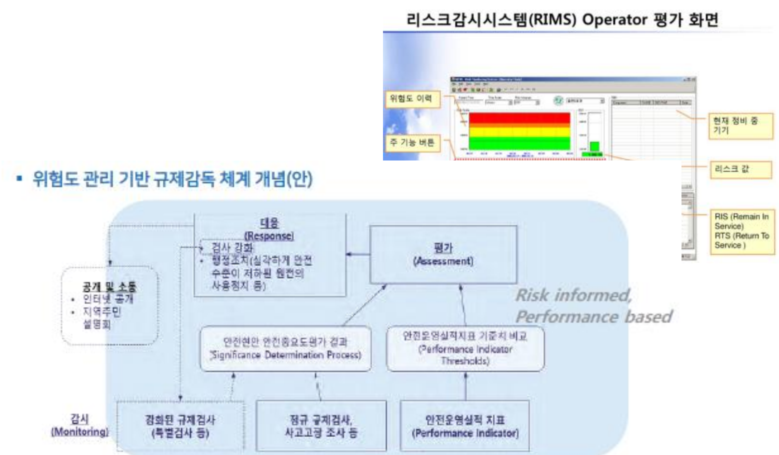
(D) 리스크 평가와 성능의 연계

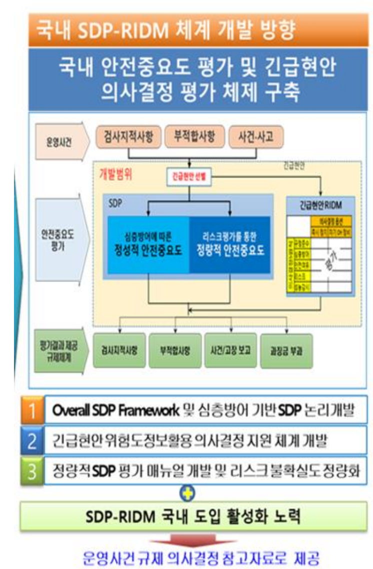
- **Performance Based Regulation**
  → Effective Resource Allocation

- **Reactor Oversight Process (ROP)**
  – USA, from 2000
  – 7 Cornerstones Evaluate: Performance Indicator
  – Signficance Determination Process (SDP)
    • 3 phase Approach
    • At 3rd phase, PSA model is used : If $\Delta CDF > 10^{-6}$, Green → white

- **Maintenance Rule**
  – Monitoring the Effectiveness of Maintenance at Nuclear Power Plants
  – Approved by NRC in 1991
    • Effective July 10, 1996
  – Objectives: To monitor the effectiveness of maintenance activities…
    • For safety-significant plant equipment
    • In order to minimize the likelihood of failures and events…
    • Caused by the lack of effective maintenance."

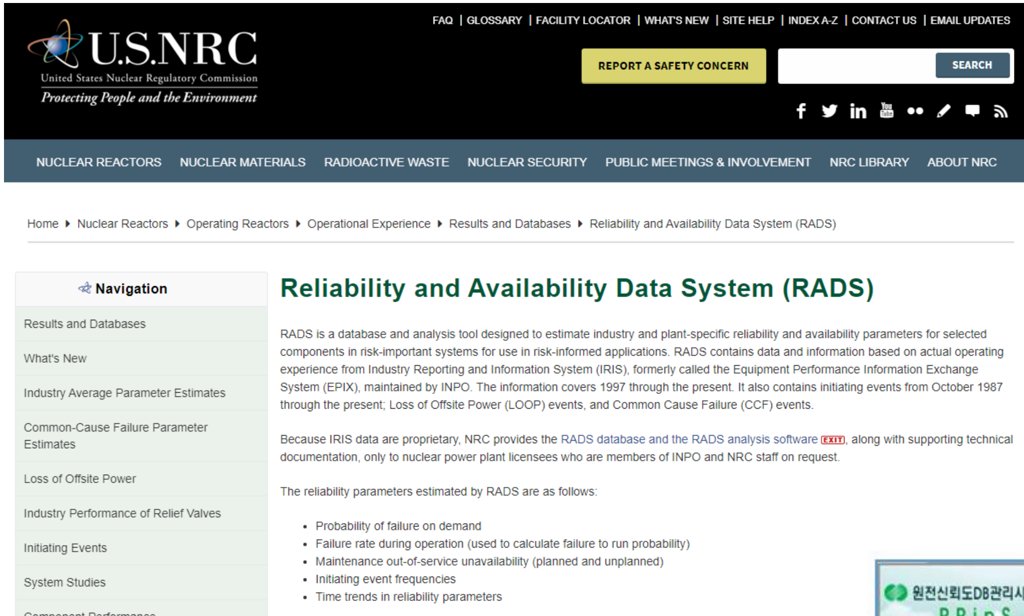






[CRI, 리스크감시시스템 개발현황 및 OLM 활용 방안, 2013.4;
변충섭, 원전 운영사건 안전중요도 기반 의사결정체계, 국내 리스크정보활용 규제 현황과 추진 방향, 2021.5;
정우진, 주요국 가동원전 규제감독 체계 및 국내 추진 방향, 국내 리스크정보활용 규제 현황과 추진 방향, 2021.5]

(E) RIPBA 관련 기반 구축: 신뢰도 DB



[Seok-Won Hwang, et al. Development of Web-Based Plant Reliability Information System (PRinS), Transactions of the Korean Nuclear Society Spring Meeting Jeju, Korea, May 10-11, 2007]

(E) RIPBA 관련 기반 구축: RIPBA 수용성

❑ in NRC

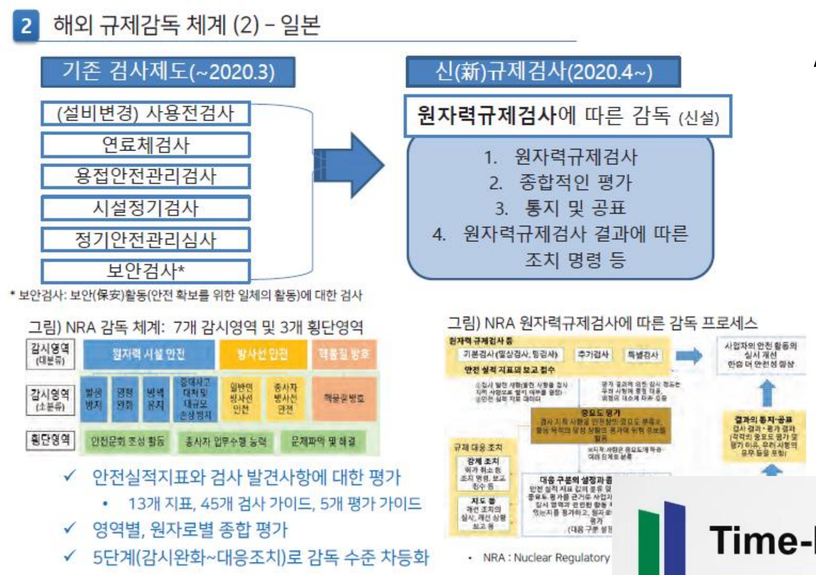
- Some NRC staff members believed the application of risk information gives away safety margin.
- NRC staff had an internal struggle with risk-informed regulation since it also required a culture change
  - The NRC staff role was changed from requiring systems that were supposed to work (at least deterministically on paper with no failure assumed except a single failure) to those which provide a high level of assurance considering possible failures for all systems and components.
  - The staff had a great deal of difficulty in dealing with determining "high level of assurance" as opposed to what they had to do in the past which was to confirm that systems were in place for certain functions with the assumption that they would perform their intended function.

❑ in Utilities

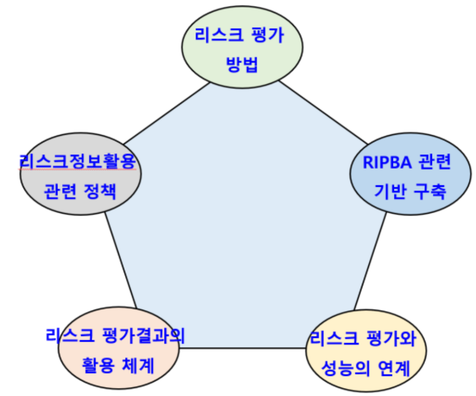
- The acceptance of PSA by the utility was met with some challenges which senior management needed to address.
  - Beyond the resistance of traditional engineers, there was a general lack of understanding of the tool.
  - A site-wide training program was initiated not only on the tool but also how it is to be used.
  - This training was expanded to the general training program for all plant staff.
- Early reluctance of the operations staff to accept the risk approach was quickly overcome by showing how this tool could help them manage risky operations.

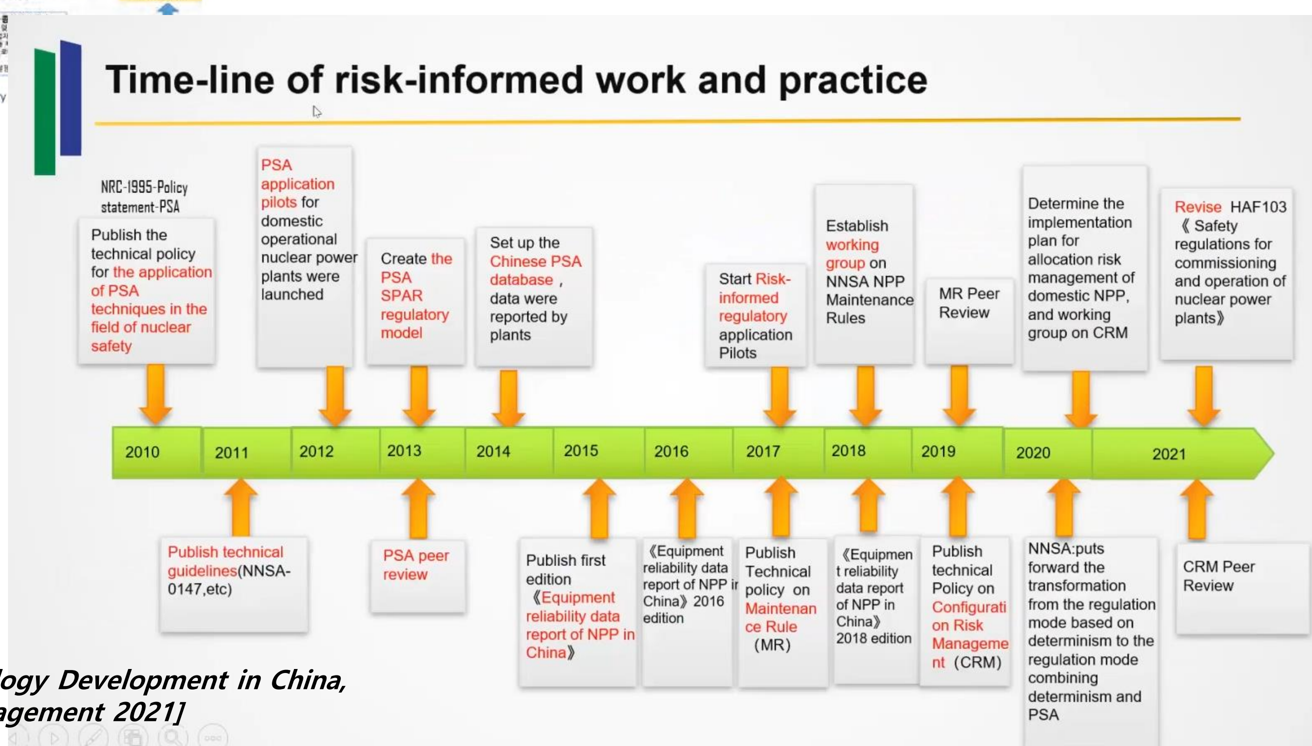
[Andrew C. Kadaka, Toshihiro Matsuob, The nuclear industry's transition to risk-informed regulation and operation in the United States, Reliability Engineering and System Safety 92 (2007) 609–618]

일본/중국 RIPBA 현황



[정수진, 주요국 가동원전 규제감독 체계 및 국내 추진 방향, 국내 리스크정보활용 규제 현황과 추진 방향, 2021.5]

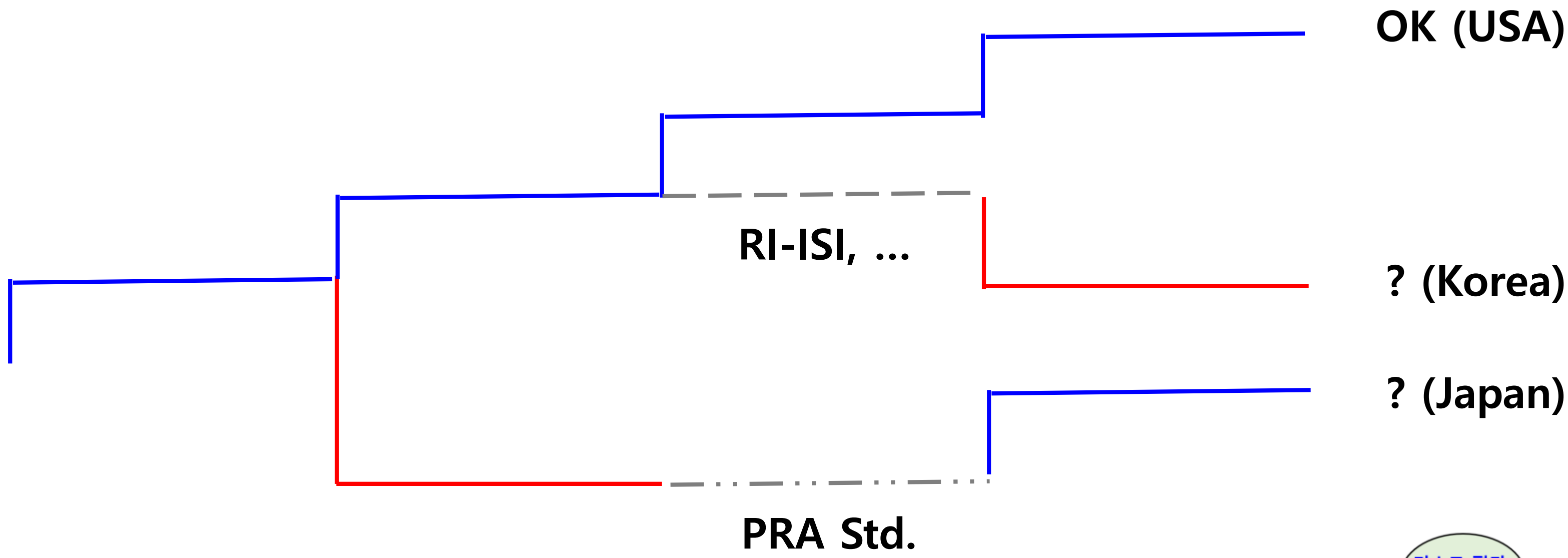


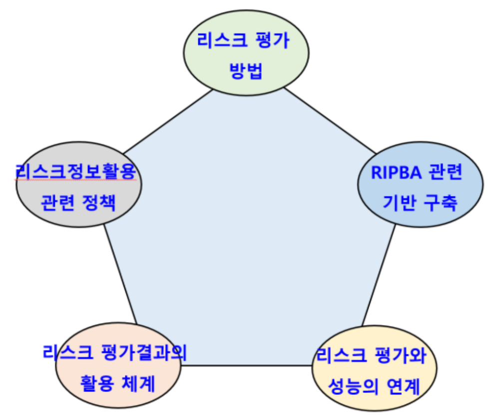


[Chu, Y. , Introduction of Risk-Informed Technology Development in China, Asian Symposium on Risk Assessment and Management 2021]

Current Status of RIPBA in Korea, USA & Japan

리스크 평가	정책	활용	성능 연계	RIPBA





Cs-137, 100TBq < 1.0E-6/yr

[양준언, Risk Communication within Nuclear Community, 미래세대를 위한 원자력안전관리와 리스크 커뮤니케이션, 2021]

국내 RIPBA 관련 현안

- ❑ **Credibility of the PSA**
  - Probability
  - Reliability Data

- ❑ **Cherry Picking**

- ❑ **Lack of Experts**
  - Lack of Official Education Program & Certification Process

- ❑ **PSA Standard**
  - Korean PSA Standard TFT

- ❑ **Safety First Application**
  - To overcome the resistance of the traditional engineers
  - → Maintenance Rule

- ❑ **Set-up a Reliable Education Program & Certification Process on PSA**
  - We may need an International cooperation for this area

국내 RIPBA 향후 추진 방안

- The introduction of risk-informed regulation cannot be done overnight due largely to the institutional obstacles that need to be overcome.
- The most useful application of the risk was the maintenance rule since it provided a foundation for making risk and priority determinations for day to day operations.
- The best way to deal with public and regulatory acceptance of the use of risk informed information is to focus on the safety benefit of such tools and approaches.
  - While there is considerable economic value in using risk management in operations, **adoption of risk informed operations and regulations should not be based on economics but on safety.**

국내 RIPBA 도입(안)

- (1) 정비규정,
  - 안전성 향상 우선 적용
  - 산업체 운영 경험
  - 교육 기회 제공 (수용성 향상)
- (2) PSA 표준 및 품질 개선
  - PSA 신뢰성 향상
  - 국내 고유 환경 반영
- (3) ROP
  - 점진적 도입
    - SDP/ASP
- 종합적 접근 필요
  - Infra (ex. RDB), 인력 양성 (교육) 등

→ Roadmap

[Andrew C. Kadaka, Toshihiro Matsuob, The nuclear industry's transition to risk-informed regulation and operation in the United States, Reliability Engineering and System Safety 92 (2007) 609–618]

국내 RIBPA 도입 로드맵

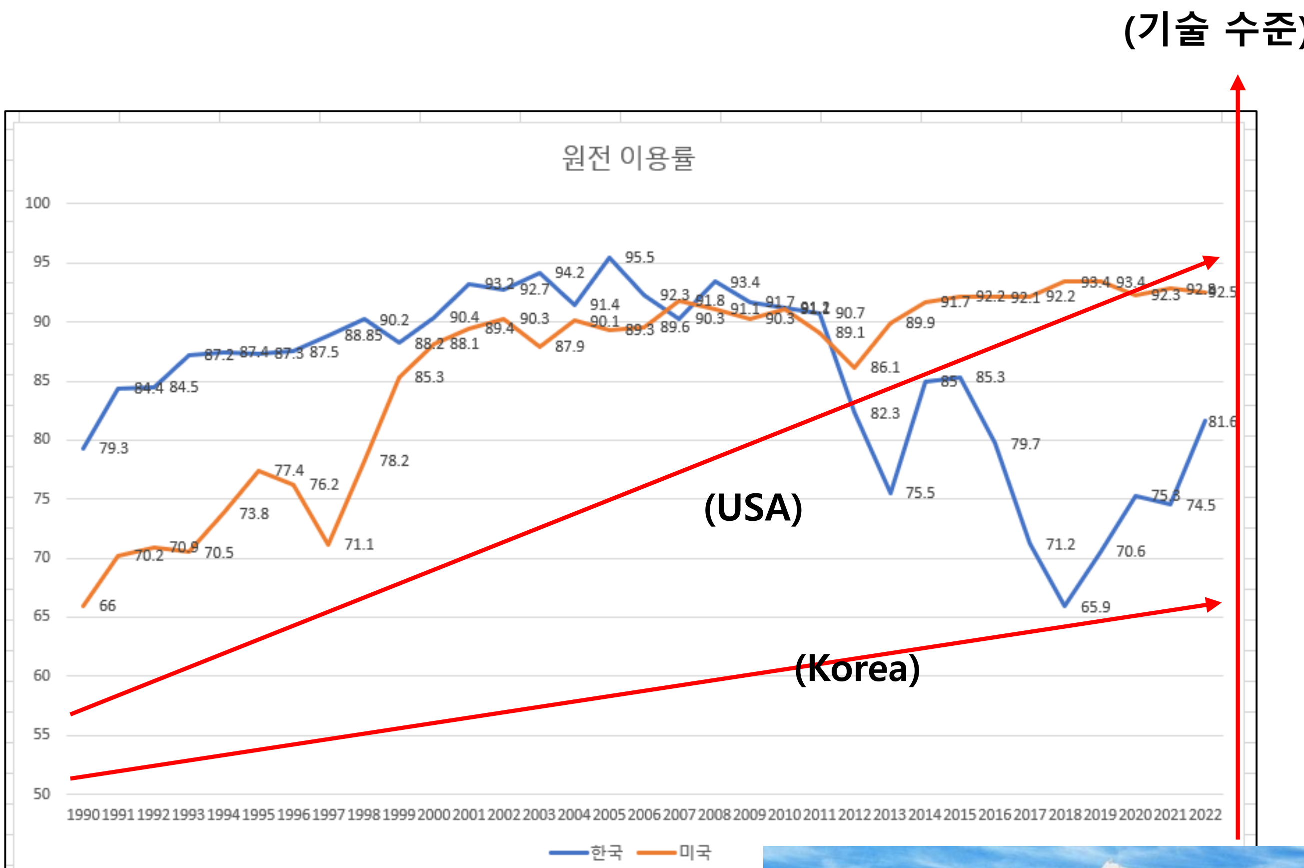
관련 분야	단기	중기	장기
리스크정보활용·성능기반 접근방식 (RIPBA)	RIPBA 시범 적용(MR/OLM, RI-TS)	RIPBA 기반 안전성 향상	
	RIPBR 시범 적용 (ROP/SDP, ASP)	RIPBR 법제화	
	국내 고유 PSA 표준/동료검토 제도 개발		
	국내 고유 PSA 표준 적용 및 PSA 모델 표준화		
리스크 평가	PSA 수행(안전목표 검증): 사고관리계획서/PSR/계속운전/신규원전(L3 PSA)		
	국내 리스크 분야 기반 및 현안 해결 기술 개발 (극한외부재해, 부지 리스크 등)	극한재해/부지 리스크 평가	
	미래 원자력 시스템(SMR 등) PSA 수행	리스크 평가 불확실성 저감	
국내 Infra 구축	국내 고유 신뢰도 DB 개선/인증	차세대 리스크 평가 기술(Dynamic PSA 기술 등)	
	리스크 커뮤니케이션 강화		
	리스크 분야 인력 양성/국제 협력 강화		

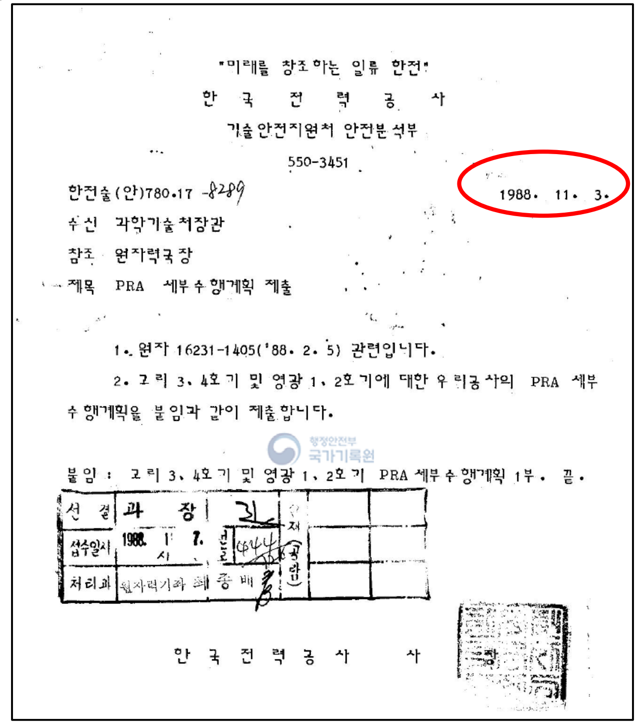
규제기관 | 산업체 | 연구계/학계 | 공통 분야

한국원자력연구원 KAERI Korea Atomic Energy Research Institute

[양준언, 규제 효율성 향상을 위한 국내 규제 체계 개선안 도출, KNS(R)-001-2023]

Where are we now?




"미래를 창조하는 일류 한전"
한 국 전 력 공 사
기술안전지원처 안전분석부
550-3451

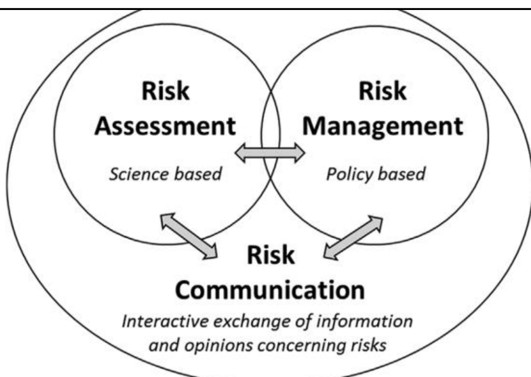
한전술(안)780.17 -8289 1988. 11. 3.

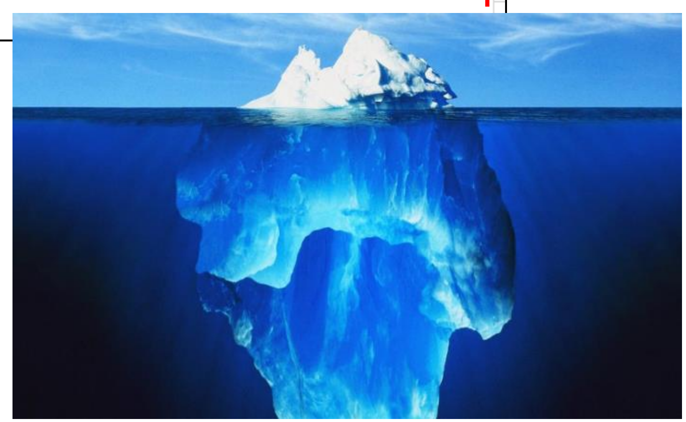
수신 과학기술처장관
참조 원자력국장
제목 PRA 세부수행계획 제출

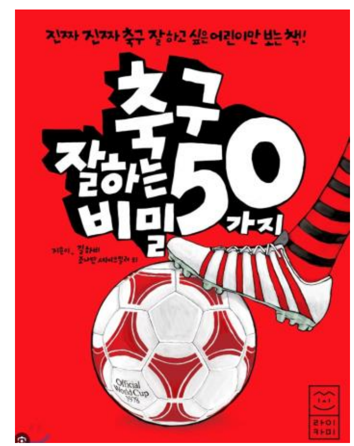
1. 원자 16231-1405('88. 2. 5) 관련입니다.
2. 고리 3, 4호기 및 영광 1, 2호기에 대한 우리공사의 PRA 세부수행계획을 붙임과 같이 제출합니다.

붙임 : 고리 3, 4호기 및 영광 1, 2호기 PRA 세부수행계획 1부. 끝.

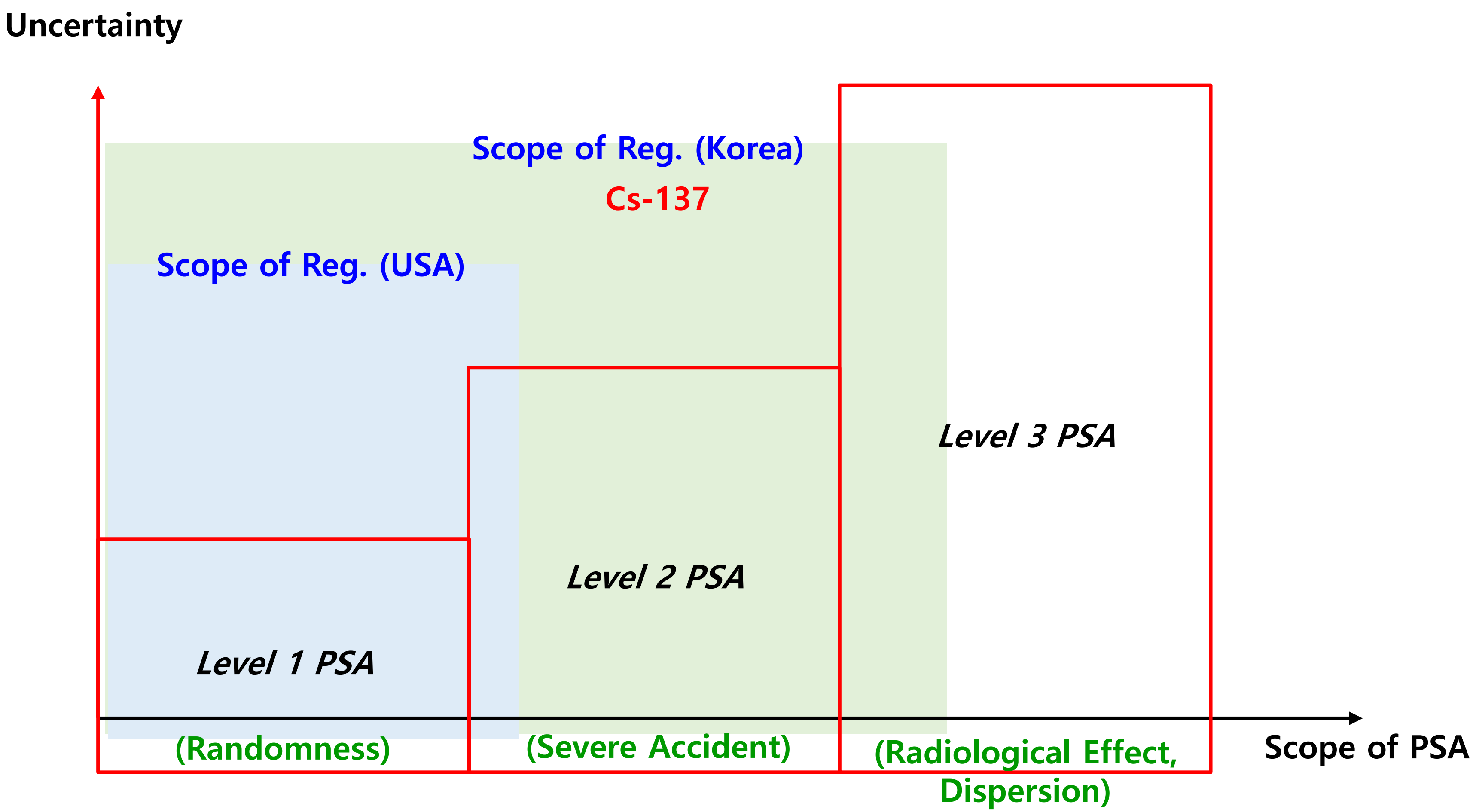
한 국 전 력 공 사 사







Scope of Reg. & Uncertainty



(DBA) Conservative vs. (SA) Best-Estimate??

한국원자력연구원 KAERI Korea Atomic Energy Research Institute

Implementation Strategies of NRC

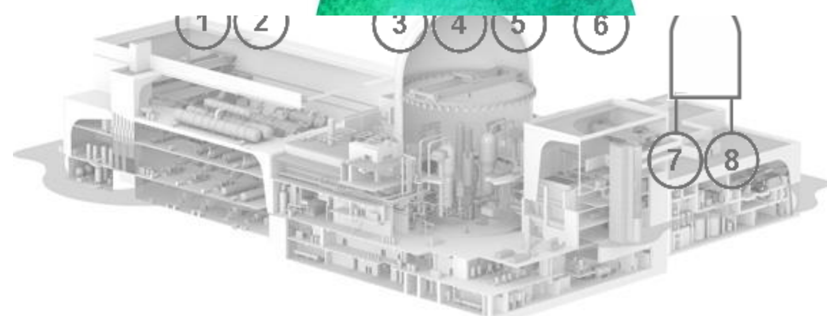
- **This transformation is a cultural change in the way people perceive their responsibilities**
  - In order to gain acceptance by the staff of PRA techniques, NRC management implemented an agency-wide training program for the staff not only on the principles of PRA but also on its applications. This is viewed as an important element in acceptance of the tool.

- **The consistent comment from both the NRC and the industry was that without top leadership support in each organization, the introduction of risk-informed regulation could not be done.**
  - There needs to be an overarching policy guidance in terms of a safety goal or regulatory framework in which to make decisions.
  - They must also have people in their organization including senior management who must also share the vision.
  - It is vital to have an integrated leadership team supporting this transformation since without such a commitment; change would be difficult, **if not impossible**

[Andrew C. Kadaka, Toshihiro Matsuob, The nuclear industry's transition to risk-informed regulation and operation in the United States, Reliability Engineering and System Safety 92 (2007) 609–618]

Thank you for your attention!

Any Questions?



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