4차 산업혁명 핵심기술의 원자력분야 연구 및 적용방안

Design Features & Development Status of the Autonomous SMR ATOM

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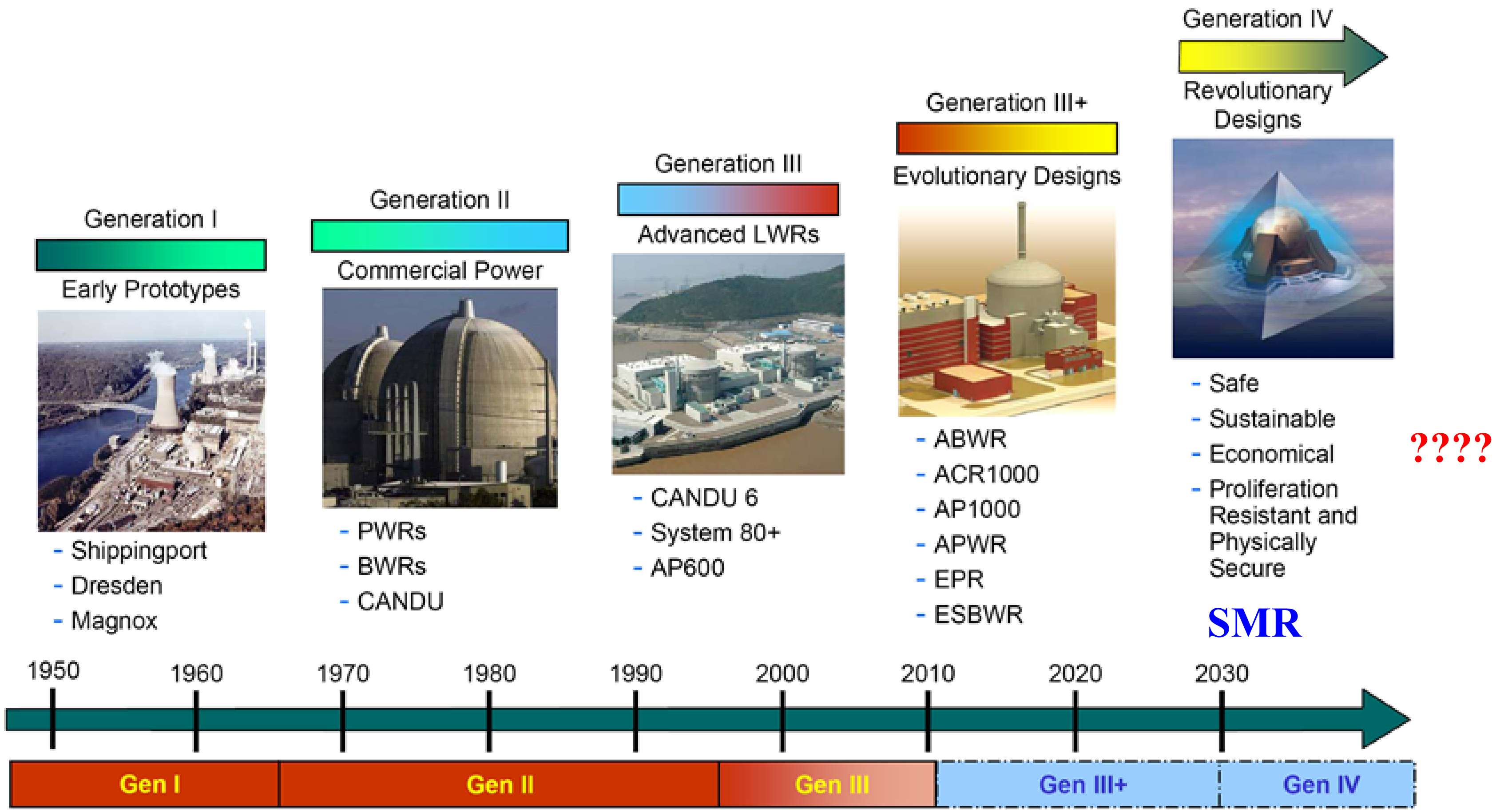
Contents

Introduction and Overview

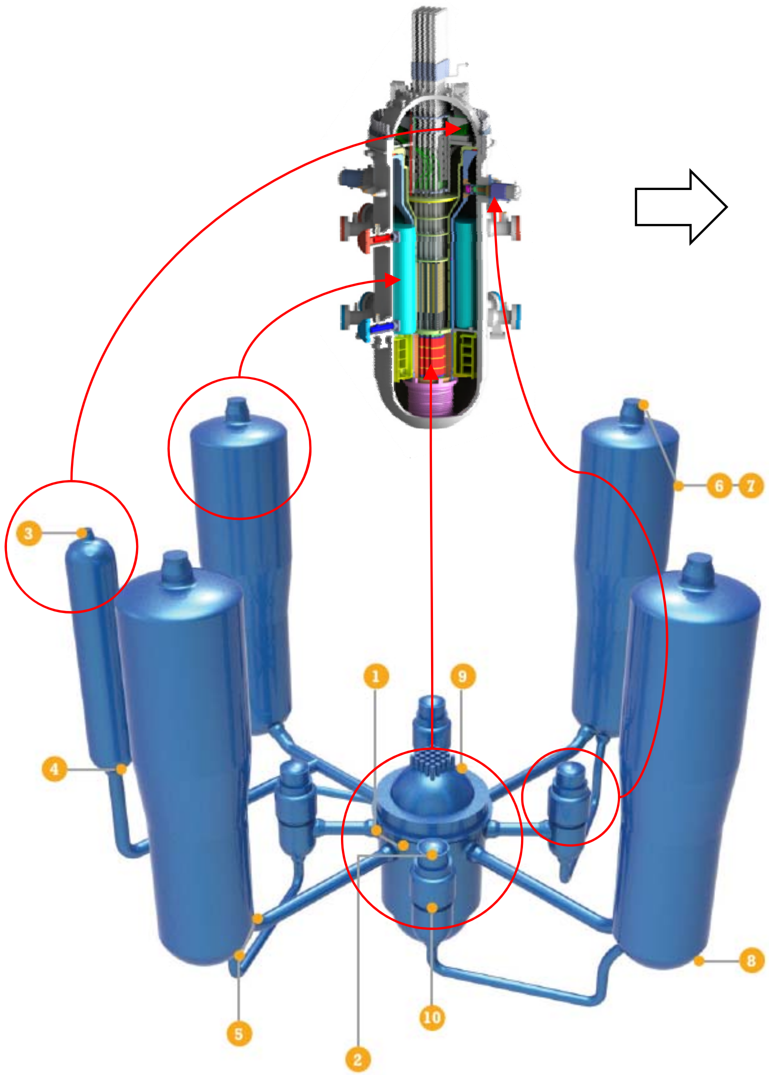
Evolution of NPPs

○ **What is beyond Gen-IV?**

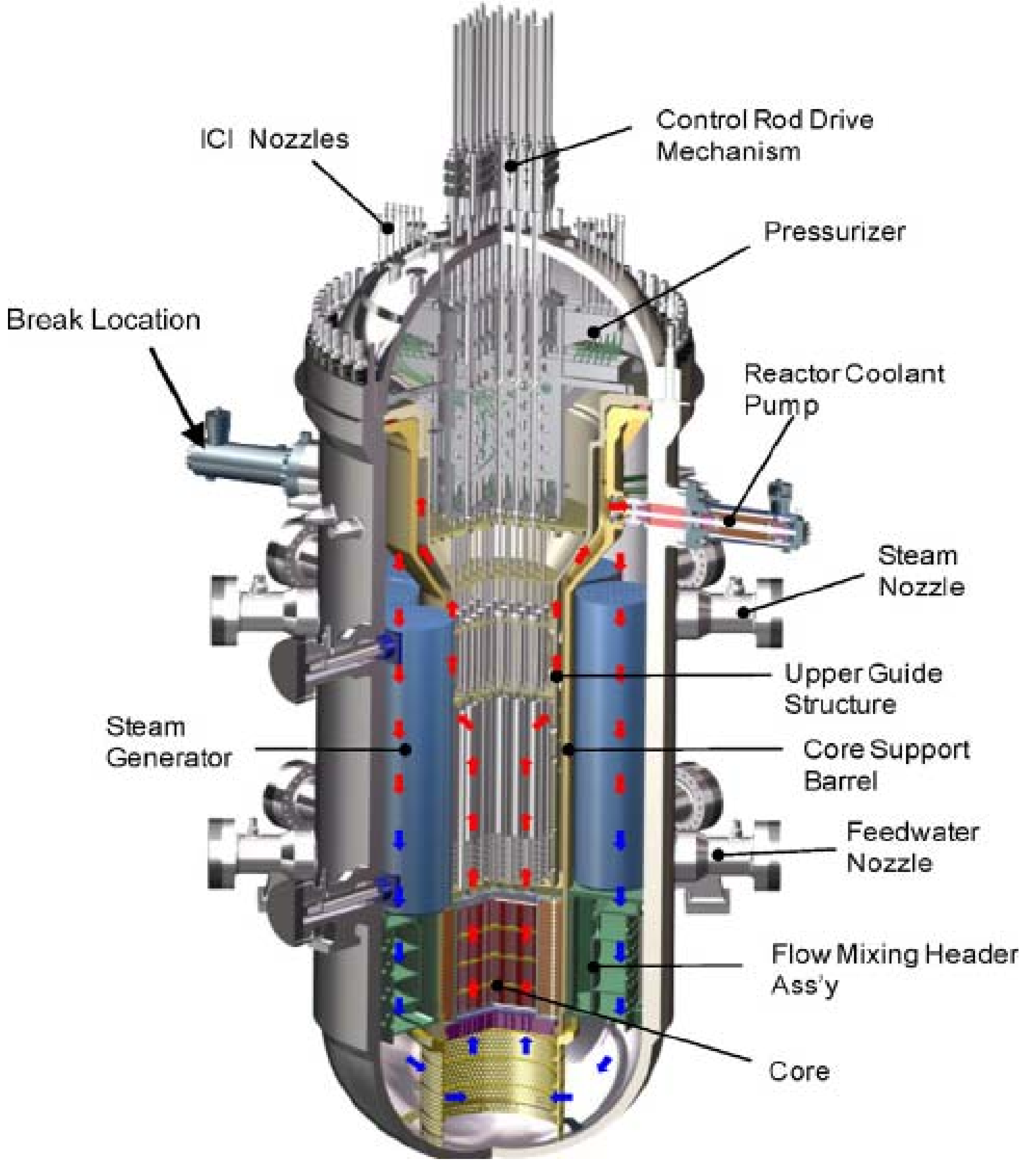


Small Modular Reactors

- Power < 300 MWe



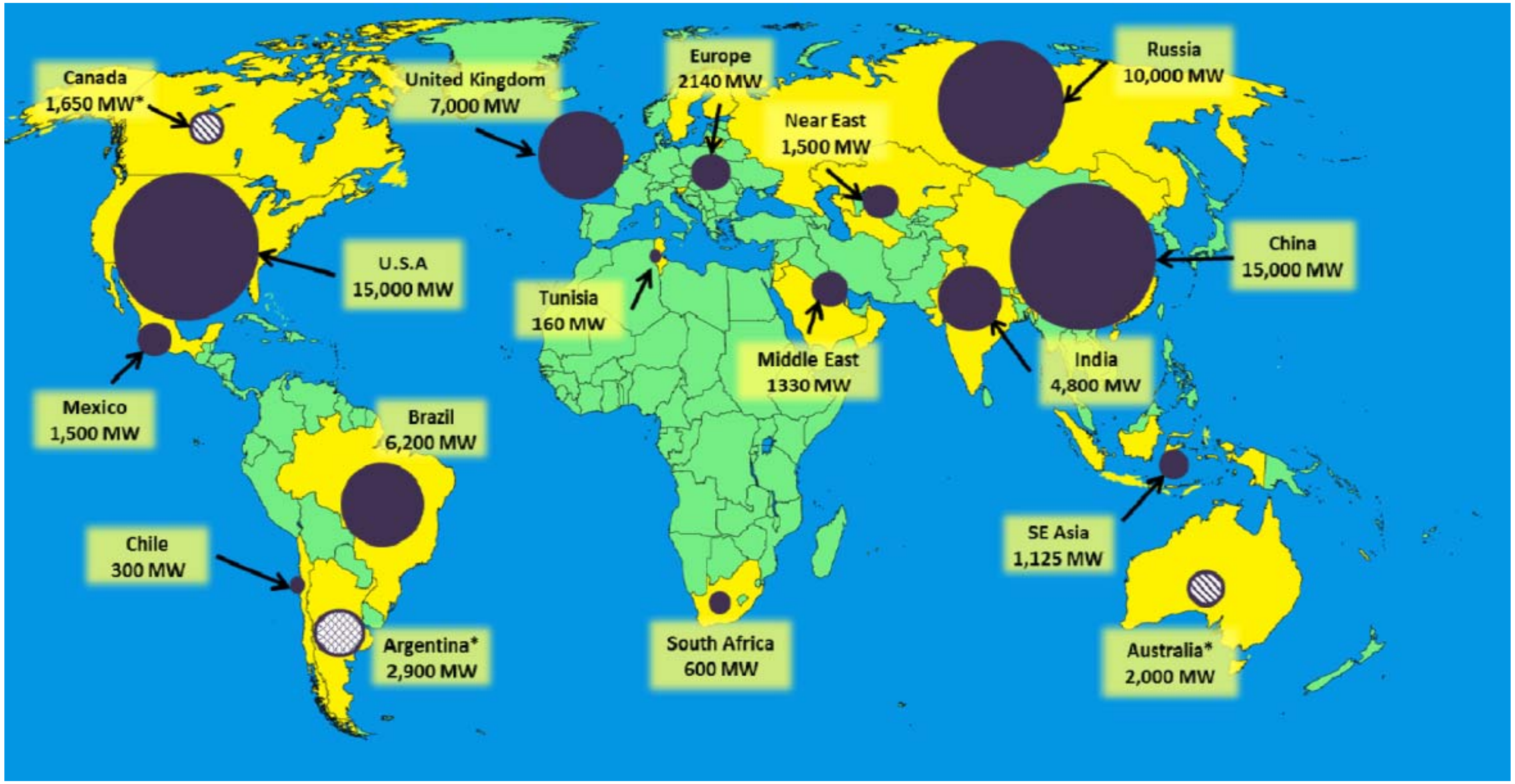
Loop-type PWR



Integral SMR (SMART)

Small Modular Reactors

- Features and advantages of SMRs
  - Extremely low probability of severe accidents
  - Low capital costs and shorter payback time
  - Possibly distributed source
  - Multiple applications (desalination and district heating etc)
  - Possible replacement of old fossil plants



SMR market in 2035 [National Nuclear Laboratory, SMR Feasibility Study, 2014]

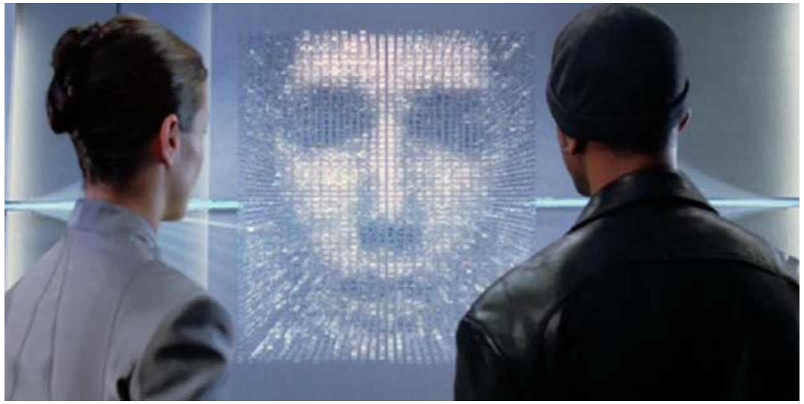
Autonomous SMR?

- **AI** with big-data
  - *Expected delivery* by Amazon!

- **Industry 4.0**
  - Unmanned factory with IoT
  - Super-connected world

Artificial Intelligence

- Deep-learning with advanced neural network
  - Operator-assisting AI & Big-Data technologies in near future



VIKI in "I-Robot"

Microsoft AI 'Cortana'

JARVIS in "Iron man"

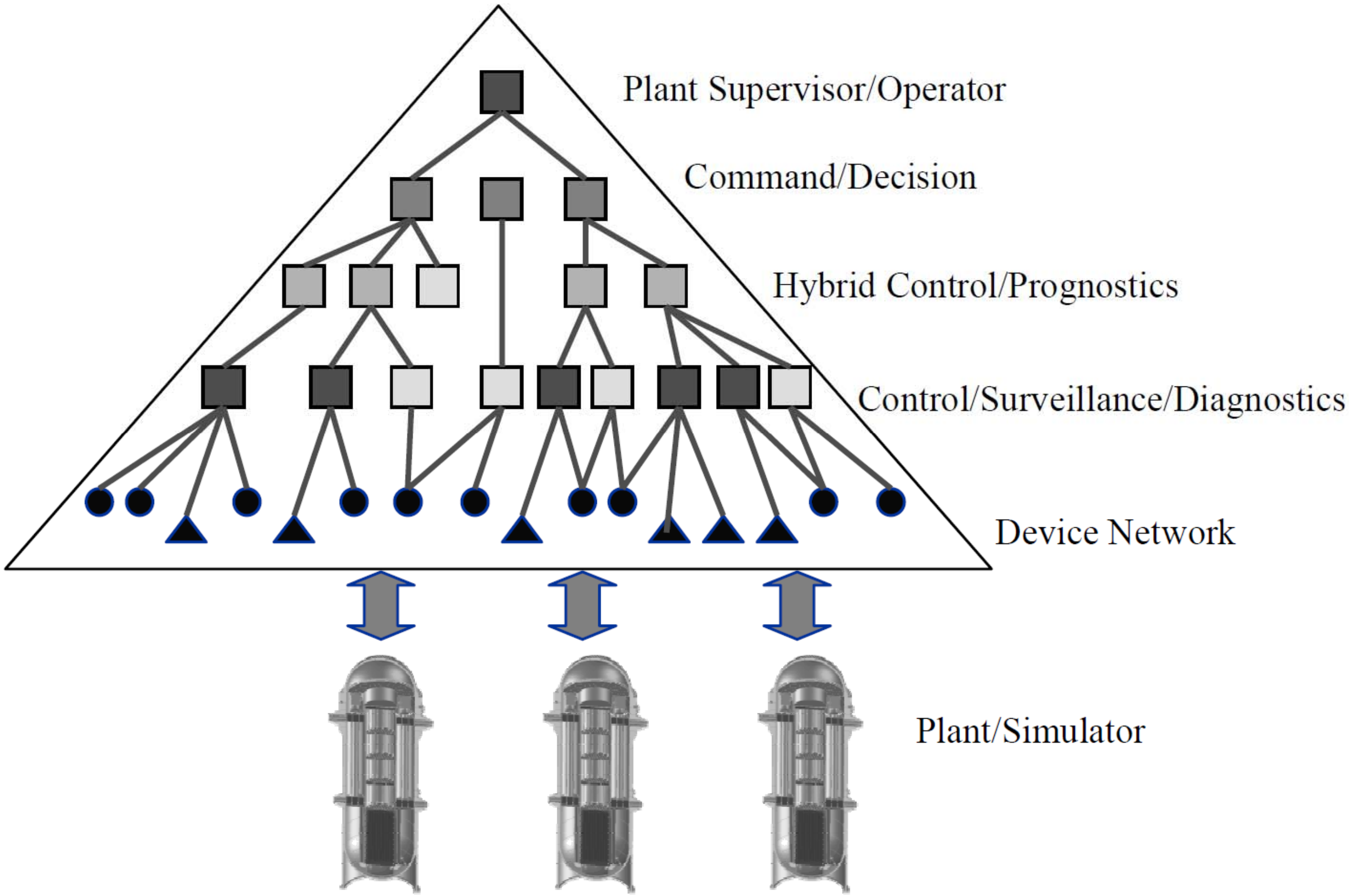
- **Reliable enough and licensable for reactor control?**

Why ASMR?

Concepts of Autonomous Operation

- Autonomous control for Gen-IV NPP, R.T. Woods, et at, ORNL
- Automatic vs Autonomous

Automation Level
Autonomous Operations
Operation by Exception
Operation by Consent
Operation by Delegation
Shared Control
Assisted Manual Control
Direct Manual Control



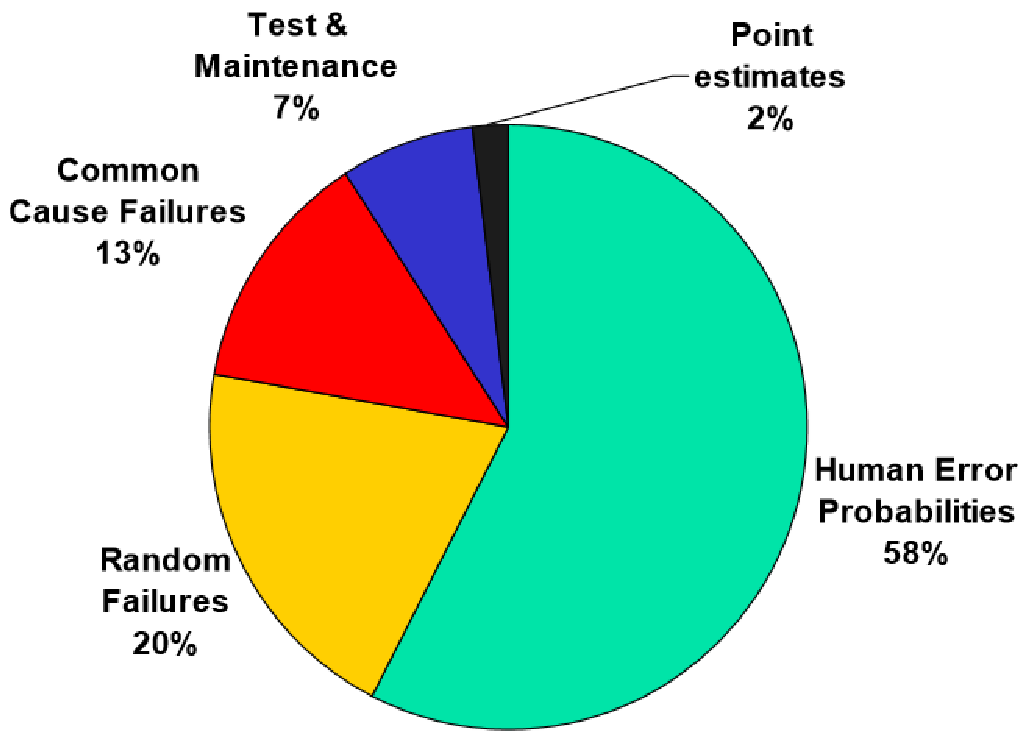
Why Autonomous SMR?

- **Improved Safety of System**
  - Eliminate potential human errors

    : 50-70% incidents essentially due to human errors
  - Holistically optimized control of the whole system → **Near-perfect system control!**
  - Optimal response to emergency situations

Contribution to CDF

(Exelon Nuclear, based on the normalized F-V importance measure)



IAEA workshop on Improvement of Safety and Economics of NPP, 2002

Why Autonomous SMR?

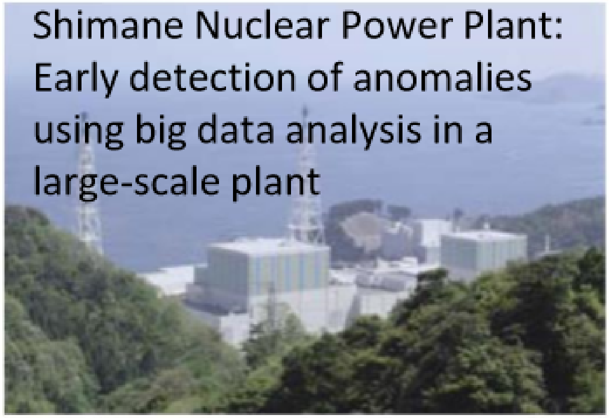
○ **Enhanced Operational Reliability & Maintenance**

– AI for each component and system (application of 'big-data' technologies)

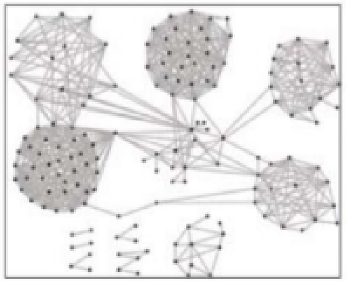
→ Early and correct diagnosis → **Living and holistic PSA**

– AI-based optimized maintenance & management

NEC http://www.nec.com



Invariant Analysis technology

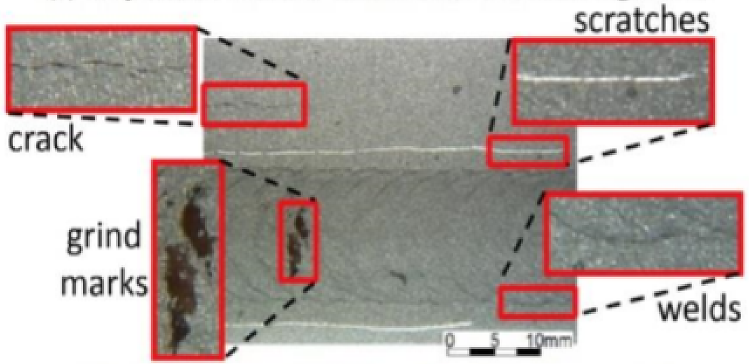


Automatically mapping the depth of relationship among all sensors during normal operation helps discover any abnormal relationships in operation.

NVIDIA https://blogs.nvidia.com

Automatically Detect Nuclear Power Plant Cracks With Deep Learning

(a) Tiny cracks with low contrast and different brightness.



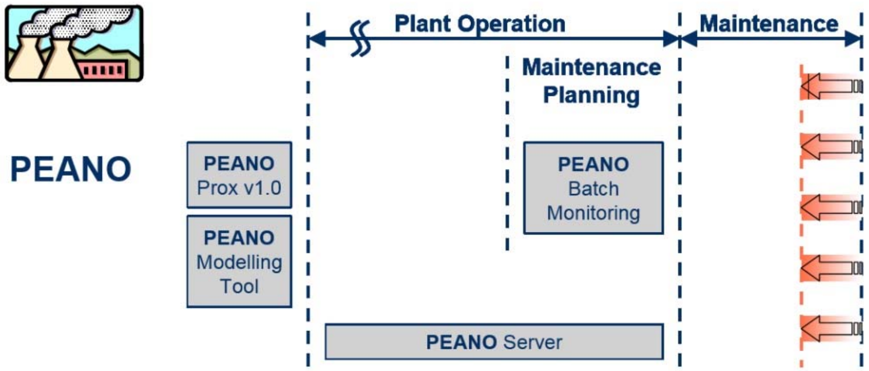
(b) Scratches, grind marks, and welds in background.

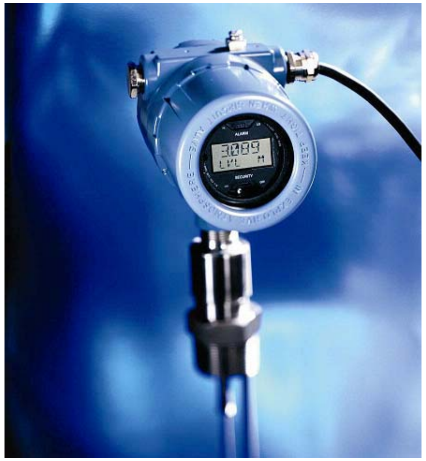
Why Autonomous SMR?

○ **Enhanced Operational Reliability & Maintenance**

- Halden reactor project : PEANO

: On-line AI-based reliability analysis of nominal and transient detector signals





○ **Improved Economy**

– Higher level of safety → Less indirect social costs

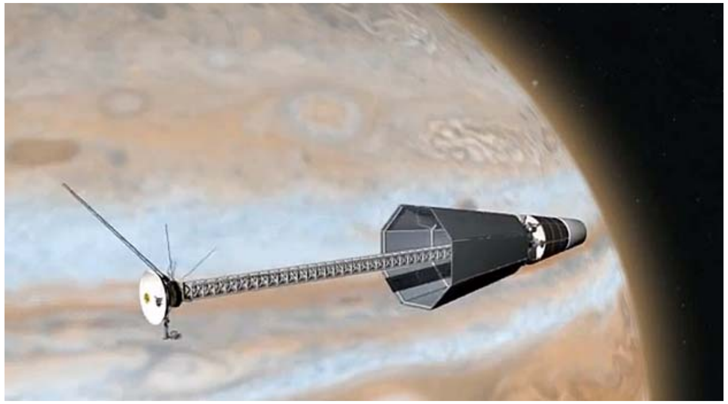
– Effective maintenance & management → optimized system operation

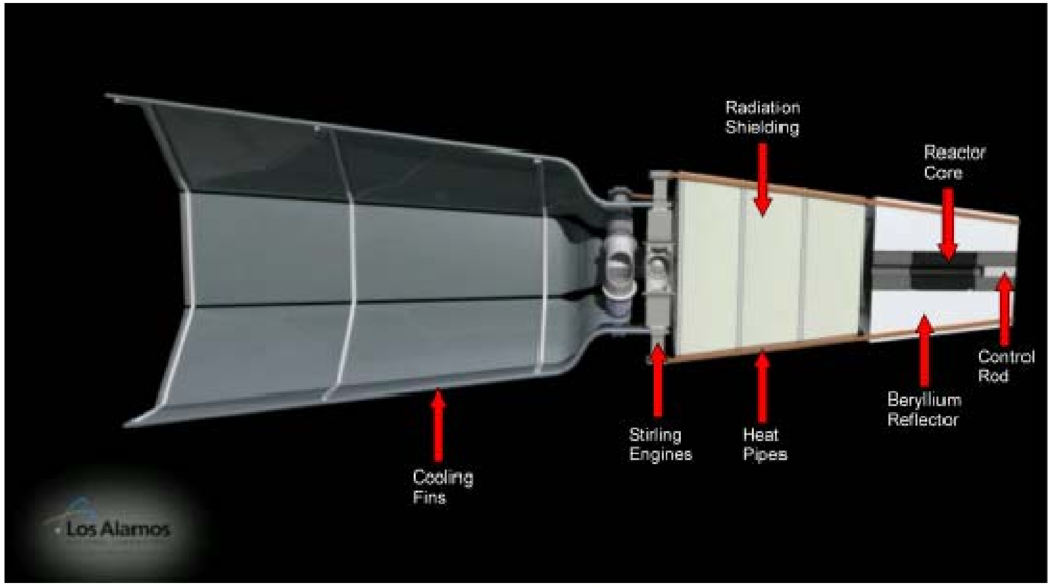
– Operable in extreme environments

Autonomous or Pseudo-Autonomous Nuclear Reactors

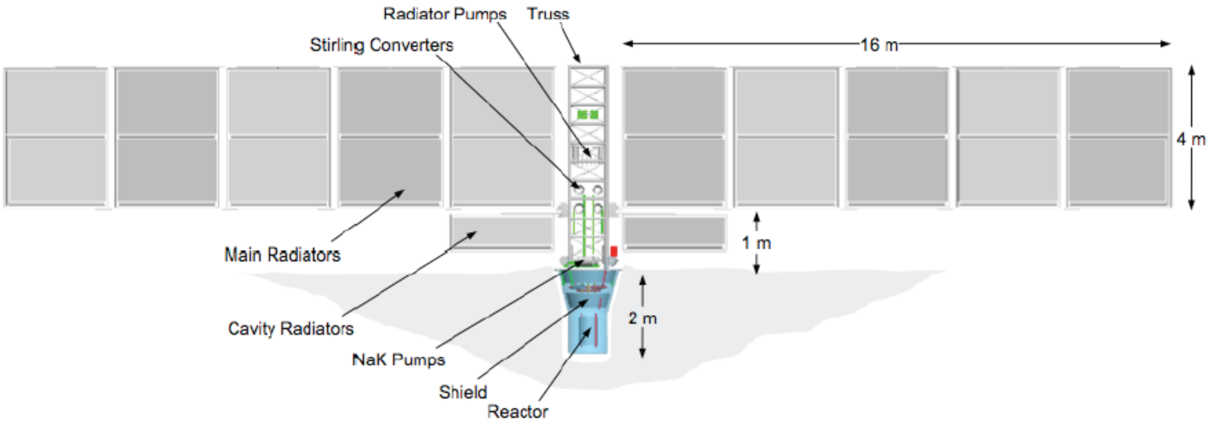
R&Ds on Space Reactors

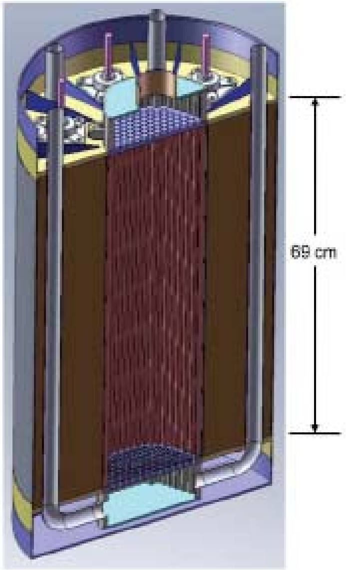
- Old space reactor remotely controlled
- LANL Heat Pipe reactor for space probe
  - Autonomous & remote control





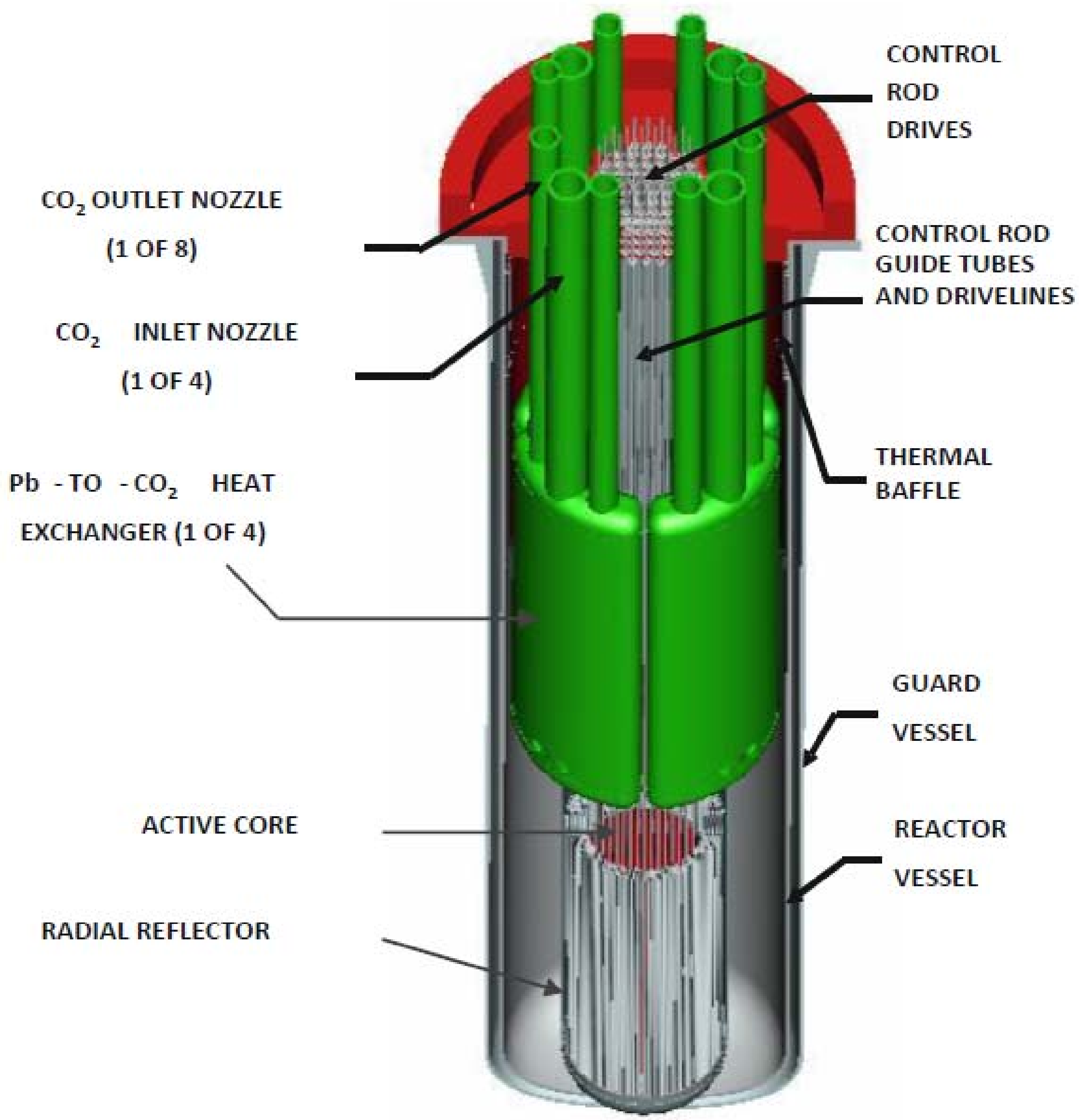
- NASA Surface Fission Power (Moon & Mars)





Small Secure Transportable Autonomous Reactor (SSTAR)

- Gen-IV concept studied by ANL, LLNL, LANL
- Lead-cooled fast reactor
- UN fuel
- Long life (10~30 years)
- SCO_2 power cycle
- **Autonomous operation**
  - Relatively easy with fast reactors
- Tamper-resistant concepts
  - Proliferation-resistance
- Pre-Conceptual study



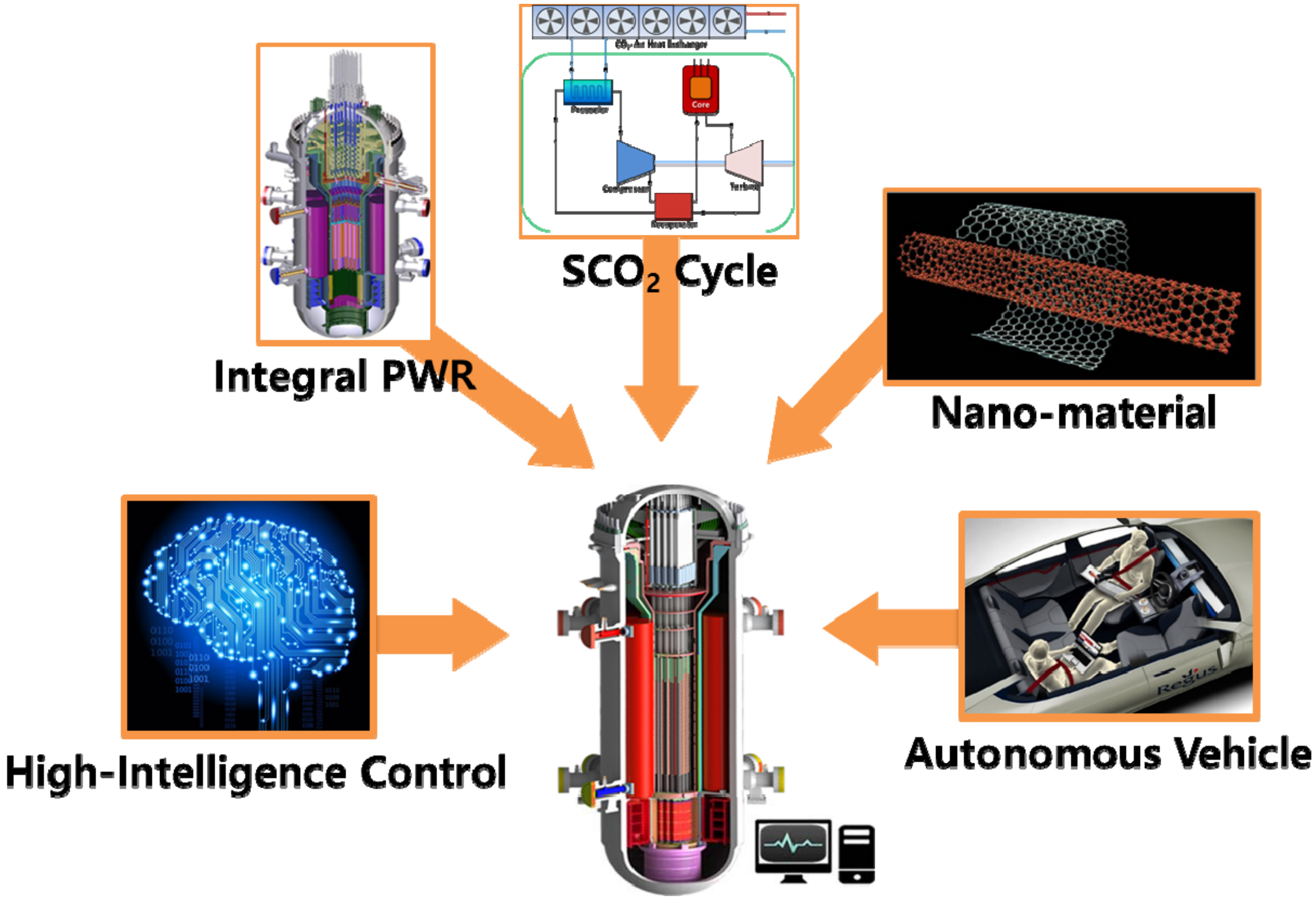
R&Ds for Autonomous SMR in CASMRR

Overview of CASMRR

- **Launch of CASMRR for SMR Innovation in 2016**
- **Participating Universities**
  - KAIST (7 Profs), UNIST (1 Prof). Ga-Chon Univ. (1 Prof), Han-Yang Univ. (1 Prof), Cho-Sun Univ. (1 Prof)
  - 11 Professors
- **Director**
  - Yonghee Kim, KAIST
- **Period**
  - July 2016 ~ December 2022
    : Possibly 2 more years
- **Budget from Korean government**
- **Research objective**
  - **Development of concepts and key technologies for autonomous SMR with unparalleled passive safety**
  - **ATOM (Autonomous Transportable On-demand reactor Module)**

Design Considerations for ATOM

○ **PWR-type SMR with ATF (Accident-Tolerant Fuel)**



Elimination of Fukushima-type Accidents

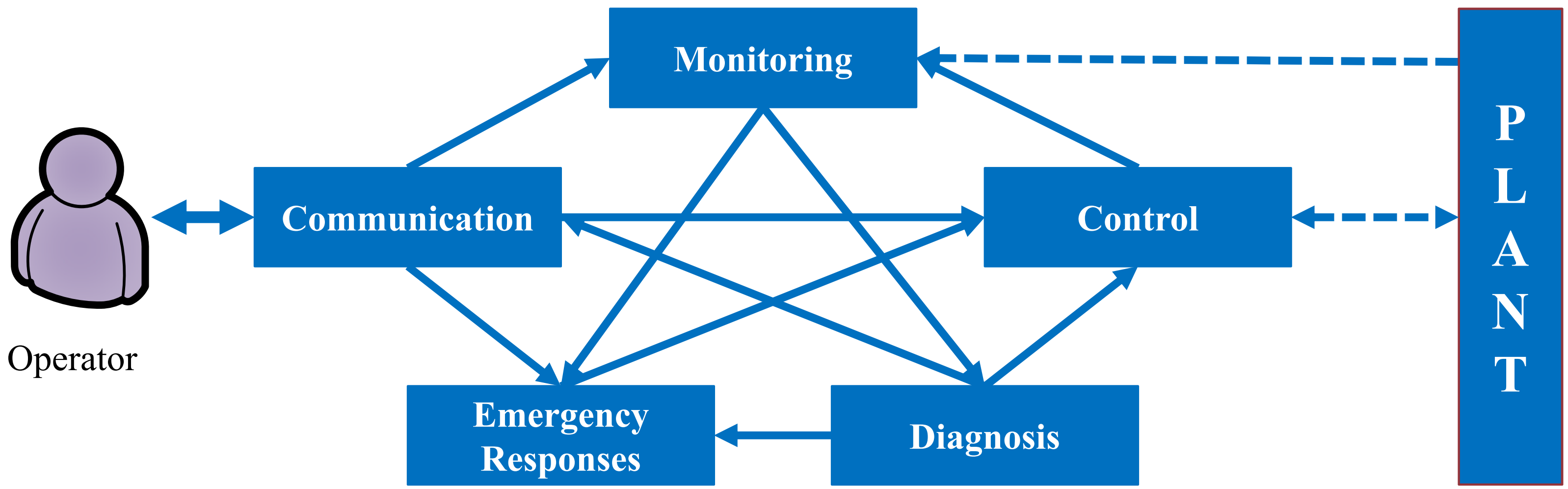
Passive Safety + Autonomous SMR
(Design Concepts of ATOM)

AI for ATOM System

- Autonomous control system with minimal human interruption for a wide range of operation

- **GAIA (Genuinely Autonomous Intelligence for ATOM)**
  - Deep-learning with advanced Neural Network
  - ACE (Alternating conditional expectation) & GMDH for system diagnosis
  - Training data from high-fidelity multi-physics simulations
    : Detailed system modelling with MARS+3D reactor code systems

- Operation mode-dependent autonomous strategies

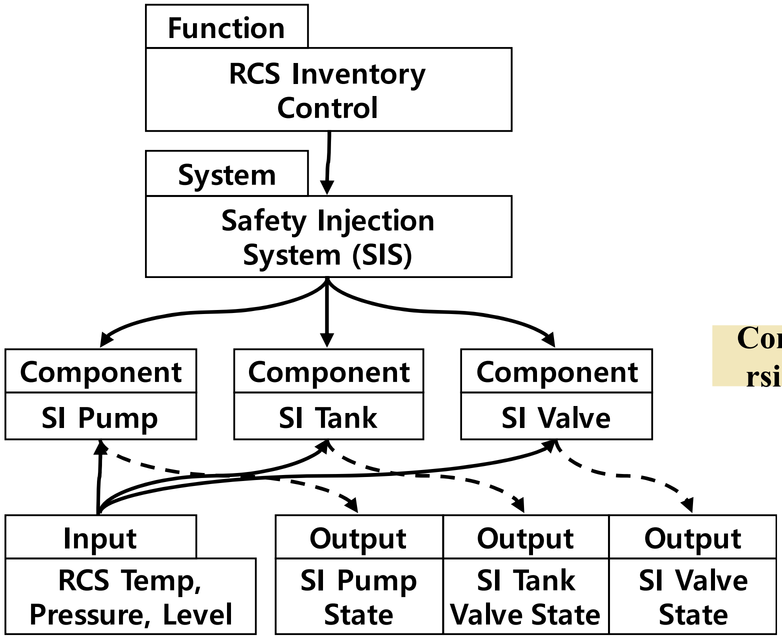


Key Functions of the GAIA System for the ATOM

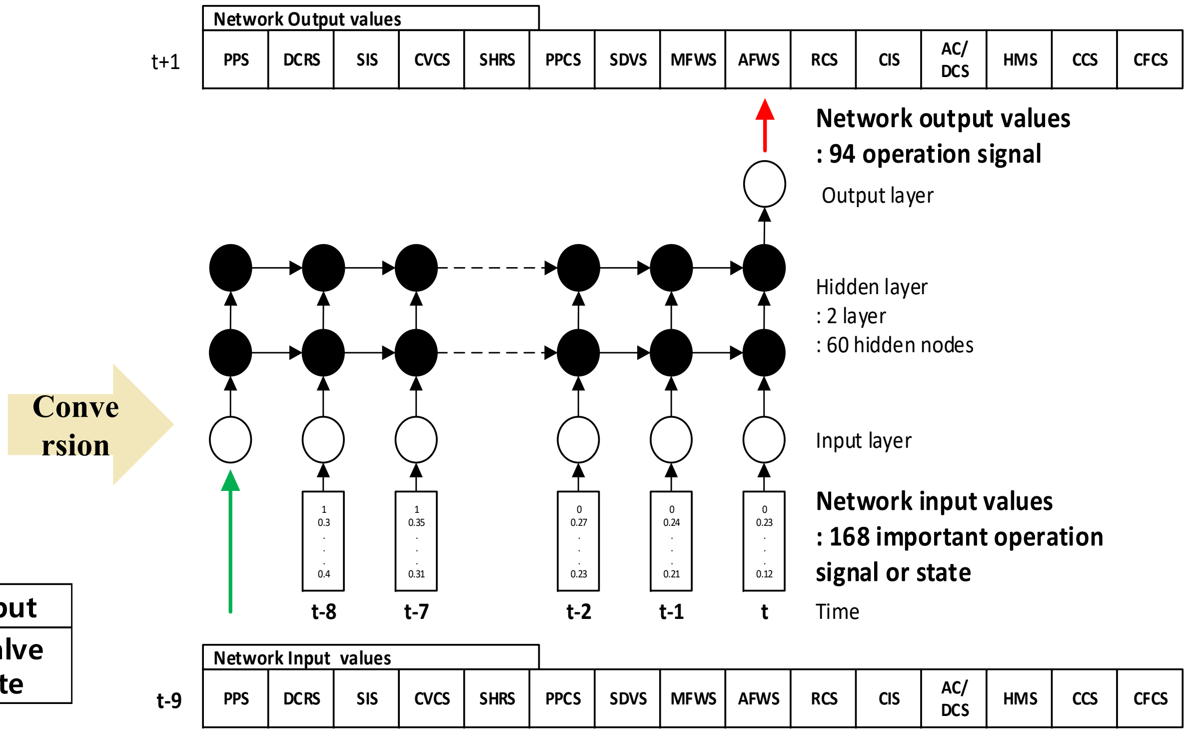
Autonomous Control for Safety Functions

○ **Autonomous Control Algorithm using the LSTM**

– LSTM: An advanced Recurrent Neural Network



<NPP Safety System>



<LSTM Network>

Autonomous Control for Safety Functions

- **Training of LSTM Network**
  - Compact Nuclear Simulator (CNS)

CNS

Reference plant	Westinghouse PWR
Electrical output	930 MWe
RCS Pressure	$160 Kg/cm^2$
Loop	3-loop
Hot leg / Cold leg Temp	325℃ / 290℃
RCS Average Temp	308℃
S/G Pressure	$64.4 Kg/cm^2$

Training Accident Scenarios
Loss of Coolant Accident (LOCA)
PORV Forced Open (LOCA)
LOCA + Fault in SI Valve
Steam Generator Tube Rupture (SGTR)
Main Steam Line Break (MSLB)
Loss of All Feed-water (LOAF)
SGTR+MSLB

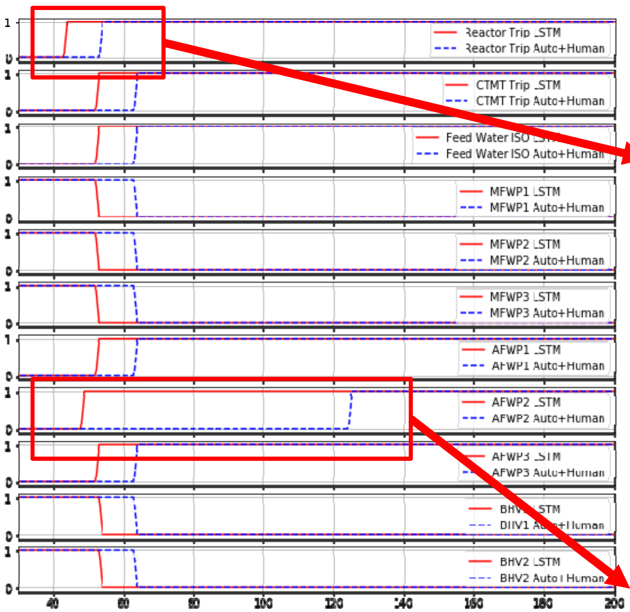
Training Data set : 225,538 set (currently)

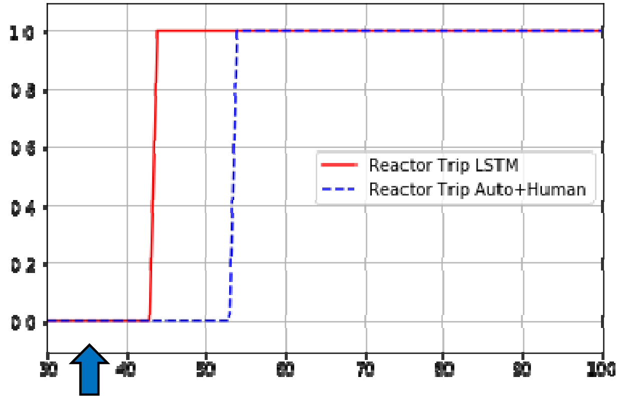
Autonomous Control for Safety Functions

○ **Validation of LSTM Network: LOCA (Hot-leg, 25cm^2)**

- Component Level: Automatic + Manual vs. Autonomous

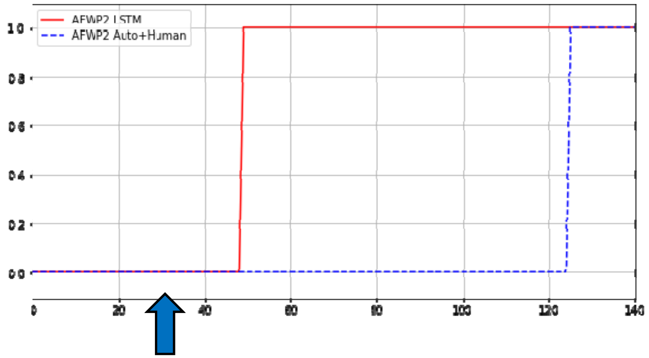
Control Action for NPP





Accident occurs at 35 sec

	Reactor Trip
Autonomous control	43 sec
Auto+man control	52 sec (+9 sec)



Accident occurs at 35 sec

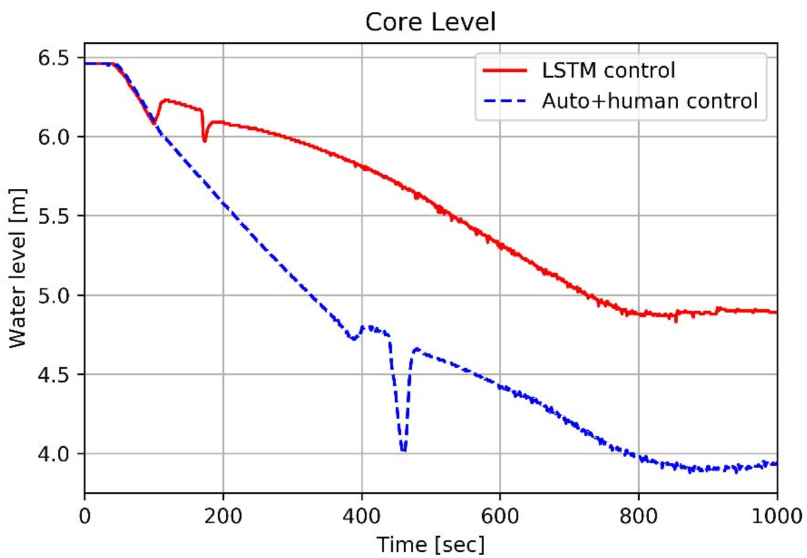
	AUX Feed Water Pump 2
Autonomous control	48 sec
Auto+man control	124 sec (+76 sec)

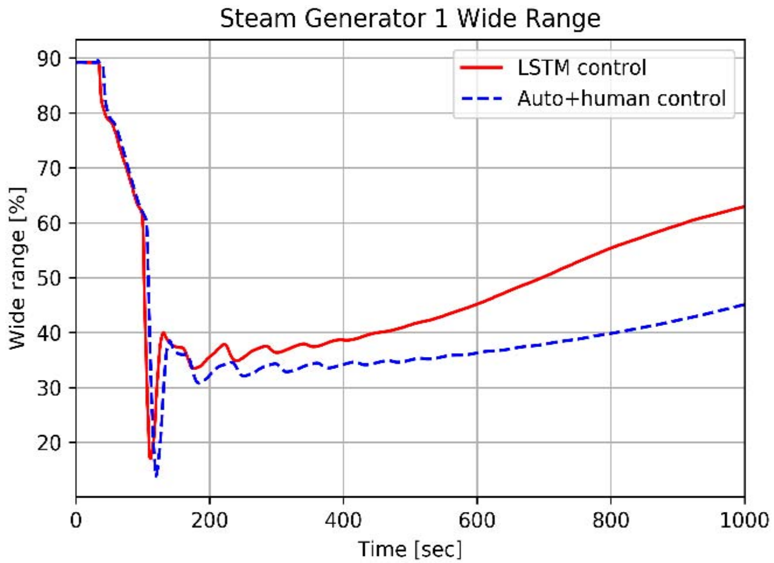
Autonomous Control for Safety Functions

○ **Validation of LSTM Network: LOCA (Hot-leg, 25cm^2)**

- Function Level: Automatic + Manual vs. Autonomous

Comparison of Safety Parameters





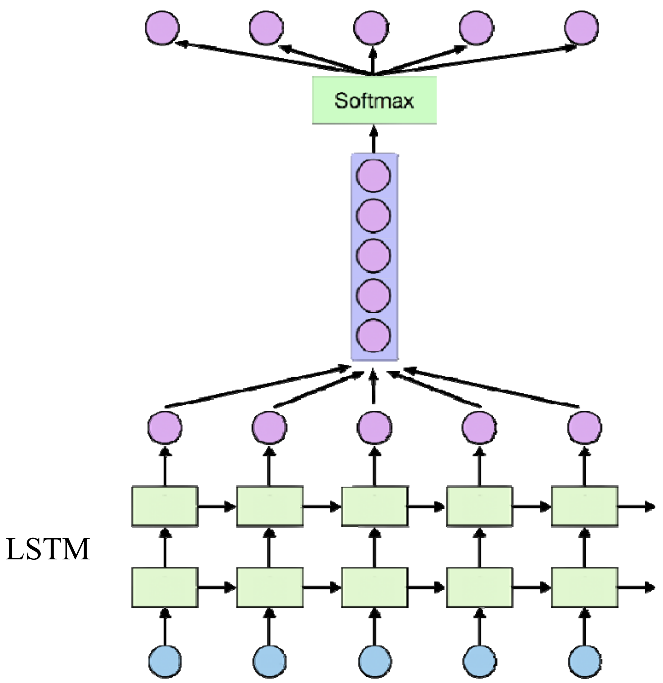
	Core water level at 1000 sec
Autonomous control	4.89 m
Auto+man control	3.91 m **(-0.98 m)**

	S/G1 wide range at 1000 sec
Autonomous control	62.95 %
Auto+man control	45.13 % **(-17.82 %)**

Autonomous Control for Safety Functions

○ Accident Diagnosis

- Objective: Diagnosing the accident to evaluate the performance of autonomous control
- Method: LSTM + Softmax function

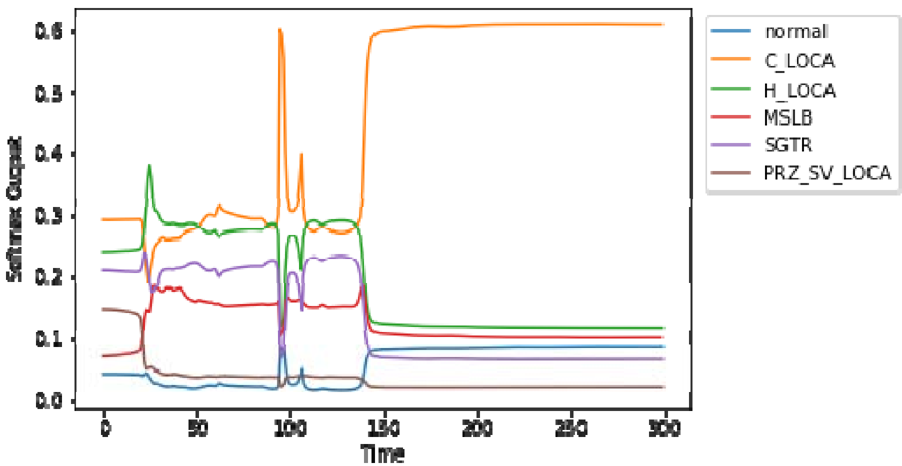


<Architecture of LSTM and Softmax>

Training: 122,609 data sets (currently)

Types of accident scenarios	Numbers
Loss of Coolant Accident (LOCA)	58
PZR Safety Valve fail	5
Steam Generator Tube Rupture (SGTR)	17
Main Steam Line Break (MSLB)	32
Total	112

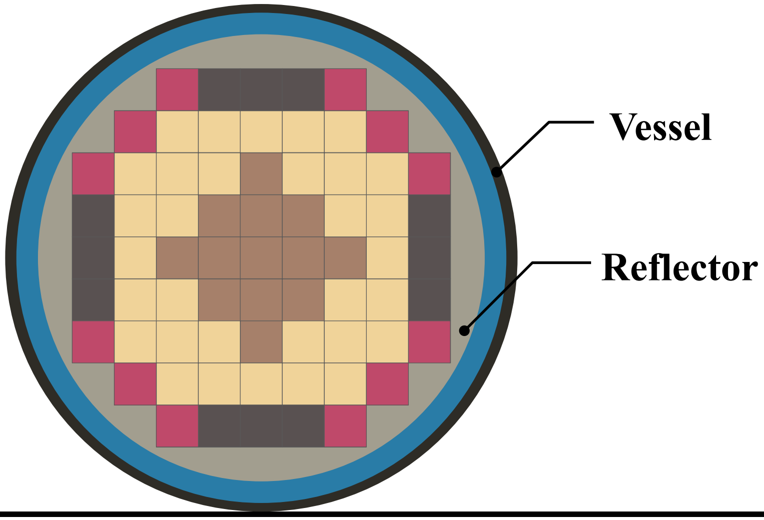
Validation: Cold-Leg LOCA (100cm^2)

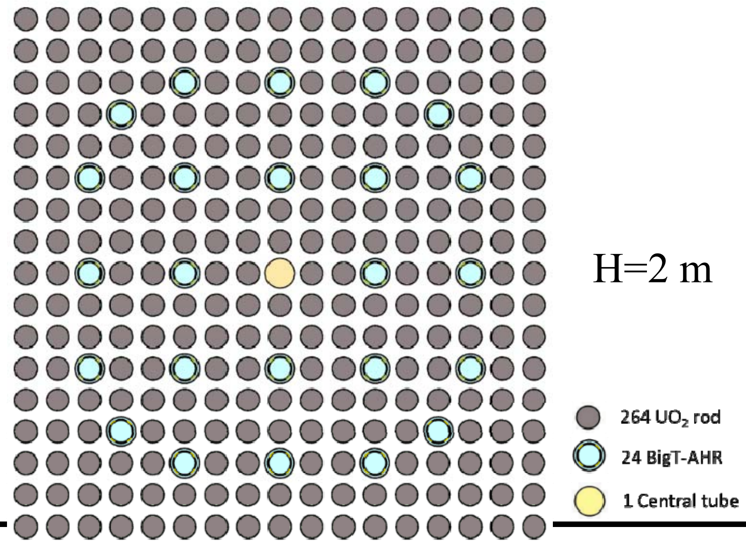


Pre-concepts of ATOM Core

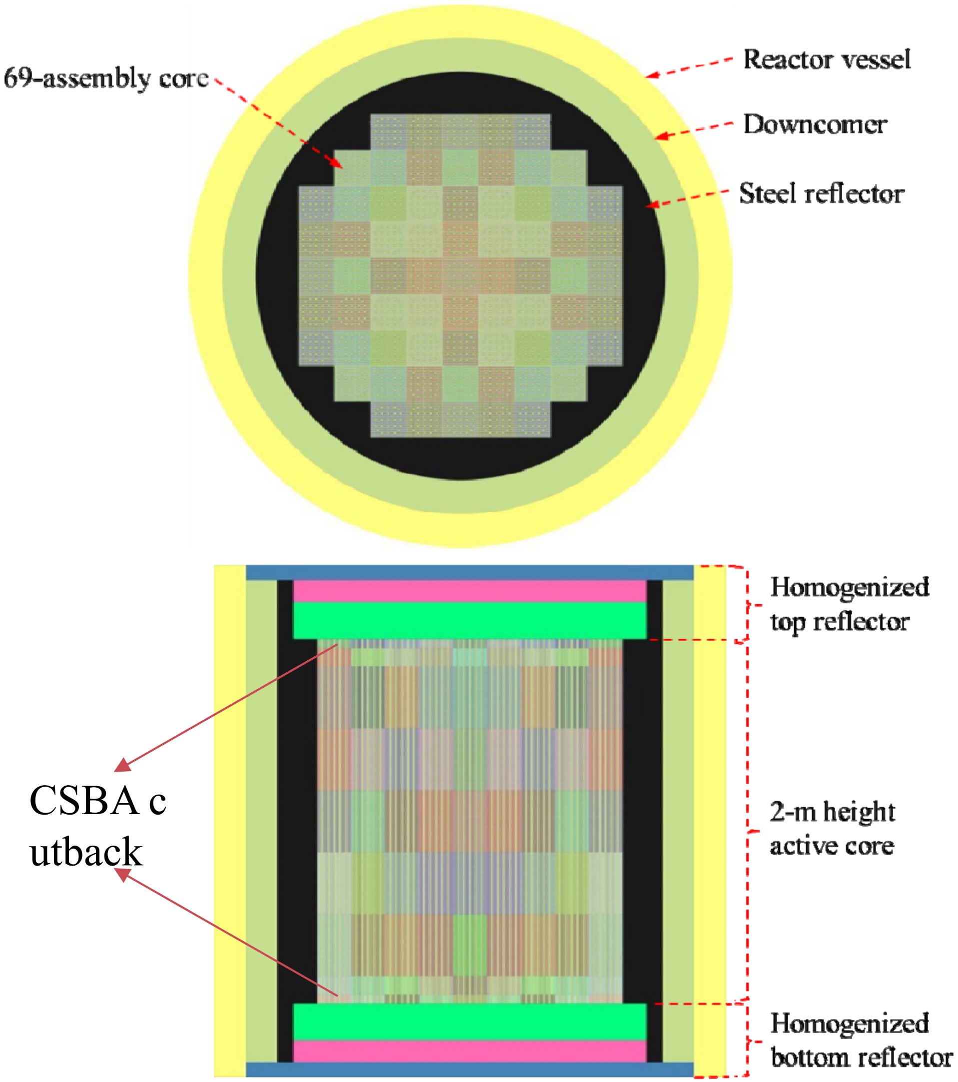
○ **Top-tier requirements**

Parameter	Value
Power	450 MWth (to be maximized)
Power density	60~80 W/cm^3
Fuel	UO_2/U_3Si_2
Core Damage Frequency (CDF)	$< 10^{-8}$
Grace Time	Indefinite
Cycle length	2~10 years
Fuel Assembly	17X17
Reactivity control	No soluble boron for Autonomous Operation
Load follow	Near-passive Load-Follow Operation





Solube-Boron-Free ATOM (SMR) Core



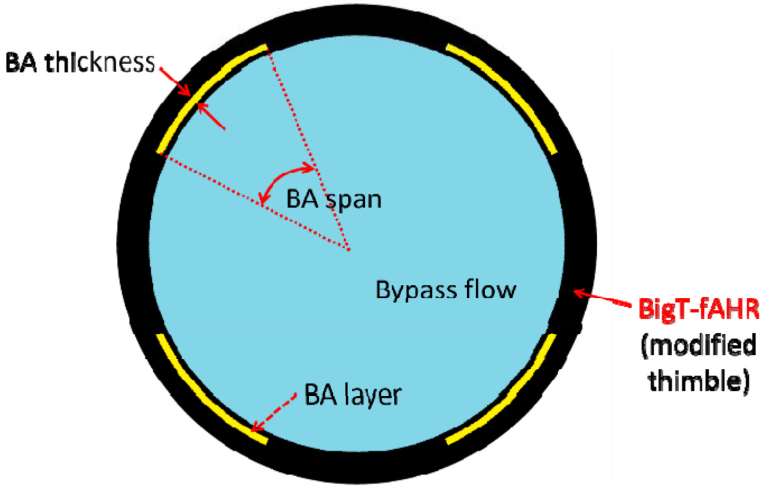
Serpent model of the ATOM core

Parameters	Target Value	Unit
Thermal power	450	MWt
Active core height	200	cm
Equivalent diameter	201.6	cm
Height-to-diameter ratio	0.993	
Power density	25.99	W/gU
Cycle length	~45	month
Fuel loading	Single-batch	
FA type	17 x 17	
Number of FAs	69	
Fuel materials	UO_2	
Fuel enrichment (max)	4.95	w/o
Reactivity swing*	< 1,000 > 400	pcm
Boron concentration	0	ppm

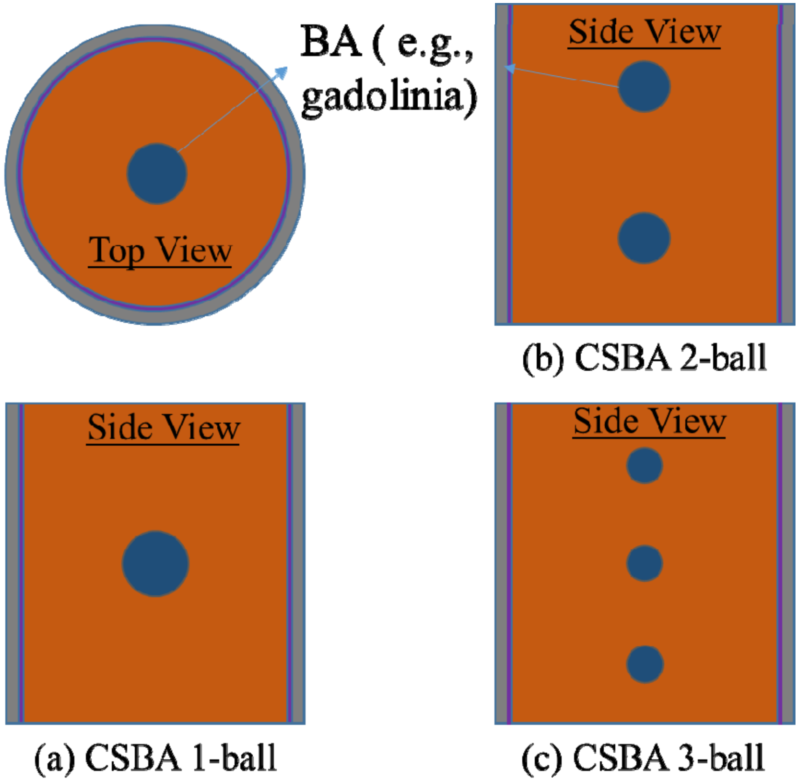
* ((max k_{eff} - 1)/max k_{eff}) x 10^5 [pcm]

New Burnable Absorbers

- ❑ **Burnable absorber-integrated guide Thimble (BigT)**
- ❑ **Centrally-Shielded Burnable Absorber (CSBA) for Gd2O3**



BigT-fAHR
(Azimuthally Heterogeneous Ring)



CSBA-loaded Fuel Pellet

CSBA Design: Variant, Ball Radius and Loading Schemes

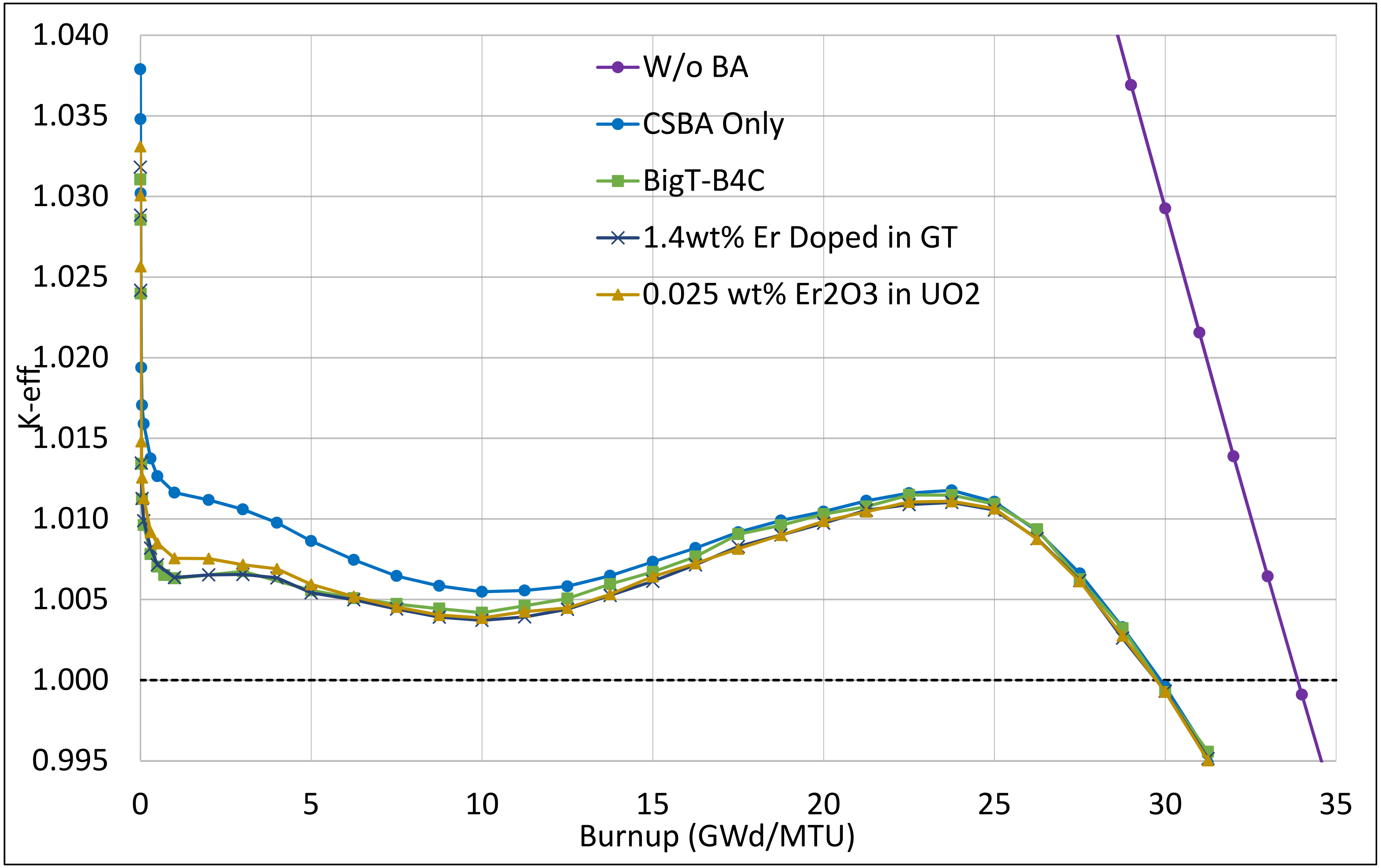
	E	F	G	H	
9	E9	F9	G9		
8	E8	F8	G8	H8	
7	E7	F7	G7	G8	G9
6	E6	F6	F7	F8	F9
5	E5	E6	E7	E8	E9

A Quarter of ATOM core

Zone A	4.95 w/o U
Zone B	4.95 w/o U
Zone C	4.95 w/o U

Case	CSBA Design (variant and ball radius, r)		
	Zone A	Zone B	Zone C
1	1-ball, r = 1.690 mm	2-ball, r = 1.260 mm	3-ball, r = 0.700 mm
2	1-ball, r = 1.690 mm	2-ball, r = 1.260 mm	2-ball, r = 0.820 mm

Neutronic Performance of CSBA-Loaded ATOM core



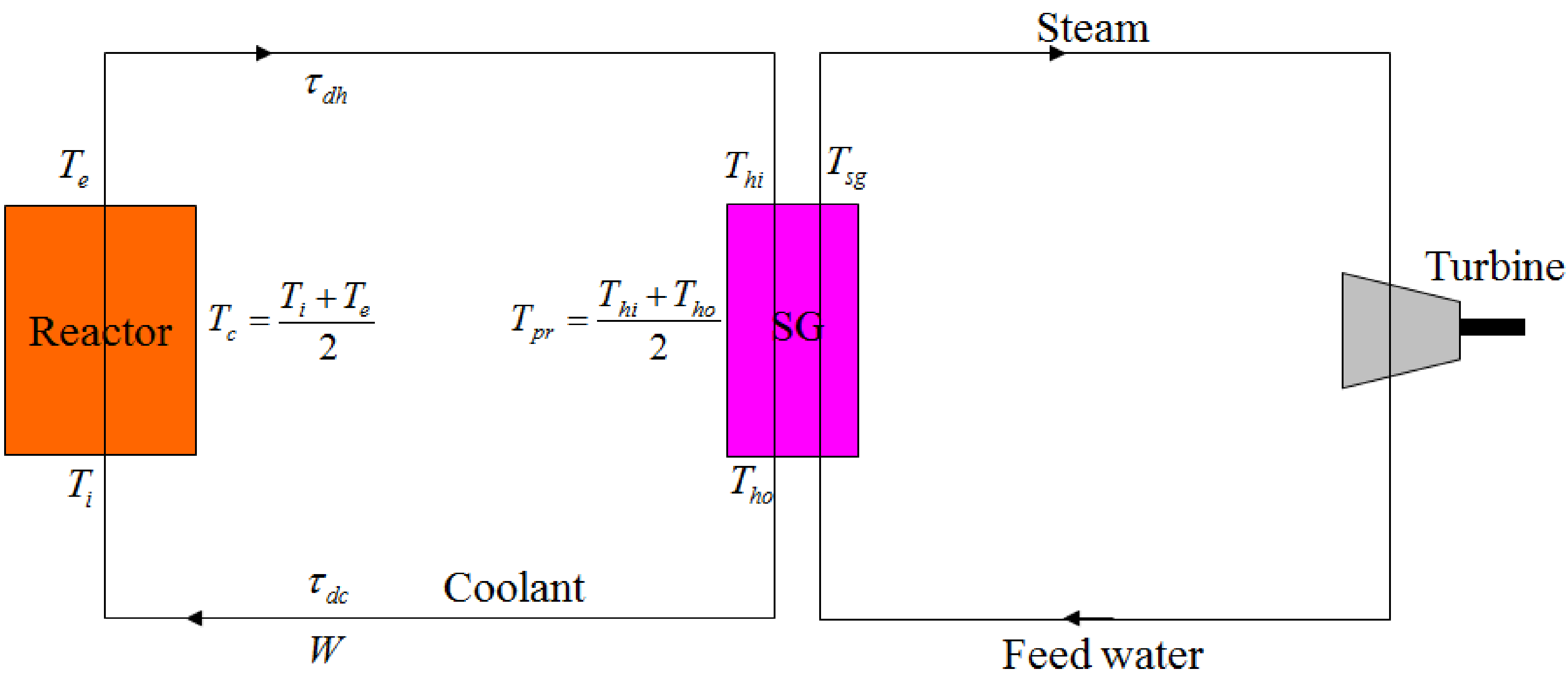
Passive Load-following and Frequency Operations (to enhance Autonomous operations)

KAIST

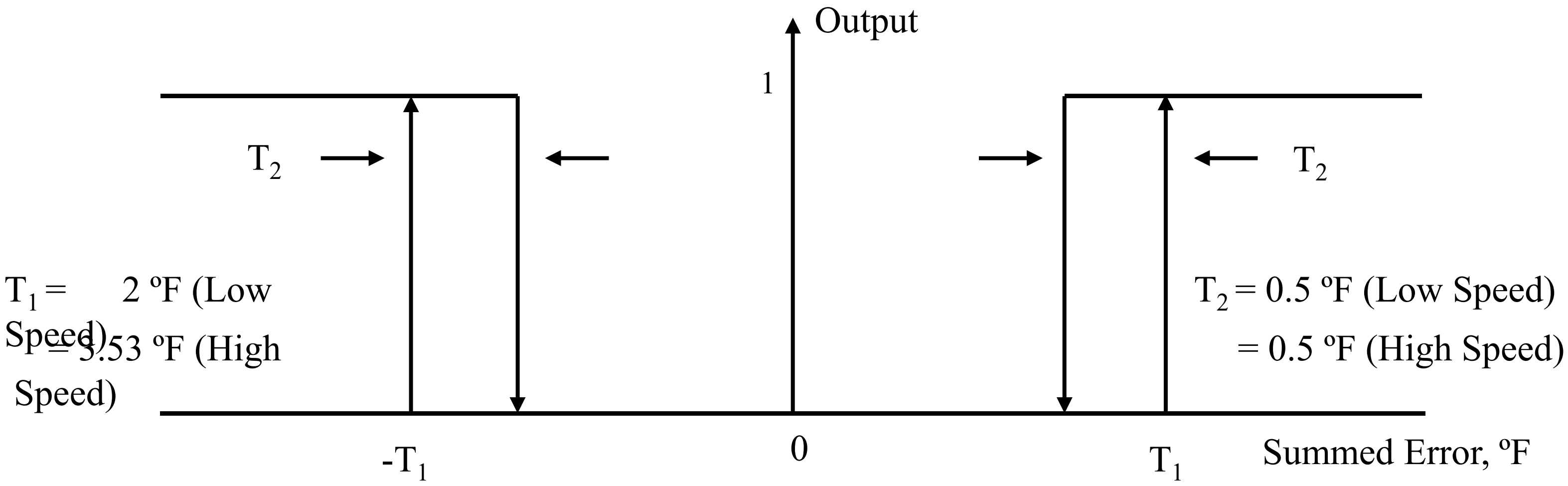
Concept of Passive Load-follow

- **No active control of the reactor power during load-follow operations**
- Control only in the feed-water flow rate and the governor value

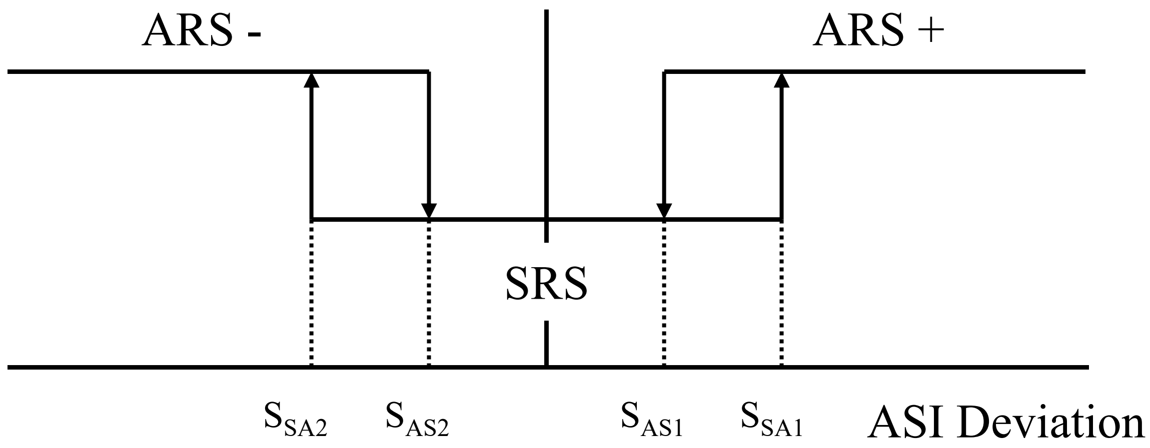
	BOC	MOC	EOC
CTC, pcm/K	-48.11	-51.49	-61.85
FTC, pcm/K	-2.36	-2.65	-3.04



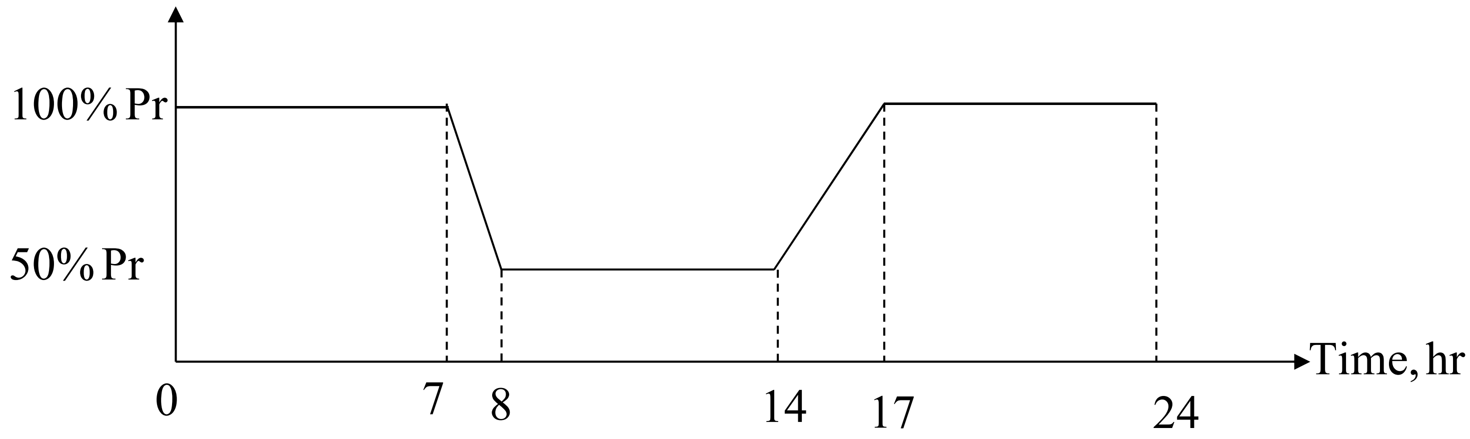
- **Coolant average T and axial shape index (ASI)**



Deviation in average coolant T



Daily Load Pattern

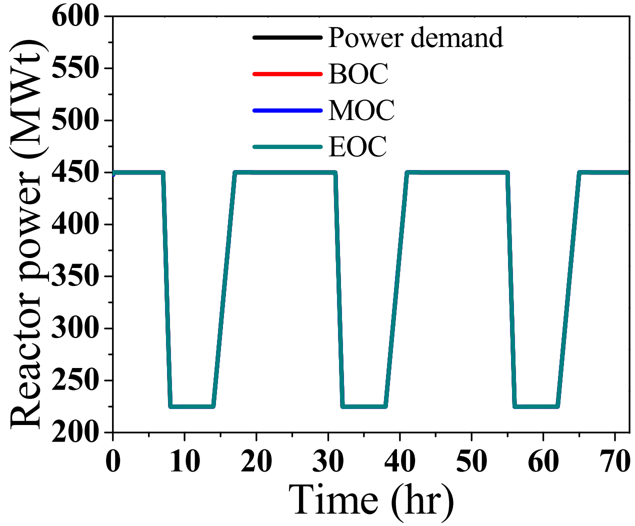


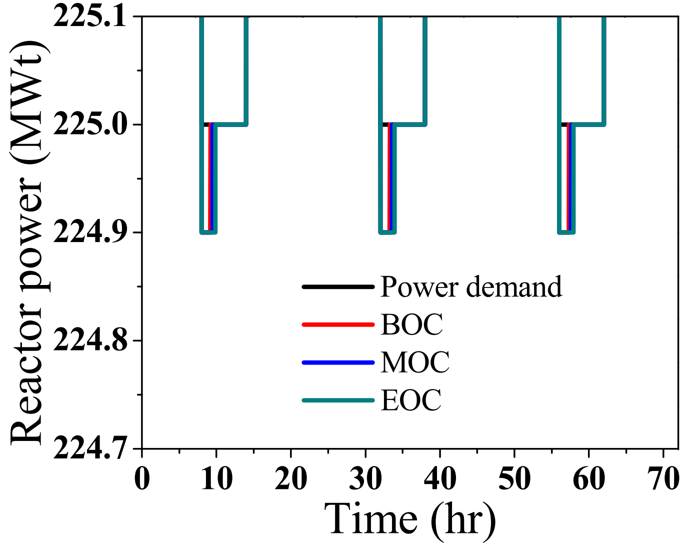
- 100-50-100 daily load pattern
- Three consecutive days of PDLFO (Passive Daily Load-Follow Operation)
- Power ramping-down rate 0.83% Pr per minute
- Power ramping-up rate 0.27% Pr per minute

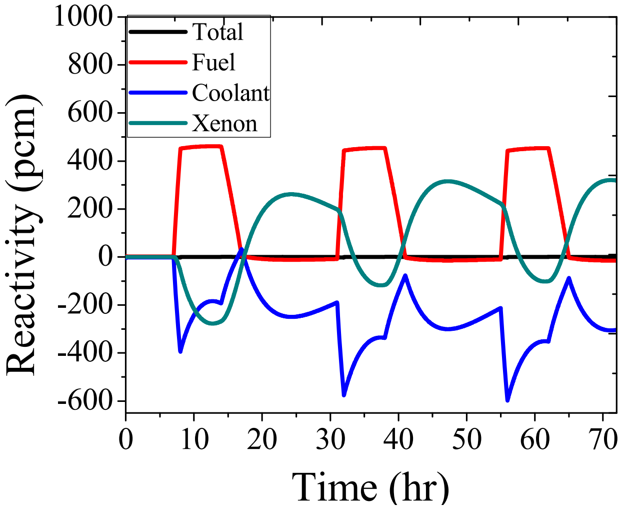
System Responses in PDLFO – (1)

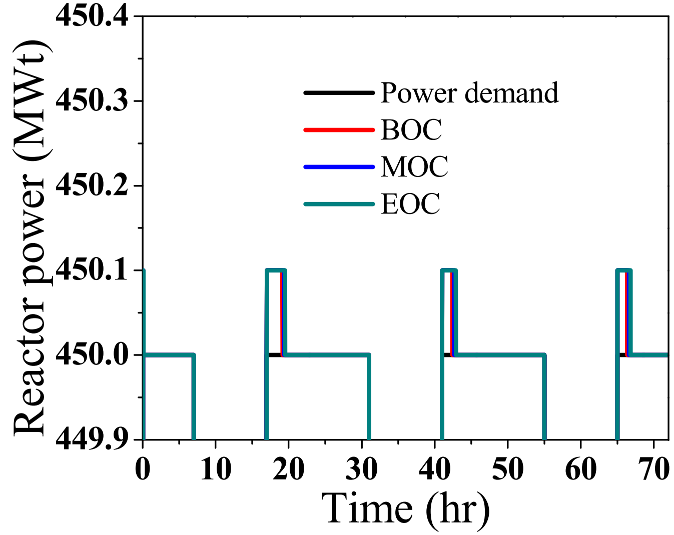
– **Rector power and power demand matches well**

– **Only 0.1 MWt power miss-match for 2 hours**









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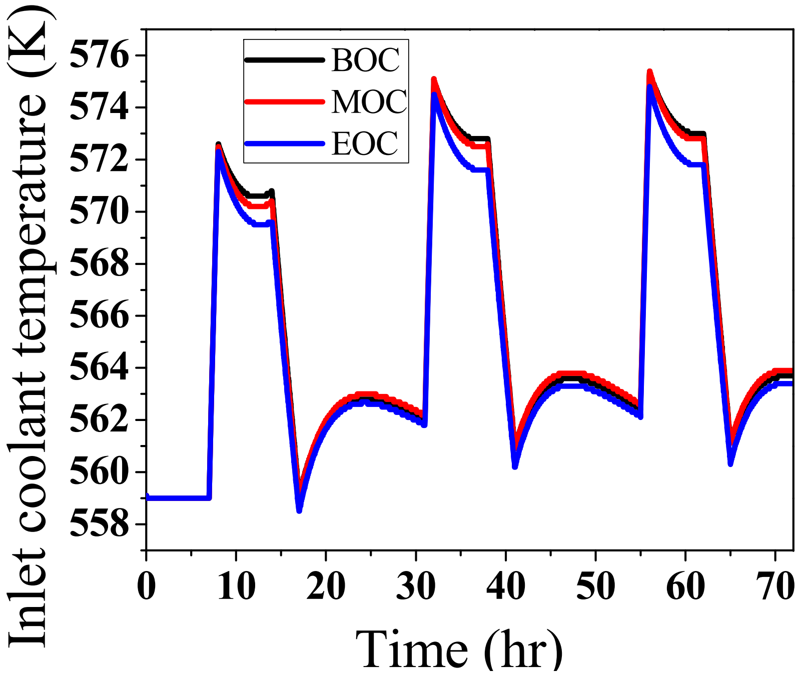
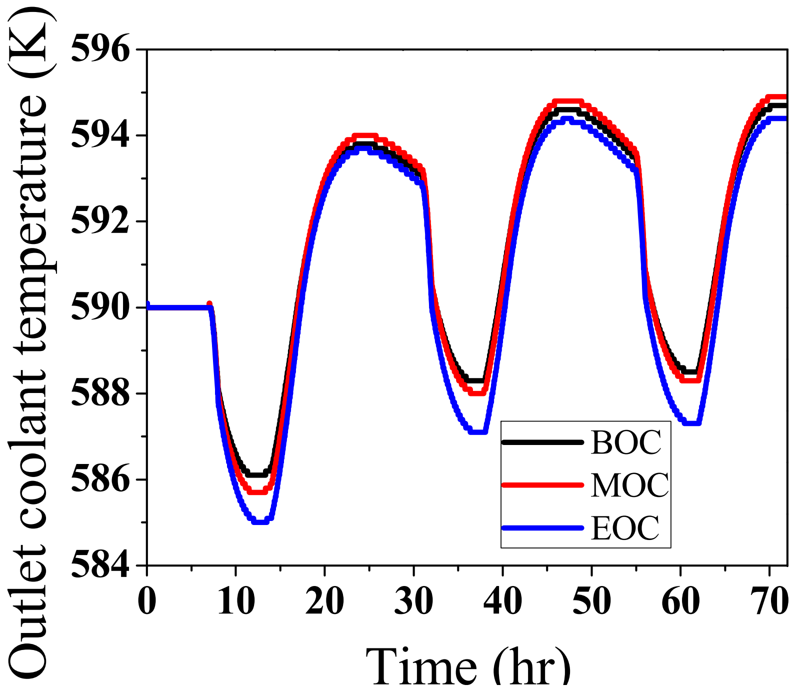
System Responses in PDLFO – (2)



- **Max possible deviation at average coolant T in standard PWRs ~ 5 F at 100% P.**



- **Max. deviation at hot leg ~ 5 K at 100% P**

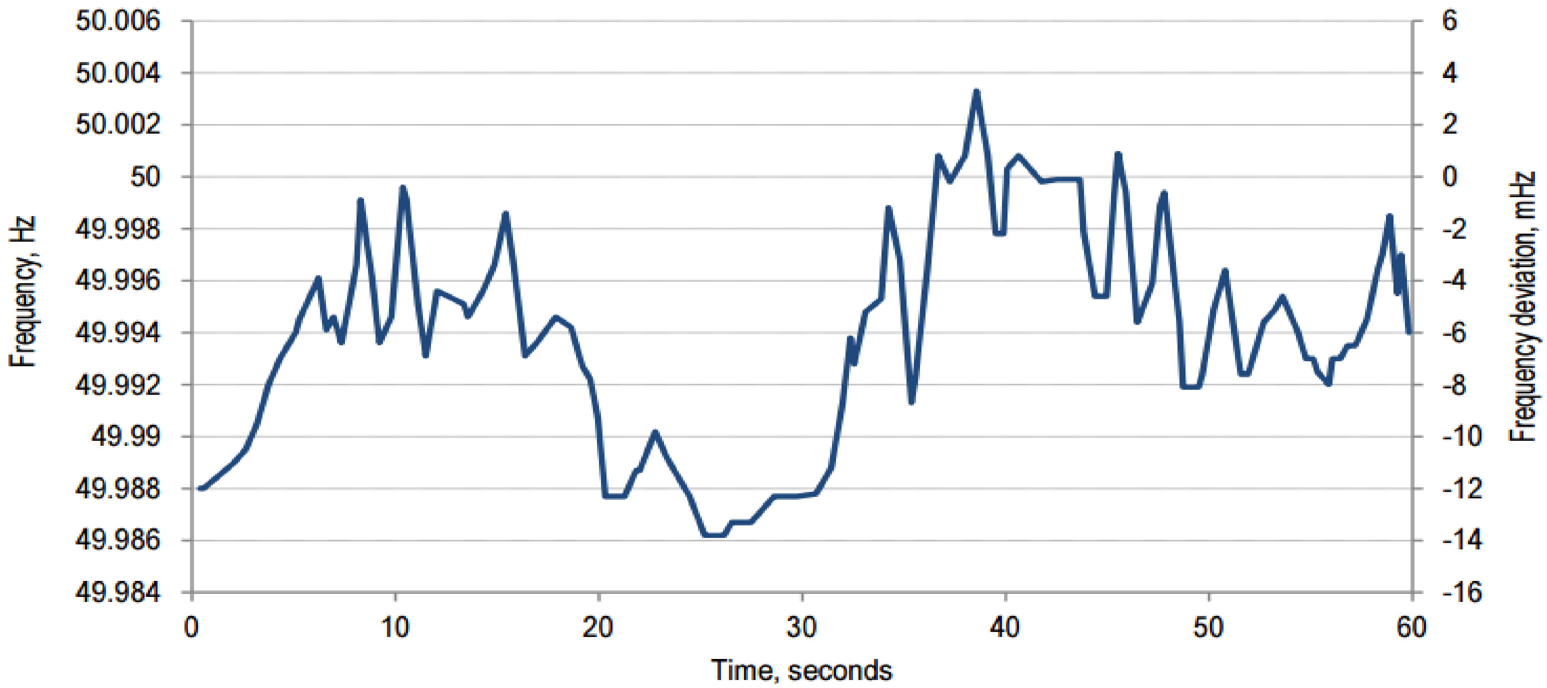
  → Bigger pressurizer or design changes

Frequency Operation in NPPs

– Power Demand can never be exactly evaluated in advance.

– There are random variations of demand resulting in frequency fluctuations.

(usually < 20 mHz)



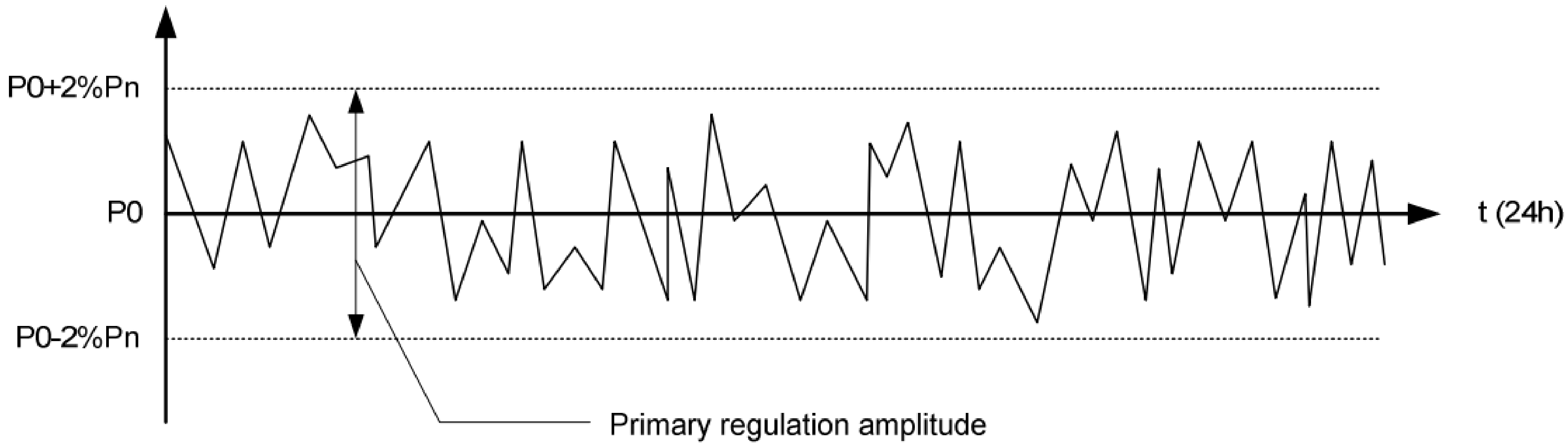
Example of the frequency variation on the grid in Europe

Source: Technical and Economic Aspects of Load Following with Nuclear Power Plants,
https://www.oecd-nea.org/ndd/reports/2011/load-following-npp.pdf

Passive Primary Frequency Operation (PPFO) – (1)

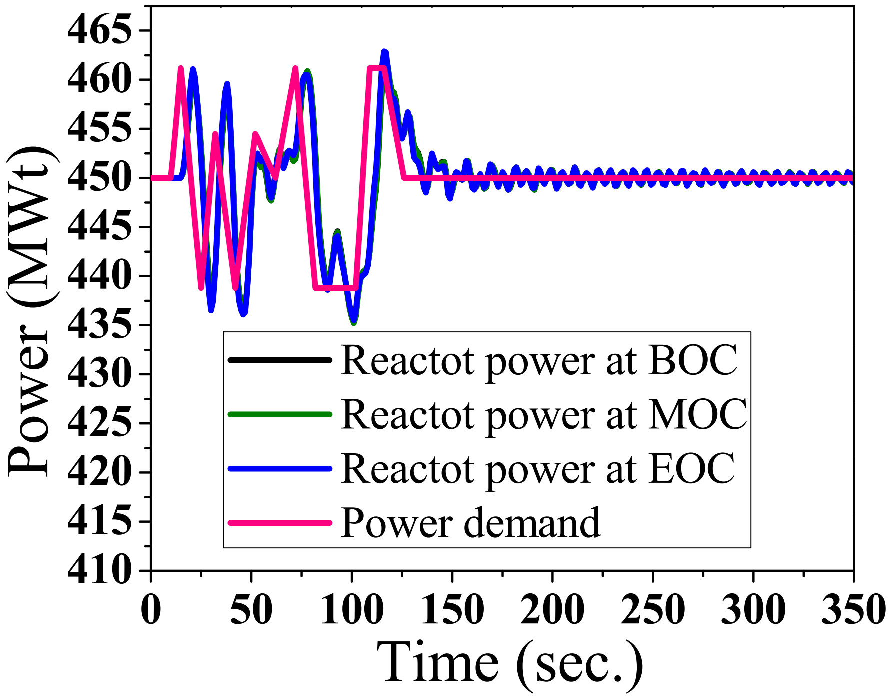
– The primary frequency regulation restores the most feasible operating system conditions in the short-term after a disturbance (about 2 to 30 seconds).

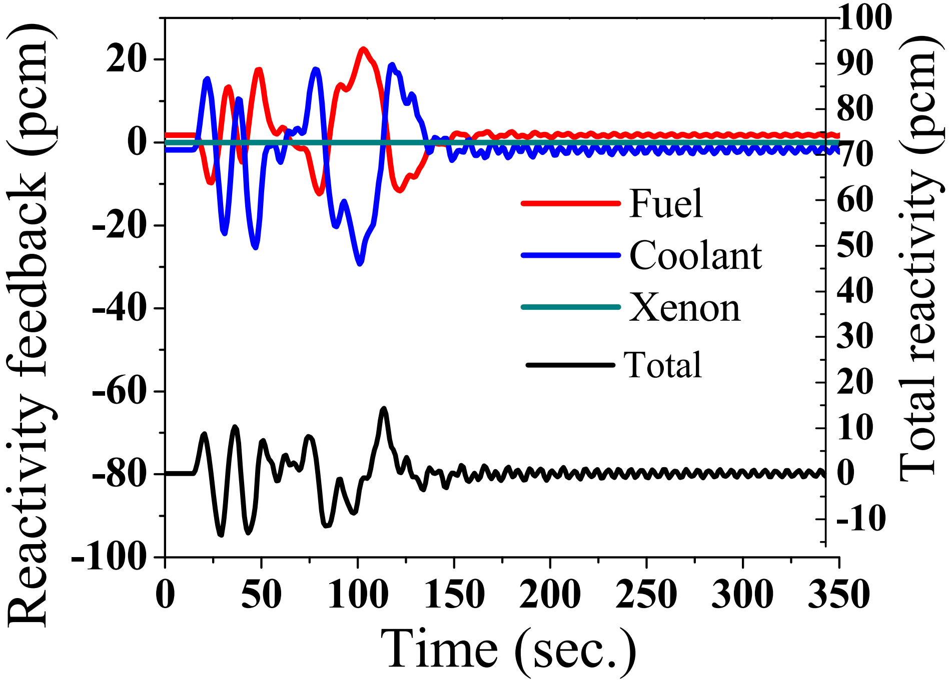
– Typically, a NPP operating in a primary control mode is required to adjust its power level within the range of ±2 % Pr within power-ramping speeds up to 0.5% Pr per second



Passive Primary Frequency Operation (PSFO) – (3)

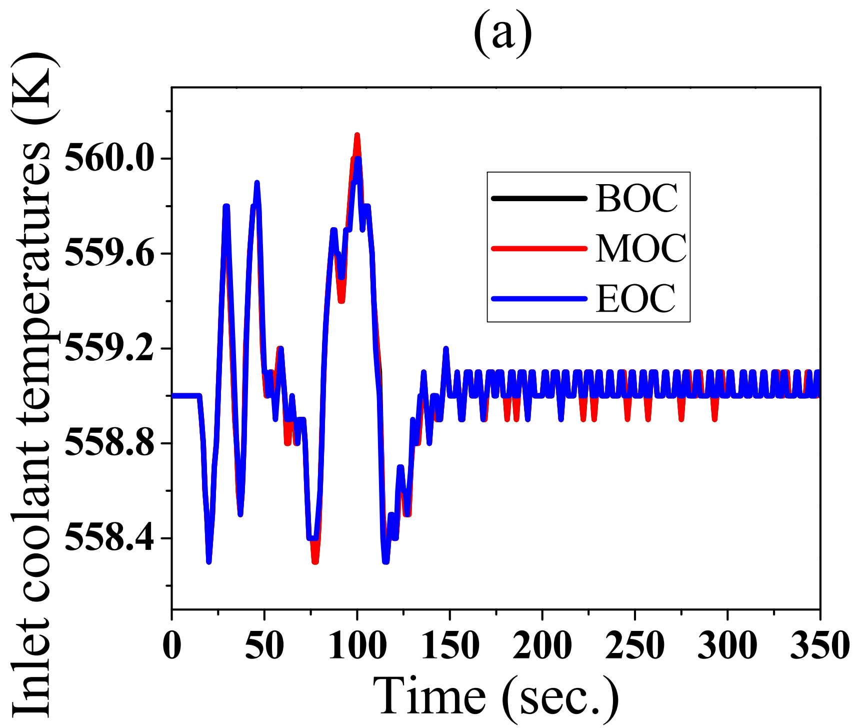
- Good matching between reactor power and power demand
- Small variation of coolant temperature

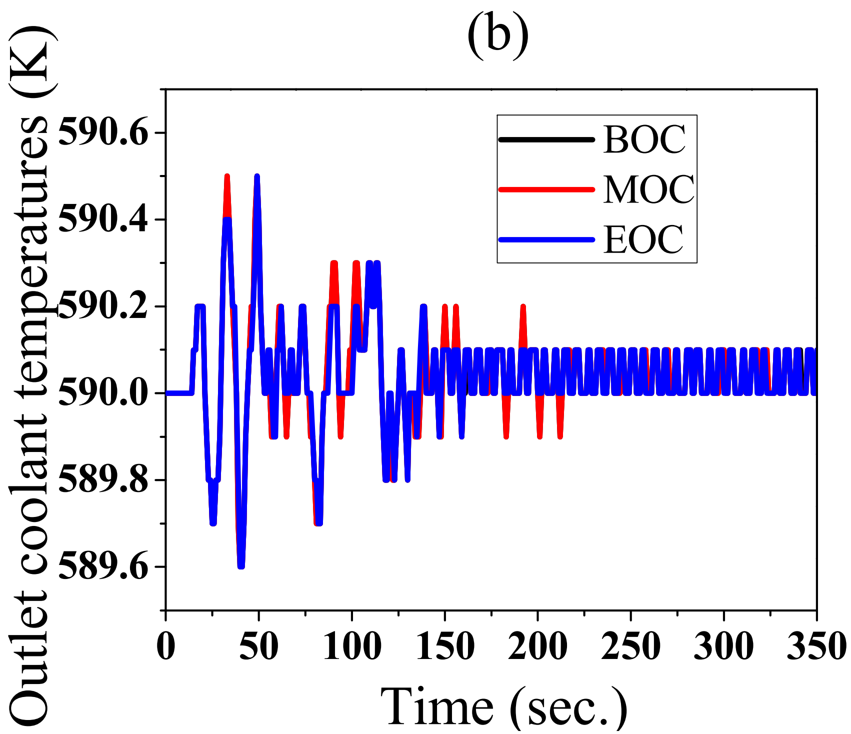




Passive Primary Frequency Operation (PSFO) – (3)

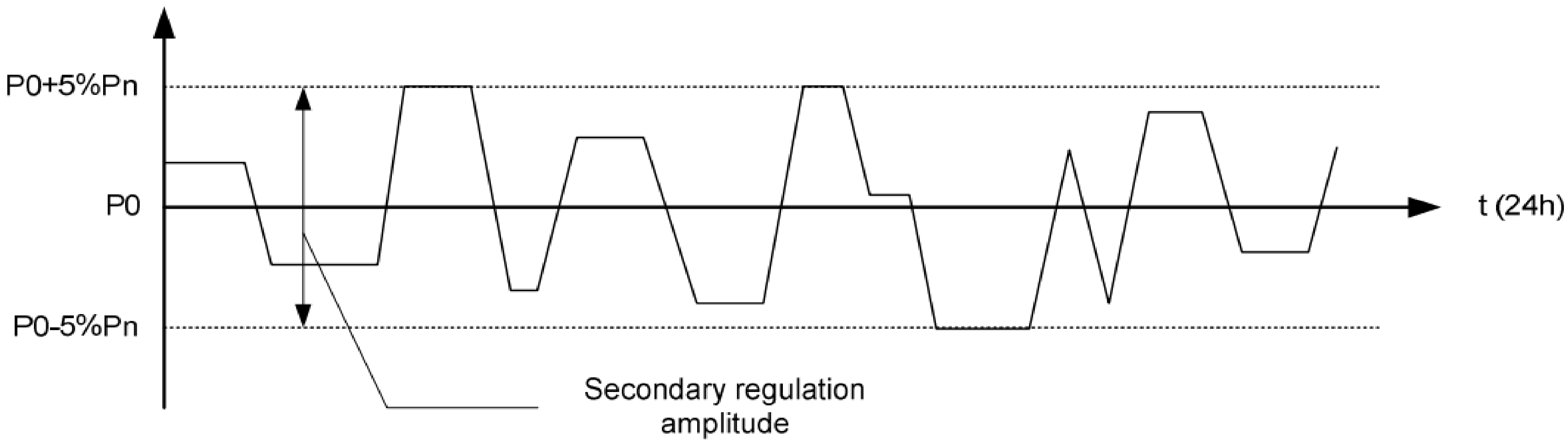
- Good matching between reactor power and power demand
- Small variation of coolant temperature < 0.6 K (well within dead-band)





Passive Secondary Frequency Operation (PSFO) – (1)

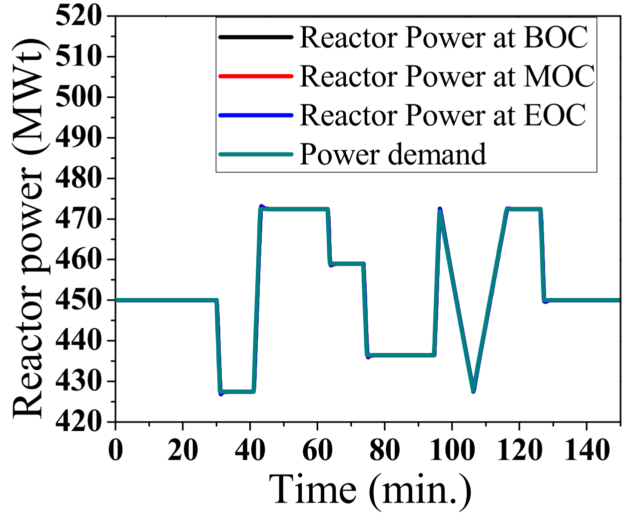
- It acts over longer timeframes (from several seconds to several minutes) and restores the exact frequency by calculating an average frequency deviation over a period of time.
- Typically, the grid operator sends a digital signal to the NPP to modify their power level by in the interval of ±5%Pr.
- The requested power-ramping speed in secondary frequency operation is 1% Pr per min up to 5% Pr per minute.



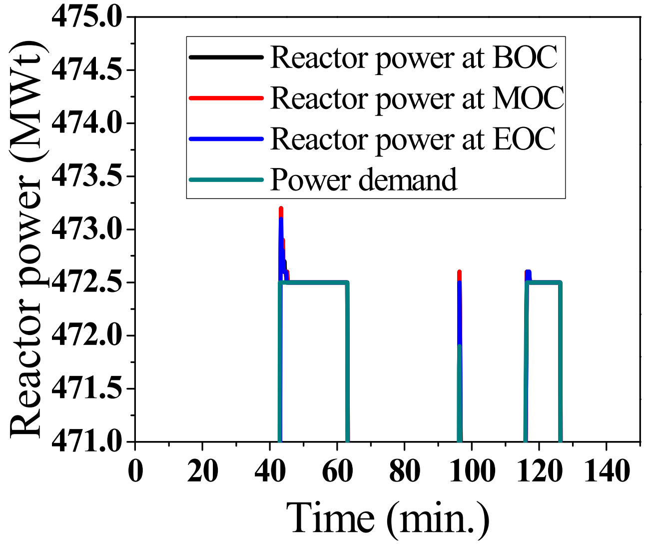
Passive Secondary Frequency Operation (PSFO) – (3)

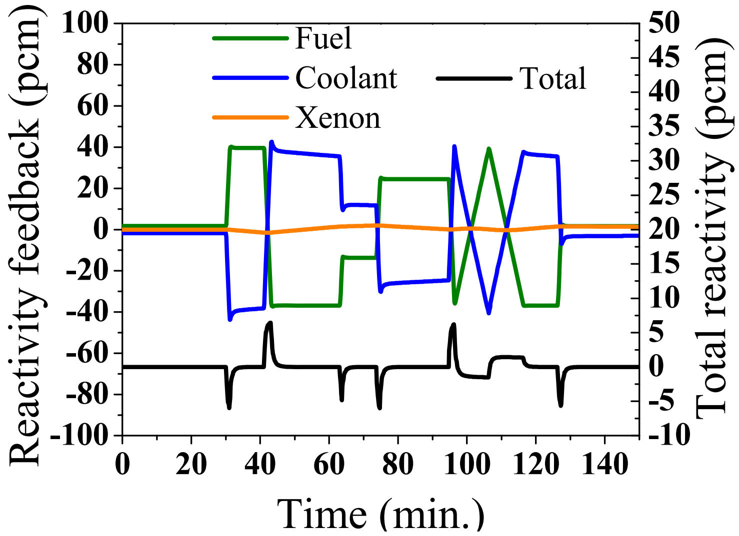
– Good matching between reactor power and power demand

– Small variation of coolant temperature

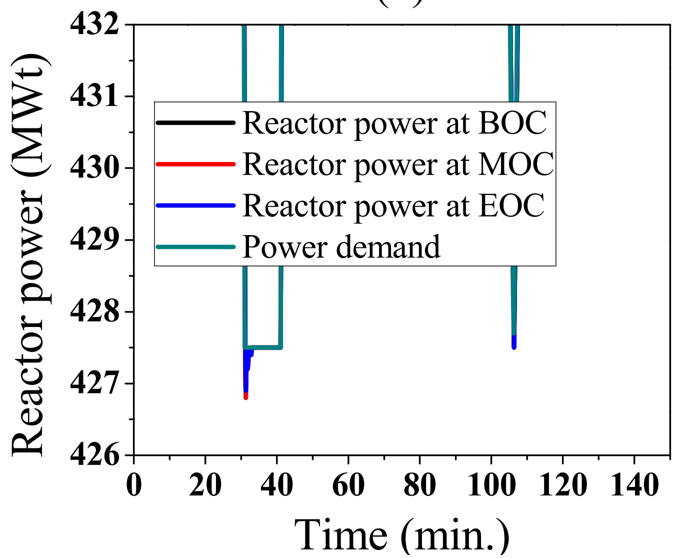


(a)



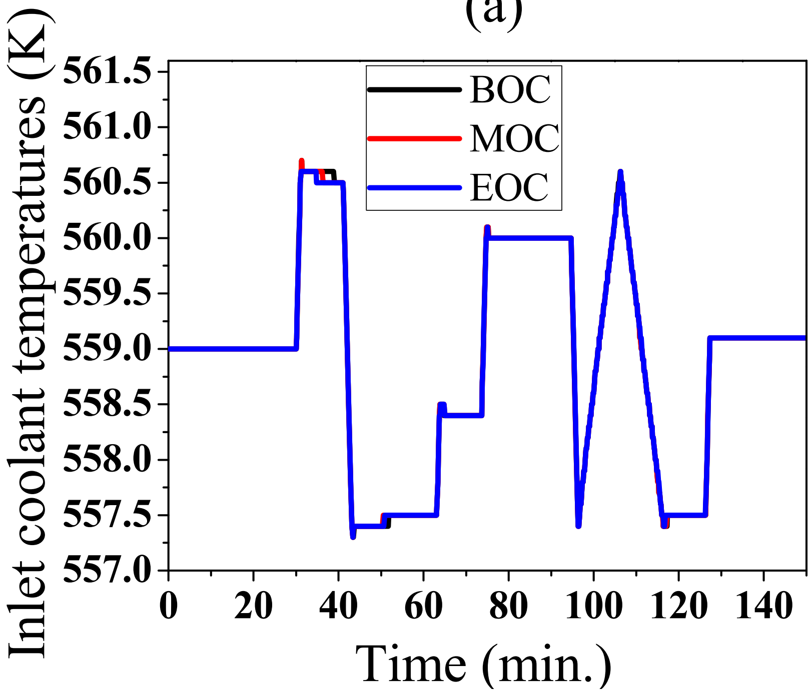


(b)



Passive Secondary Frequency Operation (PSFO) – (4)

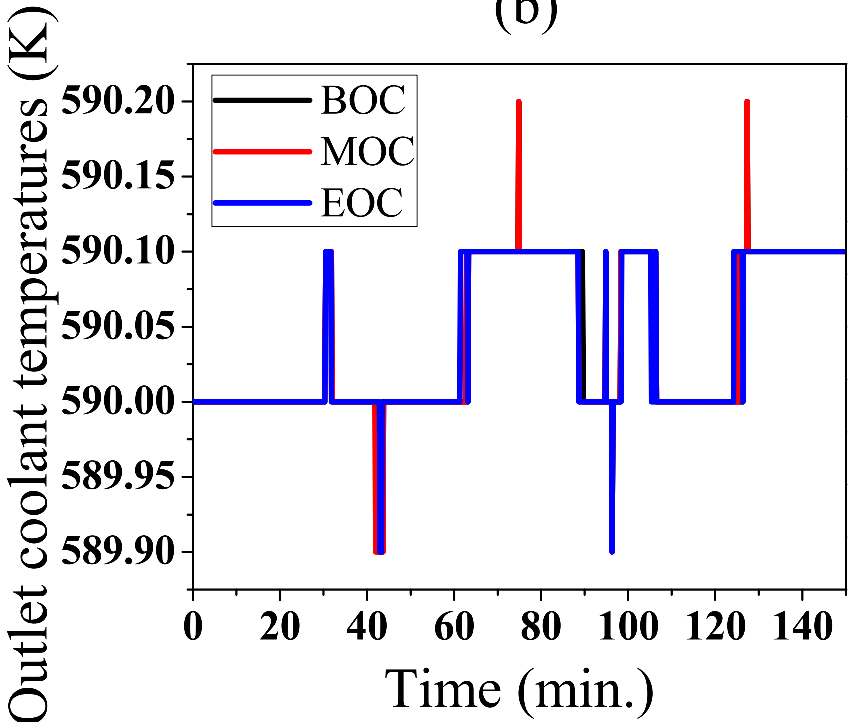
(a)



- *The variation of cold leg T ~ ± 1.5K and less than ± 0.2 K variation occurs at the hot leg*
- *±0.9K variation of the average coolant temperat ure is noticed*

(Very close to the dead-band)

(b)



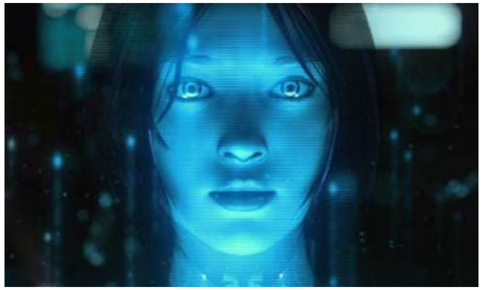
Challenges for Autonomous NPPs

○ **Generation of Training Data for AI**

- High-fidelity multi-physics simulation is enough?
- How to simulate the unexperienced accidents?
- Seamless training is possible?
- Quantification of uncertainty in measured and simulated data

○ **Licensability**

- Reliability for untrained region?
- License by Test?



○ **Cyber security**

- More stringent security measures for AI systems

○ **Redundant AI systems**

- Which is more reliable?

○ **How to do self-learning?**

Concluding Remarks

Concluding Remarks

- **Autonomous operation may significantly improve the safety and reliability of NPP systems.**

- **Elimination of soluble boron will improve the safety and economy of SMR and also it will enhance the autonomous operation of SMRs.**

- **A passive frequency control is expected to be highly feasible due to the noticeably lower power density in the SMR designs.**

- **Combination of AI and big-data technologies will substantially improve the competitiveness of the SMRs.**

Thank you!