13th International Conference on Probabilistic Safety Assessment and Management [PSAM13]

The Risk of Nuclear Power

Soon Heung Chang

Handong Global University

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Contents

I Introduction: Risk of Nuclear Power

Various Energy Chains for Human Beings

- **Sharply increasing world-wide energy demand**
  - 56% Increasing energy demand between 2010 and 2040 [EIA, 2013]

- **Accidents and Fatalities from Electrical Energy Sources**
  - Summary of severe accidents that occurred in energy chains (1969 – 2000)

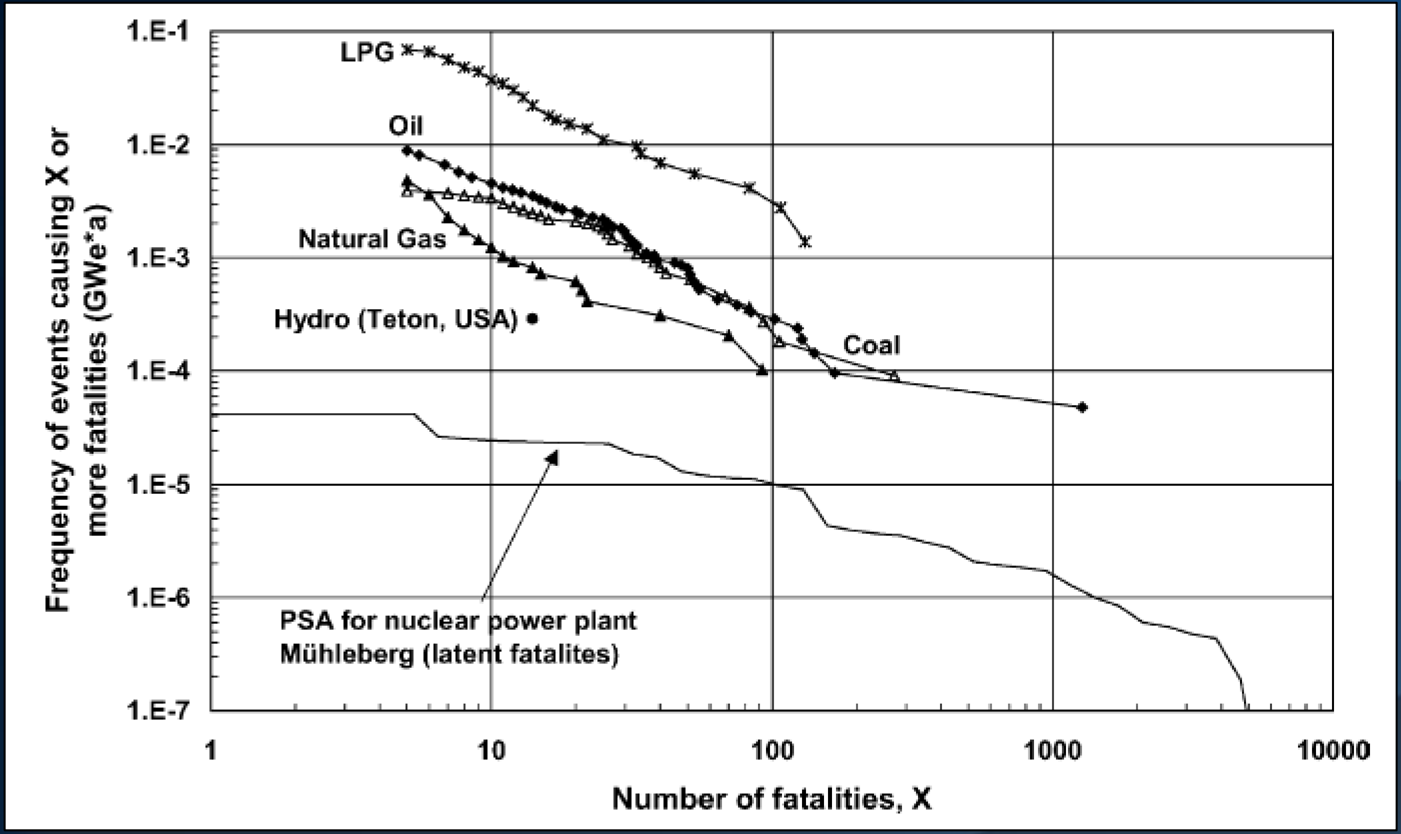
	OECD			Non-OECD		
Energy chain	**Accidents**	**Fatalities**	**Fatalities / GWe ·year**	**Accidents**	**Fatalities**	**Fatalities / GWe ·year**
Coal	75	2,259	0.157	1,044	18,017	0.597
Oil	165	3,713	0.132	232	16,505	0.897
Natural Gas	90	1,043	0.085	45	1,000	0.111
LPG	59	1,905	1.957	46	2,016	14.896
Hydro.	1	14	0.003	10	29,924	10.285
Nuclear	0	0	-	1	31*	0.048
Total	390	8,934	-	1,480	72,324	-

** These are immediate fatalities.*

Ref. "EIA, International Energy Outlook 2013, 2013" & "OECD/NEA, Comparing Nuclear Accident Risks with Those from Other Energy Sources, 2010".

Various Energy Chains for Human Beings

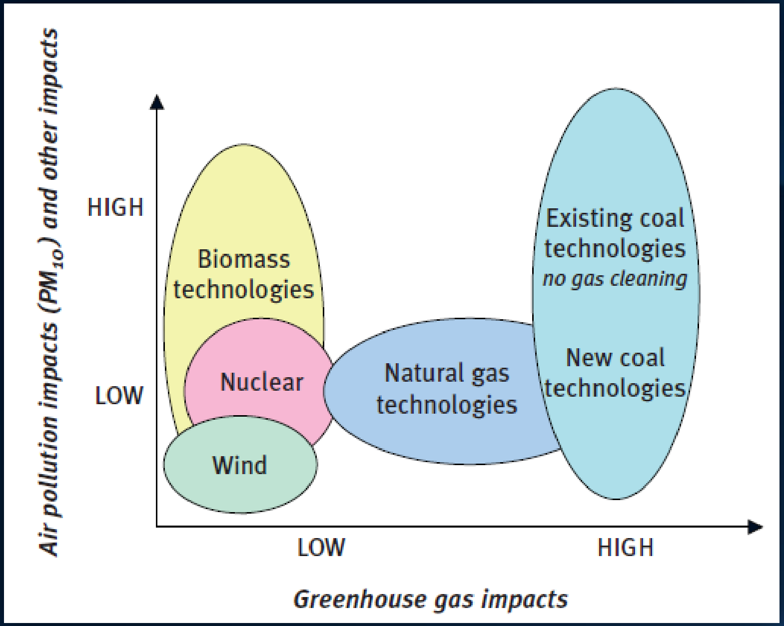
- **Fatality Risks of Electrical Energy Sources**
  - Low frequency of severe nuclear accident causing fatalities
  - Frequency-consequence curves for severe accidents in OECD countries



Ref.: S. Hirschberg et al., Severe accidents in the energy sector: comparative perspective, 2004.

Various Energy Chains for Human Beings

- **Environmental Impacts of Electrical Energy Sources**
  - **Nuclear, and Wind power :**
    Low air pollution & Low greenhouse gas emission
  - **Nuclear, Wind, and Hydro power :**
    Low external costs of electricity production



QUANTIFIED MARGINAL EXTERNAL COSTS OF ELECTRICITY PRODUCTION IN GERMANY[2] (IN € CENT PER KWH)

	Coal	Lignite	Gas	Nuclear	PV	Wind	Hydro
Damage costs							
Noise	0	0	0	0	0	0.005	0
Health	0.73	0.99	0.34	0.17	0.45	0.072	0.051
Material	0.015	0.020	0.007	0.002	0.012	0.002	0.001
Crops	0	0	0	0.0008	0	0.0007	0.0002
Total	0.75	1.01	0.35	0.17	0.46	0.08	0.05
Avoidance costs							
Ecosystems	0.20	0.78	0.04	0.05	0.04	0.04	0.03
Global Warming	1.60	2.00	0.73	0.03	0.33	0.04	0.03

Ref.: "IPCC, IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011." & "EUROPEAN COMMISION, External Costs: Research results on socio-environmental damages due to electricity and transport, 2003."

PSA in World History of Nuclear Safety

- **"Atoms for Peace" from D. Eisenhower (1954)**
- **Establishment of the IAEA (1957)**
- **The first PSA report for a NPP, WASH-1400 (1975)**
  - **Probabilistic Safety Analysis (PSA)**
    - **Quantitative risk analysis of nuclear power plants**
    - **Defining the type of consequences from accidents**
    - **Calculating frequency for each consequence by PSA**
      - Core damage
      - Radioactive-nuclides release (containment failure)
      - Dose to public
        - Early Fatality Risk
        - Cancer Fatality Risk
    - **Methodology**
      - Accident scenario : event tree
      - Branch of accident scenario : fault tree

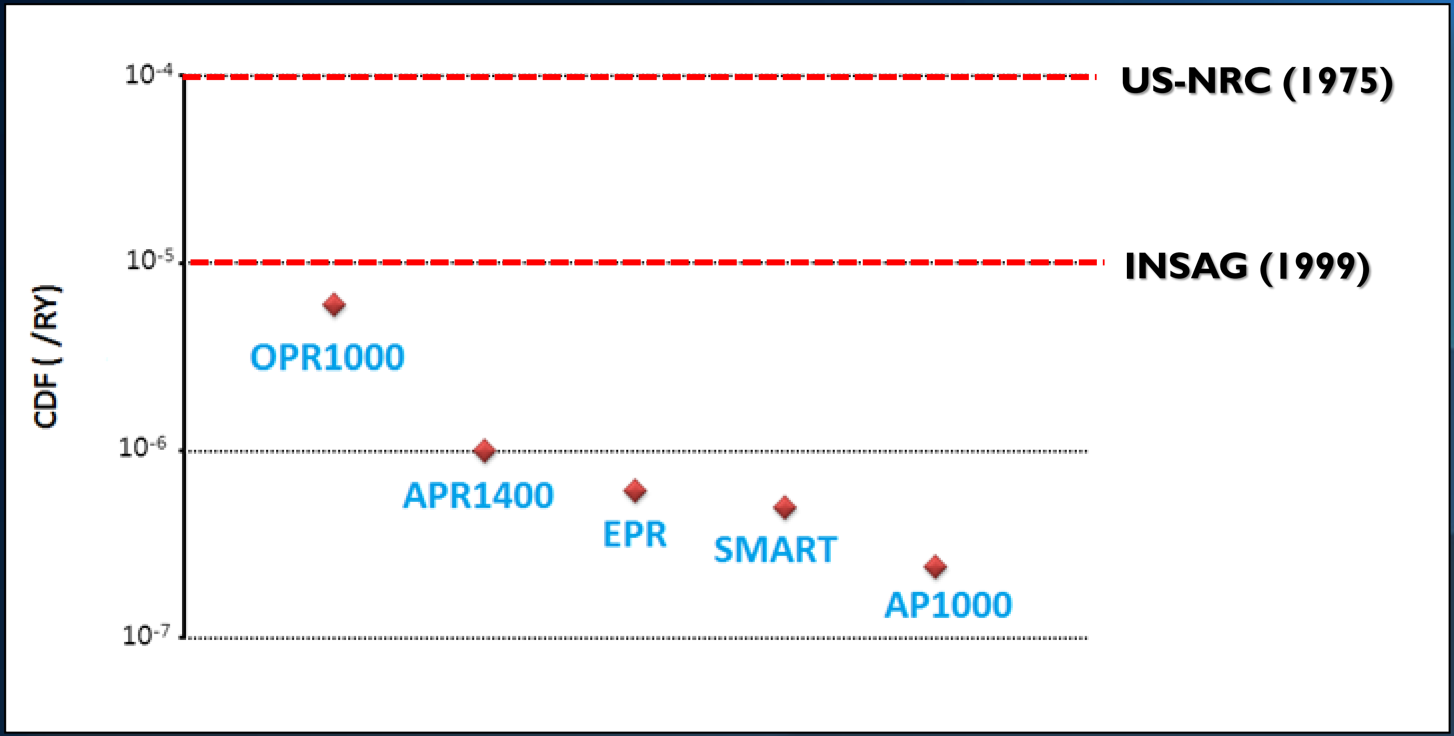
Probabilistic Safety Analysis (PSA)

- **The Key Safety Criteria:**
  "Core damage frequency (CDF)" and "Large early release frequency (LERF)"

  - **US-NRC (1975)**
    - CDF: 10^{-4} /RY
  - **EPRI for future LWRs (1990)**
    - CDF: 10^{-5} /RY
  - **INSAG Criteria (1999)** (considered as international best practices)
    - CDF: 10^{-4} /RY for existing reactors
      10^{-5} /RY for future reactors
    - LERF: 10^{-6} /RY
  - **For Gen-IV reactors**
    - Considered as 1/10 of Gen-III reactors = 10^{-6} /RY

Probabilistic Safety of NPPs

- **Core Damage Frequency (CDF) of Reactors and Safety Criteria**
  - All the operating NPPs meet the US-NRC criteria.
    - ⇒ Gen-III reactors (OPR1000, APR1400, EPR, APWR, ABWR etc.): Lower than INSAG`s criteria
  - The decrease of CDF means the enhancement of safety.



Probabilistic Safety of NPPs

- **Safety Criteria for Early and Cancer Fatality Risk of Reactors**
  - **US-NRC Criteria**
    - ⇒ **Early Fatality Risk:** **5.0×10^{-7} / RY**
    - ⇒ **Cancer Fatality Risk:** **2.0×10^{-6} / RY**
  - **Example: Shin-Kori NPPs**
    - ⇒ **Early Fatality Risk:** **~ 2.0×10^{-8} / RY**
    - ⇒ **Cancer Fatality Risk:** **~ 4.0×10^{-9} / RY**

Risk Assessment and Management: (1) US

- After recognizing the importance of PSA from WASH-1400 report (1979),
  - "Policy statement on severe reactor accidents" (1985)
  - "Safety goals for the operations of NPPs; Policy; Statement; Republication" (1986)
  - Having risk information of each NPP
- Use of PRA Methods in Nuclear Regulatory Activities (1995)
  - PRA Implementation Plan (1996-2001)
- Risk-Informed Regulation Implementation Plan (2000)
  - Implementing "Reactor Oversight Process (ROP)" (2006)
- Risk-informed and Performance based Regulation (RIPBR) (2007)
- After the Fukushima accidents,
  - Developing the Defense-In Depth (DID) with Risk-informed application and performance

    ⇒ Risk-informed Performance based DID

Risk Assessment and Management: (2) Europe

- **France**
  - Using PSA for supporting the deterministic safety assessment in regulatory process
- **Swiss**
  - Requiring PSA Level 1 and 2 for licensing under Nuclear Law (2005)
- **Belgium**
  - Operating NPPs: PSA in periodic safety review (PSR)
  - New NPPs: PSA for licensing
  - Using PSA for 10-year lifetime extension of Tihange-1 NPP
- **Sweden**
  - Requiring PSA Level 1 and 2 for licensing under Nuclear Law (2004)
  - Updating the PSA for “Living PSA” every year

Risk Assessment and Management: (3) Japan

- "Basic Policy of Nuclear Safety Regulation using Risk Information" (2003)
  - Adopting the risk information of PSA for safety regulation
  - Establishing a plan for risk-informed regulation by JNES (2005)
  - Advising performance indices for LWRs (2008)
- Proclaiming "Preservation Program" (2008)
  - New inspection program for NPPs using risk information
- PSA for offsite events (before Fukushima accidents)
  - Mostly for earthquake, not flooding
- Establishing "Standard PSA" (after Fukushima accidents)
  - PSA for various offsite events including tsunami
  - PSA Level 3
  - Using accident sequences in regulation
- Establishing and carrying out the phased strategies for PSA

Risk Assessment and Management: (4) Korea

- Implementation of PSA Based on
  - ① Post-TMI-2 implementation requirements (1979)
    - First assessment for Kori-3,4
  - ② Policy on severe accidents (2001)
    - Level 1 and 2 Assessment for all Korean NPPs (~2007)
  - ③ Post-Fukushima Implementation (2011)
    - Revisions of PSA models
    - Low-power and shutdown PSA

- Using PSA for licensing NPPs
  - Improving design concept in APR+
  - Design certificate for APR1400 and SMART

- Risk-informed application used for
  - Risk-informed integrated leak rate test (RI-ILRT)
  - Risk-informed in-service inspection (RI-ISI)
  - Risk-informed allowable outage time (RI-AOT)
  - Surveillance test interval (STI)

Risk Assessment and Management: (4) Korea

- Korea`s Legislation on Severe Accident in Nuclear Safety Act
  - Revision of Nuclear Safety Act including Severe Accident Enforcement
  - Notification No. 9 (Assessment of Accident Risk)
    - Appropriate technical suitability, details and analysis ranges of PSA
    - Quantitative Risk Goal

      ① Risk of early fatality and cancer fatality from NPPs to residents : Less than 0.1 % of total risk

      ② Occurrence probability of Cs-137 release larger than 100 TBq : Less than 1.0×10^{-6} / RY

2 Lessons of PSA from Accidents

Contribution of PSA on Nuclear Safety

- **Has PSA been effective and helpful for nuclear safety until now?**
  - **Applications of PSA on design, operation, and accident management**
    - Plant vulnerabilities
    - Intersystem dependencies
    - Optimization of systems
    - Maintenance program
    - Improvement of emergency operating procedures
    - Improvement of guidelines for severe accident management
    - Supporting emergency planning
  - **In accidents, it was proven that PSA was important.**
    - Based on PSA
      - Before accidents: "Indicating problems"
      - After accidents: "Reflecting lessons"

Ref.: IAEA-TECDOC, Applications of PSA for NPPs.

PSA, Before and After Accidents

- **TMI accident (1979)**
  - Before the accident
    - WASH-1400 (1975)
      - Emphasizing the importance of SBLOCA, more than LBLOCA`s
  - In the accident
    - SBLOCA occurred in reality (pressurizer relief valve stuck open)
    - Human errors (confusion over valve status)
  - After the accident
    - No injuries, and No measurable health effects
    - Rising importance on:
      - Human factors
      - Defense-in-Depth (DID)

PSA, Before and After Accidents

- **Chernobyl accident (1986)**
  - Before the accident
    - Importance on Defense-in-Depth
  - In the accident
    - Operator errors
    - Deficiencies on operating instructions
    - Deficiencies on design
  - After the accident
    - Rising importance on:
      - Containment
      - Safety culture
      - International cooperation

PSA, Before and After Accidents

- **After the Fukushima accidents (2011)**
  - Before the accident
    - Possibility of tsunami-waves
  - In the accident
    - Earthquake and Tsunami
    - Poor communication and delays
  - After the accident
    - Rising importance on:
      - External events (earthquake, tsunami, fire etc.)
      - Electrical power sources
      - Accident management strategy
      - Control tower

PSA, Before and After Accidents

- **Reflecting Lessons of the Fukushima accidents in nuclear safety well:**
  - **U.S.**
    - ✓ **Emergency response improvements for BDBA**
      - **FLEX (Diverse and Flexible coping capability)**
  - **France**
    - ✓ **ASN requiring improvements with complementary safety assessments**
      - **HSC (Hardened Safety Core)**
      - **Nuclear rapid response force (FARN)**
  - **Japan**
    - ✓ **New regulatory requirements by NRA**
      - **For DBA, severe accident, and external events (earthquake and tsunami)**
  - **Korea**
    - ✓ **56 post-Fukushima action items**
    - ✓ **Stress tests for all the NPPs**
    - ✓ **Legislation on Severe Accident in Nuclear Safety Act**

How to enhance PSA

- **Ways of PSA for Future**

1) Uncertainty of Basic Data and CCF
2) More Various BDBA Sequences
3) PSA for External Initiating Events
4) PSA for Multi-unit
5) PSA for Spent Fuel Pool Storage
6) Application of PSA on Accident Management
7) Living PSA Connecting to Online Inspection and Maintenance

How to enhance PSA

1) **Uncertainty of Basic Data and CCF**

- **Need of updating basic data for instruments and systems**
  - **Pumps, valves, sensors, tanks etc.**
- **Need of modeling for Human Reliability Analysis (HRA)**
  - **Human, team, organization**
  - **Man-machine interfaces**
- **Importance of Common Cause Failure (CCF)**
  - **More application of redundancy and diversity after the Fukushima accident**
  - **Critical factor for causing the failure of a certain function**

How to enhance PSA

2) More Various BDBA Sequences

- Defining the imaginable initiating events
  - Able to cause containment-bypass
- Analyzing the various accident sequences
  - Based on the results of deterministic safety analysis

How to enhance PSA

3) PSA for External Initiating Events

- Updating the frequencies of external initiating events
  - Earthquake, flooding, fire etc.
  - Finding new imaginable events
- Sequence analysis under the specified conditions
  - Harsher conditions than internal initiating events`

How to enhance PSA

4) PSA for Multi-unit

- Need of overall analysis on all the onsite plants
- Availability of shared resources for multi-unit in a site
  - Severe accident emergency response team
  - One movable 3.2MW diesel generator (as one in N+1 strategy)
- Application on accident management strategy
  - EDMG (Extensive Damage Mitigation Guideline)

How to enhance PSA

5) PSA for Spent Fuel Pool Storage

- Reflecting lessons of Fukushima unit 4
- Supplement for safety enhancement
  - Analyzing the fragility
- Evaluation of spent fuel pool storage with a plant
  - Availability of resources

How to enhance PSA

6) Application of PSA on Accident Management

- Accident management guidelines
  - Severe accident management guideline (SAMG)
  - Extensive damage mitigation guideline (EDMG)
- Prevention of the radioactive material release
  - Containment failure
  - Containment-bypass
    - SGTR, ISLOCA
- Evaluation of each mitigation step
  - External reactor vessel cooling (ERVC)
  - Containment filtered venting system (CFVS)

How to enhance PSA

7) **Living PSA Connecting to Online Inspection and Maintenance**

- **Reflecting the current design and operational features**
  - **Feedback from internal and external operational experiences**
- **Utilizing information of online inspection**
- **Integrating plant activity with the cooperation**
  - **Identifying the fragility for maintenance**

3 Nuclear Safety Enhancement through PSA

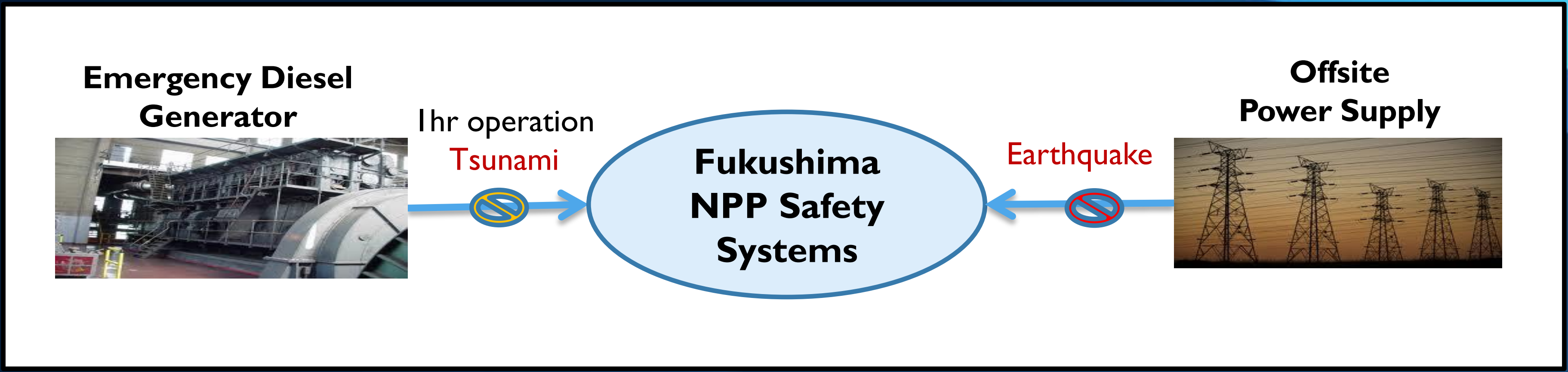
Nuclear Safety after the Fukushima Accident

- **The basic cause of the Fukushima accident :**
  'Decay Heat Removal Failure' from 'Station Black-Out'
  - All the NPPs automatically shut down by detecting earthquake.
  - **'Decay heat'** - continuously generated after the shutdown due to the fission products decay
  - **Loss of offsite power** due to Earthquake & **Loss of emergency power** due to Tsunami

⇒ **Occurrence of Station Black-Out (SBO)**

⇒ **Failure of Decay Heat Removal**

⇒ **Failure of Containment**



How to Enhance Nuclear Safety

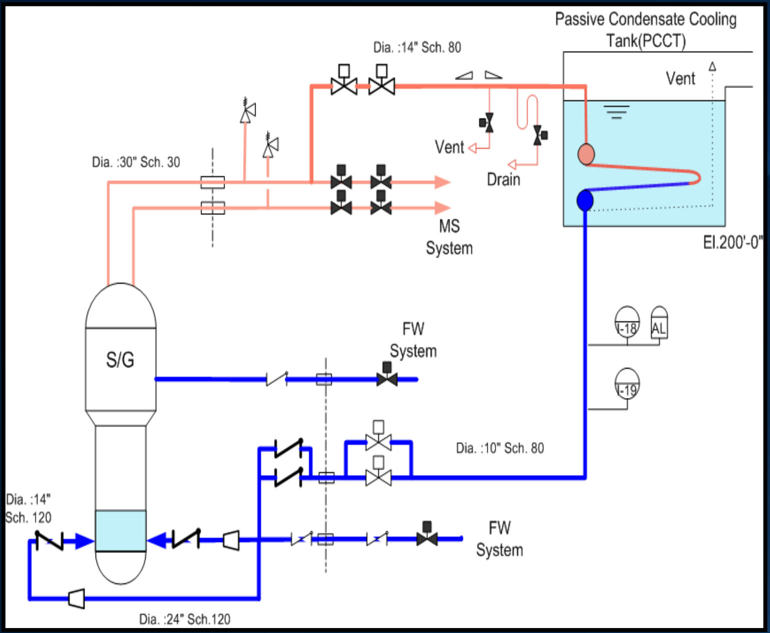
❖ **Solutions for Safety Enhancements**

1. Applying "Passive decay heat removal systems"
2. Diversifying and Hardening "Additional safety systems"
3. Protecting "Integrity of containment" by ECSBS and CFVS
4. Applying "Online inspection and maintenance"
5. Improving "Safety culture"

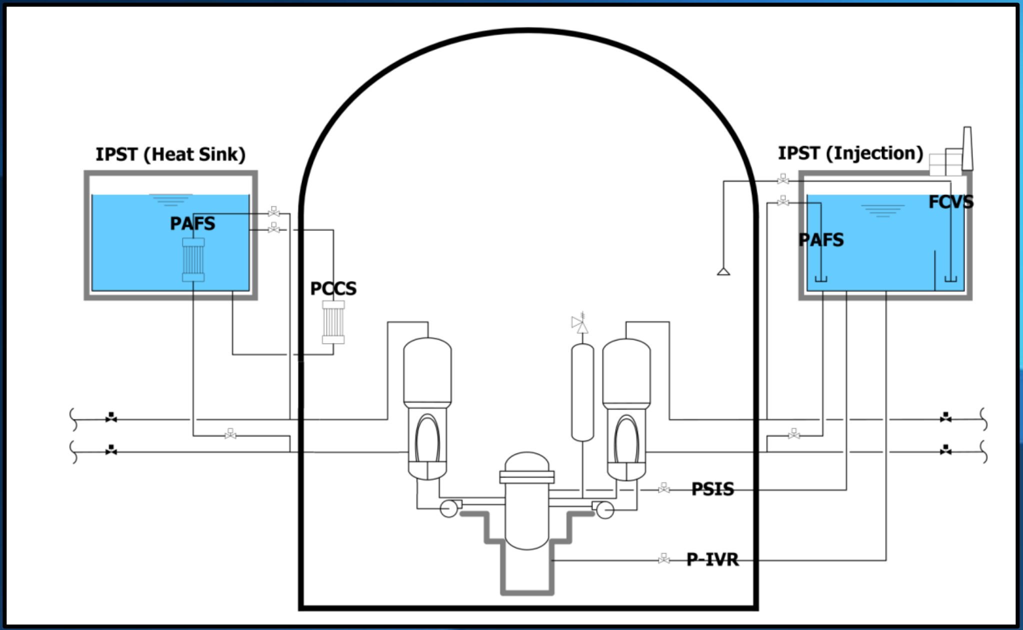
I. Applying "Passive Decay Heat Removal Systems"

❖ Passive Safety Systems

- Operated by natural phenomena (not depending on electrical power sources)
- Minimizing operator actions
- Long-term cooling (with easy water refilling from outside)
- Cheaper costs for installations than active safety system`s



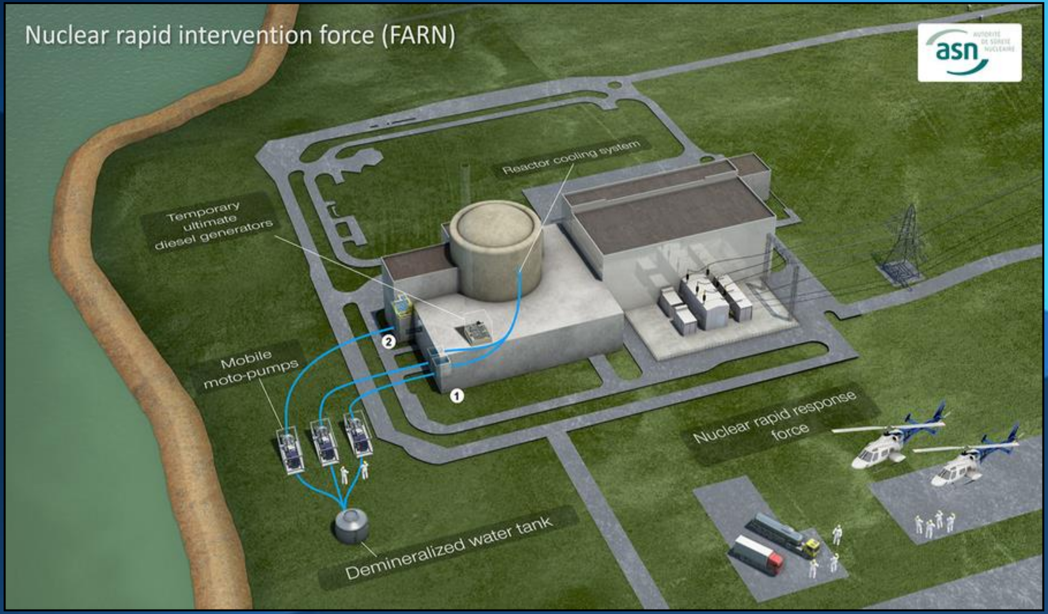
< Passive Auxiliary Feedwater System (PAFS) >



< Integrated Passive Safety System (IPSS) >

2. Diversifying and Hardening "Additional Safety Systems"

- **Diversifying safety systems : Minimizing CCF**
  - **Electrical power sources**
    - Alternative AC (AAC) power sources, and Movable electrical power sources
    - DC battery
  - **Emergency coolant supply systems**
    - Alternative pumps and water sources
  - **Emergency control rooms**
    - With seismic design
- **Hardening integrity of diversified systems**
  - **Facilities with protective shields**
  - **Underground systems and components**



< Hardened Safety Core (HSC) in France >

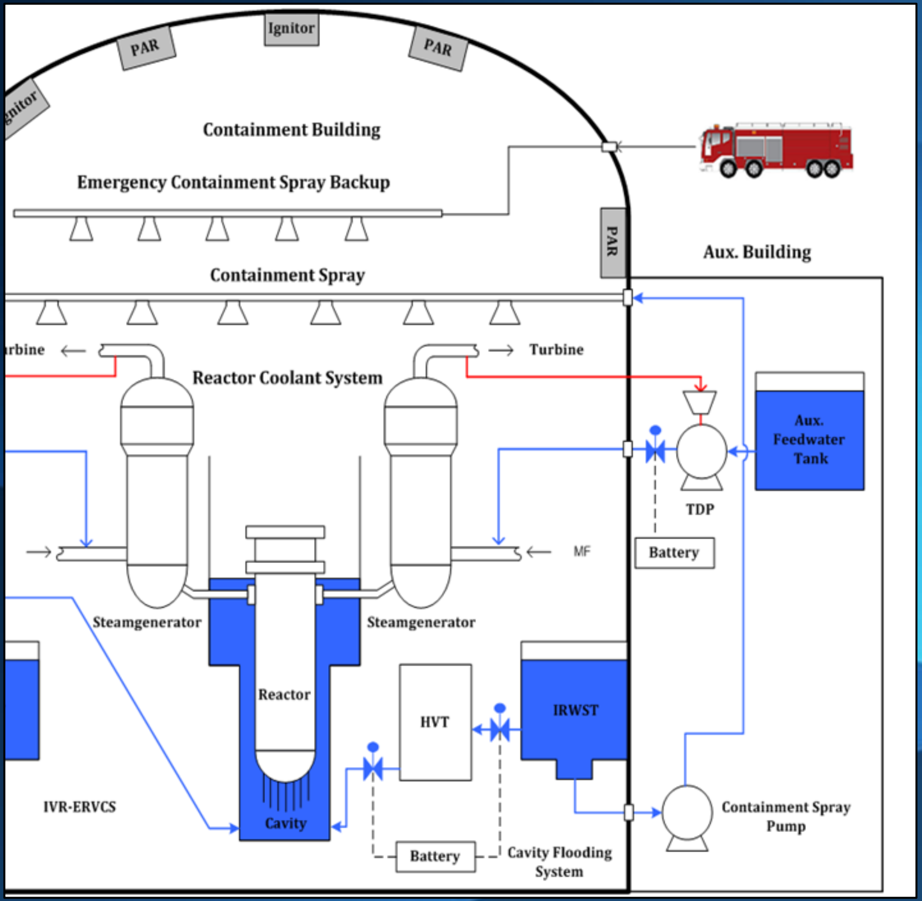
3-1. Protecting "Containment Integrity" by Cooling

- **To prevent large release of radio-nuclides**

- **Containment spray system**
  - Installed in conventional PWRs
  - The most effective for cooling

- **Emergency containment spray backup system (ECSBS)**
  - Injecting water by fire trucks through nozzles installed onsite

- **Containment heat exchangers for future NPPs**
  - Condensing steam in containment

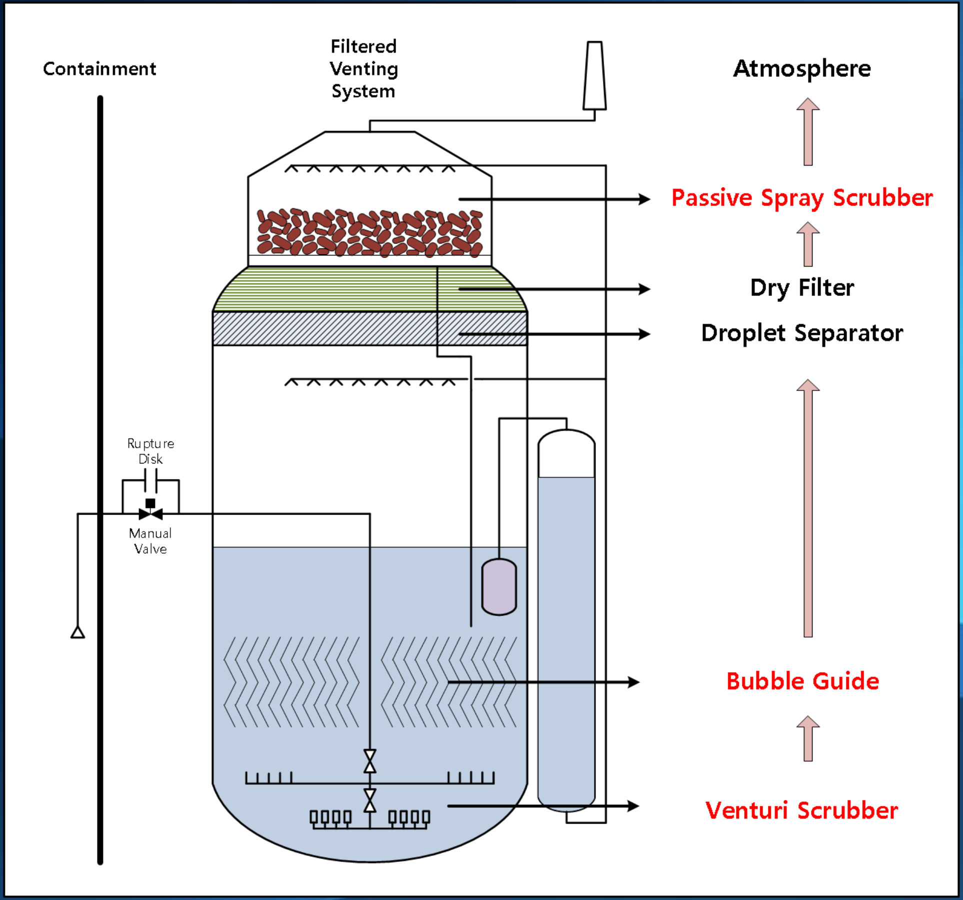


< Containment Cooling System in APR1400 >

3-2. Protecting "Containment Integrity" by Filtered Venting

- **Containment protection by controlled venting of steam and non-condensable gases**

- **Containment Filtered venting System (CFVS)**
  - Passive depressurization by pressure difference
  - Radionuclide filtering
  - Decontamination performance
    - Aerosol: 99.99 %
    - Iodine: 99.9 %



< Containment Filtered Venting System >

4. Applying "Online Inspection and Maintenance"

- **Online equipment monitoring systems**
  - Providing status information in real time
  - Determining what types of maintenance is needed

- **Online inspection and maintenance**
  - Maintaining components based on inspection and diagnosis
  - Requiring "adequate redundancy, reliability, and effectiveness" for online maintenance
  - Also available to apply predictive online maintenance using advanced signal processing techniques

5. Improving "Safety culture"

Safety Culture	Concentration of attitude and sense of organization and individual that treat safety problem as an overriding concern

Need of perception about importance of safety for all members in organization (from CEO to worker)

Need of absolute sense that success in safety is the best

Sense of duty to completely follow the procedure (Manual)

5. Improving “Safety culture”

❖ Composition of safety culture

4 Closing Remarks

Closing Remarks –(1/3)

- Low early-fatality risk of nuclear power from accidents, and Low environmental impact

- PSA has been useful, and will be effective and necessary more than ever.
  - TMI: Occurrence of SBLOCA (issued before) + Human error
  - Chernobyl: Importance of containment
  - Fukushima
    - External events (earthquake, tsunami, fire etc.)
    - Electrical power sources
    - Accident management strategy
  - Increasingly utilizing "Risk-Informed Application and Regulation" in many countries
  - Korea`s quantitative criterion
    - 100TBq of Cs-137, less than 10^{-6} / RY

Closing Remarks –(2/3)

- How to Enhance PSA
  1) Uncertainty of Basic Data and CCF for both Machines and Humans
  2) More Various BDBA Sequences (causing Containment-Bypass etc.)
  3) PSA for External Initiating Events
  4) PSA for Multi-unit
  5) PSA for Spent Fuel Pool Storage
  6) Application of PSA on Accident Management (SAMG & EDMG) for ERVC, CFVS etc.
  7) Living PSA Connecting to Online Inspection and Maintenance

Closing Remarks –(3/3)

- Worldwide NPPs are safe within safety criteria for fatality risk.
  - Needed to enhance the safety of NPPs continuously

- How to Enhance Nuclear Safety through PSA
  1) Applying Passive Safety Systems
  2) Diversifying and Hardening Additional Safety Systems
  3) Cooling and Filtered Venting for Integrity of Containment
  4) Applying Online Inspection and Maintenance
  5) Establishing the Firm Safety Culture

Thank You