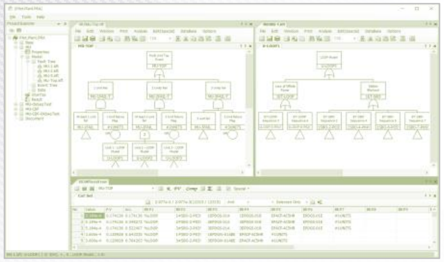
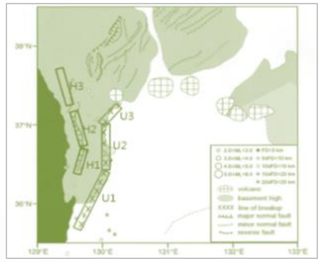
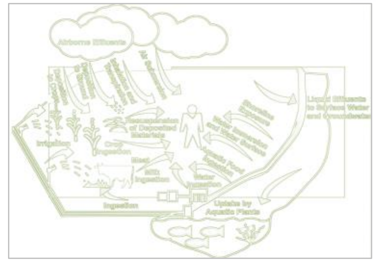
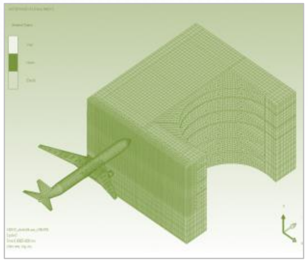
www.kaeri.re.kr









SMR 환경 인적수행도 자료수집 – 개요

박진균

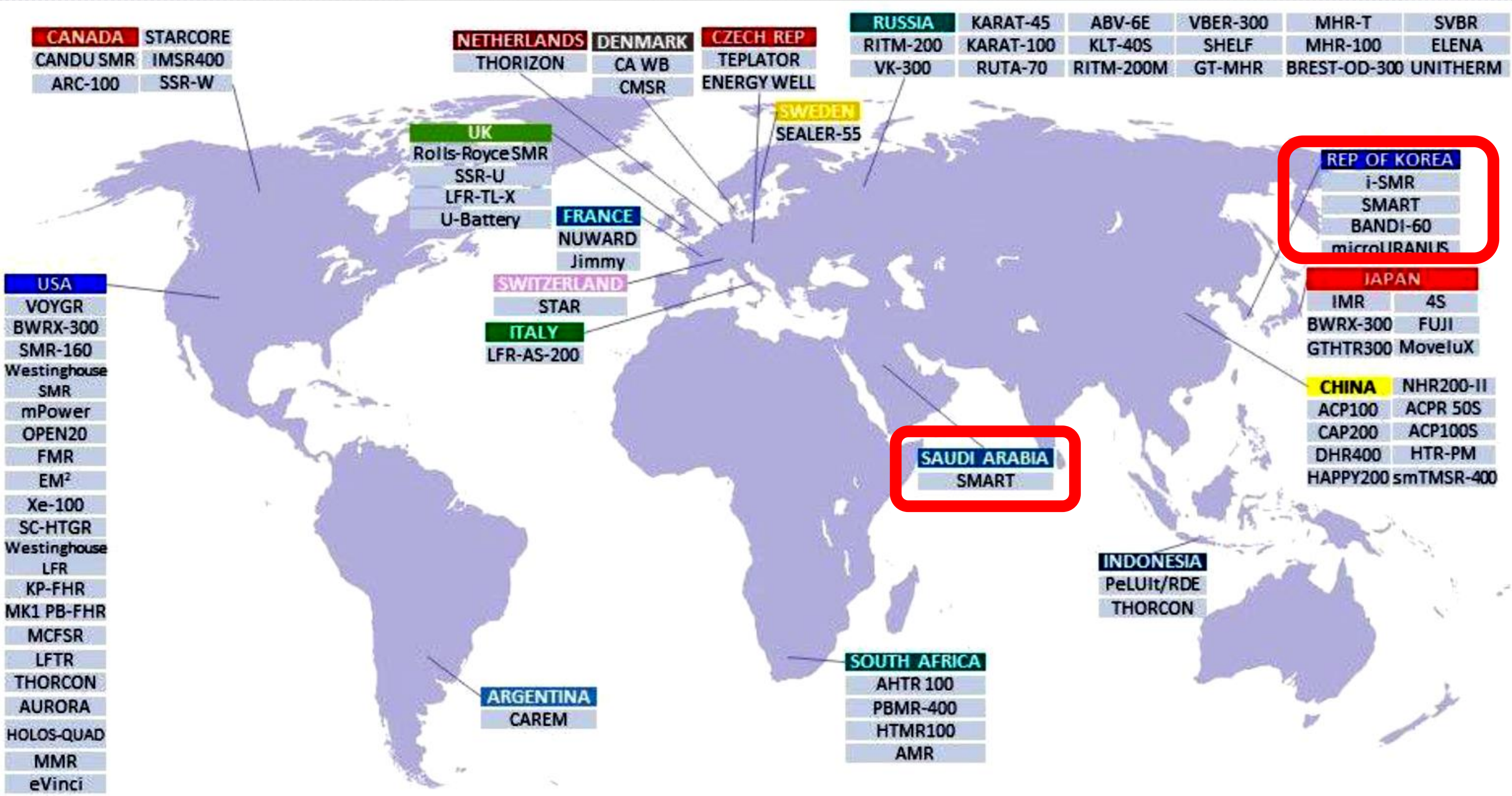
한국원자력연구원, 리스크평가연구부

SMR 운전관련 국내 인간공학/인적수행도 현안 workshop

한국원자력학회 원자력계측제어, 인간공학 및 자동원격 연구부회

2025. 5. 21.(수) 14:00~18:00·제주국제컨벤션센터, 4층 402B호

Small modular reactor (SMR): A new design paradigm



https://nucleus.iaea.org/sites/smr/SitePages/HomeSmrPlatform.aspx

Small modular reactor (SMR): A new design paradigm

- **IAEA/NRC definition**
  - < 300MWe (< 1000MWt)
  - One or more modules (multi-modules) can be operated with respect to diverse purposes.
  - Load following, hydrogen generation, etc.
- **As of 2024, 68 SMRs are under development.**
  - Pressurized/Boiled water cooled SMRs
  - High temperature gas cooled SMRs
  - Molten salt cooled SMRs

Design	Output MW(e)	Type	Designers	Country	Status
WATER COOLED SMALL MODULAR REACTORS					
CAREM	30	PWR	CNEA	Argentina	**Under construction**
ACP100	125	PWR	CNNC	China	**Under construction**
NUWARD	2 × 170	PWR	EDF, CEA, TA, Naval Group	France	Conceptual design
SMART	107	PWR	KAERI and K.A.CARE	Republic of Korea	Standard design approval received
KLT-40S	2 × 35	PWR in floating NPP	JSC Afrikantov OKBM	Russian Federation	**In operation**
RITM-200N	2 × 53	PWR	JSC Afrikantov OKBM	Russian Federation	Detail design
UK SMR	443[a]	PWR	Rolls-Royce and Partners	United Kingdom	Conceptual design
NuScale	6 × 77	PWR	NuScale Power Inc.	United States of America	Received US NRC certification
BWRX-300	270–290	BWR	GE-Hitachi Nuclear Energy and Hitachi GE Nuclear Energy	United States of America and Japan, Canada	Pre-licensing
HIGH TEMPERATURE GAS COOLED SMALL MODULAR REACTORS					
HTR-PM	210	HTGR	INET, Tsinghua University	China	**In operation**
GTHTR300	100–300	HTGR	JAEA	Japan	Pre-licensing
Xe-100	82.5	HTGR	X-Energy LLC	United States of America	Basic design
FAST NEUTRON SPECTRUM SMALL MODULAR REACTORS					
EM²	265	GMFR	General Atomics	United States of America	Conceptual design
MOLTEN SALT SMALL MODULAR REACTORS					
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual design
KP-FHR	140	Pebble bed salt cooled Reactor	KAIROS Power, LLC.	United States of America	Conceptual design
MICROREACTORS					
U-Battery	4	HTGR	Urenco	United Kingdom	Conceptual design
MMR	5–10	HTGR	Ultra Safe Nuclear Corporation	United States of America, Canada	Conceptual design
Aurora	1.5	FR	OKLO, Inc.	United States of America	Conceptual design

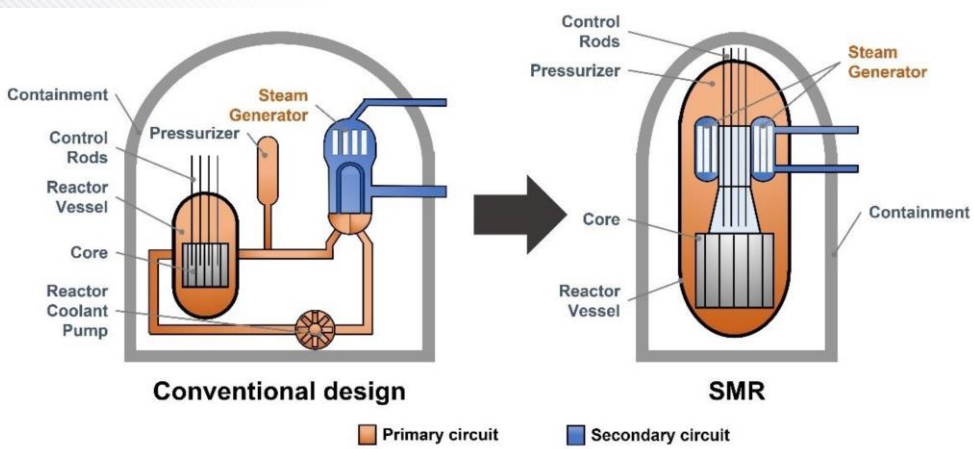
Note: CNEA — National Atomic Energy Commission (of Argentina); CNNC — China National Nuclear Corporation; EDF — Électricité de France; CEA — French Alternative Energies and Atomic Energy Commission; KAERI — Korea Atomic Energy Research Institute; K.A.CARE — King Abdullah City for Atomic and Renewable Energy, Saudi Arabia.

https://nucleus.iaea.org/sites/smr/SitePages/HomeSmrPlatform.aspx

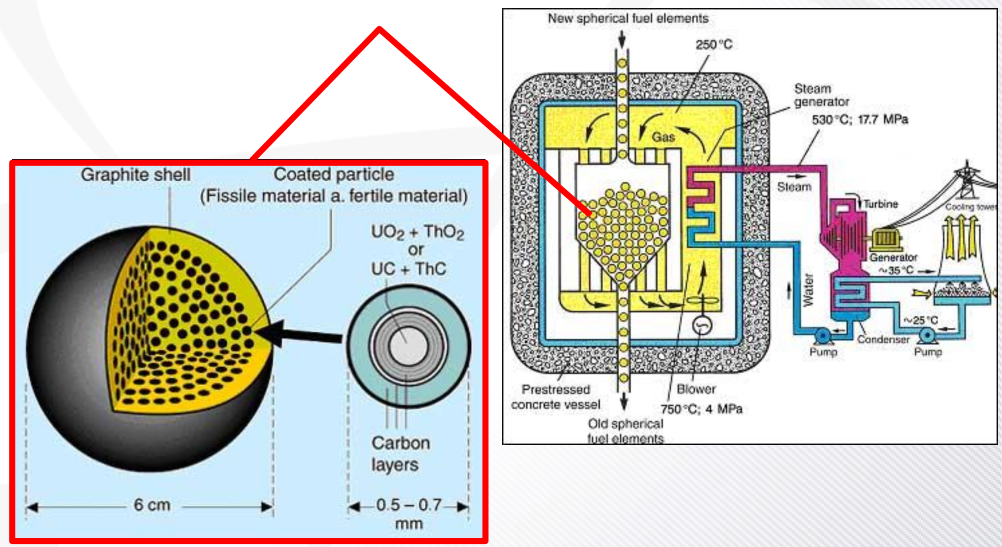
Technical challenges of SMRs

Research needs recommended by OECD/NEA

- **Technology improvement**
  - Passive safety systems
  - Digital I&C with automations
  - Artificial intelligence (?)
- **New technology development**
  - Pebble-bed reactor of a high temperature gas cooled SMR

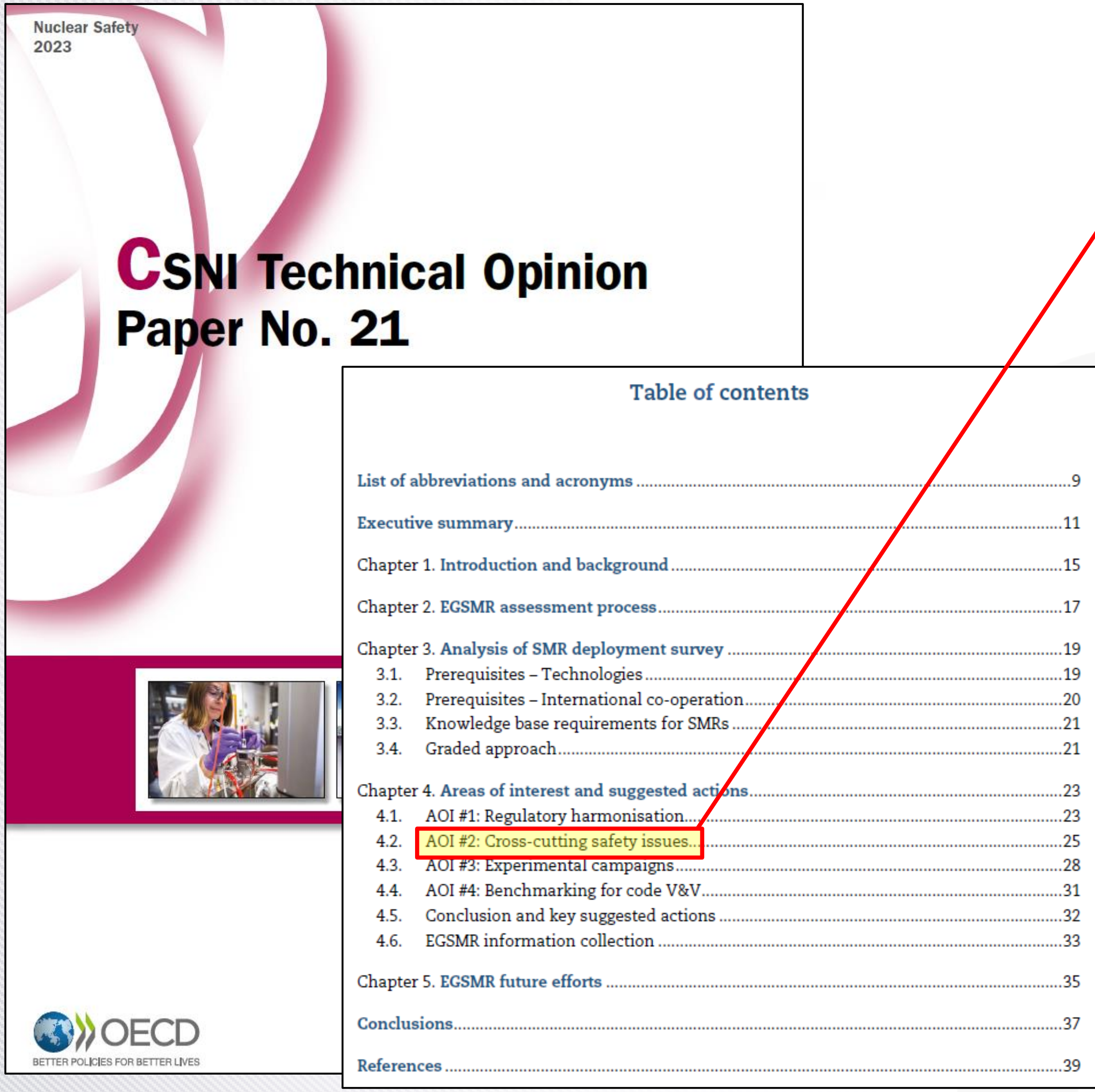


https://www.mdpi.com/1996-1073/16/13/5168



https://www.euronuclear.org/glossary/pebble-bed-reactor/

Research needs: Safe deployment of SMRs



Nuclear Safety
2023

CSNI Technical Opinion Paper No. 21

OECD
BETTER POLICIES FOR BETTER LIVES

Table of contents

1. Application of defense in depth with **passive safety systems**/features
2. PSA for innovative/FOAK designs
3. Investigation of emergency planning zones (EPZs) and emergency response requirements for SMRs
4. **Fuel** safety of SMRs
5. **Human factors (e.g., remote operations and multi-unit/multi-module plants)**
6. **Multi-unit/multi-module** design aspects to determine the impacts on safety including shared systems, adjacent unit/module accidents and common mode failures
7. Safety and security aspects related to the transport of fueled nuclear modules and transportable/floating nuclear power plants
8. Interconnections between SMRs and **associated process applications** (e.g., hydrogen production and heat generation process)

Big jumps in Human Factors: Main control room design

Manual operation with analog I&C technologies for managing a **single unit**

Human performance (reliability) is important.

Digital I&C systems with a high level automation to manage **multi-modules**

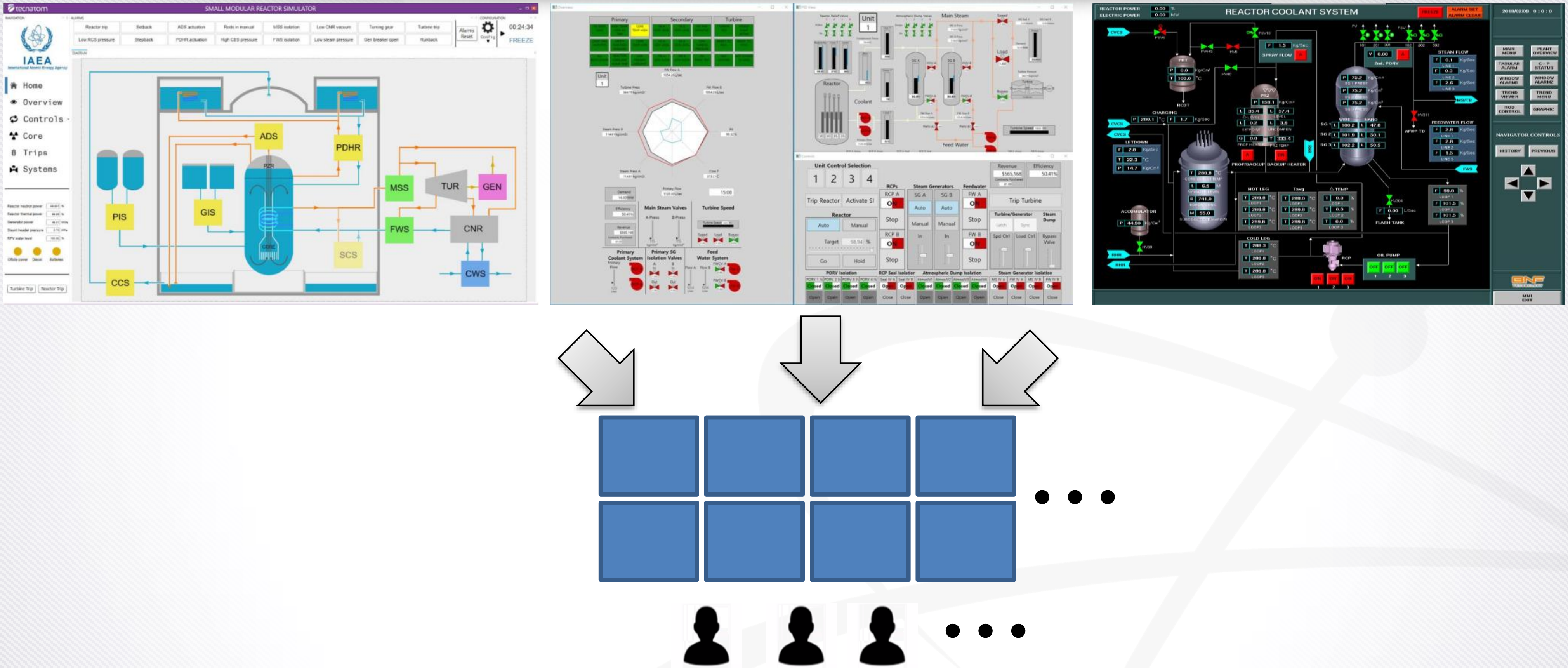
Urgent issue: Collection of human performance data

Human performance?

https://www.dtoday.co.kr/news/articleView.html?idxno=45508

Source of information		
	Operation experience (e.g., Framatome)	NO for SMRs
	Full scope simulators	Few simulators
	Laboratory experiments	
	Interview/subjective opinions from experts	Uncertainty

Alternative way to collect human performance data

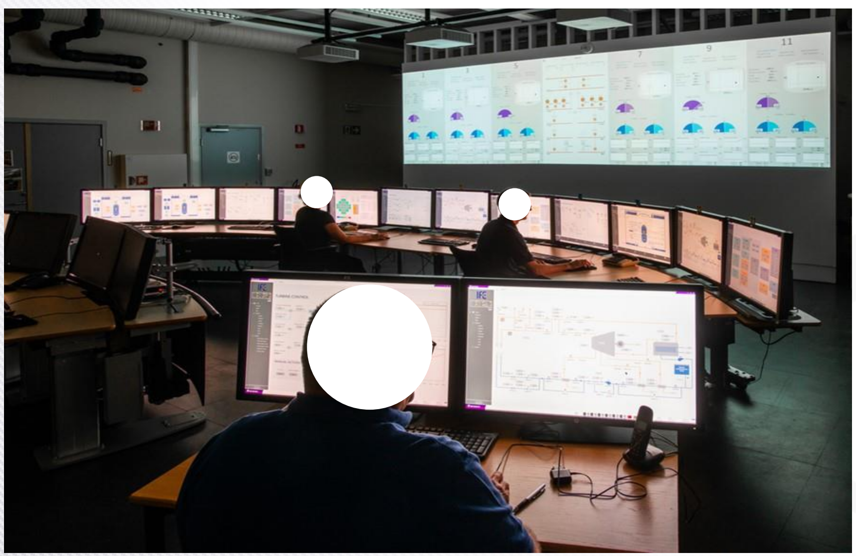


Many organizations are planning/conducting experiments to explore the effect of human performance issues on a multi-module operation environment.

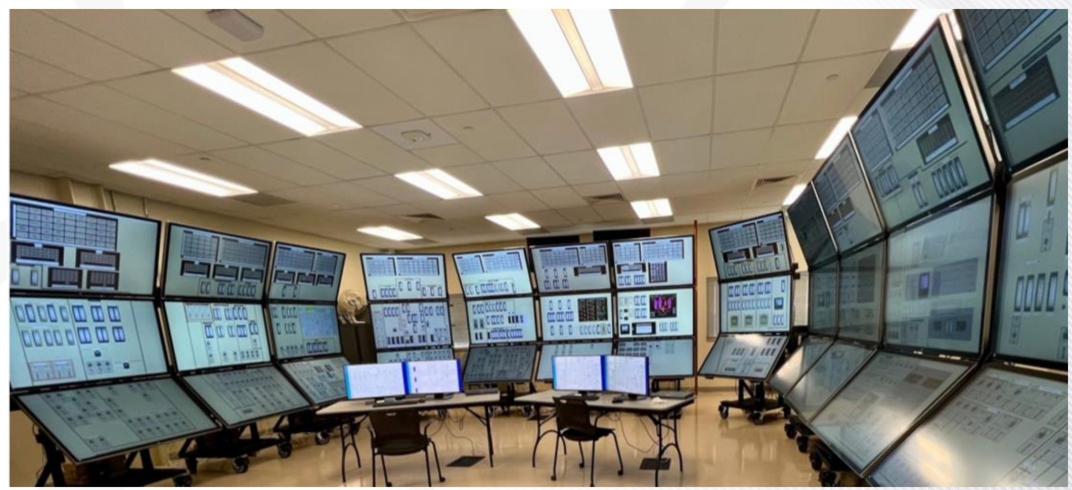
Human performance data collection: Worldwide status

- **IFE (Institute for Energy Tech.)**
  - Established SMR simulators in **2021** by integrating **6 iPWR** simulators
  - A series of experiments have conducted with US operators.
  - Additional data collection campaign is undergoing.

- **INL (Idaho National Lab.)**
  - Human System Simulation Laboratory (**HSSL**) originally built in 2012 to support control room modernization
  - New **HSSL-2** is being built (**2026**) for advanced reactors including SMRs.
  - Human performance data will be collected for multi-module operations.



https://ife.no/en/service/cutting-edge-smr-simulator-and-expert-services/



https://www.sciencedirect.com/science/article/pii/S1738573322005174

_Cooperation with IFE, INL and NRC

- **Constructing a consortium with four organizations**
  - To share human performance data collected from each organization
  - Primary outputs will be published by white papers and technical reports
- **U.S. NRC**
  - Simulator studies toward understanding the impact of new technology (e.g., SMRs and microreactors)

Korea Atomic Energy Institute

KAERI

Institute for Energy Technology

IFE

U.S. Nuclear Regulatory Commission

U.S.NRC

Idaho National Laboratory

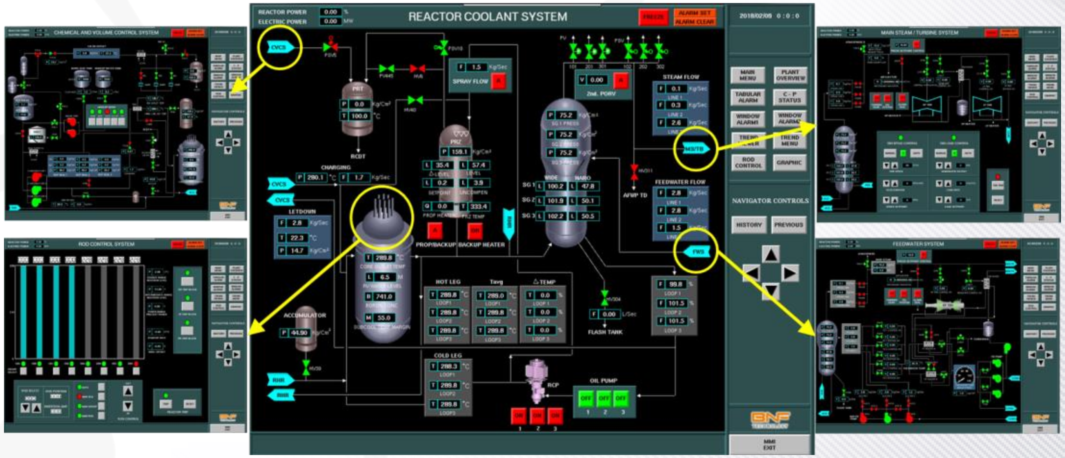
INL Idaho National Laboratory


Status in Korea

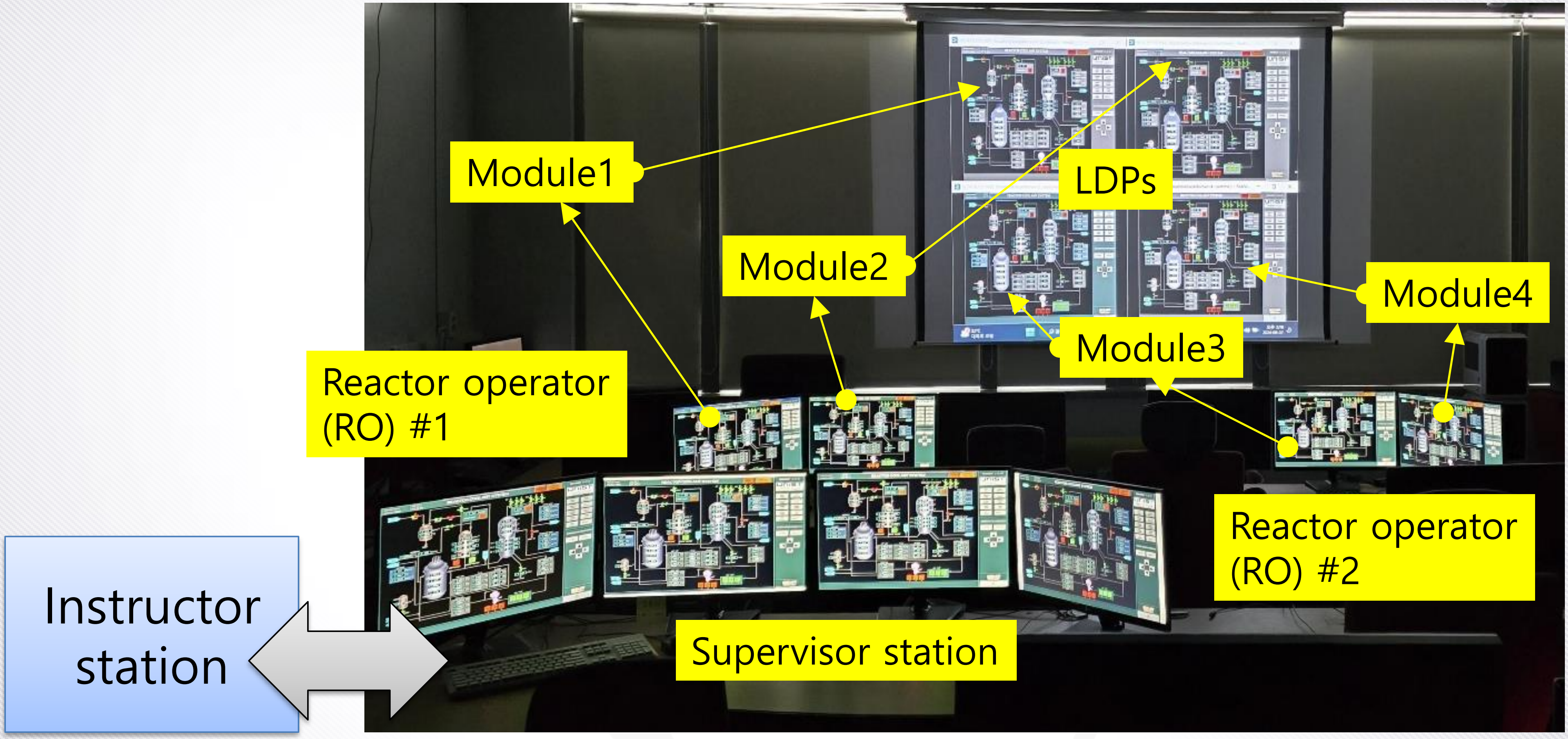
Human performance data collection: Korea (1/4)

- **A large number of experiments to investigate the performance of human operators in the iSMR operation environment.**
  - Four modules with 2 reactor operators (ROs) and one shift supervisor (SS)
  - Two modules per operator
  - Two display screens per module

- **Experiment facility was developed by integrating four CNSs (Compact Nuclear Simulator)**
  - Westinghouse 3-loop PWR
  - Partial-scope simulator for training
  - Emulating the primary, secondary, electrical systems and containment.



Human performance data collection: Korea (2/4)



Human performance data collection: Korea (3/4)

Experiment overview

- Performance measures
  - Error rate
  - Task completion time
  - Workload
  - Situation awareness
- Accidents/Transients
  - Loss of Coolant Accident (LOCA)
  - Steam Generator Tube Rupture (SGTR)
  - Excessive Steam Demand Event (ESDE)
- Number of trials
  - About **250 experiments** are expected.
- Subjects
  - Graduate/undergraduate **students**
  - Several **control room operators**

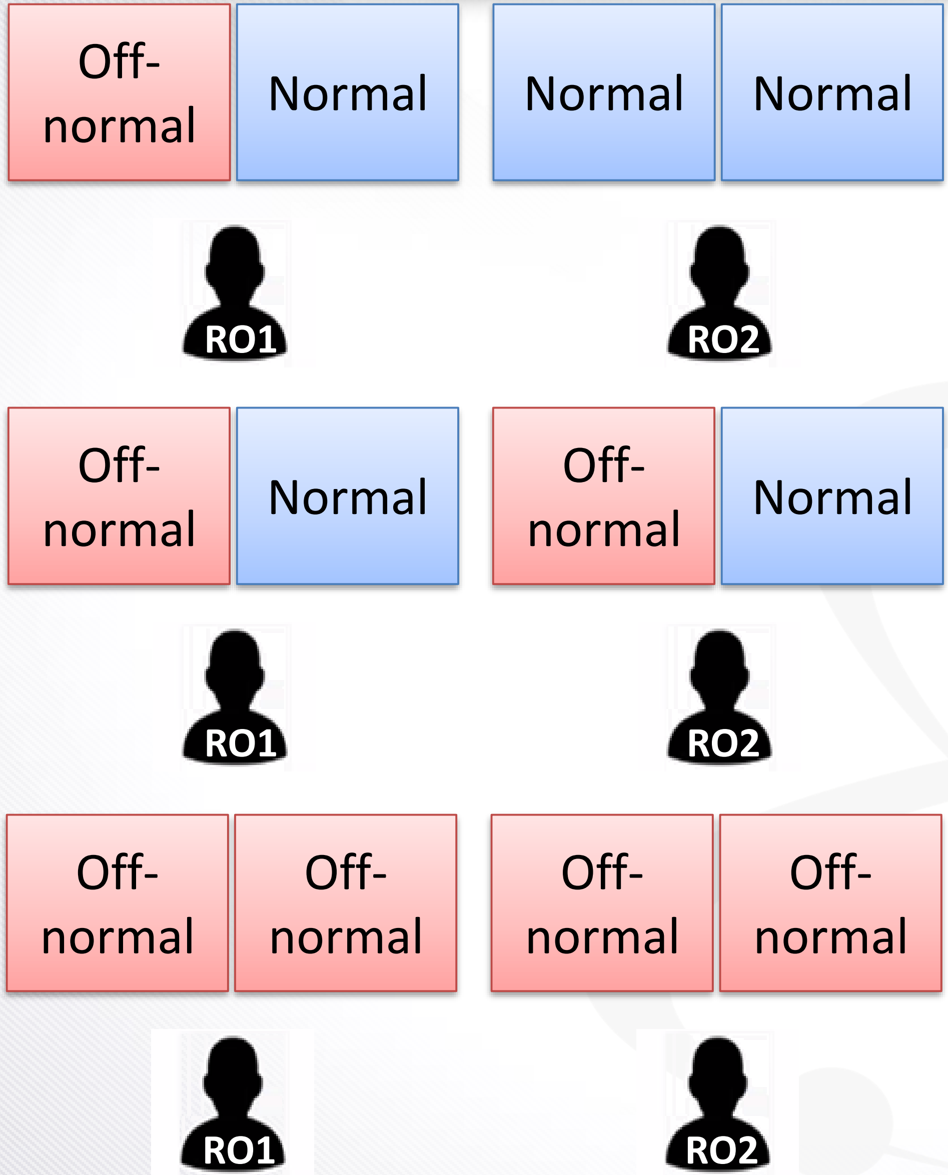
Expected timeline

- Preliminary experiment (Pilot test): July 2024
- Main experiment (Phase 1): August to December 2024
- Main experiment (**Phase 2**): January to June 2025
- Main experiment (Phase 3): June to October 2025
- Additional experiment (if needed): in 2026

Human performance data collection: Korea (4/4)

Controlled variable	Description	Condition
Number of off-normal modules per operator	Number of modules assigned to operator what are in off-normal conditions.	• 0.5 module/operator • 1.0 module/operator • 2.0 modules/operator
Homogeneity of off-normal conditions	Whether the operator should have different mental models or not. For instance, in case that accidents occurs in two modules controlled by one operator and the accidents are different, the operator should apply "different mental models" to each module for the mitigation.	• Different or Identical *(This condition only appears when 'Number of modules/operator' is 2.0.)*
Surveillance	Whether there is a supervisor who can monitor the operator's performance, and detect and recover errors	• Yes or No
Passive system status indication	Whether there is any information with which the operator can recognize status of passive systems (e.g., alarm or indicators).	• Yes or No
Automatic system status indication	Whether there is any information with which the operator can recognize status of automatic systems (e.g., alarm or indicators)	• Yes or No

_Number of off-normal modules/operator



$$\frac{\text{1 off−normal mudule}}{\text{2 operators}} = 0.5$$

$$\frac{\text{2 off−normal mudules}}{\text{2 operators}} = 1.0$$

$$\frac{\text{4 off−normal mudules}}{\text{2 operators}} = 2.0$$

_Homogeneity of off-normal conditions

LOCA	Normal	Normal	Normal

RO1 RO2

RO1: **Single** mental model for an off-normal condition

SGTR	Normal	ESDE	Normal

RO1 RO2

RO1/RO2: **Single** mental model for individual operator

RO1 and RO2: **Different** mental models with two off-normal conditions

LOCA	SGTR	SGTR	ESDE

RO1 RO2

RO1: **Homogeneous (similar)** mental model

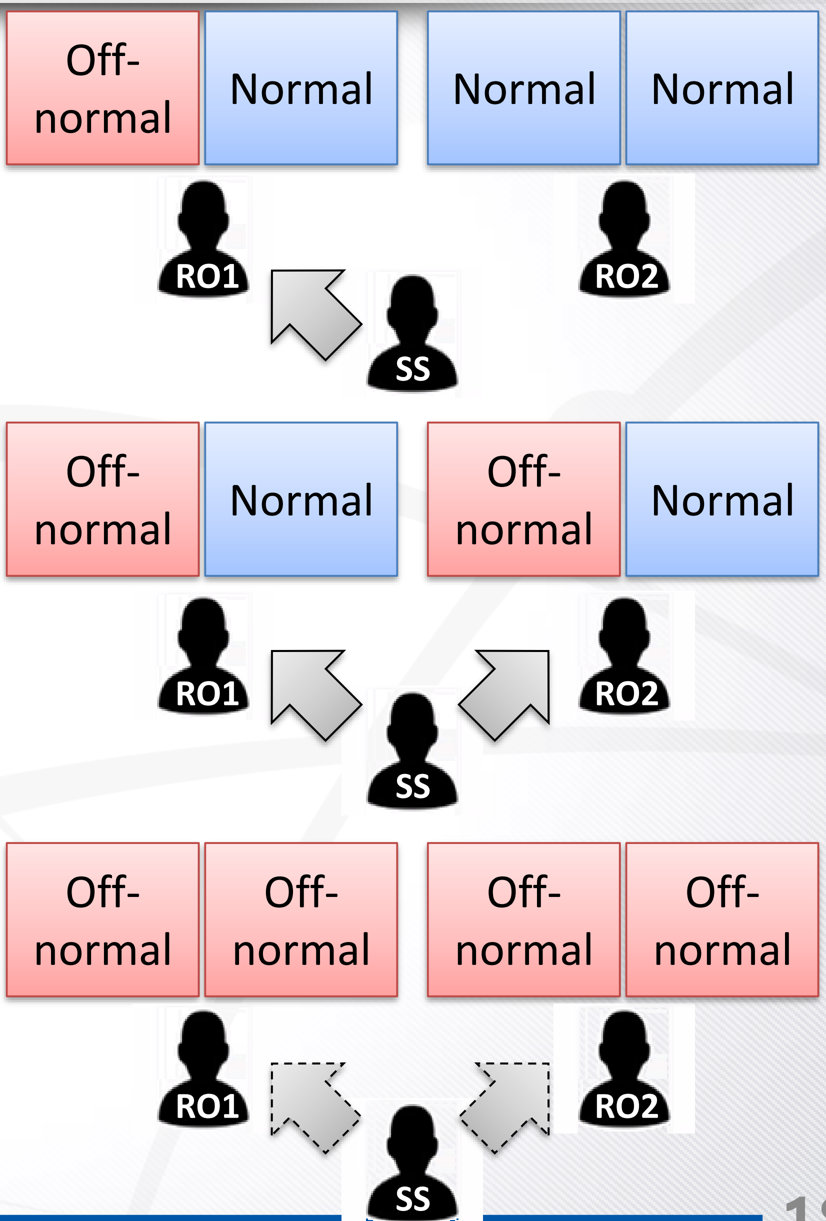
RO2: **Different** mental models

LOCA	LOCA	SGTR	ESDE

RO1 RO2

_SS's surveillance

- **SS needs to independently check the performance of an RO exposed to one more off-normal conditions.**
  - Helpful for the RO
- **The number of surveillance tasks loaded to SS will drastically increase in proportional to the number of off-normal conditions.**
  - The support of the SS to an RO will not be possible in an extreme condition.




Q&A