International Conference on Topical Issues in Nuclear Installation Safety:
Defence in Depth – Advances & Challenges for Nuclear Installation Safety
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Nuclear Safety R&D for Knowledge-Based Implementation of Defence in Depth

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Outline

- ❑ **Fukushima Accident**
- ❑ **Defence in Depth (DID)**
- ❑ **Knowledge-Based Implementation of DID & Nuclear Safety R&D**
- ❑ **Nuclear Safety R&D in Korea**
- ❑ **Concluding Remarks**

Fukushima Accident (1)

❑ Overall Progression

Incomplete Design, Siting & Emergency Preparedness	Extreme Earthquake + Tsunami	Loss of Core Cooling	Hydrogen Explosion	Large Release of Radioactive Materials
- Site characteristics - Severe accident - Emergency response preparedness	- Loss of power - Loss of heat sink & key components - Loss of reactor instrumentation - Harsh environment	↓ Core Melt & Hydrogen Generation	+ Reactor Building Damage	↓ Contamination of Land & Sea

Securing Safe Cooling of Damaged Reactors/SFPs and Controlling Further Radioactive Releases

Decontamination, Decommissioning and Disposal of Facility (incl. Environmental Restoration)

Fukushima Accident (2)

❑ Key Characteristics

- **Severe Accident Initiated by Extreme Natural Disaster**
  - TMI & Chernobyl: Design/equipment failure + human factors
  - Fukushima: Natural disaster+ design failure + human factors
  - Prolonged losses in electricity supply & safety-related equipment due to earthquake/tsunami
- **Severe Accident in Multiple Units and Crisis for a Long Time**
  - Extensive core melting in three (3) reactors
  - Hydrogen explosion in three (3) reactor buildings
  - Damage in the reactor vessels and containment vessels
  - Threat to the safety of spent fuels in SFPs
  - Several months for escaping from urgent situation
- **Extensive Contamination of (Atmosphere,) Land and Sea due to the Release of Radioactive Materials**
  - Large radioactive release: 10~20% of Chernobyl, INES Level 7
  - No immediate casualty due to radiation exposure
  - Extensive contamination & ~115,000 evacuees

Successful in minimizing radiation exposure; but extensive contamination, societal crisis & enormous economic impact

Fukushima Accident (3)

❑ Fundamental Causes: Lack of Preparation

- **Insufficient Consideration of Japan-Specific Site Characteristics in Constructing US-Designed BWRs**
  - Earthquake ? 0.18g → 0.447g vs. 0.561g
  - Tsunami ? 3.1m → 5.7m vs. 15m
  - Location of EDGs, DC batteries, etc.
- **Decision Making without Sufficient Knowledge**
  - Over-confidence on NPP safety: severe accident, external events
  - Insufficient exchange/transfer of information among and within relevant organizations
  - Isolation of industry & regulator from other academic sectors
- **Insufficient Safety Culture**
  - Past records of TEPCO's weak safety culture
  - Insufficient learning from past experience & research findings
- **Institutional & Regulatory Failure**
  - Insufficient regulatory independence: METI > ANRE > NISA
  - Limited role of experts/professionals

Fukushima Accident (4)

❑ Technical Aspects (1)

- **Lack of Countermeasures against Large-Scale Tsunami(s)**
  - Design basis tsunami + Improper provision against BDB tsunami
  - Improper location of safety-important facilities, incl. basement and/or first floor location of EDGs and DC batteries
- **Insufficient Countermeasures against Severe Accident**
  - Weakness of Mark-I containment highlighted in 1980's & 1990's
  - Effectiveness of Severe Accident Management Program implemented in 1990's
  - Incomplete SAMGs & insufficient training w.r.t. SBO conditions
  - Insufficient understanding of major players on severe accident issues
  - Instrumentation for severe accident conditions
- **Deteriorated Working Environment**
  - Roads closed by earthquakes & tsunamis
  - Large amount of debris preventing on-site movement
  - Continuous aftershocks with frequent tsunami alerts
  - Complete loss of lighting inside containment
  - Telecommunication networks, etc.

Fukushima Accident (5)

❑ Technical Aspects (2)

- **Improper Management of Accident Conditions**
  - Misjudgment on the operational status of Unit 1 isolation condensers
  - Poor handling of water injection at Unit 3: Manual stop of HPCI without checking the status of DC batteries to open SRVs
  - Late operation of containment vent valves
- **In-sufficient Understanding of Reactor Conditions**
  - Unreliable information on reactor water levels
  - Misunderstanding (?) of the states of the damaged cores
  - Insufficient/ineffective information sharing among major players
  - No prompt advices from external experts
- **Severe Accidents in Multiple Units**
  - Initial emergency at 10 units (Fukushima-I & II) of TEPCO with limited resources
  - Long-lasting severe situation in 4 units
  - Effects of hydrogen explosions and/or radioactivity releases from neighboring units

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Defence in Depth (DID) (1)

❑ Defence in Depth (DID)

- **Objectives:**

  Accident Prevention + Accident Mitigation

- **Approaches:**

  Multiple Physical Barriers
  + Multiple Levels of Protection

- **Basic Assumptions**
  - There will be errors in design
  - Equipment will occasionally fail
  - People will occasionally make mistakes

Defence in Depth (DID) (2)

❑ DID – Multiple Levels of Protection [INSAG-12]

Levels	Objective	Essential Means
Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction & operation
Level 2	Control of abnormal operation and detection of failures	Control, limiting & protection systems and other surveillance features
Level 3	Control of accidents within the design basis	Engineered safety features & accident procedures
Level 4	Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents	Complementary measures & accident management
Level 5	Mitigation of radiological consequences of significant release of radioactive materials	Off-site emergency response

Defence in Depth (DID) (3)

❑ DID Issues for Fukushima Accident

- **An example of the incomplete implementation of DID**
- **Simultaneous loss of multiple protection levels**

Defence Levels		DID Issues for the Fukushima Accident
Multiple Barriers		- Weakness of Mark-I containment - Location of SFP (at high elevation of the reactor building)
Multiple Levels of Protection	Level 1	- Vulnerability of Mark-I containment - Design basis external events (earthquake, tsunami, etc.)
	Level 2	- Provisions against SBO - Loss of UHS
	Level 3	- Provisions against SBO - Location of safety important equipments, loss of UHS - Instrumentation/monitoring
	Level 4	- Provisions against SBO - Mitigation features for hydrogen control, venting, etc. - Accident management procedures & operator training
	Level 5	- Emergency evacuation & medical treatment - Radiation monitoring

Defence in Depth (DID) (4)

❑ 3-Steps for Prevention & Mitigation of Accidents

High Level of Installation Safety
(Incl. siting, construction & maintenance)

- Improved DID & its implementation
- Continuous safety enhancement based on R&D findings & operating experiences

Best Procedures & Training
(EOP, SAMG, EDMG, etc.)

- Thorough analyses with best available scientific knowledge
- Imagine the unimaginable
- Use of both on-site & off-site resources
- Practical training & education

Creative Response in case of Unprepared Events

- High-quality trained & experienced staff
- Understanding of underlying physics & design characteristics
- Advisory expert groups with sufficient knowledge on plant details

Knowledge-based implementation of defence in depth is a key factor for securing a high/acceptable level of safety.

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Knowledge-Based Implementation of DID & Nuclear Safety R&D (1)

Do "Right" Thing "Right"
for Securing a High Safety Level

By

Fully Utilizing the Best Available Scientific Knowledge, Resources and Human Wisdom

in

Effective Communication with Stakeholders

Knowledge-Based Implementation of DID & Nuclear Safety R&D (2)

❑ Knowledge-Based DID Implementation

- **3 Elements : Knowledge Generation + Effective Communication + Applications/Implementation**
- **Generation of Knowledge**
  - Nuclear safety R&D utilizing the best available infrastructure & resources
  - Analysis of operating experiences including accidents
  - Organization of knowledge/information into ready-to-use forms
- **Effective Communication of Knowledge/Information**
  - Transfer & sharing of information
  - Collaborative R&D among stakeholders
- **Application of Knowledge/Information**
  - Knowledge-based decision making
  - Continuous safety improvement using new knowledge
  - Thorough assessment & verification during DID implementation
  - Improved HMI for emergency operation & accident management

Knowledge-Based Implementation of DID & Nuclear Safety R&D (3)

❑ Requirements of Nuclear Safety R&D [INSAG-16,2003]

- **Maintaining necessary technical expertise** in all safety disciplines through a vigorous educational process
- **Enhancement of analytical tools and techniques** to better quantify safety margins and to facilitate better decisions
- **Maintaining experimental facilities** to provide data to elucidate basic physical processes, to confirm and validate analytical tools, and to respond to new safety problems
- **Maintaining a pool of safety experts** in institutions firmly rooted in the pursuit of excellence with current knowledge of research in all disciplines relating to safety
- **Attraction of capable scientists and engineers** through major nuclear research projects
- **Achieving the public confidence** by a mature regulator possessing the necessary tools and expertise

Knowledge-Based Implementation of DID & Nuclear Safety R&D (4)

❑ Nuclear Safety R&D

- Scientific investigation and technology development for assessment, verification & improvement of nuclear safety

Nuclear Safety Research

Original Knowledge

Assessment & verification infrastructure

Experts

Knowledge Based Decision Making

Resolution of safety issues

Verification & enhancement of oper. reactor safety

Development of adv. & innovative design concepts

Effective & reliable regulation

Improved operation & maintenance

Safe & Economical Nuclear Technology Utilization with Strong Public Support

Knowledge-Based Implementation of DID & Nuclear Safety R&D (5)

❑ Important Areas for Nuclear Safety R&D

- Strengthening of multiple physical barriers
- Design basis site characteristics and effects of extreme/combined external hazards
- Robustness of electrical systems and ultimate heat sinks
- Severe accident phenomena (hydrogen, fission products, etc.), mitigation measures & management procedures
- Multi-unit accident scenarios & management
- Risk assessments & their applications to NPP design, operation, and accident management
- Passive systems for prevention & mitigation of severe accidents
- Instrumentation & monitoring at deteriorated plant conditions
- Safety of spent fuel storage facilities
- Strengthening of emergency planning & preparedness
- Effects of low-level radiation

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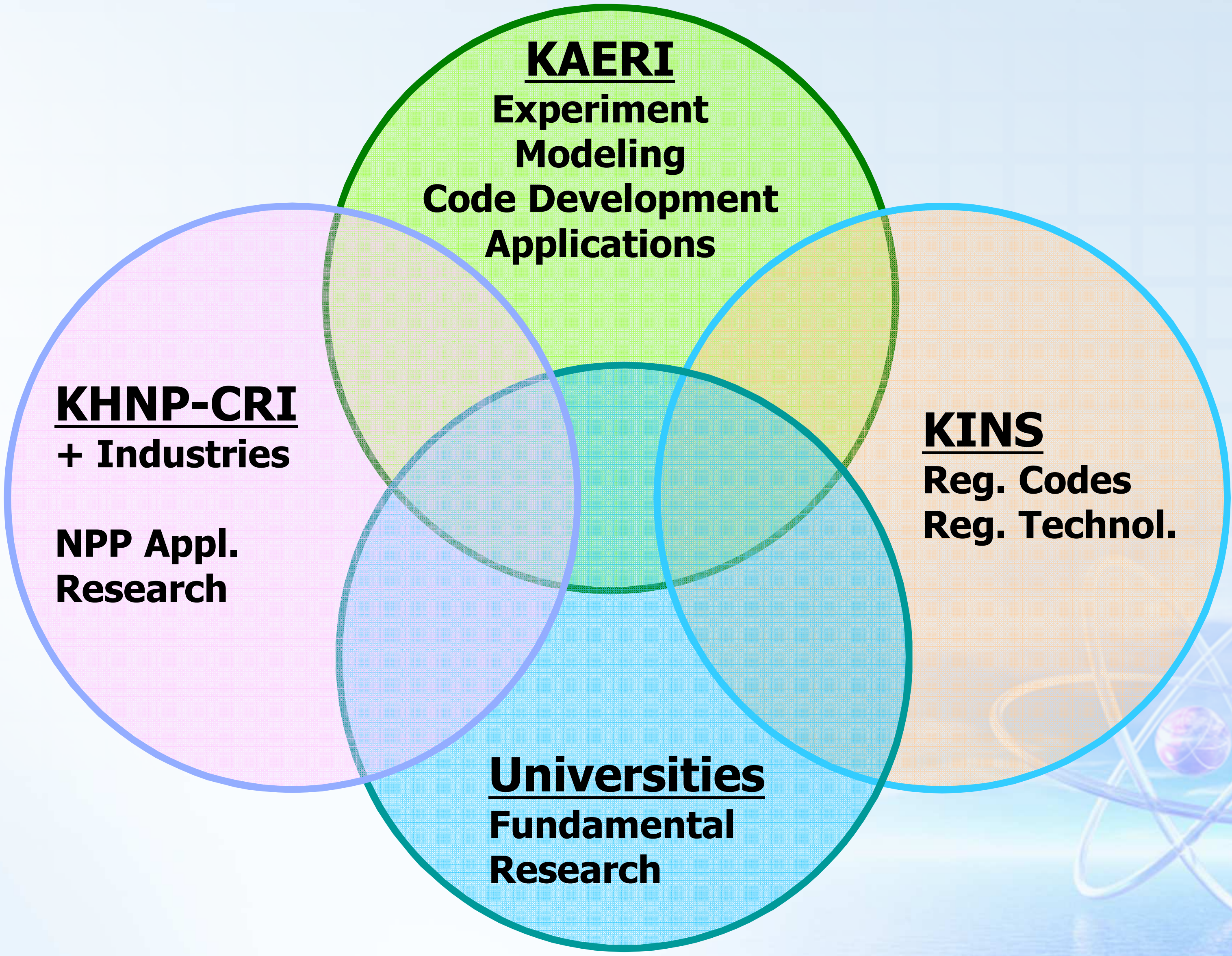
Nuclear Safety R&D in Korea (1)

❑ Major R&D Organizations



Nuclear Safety R&D in Korea (2)

❑ National R&D Programs on Nuclear Safety

Fukushima Lessons

Basic Infrastructure	Infrast. Strengthening & Core Tech. Devel.	Outcome Max. & Tech. Leadership	Global-Leading Safety R&D
(1992-1996)	(1997-2006)	(2007-2011)	(2012-)

MOST's Nuclear Technology R&D
- Mid- & Long-term Nuclear R&D Program

MEST's 5-year R&D Program for Nuclear Technology

MSIP's 5-year R&D Program for Nuclear Technology

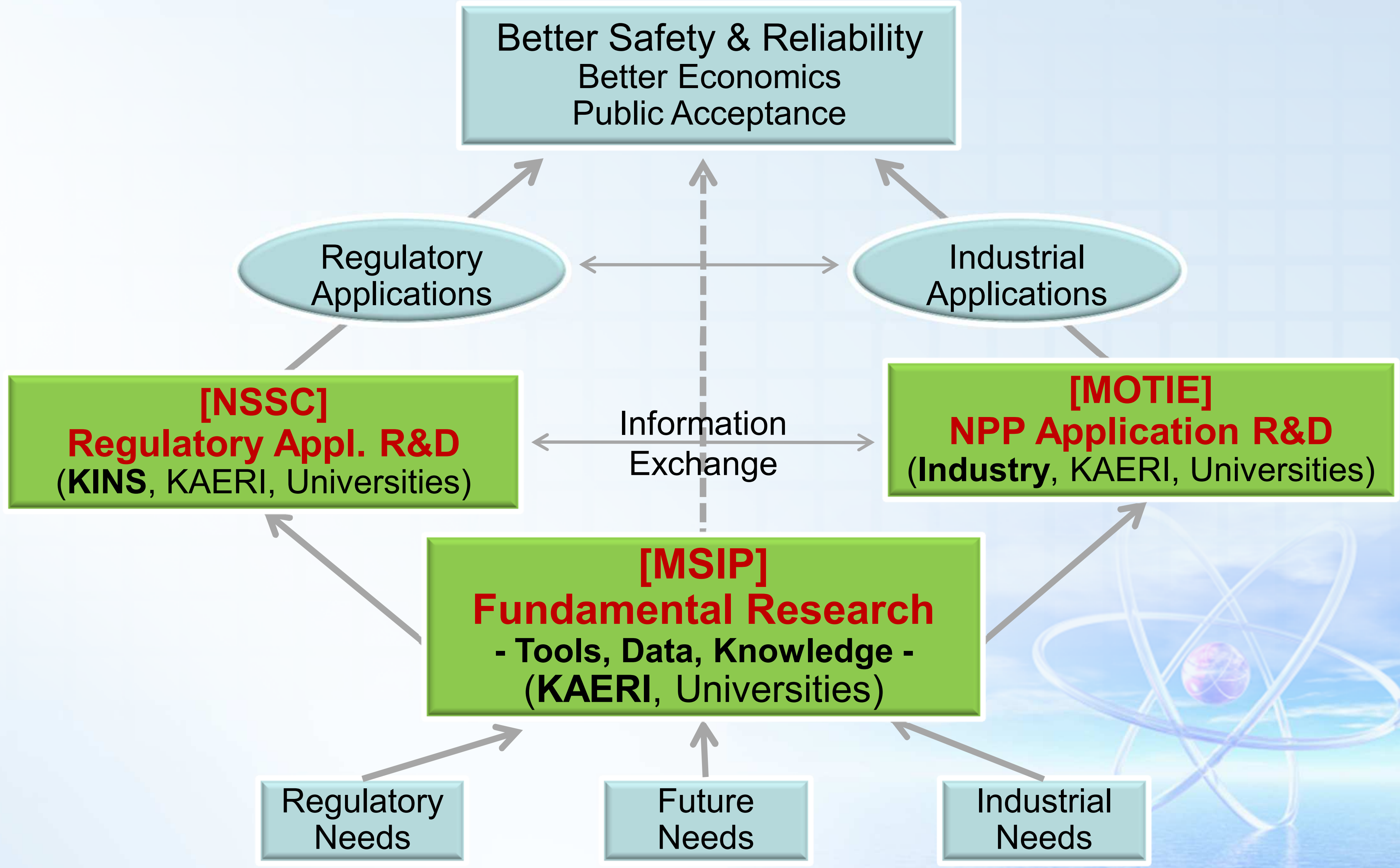
MKE's Program for NPP Technology Advancement (NuTech-2012)

MOTIE's Program for NPP Technol. Advancement (NuTech-2030)

NSSC's Regulatory Research

- MOST(Ministry of Science & Technology)
  => MEST (Ministry of Education, Science & Technology)
  => MSIP (Ministry of Science, ICT & Future Planning)
- MKE (Ministry of Knowledge Economy)
  => MOTIE (Ministry of Trade, Industry & Energy)
- NSSC (Nuclear Safety & Security Commission)

❑ NPP Safety Research & Applications



Nuclear Safety R&D in Korea (4)

❑ Basic Directions for KAERI's NSR

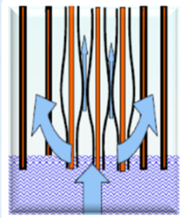
- **Incorporation of Lessons from Fukushima Accident**
  - Beyond DBA or Design Extension Conditions
  - Severe accident mitigation & management
  - Dispersion & environmental/human impacts of radioactive materials
  - Risk assessment methodology covering external & multi-unit events
  - Application of passive & inherent safety features
- **Production/Supply of Reliable & Best Outputs to Regulator & Industry for Knowledge-Based Decision Making**
- **Maximum Utilization of Existing R&D Infrastructure**
  - Hardware, Software, Manpower, etc
- **Close Collaboration with Domestic Organizations & Experts**
  - Effective utilization of resources
  - Effective transfer & utilization of the best available knowledge
- **Effective International Collaboration**
  - Multinational collaboration through OECD/NEA, IAEA, etc.
  - Bilateral collaboration
  - Active participation & hosting of international cooperative programs

Nuclear Safety R&D in Korea (5)

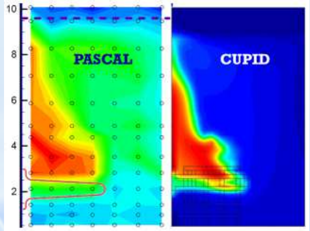
❑ Thermal-Hydraulic Safety

- **Securing Ultimate Heat Sinks for Severe Accident Prevention**
  - Integral simulation of extreme situations (e.g., Prolonged SBO) using the ATLAS facility
  - Development/verification/assessment of passive safety features for advanced reactor systems
  - Coolability of deformed fuels: tests & analyses
- **Advanced Simulation of T/H Behaviors**
  - Development & application of component T/H analysis code, CUPID
  - Coupled analysis of neutronics, component T/H, and system T/H
  - Development of advanced physical models based on high-precision experiments

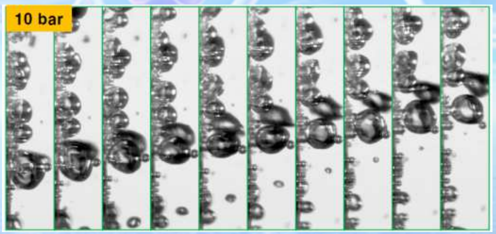
ATLAS



Deformed core + Fuel relocation



Pool Mixing Test & Analysis for Passive System

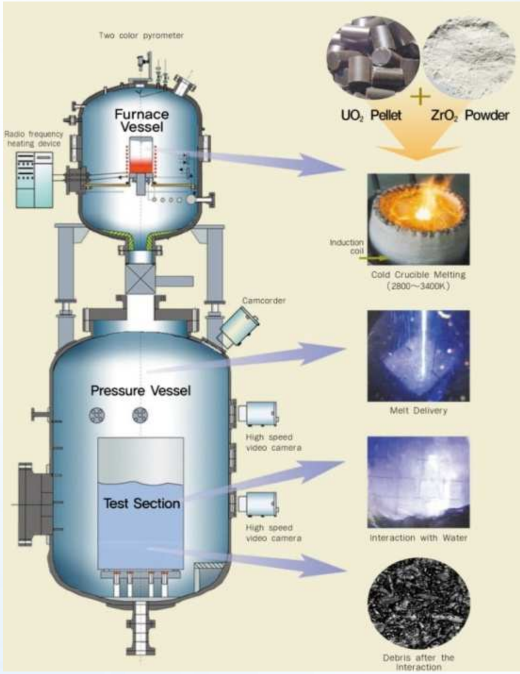


Subcooled Boiling Test & Modeling

Nuclear Safety R&D in Korea (6)

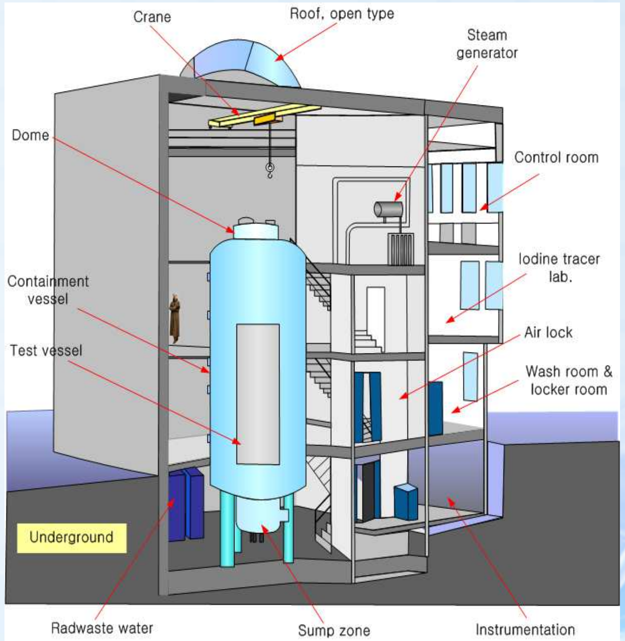
❑ Severe Accident: Develop Effective Mitigation Measures

Develop Severe Accident Analysis Code and Methodology: COMPASS+SPACE



TROI : OECD/SERENA
Steam Explosion

VESTA:
Corium-Structure Interaction



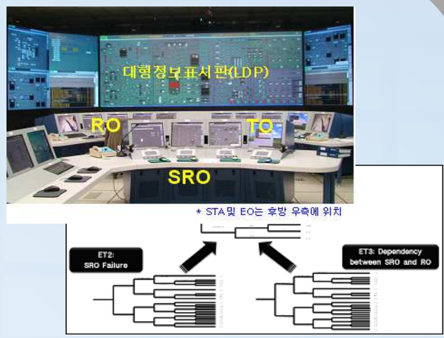
Integrity of Containment:
Hydrogen, Filtered Venting, Fission Product

Nuclear Safety R&D in Korea (7)

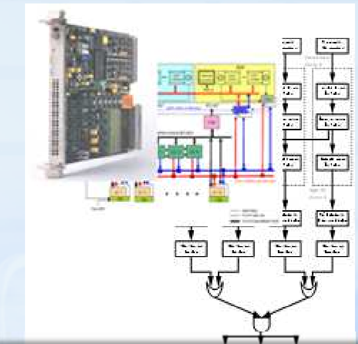
❑ Risk Assessment & Management

- **Full-Scope Risk Assessment Framework**
  - Internal(including fire/flooding)/ external events (seismic, tsunami, airplane crash, and other external events such as the super typhoon, etc.)
  - Full-power/low-power/shutdown mode PSA
  - Assessment of SFP risks & multi-unit risk
  - New system characteristics: passive systems, digital I&C, etc.
  - Improvement of the PSA engine, FTREX
- **Site Risk Profiles for Korean NPPs**
- **The technical basis for the integrated EOP/SAMG/EDMG and risk-informed Emergency Preparedness**

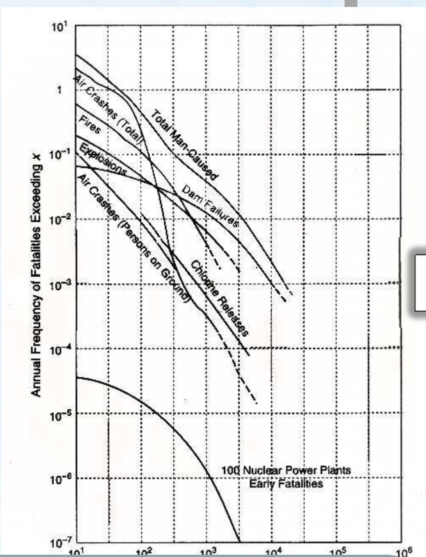
Development of Basic PRA Technology



Sim.-based HRA Handbook



DI&C PSA Tech. & DB

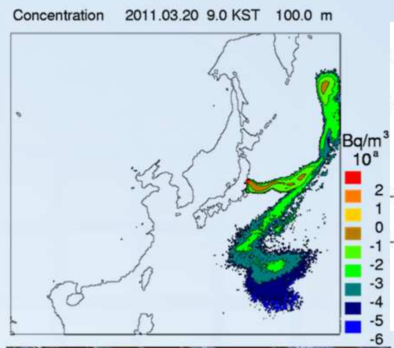


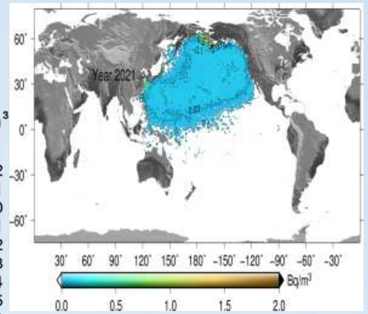
Development of Korean Total Site Risk Profile

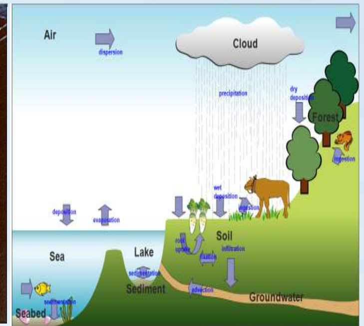
Nuclear Safety R&D in Korea (8)

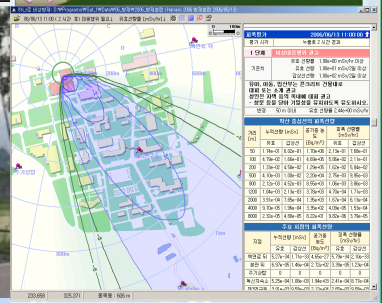
❑ Radiological Environmental Safety

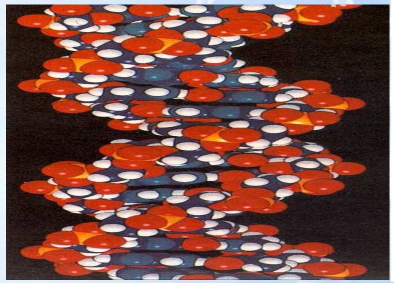
- Prediction of short & long-ranges air dispersion : **FADAS, LADAS codes**
- Prediction of marine dispersion : **LORAS code**
- Radiological dose assessment in rural (agricultural) & urban environments : **ECOREA, METRO-K codes**
- Radiological impact assessment to non-human species : **K-BIOTA code**
- Research about radiation resistance-related genomics
- Low dose effect of radiation, H-3 biological effect
- Retrospective radiation dosimetry and measurement



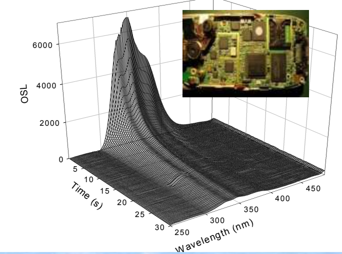








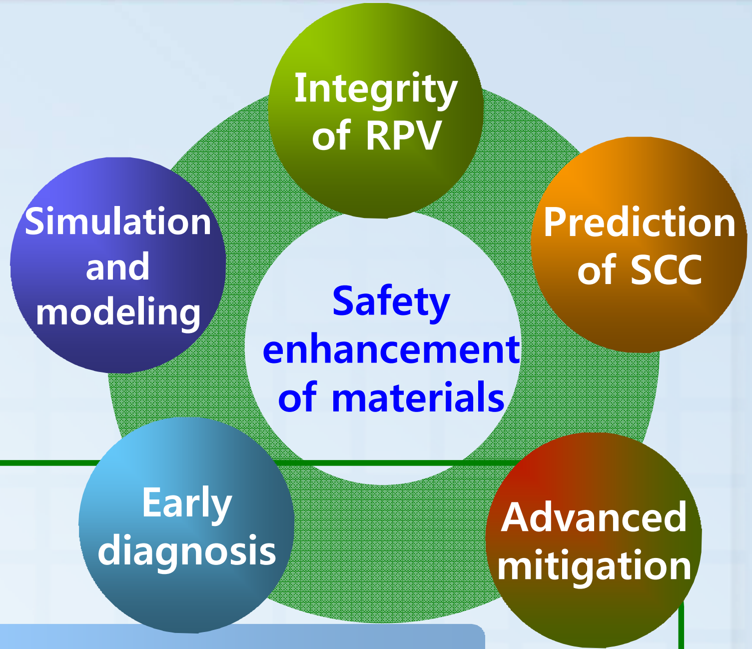
3-D OSL spectrum ($LiAlO_2$)

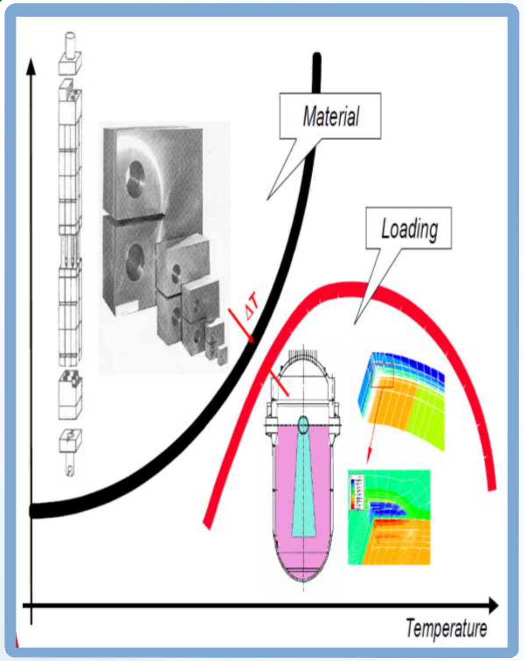


Nuclear Safety R&D in Korea (9)

❑ Materials Safety

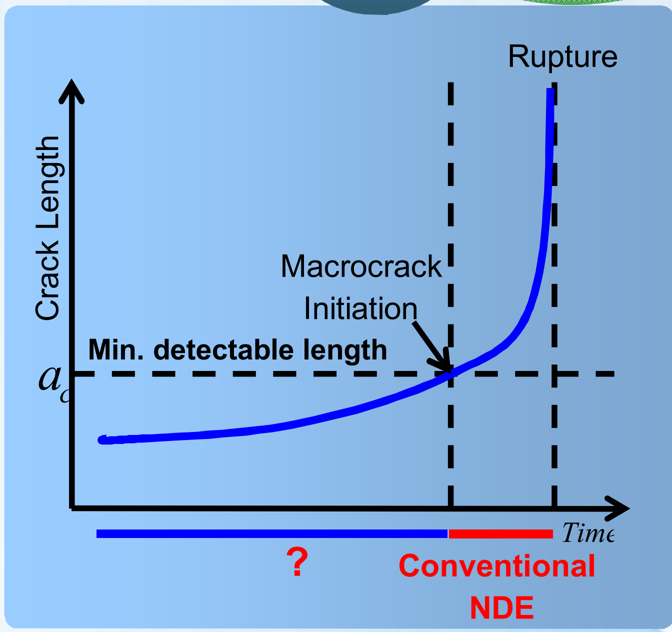
Enhance Long Term Operation Safety of Nuclear Materials





PTS Safety
Simulation & Modeling

SCC Prediction
& Mitigation



Eearly Diagnosis

Nuclear Safety R&D in Korea (10)

International Collaboration

Post-Fukushima Activities

- Active participation in IAEA/UNSCEAR/NEA programs
- Bilateral cooperation with Japanese organizations

OECD/NEA Programs

- Active participation of CSNI & CNRA Programs/Projects
- Hosting of selected programs: ISP-50 with ATLAS, SERENA Project with TROI, Rod bundle CFD benchmark with MATiS, etc.
- Proposal of new projects: OECD-ATLAS (proposed), SERENA-2 (under preparation) and others

IAEA Programs

- Participation of CRPs in various NSR areas

Bilateral Cooperation with Foreign Organizations

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Concluding Remarks

- Continuous safety enhancement for existing & new NPPs
- Knowledge-based implementation of DID for harmonized prevention & mitigation of severe accidents
  - Investigation/prevention of scenarios leading to severe accidents
  - Understanding & mitigation of severe accident phenomena
  - Minimization of radioactive releases & effective emergency responses
- Safety R&D for 'reliable' & 'best-achievable' knowledge
  - Proper combination of experiment & analysis technology: Role of experts with capability in both areas
  - Underlying physics and advanced models & simulation
  - Best knowledge by best people & infrastructure
  - Continuous re-evaluation of safety criteria & approaches based on the state-of-the art knowledge
  - Effective domestic & international collaboration
  - Effective communication of R&D outcomes
- Fukushima lessons incorporated in Korea's NSR Programs

Thank You Very Much
for Your Attention !

감사합니다.