Sensitivity of Integral Reactor Configurations to Parametric Fluctuations

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1. Objective

- Focus on the reactor transient behaviors in the IAEA integral-PWR(i-PWR) simulator.
- Quantify sensitivities of the observable balance of plant performance parameters to fluctuations.
- Analysis of the oscillations and trends during nominal daily operation conditions, especially for the normalized power and generator load.

2. Summary of the i-PWR simulators features and capabilities

- i-PWR is one type of SMRs
- IAEA defines SMR electrical power level as below 300 MWe
- Advantages:
 - Reduce the emergency planning zone (EPZ)
 - Minify the number of vessels and pipes to decrease the leakage probability
 i-PWRs have a larger volume of pressurizer and reactor coolant water inventory.
 i-PWR pipes' diameter is smaller than PWRs



Figure 1. The main design differences between PWR (left) and

i-PWR (right)

Core

i-PWR Type

6. Results

Base load:

$\begin{array}{c c c c c c c c c c c c c c c c c c c $	•	When the normalized power setpoints	Setpoint of normalized power (%)	Time (hr)	Range $(%)$	Mean (%)	Standard
decrease, incrementing trend.have an10061.6232 97.6126 0.1064 121.6213 97.6282 0.0825241.9621 97.5028 0.1744• The 75% cases and 50% cases have the opposite trend of 100% normalized48 2.7536 97.1414 0.409572 3.4162 96.7771 0.6523power case756 2.5118 75.0420 0.3437 power case12 2.5278 75.0248 0.3609 • The normalized power at 25 % of cases48 2.6057 75.1703 0.4712 has a maximum standard deviation value at running 6 hours.506 2.5849 49.9514 0.4103 • 75% of normalized power cases have a bigger standard deviation for 24 hours256 13.5606 20.0192 5.9461 situation256 13.5606 20.0192 5.9461		i in international power serpoints	Setpoint of normalized power (78)		Kange (70)	Wiedii (70)	deviation (%)
incrementing trend.12 1.6213 97.6282 0.0825 • The 75% cases and 50% cases have the opposite trend of 100% normalized24 1.9621 97.5028 0.1744 • The 75% cases and 50% cases have the opposite trend of 100% normalized756 2.5118 75.0420 0.3437 power case756 2.5118 75.0248 0.3609 • The normalized power at 25 % of cases has a maximum standard deviation value72 2.5978 75.1544 0.4010 at running 6 hours.72 2.6334 49.9514 0.4103 • 75% of normalized power cases have a bigger standard deviation for 24 hours256 13.5660 20.0192 5.9461 situation256 13.5709 16.8194 5.7291		decrease, the ranges have an	100	6	1.6232	97.6126	0.1064
$\begin{array}{c c c c c c c c c c c c c c c c c c c $		incrementing trend		12	1.6213	97.6282	0.0825
• The 75% cases and 50% cases have the opposite trend of 100% normalized 48 2.7536 97.1414 0.4095 72 3.4162 96.7771 0.6523 90 power case 75 6 2.5118 75.0420 0.3437 90 power case 12 2.5278 75.0248 0.3609 24 2.5941 75.0044 0.5499 • The normalized power at 25 % of cases 48 2.6057 75.1703 0.4712 has a maximum standard deviation value 72 2.5978 75.1544 0.4010 at running 6 hours. 50 6 2.5849 49.9743 0.4144 24 2.6859 49.9856 0.4576 75% of normalized power cases have a 48 3.1650 50.0468 0.5910 bigger standard deviation for 24 hours 25 6 13.5660 20.0192 5.9461 situation 12 13.5709 16.8194 5.7291		merennenning trend.		24	1.9621	97.5028	0.1744
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24 2.5941 75.0044 0.5499 • The normalized power at 25 % of cases has a maximum standard deviation value 48 2.6057 75.1703 0.4712 has a maximum standard deviation value 50 6 2.5849 49.9514 0.4103 at running 6 hours. 50 6 2.6334 49.9743 0.4144 24 2.6859 49.9514 0.4103 at running 6 hours. 12 2.6334 49.9743 0.4144 24 2.6859 49.9856 0.4576 • 75% of normalized power cases have a bigger standard deviation for 24 hours 72 3.1703 50.1769 0.5275 situation 25 6 13.5660 20.0192 5.9461 12 13.5709 16.8194 5.7291		nower case		12	2.5278	75.0248	0.3609
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has a maximum standard deviation value 72 2.5978 75.1544 0.4010 at running 6 hours. 50 6 2.5849 49.9514 0.4103 at running 6 hours. 12 2.6334 49.9743 0.4144 24 2.6859 49.9856 0.4576 75% of normalized power cases have a 48 3.1650 50.0468 0.5910 bigger standard deviation for 24 hours 25 6 13.5660 20.0192 5.9461 situation 12 13.5709 16.8194 5.7291	•	The normalized power at 25 % of cases		48	2.6057	75.1703	0.4712
Interview 50 6 2.5849 49.9514 0.4103 at running 6 hours.12 2.6334 49.9743 0.4144 24 2.6859 49.9856 0.4576 75% of normalized power cases have a48 3.1650 50.0468 0.5910 bigger standard deviation for 24 hours256 13.5660 20.0192 5.9461 situation256 13.5709 16.8194 5.7291		has a maximum standard deviation value		72	2.5978	75.1544	0.4010
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$\begin{array}{cccccccccccccccccccccccccccccccccccc$	•	75% of normalized nower cases have a		24	2.6859	49.9856	0.4576
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25 6 13.5660 20.0192 5.9461 situation 12 13.5709 16.8194 5.7291		bigger standard deviation for 24 hours		72	3.1703	50.1769	0.5275
Situation 12 13.5709 16.8194 5.7291		•	25	6	13.5660	20.0192	5.9461
		situation		12	13.5709	16.8194	5.7291
• The 50% normalized power running 48 $\frac{24}{13.6537}$ $\frac{13.6537}{18.2907}$ $\frac{18.2907}{5.7824}$	•	The 50% normalized power running 48		24	13.6537	18.2907	5.7824

- IAEA SMR simulator:
 - Open Source.

HomeOverview

🗘 Controls

§ Trips ୲ୠ Systems

Reactor neutron power (#15%) 5 Reactor thermal power (#11) 5 Generator power (#11) 5 Generator power (#11) MWe Steam header pressure (270) WF RPV water level (1000) 5 Ottste power (Diese) (Batteries

- Do not reflect a specific vendor's design.
- Easy to operate on PC.

		Simulator	IAEA	PCTRAN- NuScale	Modelica code- based model	Fortran based model		
~	1 . 1 .	Open source	0	Х	Х	Х	X	
tic v	vendor's design.	Max reactor power (MWth)	150	160	160	500	150	
•		Max generator load (MWe)	45	60	53	158	45	
rop		Neutronic model	NEMO ^a	Point Ro	actor Kinetic equation with six precursors			
IOR um Turning gea sure Gen breaker o	ar Turbine trip Pen Runback Acito ADDITION	Thermal hydraulic		Lumped-loop approach with two-phase critical	2-D conduction at	nd conservation	Handsmadel	
80	Boric acid concentration 763.42 ppm Mode of operation	model	TRAC_R1°	flow	law		Hann's model	
10.20.20	Boric acid setpoint	Steam Generator model	Helical	Helical	Helical	Helical	Three lumps	
	Control rods reactivity 0 00 pcm 100 00 %AAKK Fuel reactivity (Doppler) 79 65 pcm 100 08 %AKK Moderator temp, reactivity 424 49 pcm 99 58 %AKK	Coupling hybrid energy system	х	х	0	0	N/A	
	Boron reactivity -2246 62 pcm 97.00 %AKK Xenon reactivity -24/8 21 pcm 97.83 %AKK Total reactivity 0.02 pcm 100.00 %AKK	Environment platform	Windows	Windows	Matlab simulink	Matlab simulink	Siemens PTI PSS/E	
	FUEL TEMPERATURES Max clad surface temperature Average clad surface temperature Average fuel temperature Beak fuel temperature Strenge Tuel temperature	Based design model	N/A	NuScale	N/A	IRIS, NuScale, SMART	NuScale	
rview	of the IAEA model.	Developer	Tecnatom	Micro-simulation Technology	ORNL, INL, NC state university	ORNL, INL	IEEE	

PWR Type

Table 1 The overview and comparison of i-PWR simulators.

3. Introduction of IAEA simulator

• The IAEA i-PWR model simulator was developed by Tecnatom in 2017.

hours has a larger value of standard deviation.

 48
 13.8350
 21.6550
 5.5168

 72
 13.8264
 22.8423
 4.5773

 Table 2 The statistical normalized power results of steady state scenarios

- Max standard deviation values of generator load are reactor operating 6 hours or 72 hours cases
- Max range values are either operating reactor for 24 hours or 72 hours
- The normalized power oat full power level, and the generator load at 75% power level have smaller range values
- In brief, 100% normalized cases have smaller standard deviation values in the normalized power and the generator load
- Only normalized power at 100% and 25% have strong relative to normalized power and generator load's range and standard deviation

Setpoint										
Normalized	Ideal			Mean	Standard					
Power (%)	Generator load	Time (hr)	Range (MW)	generator	deviation					
	(MW)			load (MW)	(MW)					
100	45	6	1.0084	44.2241	0.0507					
		12	1.0125	44.2315	0.0388					
		24	1.1647	44.1745	0.0806					
		48	1.5545	44.0028	0.1946					
		72	1.8704	43.8276	0.2997					
75	33.75	6	0.5800	32.8051	0.1224					
		12	0.5819	32.7693	0.1212					
		24	0.5866	32.7100	0.1109					
		48	0.5737	32.7475	0.0984					
		72	0.5795	32.7287	0.0936					
50	22.5	6	0.7778	20.2318	0.1331					
		12	0.8121	20.1901	0.1283					
		24	0.8158	20.2211	0.1340					
		48	0.8024	20.3588	0.1817					
		72	0.8061	20.4472	0.1909					
25	11.25	6	7.8123	6.7790	2.6482					
		12	7.7331	5.3714	2.5531					
		24	7.8462	5.9908	2.5788					
		48	8.1013	7.7749	2.6048					
		72	8.0450	8.3930	2.2937					

Table 3 The statistical generator load results of steady state scenarios.

Load-following:

- The average 50% normalized power and generator load of France's daily operation for six hours is slightly less than Germany's recommended operation for 12 hours
- For 100% of normalized power, both values of the normalized power and the generator load are similar.
- For the range side, the generator load at 50% setpoint power level of Germany recommending operation has a remarkably large value
 For standard deviation, it can be noticed that 100% normalized power setpoint result of the normalized power and the generator load are noticeable smaller than 50 %. This relationship also matches the steady-state result owing to the function of the pressurizer and main steam valves to adjust the steam input.
 It shows the range values of 50 % are larger than 100% no matter in France or Germany recommended setups that are correlative to the normalized power of steady-state scenarios

- The build-in fuel is UO₂ with 4.95% enrichment with 17X17 fuel pins with 24 assemblies. (Figure 2)
- 150 MWth and 45 MWe (when reactor runs full power of the reactor)
- Saturation temperature is 344.8°C at 15.5 MPa
- Helical type steam generators

Figure 2. The reactor core over

- Passvie safety system includes ADS, PDHR, PIS, and GIS. (Figure 3)
- Advantages of the IAEA SMR simulator:
 - Open Source.
 - Do not reflect a specific vendor's design.
 - Easy to operate on PC.



4.Methods and Scenarios

Category	Scenarios	Normalized power setpoint (%)	Operating time (hr)	Parameters	Annotation	 Select plant mode Load initialization (IC#1)
Base-load						- • Load Initialization $(IC + I)$
	1	100	6			Natural circulation status
	2	100	12			i tutului eli euluitoli stutus
	3	100	24			• Select auto mode of control rods
	4	100	48			
	6	75	6	Generator load.		• Boric concentration uses the simulator de
	7	75	12	Normalized power,		(762mm)
	8	75	24	Average generator load,		(705ppiii)
	9	75	48	Average normalized		• Set nower demand noints to achieve my
	10	75	72	power, Range of generator		Set power demand points to demeve my
	11	50	6	load, Range of normalized		scenarios setups
	12	50	12	power, Standard deviation		
	13	50	24 48	of generator load and Standard deviation of		• Reactor power rate:
	14	50	72	normalized nower		$- D_{a} = \frac{1}{2} $
	16	25	6	normalized power		Base load: 3%/min
	17	25	12			Load following: 3, 5%/min
	18	25	24			- Load-following. $5 \sim 5 / 0/11111$
	19	25	48			
	20	25	72			
Load-followi	ng 1	100-50-100	12-3-6-4	Generator load, Normalized power, Average generator load, Average normalized	Based on France daily operation	
	2	100-50-100	12-12	power, Range of generator load, Range of normalized power, Standard deviation of generator load and Standard deviation of normalized power	Based on Giorgio Locatelli et.al and Germany recommended daily operation	Table 2The overview of scenarios setup descriptionsand parameters will be analyzed.

Type of daily operation	Operating time	Normalized power setpoint	Average		Range		Standard deviation	
France			Normalized power (%)	Generator load (MW)	Normalized power (%)	Generator load (MW)	Normalized power (%)	Generator load (MW)
	6	50%	49.9924	20.2199	2.957	1.7748	0.3927	0.1365
	12	100%	97.6280	44.2314	1.662	1.0123	0.0818	0.0389
Germany								
Recommend	12	50%	50.0254	20.2259	2.7181	5.4993	0.4141	0.2130
	12	100%	97.6249	44.2301	1.6227	1.0070	0.0848	0.0407

a. The values are based on the IAEA simulator digital results.

Table 4 The statistical normalized power and generator load results of load following scenarios.

7. Conclusion

- The oscillations of normalized power are relative control rod worth and xenon reactivity fluctuations.
- Lower normalized power level is more sensitive to neutron poision.
- 100% of cases have a smaller standard deviation of normalized power and generator load.
- 75% and 50% of cases' transient behaviors are similar. The 50% of cases present delayed responses.
- 25% of cases are deeply affected by neutron poisons.
- The fluctuations of generator load are relative to normalized power and the standard deviation of generator load is lower than normalized power.
- The standard deviation of normalized power becomes larger when increasing simulation time except in 25% cases.
- Both load-following cases' range values of normalized power and generator load at lower power levels are larger than at higher power levels.
- The load-following cases' statistical normalized power and generator load results are similar to base-load cases.



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