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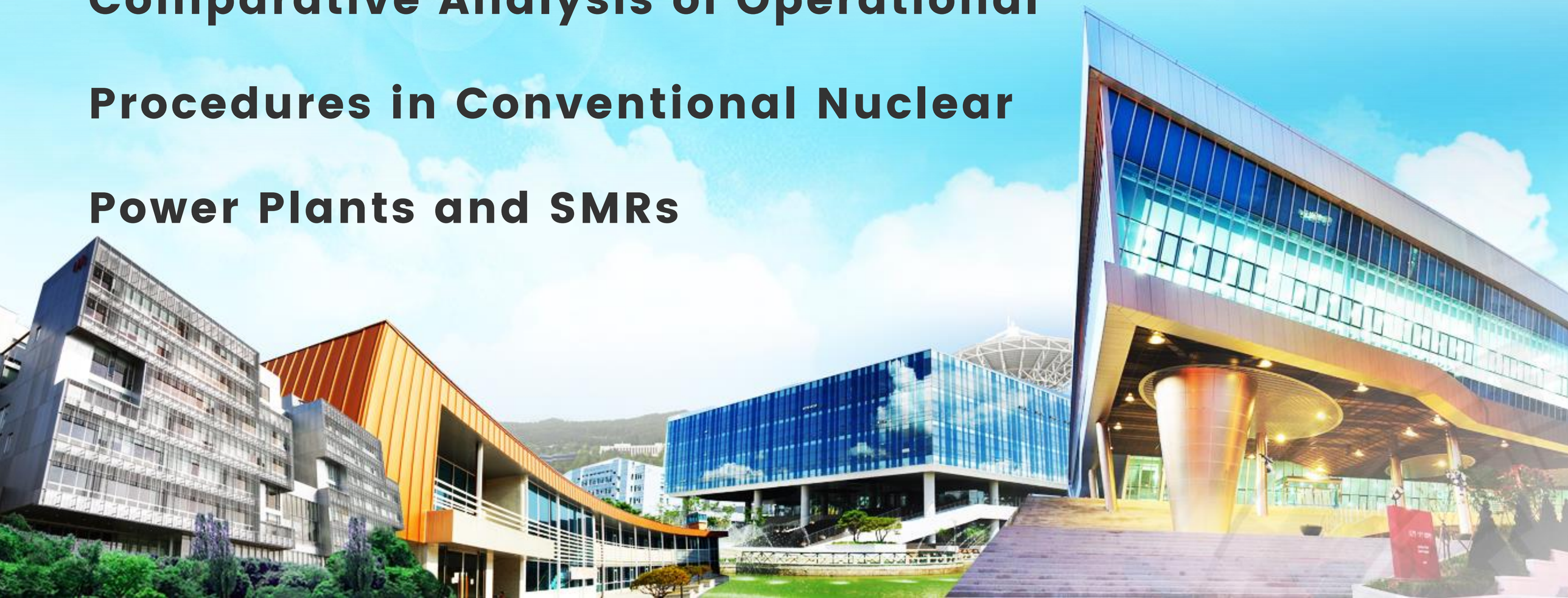
Comparative Analysis of Operational Procedures in Conventional Nuclear Power Plants and SMRs



Presentation Outline

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Introduction

Importance of Emergency Operating Procedures (EOPs)

- EOPs are designed to guide operators during emergencies by providing structured responses to mitigate the consequences of equipment failures, accidents, and plant transients [1].
- **Important features that need to be included in EOPs [1]:**
  - Event-oriented or function-oriented;
  - Immediate and subsequent operator actions;
  - Clear and readable by operators.
- Following the TMI accident, the U.S. Nuclear Regulatory Commission (NRC) mandated the implementation and periodic review of EOPs as part of its broader regulatory framework [2].

[1] U.S. Nuclear Regulatory Commission. (1982). Guidelines for the Preparation of Emergency Operating Procedures. NUREG-0899

[2] U.S. Nuclear Regulatory Commission. (1989). Lessons Learned from the Special Inspection Program for Emergency Operating Procedures. NUREG-1358.

I Introduction

Research Motivation

- **Problem Statement:**
  i. Small Modular Reactors (SMRs) is a new NPP technology.
  ii. New design characteristics = New conduct of operations.
  iii. No studies addressing how SMR EOPs should be developed.

Table 1: Potential Human Performance Issues in SMRs [1]

ConOps Dimension	Human Performance Issue
Plant Mission (Section 6.1)	New Missions
	Novel Designs and Limited Operating Experience from Predecessor Systems
Agents' Roles and Responsibilities (Section 6.2)	Multi-unit Operations and Teamwork
	High Levels of Automation for All Operations and Its Implementation
	Function Allocation Methodology to Support Automation Decisions
Staffing, Qualifications, and Training (Section 6.3)	New Staffing Positions
	Staffing Models
	Staffing Levels
Management of Normal Operations (Section 6.4)	Different Unit States of Operation
	Unit Design Differences
	Operational Impact of Control Systems for Shared Aspects of SMRs
	Impact of Adding New Units While Other Units are Operating
	Managing Non-LWR Processes and Reactivity Effects
	Load-following Operations
	Novel Refueling Methods
	Control Room Configuration and Workstation Design for Multi-Unit Teams
	HSI Design for Multi-unit Monitoring and Control
	HSIs for New Missions (e.g., steam production, hydrogen)
Management of Off-normal Conditions and Emergencies (Section 6.5)	Safety Function Monitoring
	Potential Impacts of Unplanned Shutdowns or Degraded Conditions of One Unit on Other Units
	Handling Off-Normal Conditions at Multiple Units
	Design of Emergency Operating Procedures (EOPs) for Multi-Unit Disturbances
	New Hazards
	Passive Safety Systems
	Loss of HSIs and Control Room
	PRA Evaluation of Site-wide Risk (i.e., across all units)
	Identification of Risk-Important Human Actions (RIHAs) when One Operator/Crew is Managing Multiple SMRs
Management of Maintenance and Modifications (Section 6.6)	Modular Construction and Component Replacement
	New Maintenance Operations
	Managing Novel Maintenance Hazards

[1] O'Hara, J., Higgins, J., & Pena, M. (2012). Human-Performance Issues Related to the Design and Operation of Small Modular Reactors (NUREG/CR-7126, BNL-NUREG-96654-2011). U.S. Nuclear Regulatory Commission..

Research Motivation(cont.)

- **Objective:** The focus of this study is to suggest how SMRs may approach emergencies based on their unique design characteristics, potentially leading to deviations from conventional NPP practices to make the current EOPs more feasible in a multi-module SMR context.
- **Scope:**
  i. Scrutiny of SMR Design Characteristics Relevant to EOPs;
  ii. How EOPs in Conventional NPP are constructed;
  iii. Take-home recommendations for SMR EOPs.

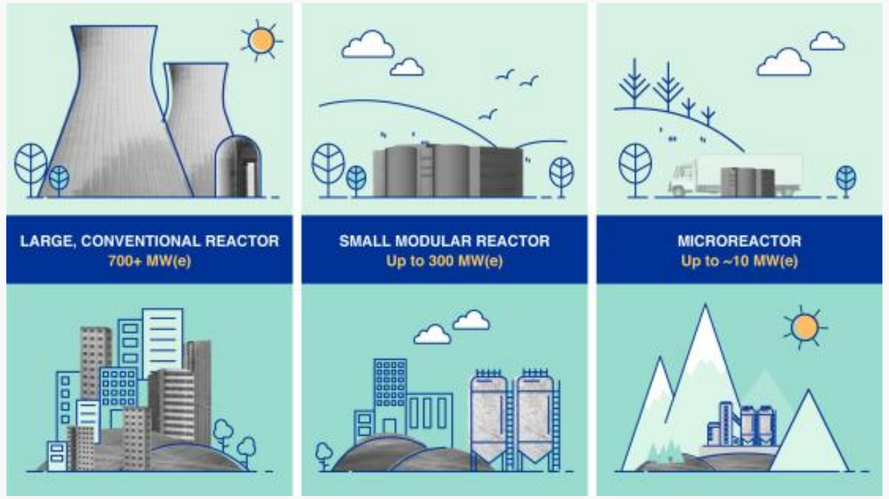

Image source:

https://www.iaea.org/newscenter/news/what-are-small-modular-reactors-smrs

Identification of Key SMR Design Characteristics

Generalized Characteristics of SMR Operations

Table 1: Comparison of Design Characteristics between SMRs and Conventional NPPs Relevant to EOPs

DImensions	Conventional NPP Design Characteristics	SMR Design Characteristics
Roles and Responsibilities	Single Unit MCR Operation	Multi-module MCR Operation
	Electric Power Generation	Electrical Power Generation and other plant purposes (e.g., hydrogen production)
	Manual Intervention by Operators	Higher Automation
Staffing	Normal Staffing Levels	Lower Staffing Levels than Conventional NPP
Off-Normal Operations	Rely More on Active Systems for Cooling	More Use of Passive Systems for Cooling
	Less Utilization of Shared Systems	More Shared Systems Among Modules
	HSI for Plant Evolution Included	HSI Tailored for Modular Control and Operations
	Known Hazards with LWR Plants	New Hazards with Non-LWR Plants

[1] Blackett, C., Eitrheim, M. H. R., & Bye, A. (2022). The Challenge of Assessing Human Performance and Human Reliability for First-of-a-Kind Technologies.

[2] O'Hara, J., Higgins, J., & Pena, M. (2012). Human-Performance Issues Related to the Design and Operation of Small Modular Reactors (NUREG/CR-7126, BNL-NUREG-96654-2011). U.S. Nuclear Regulatory Commission..

[3] Reyes, J. N. (2012). NuSCALE PLANT SAFETY IN RESPONSE TO EXTREME EVENTS. In NUCLEAR TECHNOLOGY (Vol. 178).

EOPs in Conventional NPP

Current EOP-Making Approach in Conventional NPP:

Licensees are required to document these in a procedures generation package [1]:

- **Generic Technical Guidelines (GTG):** Provides the technical basis for EOP development by outlining the critical safety functions (CSFs) operators must maintain during an emergency.
- **The Writer's Guide:** Details the form and structure that the EOP writer should follow in preparing EOPs.
- **Validation Program**
- **Training Program**

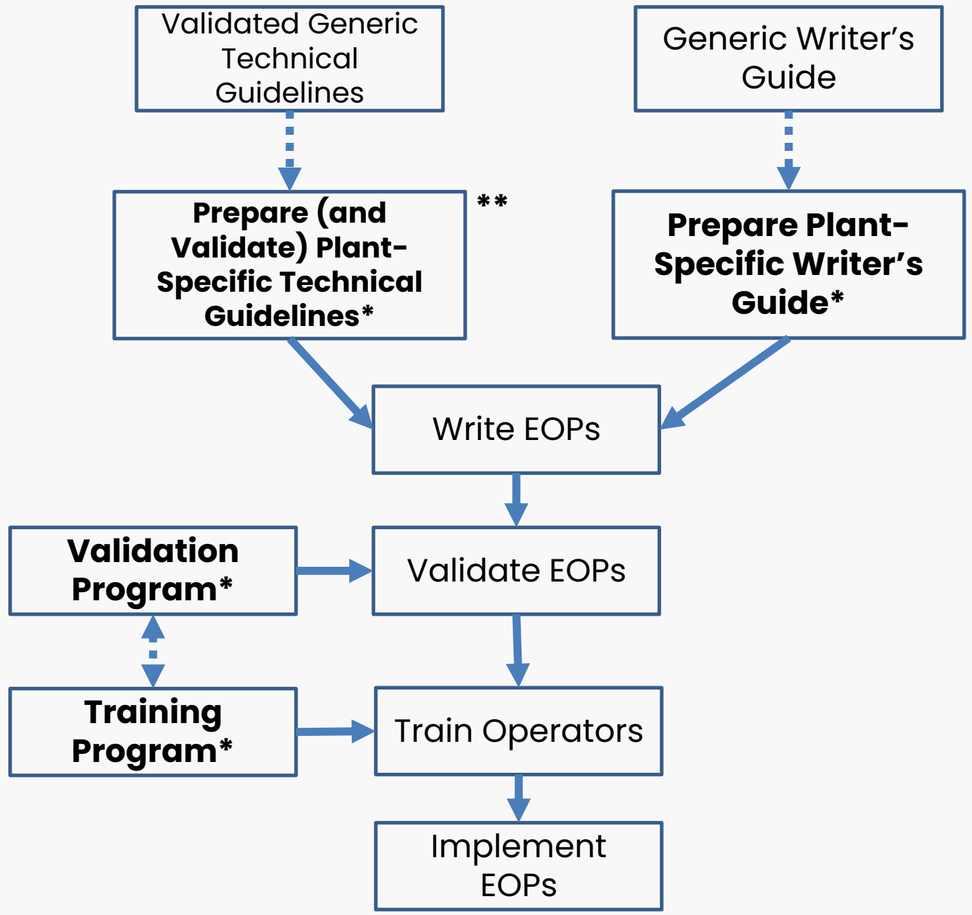

Figure 1: Sample Program for Developing EOPs [2]

[1] U.S. Nuclear Regulatory Commission. (1989). Lessons Learned from the Special Inspection Program for Emergency Operating Procedures. NUREG-1358.

[2] U.S. Nuclear Regulatory Commission. (1982). Guidelines for the Preparation of Emergency Operating Procedures. NUREG-0899

Important Information in EOPs

Generic EOP Development Method Includes Development of the Following Plant Specific Components [1]:

- Defined symptom/state-based entry conditions;
- Plant stabilization following reactor trip;
- Initial diagnosis;
- Event or state-based recovery procedures;
- Integrated event-based or state-based continuous diagnosis;
- Monitoring and recovery of safety functions;
- Contingency procedures to re-establish vital systems and recovery systems;
- Instrument response under accident conditions;
- Hazardous conditions within the plant present, under which on-site emergency workers may be required to take response actions associated with the application of the EOPs.

[1] International Atomic Energy Agency (IAEA). Development and Review of Plant Specific Emergency Operating Procedures. Vienna: International Atomic Energy Agency, 2006, p. 21.

EOPs Structure in Conventional NPP

Different EOP formats that are commonly used in the world [1]:

- One column (mostly used for abnormal procedures)
- Two-column (flow chart, etc.)

Selection between them should be based on these factors:

i. Quality of the support documents (colors, diagrams, use of various ergonomic concepts, etc.);
ii. Cultural influences on the operator;
iii. Format of the other operating documents, etc.

Possible Options Regarding the Computerization of EOP Usage in the Control Room [1]:

- Full paper EOPs, no computerization;
- Stand-alone computerized EOPs;
- On-line computerized EOPs.

[1] International Atomic Energy Agency (IAEA). Development and Review of Plant Specific Emergency Operating Procedures. Vienna: International Atomic Energy Agency, 2006, p. 21.

Differences of EOPs in SMRs

- Higher automation and increased utilization of passive systems in SMRs ensure that there are no severe accidents; hence, there might **not be any event-based procedures**.
- **Crew complement** in SMR EOPs is different due to lower staffing levels.
- Some tasks for recovery of safety functions might be automated. Therefore, **operators' roles** in SMR EOPs might change from manual intervention to mostly monitoring and intervening only when the passive/automated systems fail.

[1] O'Hara, J., Higgins, J., & Pena, M. (2012). Human-Performance Issues Related to the Design and Operation of Small Modular Reactors (NUREG/CR-7126, BNL-NUREG-96654-2011). U.S. Nuclear Regulatory Commission.

[2] International Atomic Energy Agency (IAEA). Development and Review of Plant Specific Emergency Operating Procedures. Vienna: International Atomic Energy Agency, 2006, p. 21.

[3] Blackett, C., Eitrheim, M. H. R., & Bye, A. (2022). The Challenge of Assessing Human Performance and Human Reliability for First-of-a-Kind Technologies.

Recommendation for SMR EOPs

IV Recommendation for SMR EOPs

SMR Design Characteristics	Insights
Multi-module MCR Operation	Tasks in SMR EOPs should be arranged in a way that prioritizes affected modules.
Electrical Power Generation and Other Plant Purposes (e.g., hydrogen production)	SMR EOPs should include work processes outside of nuclear power generation.
Higher Automation	Level of Automation (LoA) in SMR EOPs must be clearly defined for each task.
Lower Staffing Levels than Conventional NPP	Roles and responsibilities of each operator must be revised in SMR EOPs.
More Use of Passive Systems for Cooling	Steps to monitor and verify the success of passive systems must be included in SMR EOPs.
More Shared Systems Among Modules	SMR EOPs must guide the operators to manage shared resources efficiently across modules.
HSI Tailored for Modular Control and Operations	SMR's HSI must be designed to fit all modules' critical information for operators to conduct EOPs.
New Hazards with Non-LWR Plants	These new hazards must be understood and addressed in SMR EOPs.

[1] O'Hara, J., Higgins, J., & Pena, M. (2012). Human-Performance Issues Related to the Design and Operation of Small Modular Reactors (NUREG/CR-7126, BNL-NUREG-96654-2011). U.S. Nuclear Regulatory Commission..

[2] Boring, R. L., & Gertman, D. I. (2012). Human Reliability Analysis for Small Modular Reactors.

[3] Blackett, C., Eitrheim, M. H. R., & Bye, A. (2022). The Challenge of Assessing Human Performance and Human Reliability for First-of-a-Kind Technologies.

Conclusion

Conclusion

SMR design characteristics must be taken into account during EOP development.

Future Work

Conduct multi-module experiments with simulators to validate the usability of the suggested approaches.

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Thank you for listening!