Approaches to and Preparation for the Operation of SMRs

Based upon IAEA TECDOC-2110

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Joint IAEA-ICTP Workshop on Reactor Physics, Thermal Hydraulics and Plant Design Engineering of Small Modular Reactors (SMR4212)

16 Apr. 2026

Self Introduction

Jaehun JUNG

- Consultant(Cost Free Expert) at Nuclear Power Engineering Section

- **KHNP, Republic of Korea for 22 years**
  - ✓ 12 years at NPPs, 10 years at Headquarters
  - ✓ Plant Operation, Investigation of NPP Accident, Safety Culture Management
  - ✓ My last position: General Manager on Nuclear Policy Management
- **Educational Background and Others**
  - ✓ Senior Reactor Operator of PWR900MW(WH): 2007
  - ✓ Master of Business Administration Degree: 2018
  - ✓ Bechelor of Mechanical Engineering: 2002
  - ✓ World Nuclear Summer Institute: 2012

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Background and Objective of TECDOC

Background

- A growing interest in SMR technology in Member States.
- 2 NPPs with SMR are in commercial operation (China & Russia).
- 3 units under construction for operation by 2030, several units to start construction for operation 2030 – 2035.

Objective

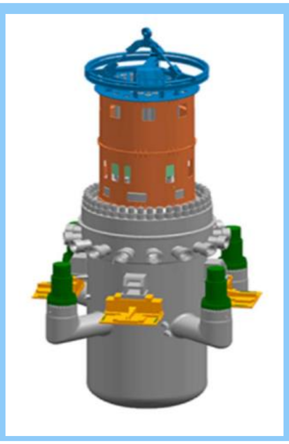
- Technical Guidance on Operation Readiness for SMRs
  - ✓ Technical information for operation of near term deployable SMRs.
  - ✓ Operational readiness and Strategy based on current operating SMRs and conventional NPPs.

Timeline of the TECDOC Development

Feb 2022	Initiation of Publication Process
May/Nov 2022	Consultancy Meeting #1 / #2
May 2023	Consultant meeting #3
Aug 2023	Technical Meeting
Oct 2023	Consultant meeting #4
Feb 2024	Final Consultant meeting
Mar 2024	Revision and Internal Process for Publication
Dec 2025	Publication completed (IAEA website upload)

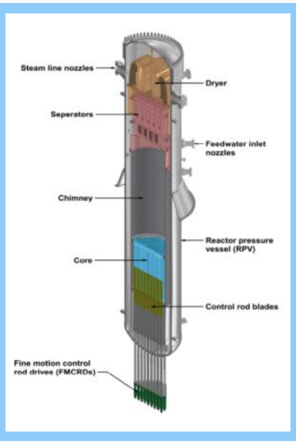
Participants of MSs (SMR)

ACP100 (CNNC, China)



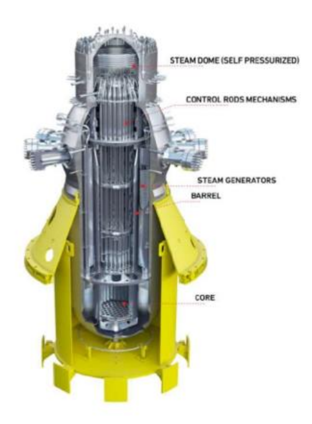
Value
Integral PWR
Light water / Light water
385MW(t) / 125MW(e)
Forced circulation
UO_2 / 17 × 17 square (57)
Passive
Under construction

BRWX-300 (GE-Hitachi, USA&Japan)



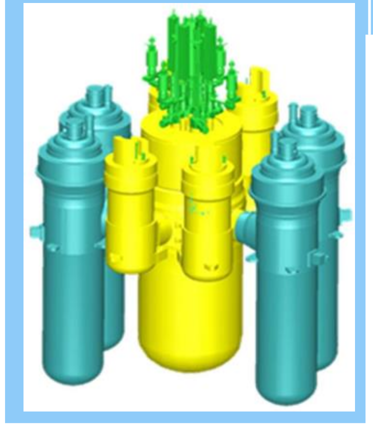
Value
Boiling water reactor
Light water / Light water
870MW(t) / 300MW(e)
Natural circulation
UO_2 / Square Lattice (240)
Passive
Under construction

CAREM (CNEA, Argentina)



Value
Integral PWR
Light water / Light water
100MW(t) / ~30MW(e)
Natural circulation
UO_2 / Hexagonal (61)
Passive
Under construction

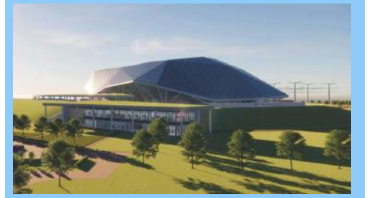
KLT-40S (Rosatom, Russia)



Value
PWR
Light water / Light water
150MW(t) / 35MW(e)
Forced circulation
UO_2 / Silumin Matrix (121)
Active (partially passive)
In Operation

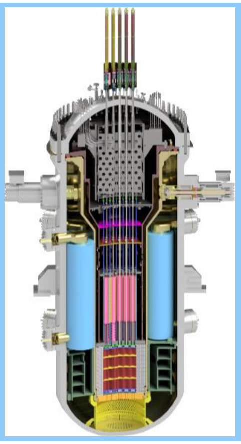
Participants of MSs (SMR)

Rolls-Royce (Rolls-Royce, UK)



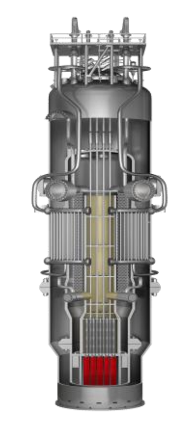
Value
3-loop PWR
Light water / Light water
1385MW(t) / 470MW(e)
Forced circulation (Natural Backup)
UO_2 / 11 × 11 square (121)
Passive and Active
Mature Conceptual Design

SMART(KAERI, Rep. of Korea)



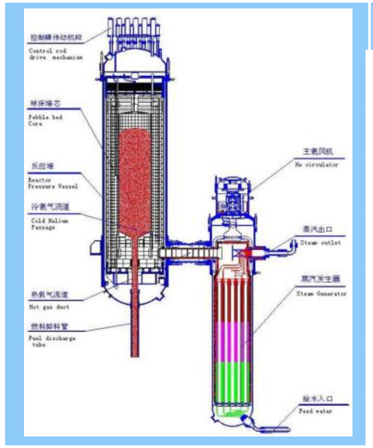
Value
Integral PWR
Light water / Light water
365MW(t) / 107MW(e)
Forced circulation
UO_2 / 17 × 17 square (57)
Passive
Detailed Design

VOYGR^{TM} (Nuscale, USA)



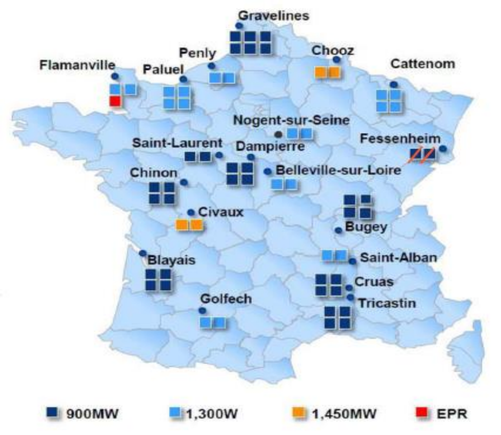
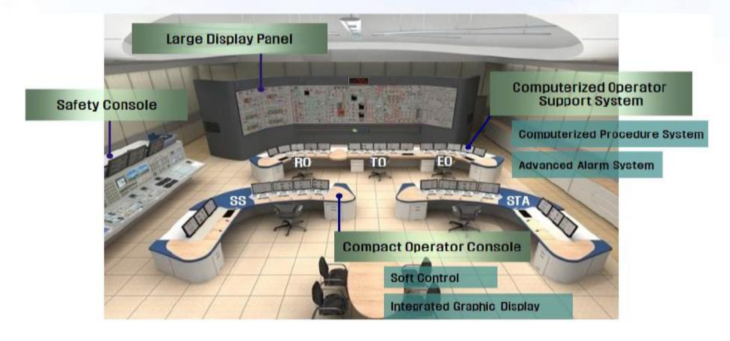
Value
Integral PWR
Light water / Light water
250MW(t) / 77MW(e)
Natural circulation
UO_2 / 17 × 17 square (37)
Passive
Received Standard Design Approval

HTR-PM (Huaneng, China)



Value
High Temp. gas cooled Reactor
Helium / Graphite
2 × 250MW(t) / 210MW(e)
Forced circulation
Spherical elements with coated particle fuel (420,000 per module)
Combined Active and Passive
In Operation

Participants of MSs (Large NPP)

Darlington NPPs (Ontario Pow.)	NPPs in France (EDF)	Saeul NPPs (KHNP)
		
• CANDU PHWR 4 Reactor Unit – Designed in 1970s – Operation in 1990s • Each 2776 MW(t) /878 MW(e) • 1 Integrated Main Control Room covering 4 units	• NPP units in France • Flexible design capabilities – Daily / Cycle / Monthly shape / Per reactor / Fleet overview	• APR1400 • 2 Reactor units / 2 two identical MCR • Fully digitalized control system and Human Machine Interface
1 MCR for 4 Units	**Flexible Operation**	**Digitalized Control System and HMI**

Outline of Publication

Section 1: Introduction	• Background, Objective, Scope, and Structure
Section 2: Perspective of near-term deployable SMRs	• Key features of near-term deployable SMRs; Water-cooled SMRs, modular HTGRs
Section 3: Key aspects of SMR Plant Operations	• LCOs in Tech Spec, safety limit, diff. between large NPPs and SMRs, Operator Consoles and Interface, Startup and Operational Approach (operating proc. & guidelines)
Section 4: Control and Maneuver Approach of SMRs	• Control of NSSS [diff: large NPP vs SMR]; Control of BOP; Power-flow-map for startup (BWR and natural circulation PWR); Flexible operation
Section 5: Impact of Operation to Fuel Integrity	• General fuel integrity, fuel integrity due to flexible operation, specific fuel design and characteristics
Section 6: Operating Management and HMI	• Arrangement of MCR crews in SMRs, Roles and Responsibility of MCR crews, Human Machine Interface
Section 7: Summary and conclusions	• Summary and main conclusions regarding the status of conduct of operation of SMRs; Recommendations, etc.

Scope

1. Key aspects of SMR Plant Operations

- Modes of plant operation
- Limiting Conditions for Operation (LCOs) in T.S
- Start-up and operation approach
- Normal operating procedures and guidelines

2. Control and Maneuver Approach

- Control of Nuclear Steam Supply System (NSSS)
- Control of Balance of Plant (BOP) system
- Power-flow map for normal and transient operation
- Flexible and load following operation

3. Impact of Operation to Fuel Integrity

- General fuel integrity of SMRs
- Fuel integrity of SMRs due to flexible operation,
- Specific fuel design and characteristics

4. Operating Management and Human Machine Interface

- Arrangement of MCR crews
- Roles and Responsibility of MCR crews
- Human Machine Interface

What makes SMR Different?

❑ Why SMR Now?

- Energy transition & renewables variability
- Need for flexible, smaller, deployable reactors
- Multi-purpose: electricity + hydrogen + desalination + etc.

❑ Differences

Feature	Large NPP	SMR
Size	GW-scale	10–300 MW
Safety	Active systems	Passive systems
Operation	Base-load	Flexible/load-following
Construction	Site-built	Factory-built modules
Staffing	Large crews	Small, automated crews

SMR Operation Philosophy

- ❑ **Simpler Systems**
  - ✓ Integrated and simplified system design
  - ✓ Fewer components and interfaces
- ❑ **More Automation**
  - ✓ Advanced digital control systems manage routine operations
  - ✓ Consistent and optimized plant performance
- ❑ **Inherent & Passive Safety**
  - ✓ Safety functions based on natural forces (gravity, natural circulation)
  - ✓ Extended grace period for operator response
- ❑ **Multi-Module Coordination**
  - ✓ Multiple reactor modules operated from a single control room
  - ✓ Flexible power adjustment through module dispatch

➢ Operator Role Shift

- **From Manual Control → To Supervisory Control**

How SMRs Operate?

1. Modes of Operation

- Plant operating statuses classified under one of several modes corresponding to combination of reactivity, coolant temp., etc.

< APR1400 >

Mode	Title	Reactivity condition (K_{eff})	Rated thermal power (%)	Reactor coolant average temperature (T_{avg}/ °C)
1	Power operation	≥ 0.99	> 20	n.a.
2	Startup operation	≥ 0.99	≤ 20	n.a.
3	Hot standby	< 0.99	n.a.	➢ 215
4	Safe shutdown	< 0.99	n.a.	$93 < T_{avg} \leq 215$
5	Cold shutdown	< 0.99	n.a.	≤ 93
6	Refuelling operation	n.a.	n.a.	n.a.

< KLT-40S >

Mode	Title	Reactivity condition (K_{eff})	Reactor cold/hot leg coolant temperature (°C)
1	Power operation	≥ 0.99	280/316
2	First criticality	≥ 0.99	280/316
3	Hot shutdown	< 0.99	> 99
4	Cold shutdown	< 0.99	≤ 99
5	Shutdown for repair/refuelling	n.a.	≤ 60

< HTR-PM >

Mode	Title	Reactivity (k_{eff})	Rated thermal power (%)	Average core temperature (T_{avg}/°C)
1	Power operation	≥ 0.99	≥ 30	N/A
2	Startup	≥ 0.99	< 30	N/A
3	Normal shutdown	< 0.99	N/A	≥150
4	Cold shutdown	< 0.99	N/A	$150 > T_{avg} \geq 50$
5	Maintenance Shutdown	< 0.99	N/A	< 50

➢ **Fewer Modes, Load-following flexibility, Extended fuel cycle, Modular operation., etc**

How SMRs Operate?

2. Operating Limit and Conditions

- A set of parameters with limiting values that are necessary for the safe operation of the plant in Tech. Specification.

Parameter	APR1400	KLT-40S	SMART	VOYGR
Safety Limits	• DNBR[1] ≥ 1.29 • Peak fuel Temp. ≤ 2805°C • RCS Pr. ≤ 19.0 Mpa	• Rx Power (6Cond.) • Power doubling period (15sec.) • RCS Pr. (5Cond.) • Primary coolant flow rate • Feed water Rate	• DNBR[1] ≥ 1.50 • LHR[2] ≤ 622 W/cm • RCS Pr. ≤ 18.7 Mpa	• CHF[3] correlation - NSP4 ≤1.21 - NSPN-1 ≤ 1.15 • Fuel Temp. : $1.37\times10^{-3}\times$burnup, MWD/MTU)°F • RCS Pr. ≤ 16.7 Mpa

* 1) DNBR: Dep. Of Nuclear Boiling Ratio, 2) LHR: Linear Heat Ratio, 3) CHF: Critical Heat Flux

➢ **Passive safety functions, Long operating intervals, Modular safety interactions., etc**

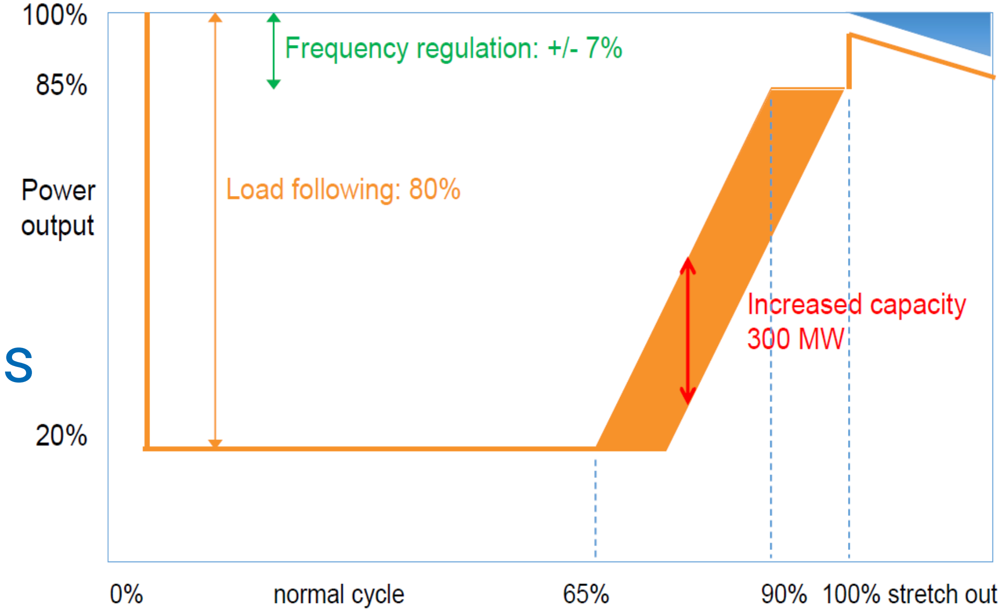
How SMRs Operate?

3. Flexible Power Operation (Large NPPs)

NPPs in France

- Load following (Agreed with the grid operator)
  - ✓ 2 Large variations/day
  - ✓ Ramp up / down in 30min
  - ✓ Down to 20% nominal power
- Frequency Control : Automatic load variations
  - ✓ Frequency Inertia
  - ✓ Voltage control

<Flexible design capabilities of French PWR>



➢ Effects of Flexible Operation

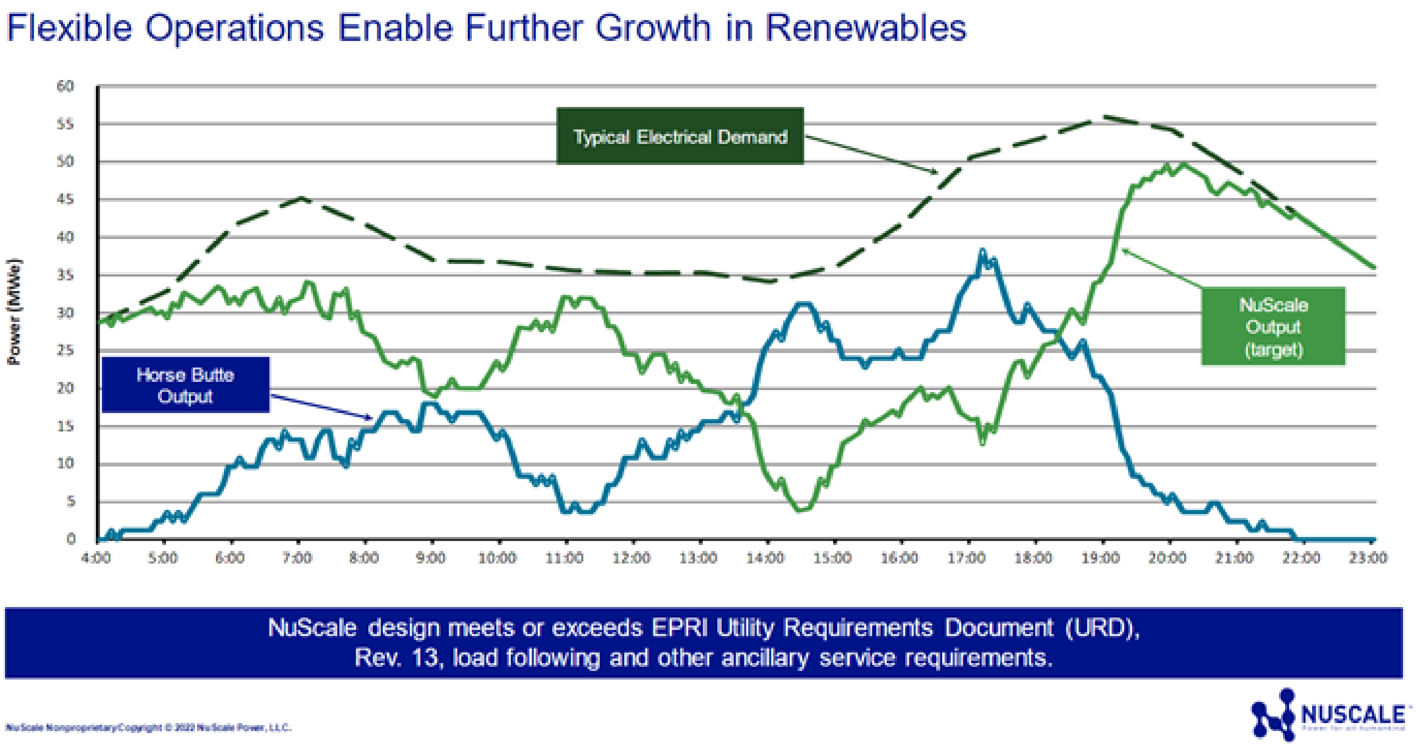
- ✓ Environment : No noticeable radioactive release
- ✓ Chemistry & Worker : No noticeable impact and nor radiological condition
- ✓ Operations & Maintenance : **No impact on the plant lifetime and corrective maintenance**

How SMRs Operate?

4. Flexible Power Operation (SMR)

VOYGR™

- Module dispatch
  - ✓ Up : HSD → 100% (13 hr)
  - ✓ Down : 100% → HSD (30 min)
- Reactor power change
  - ✓ Up : 50 → 100% (60 min)
  - ✓ Down : 100 → 50% (15 min)
- Turbine bypass
  - ✓ Up : 20 → 100% (27 min)
  - ✓ Down : 100 → 20% (8 min)

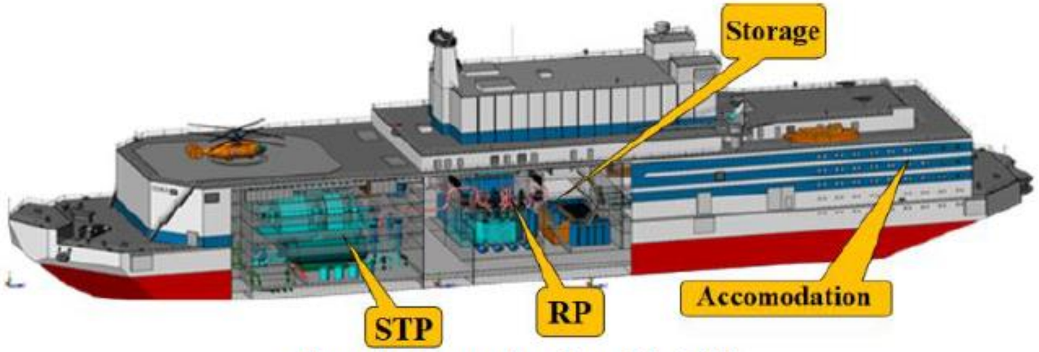


How SMRs Operate?

4. Flexible Power Operation (SMR)

KLT-40S

- Both Automation and Manual Operation
  - ✓Regulate reactivity
  - ✓Feedwater flow rate
  - ✓Turbine bypass flow rate



General cross-section view of the FPU

- Reactor control and protection system that ensure the NSSS safety of in all operation modes
  - ✓Small load changes: Control rods Movement
  - ✓Significant load change: Water exchange with dissolved absorber concentration in RCS

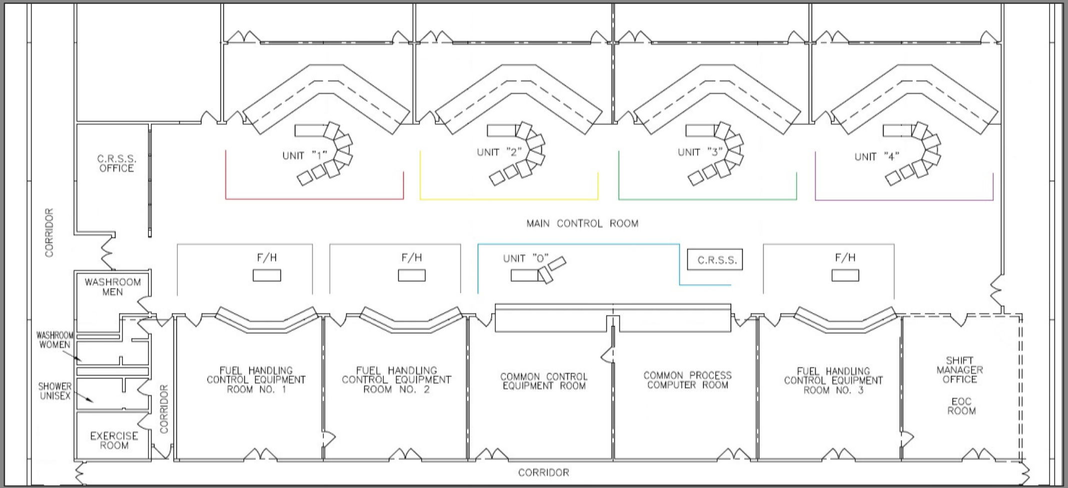
SMART

- Reactivity change: Single bank movement

How SMRs Operate?

5. MCR Arrangement & Human Man Interface (Large NPPs)

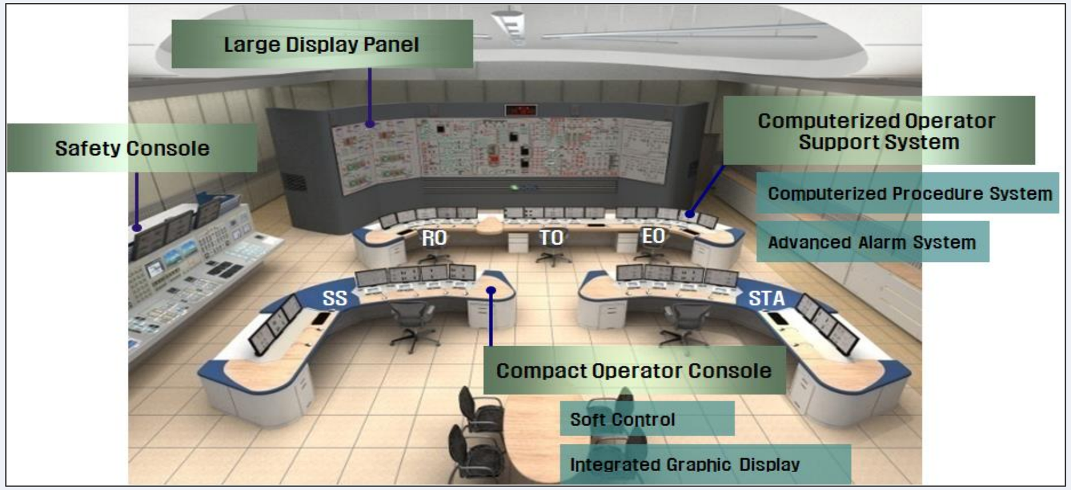
Darlington Unit #1~4 (CANDU)



MCR Crews (12)

- 6 Authorized Nuclear Operators (ANO)
- 2 Unit #0 Control Room Operators (CRO)
- 1 Control Room Shift Supervisor (CRSS)
- 1 Shift Manager (SM)
- 1 FH Control Room SNO
- 1 FH Panel Qualified Operator (PQO)

Saeul Unit #1 (APR1400)



MCR Crews (5)

- 1 Reactor Operator (RO)
- 1 Turbine Operator (TO)
- 1 Electrical Operator (EO)
- 1 Shift Technical Advisor (STA)
- 1 Shift Supervisor (SS)

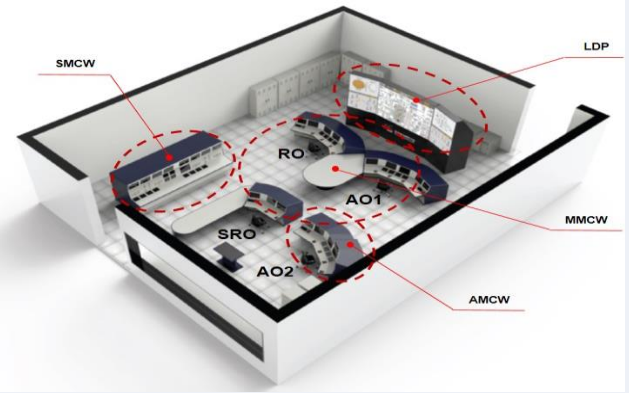
How SMRs Operate?

5. MCR Arrangement & Human Man Interface (SMR)

KLT-40S

- **2 Set of Units/12 Crews**
- 1 Plant Supervisor
- 2 lead unit Control Eng.
- 1 Rx. Dep. Operator
- 1 Sen. Tur. Operator
- 2 Aux. Tur. Operators
- Elec. Eng. / Mech. Eng. / I&C Eng. etc

SMART



- **MCR Crews (4)**
- 1 SRO
- 1 RO
- 2 Assistant operator : TO & Whole system and support RO/TO

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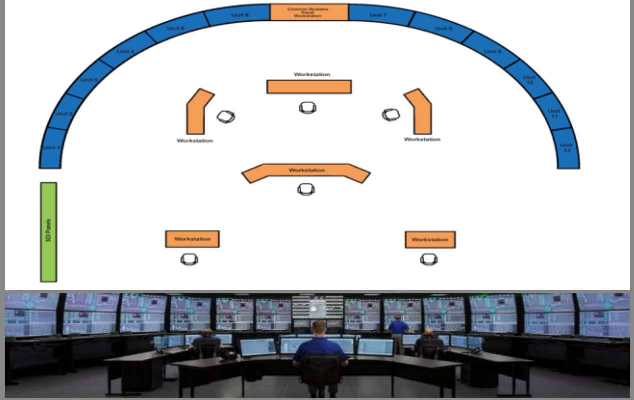
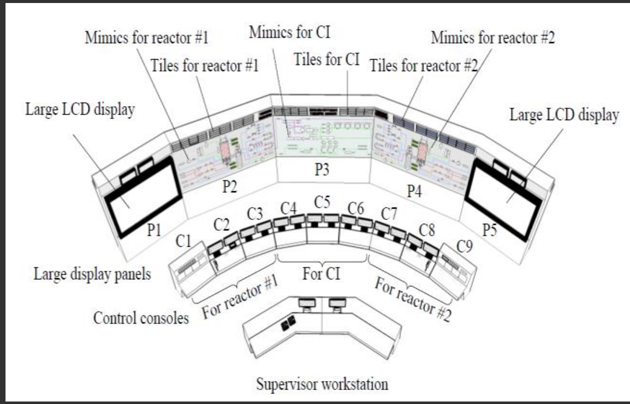


- **1 MCR for 12 Modules**
- **3 Minimum Licensed operators**
- 1 RO : Unit 1 NSSS Module
- 2 SRO : Shift Manager / Control Rm Supervisor

HTR-PM



- **1 MCR for 2 Modules**
- **MCR Crews (4)**
- #1 RO : Unit1
- #2 RO : Unit2
- 1 CO : Turbine module
- 1 SO : General coordination and management

Challenges and Future Outlook

- ❑ **SMR Potential**
  - ✓ 70+ designs under development
  - ✓ Flexible, modular, multi-application (power, hydrogen, desalination)
- ❑ **Knowledge Gaps**
  - ✓ Limited operational data and experience
  - ✓ Need for global sharing of lessons learned
- ❑ **Operations & Safety**
  - ✓ Conventional NPP modes + stricter OLCs
  - ✓ Testing phases validate safety & readiness
- ❑ **Technology & Control**
  - ✓ Advanced automation, inherent safety, flexible operation
  - ✓ Challenges: fuel performance & integrity under variable loads
- ❑ **MCR & Staffing**
  - ✓ Smaller, automated crews with digital HMIs
  - ✓ Efficient yet capable of robust emergency response

Conclusion & Takeaways

- ❑ **SMR is Not Just a "Small NPP“**
- ❑ **Radical Shift in Operational Paradigm**
- ❑ **Evolution of the Operator's Role**
- ❑ **Automation and Digitalization as Core Enablers**
- ❑ **Multi-Module Operation: A New Frontier**
- ❑ **An Evolving Technology (Work in Progress)**

"SMRs are not just reactors—they are integrated energy systems."

Thank you

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