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A Characterization Study of Nuclear Reactors Through Xenon Isotopic Activity Ratios

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Contents

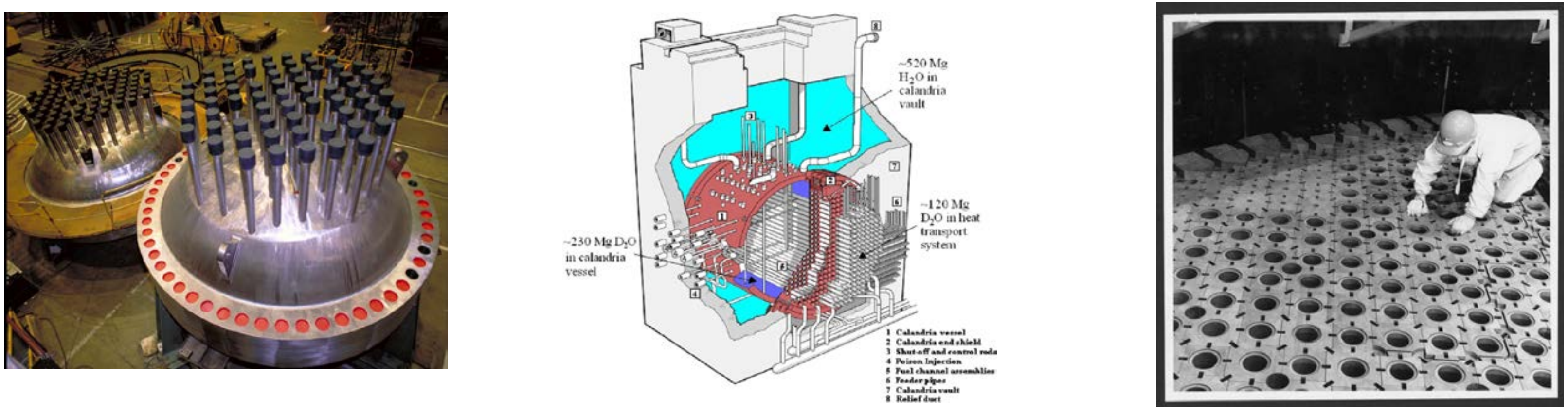
1. Introduction

- So far, there have been six nuclear tests in neighboring countries, and despite the nuclear test ban treaty, continued nuclear activities can lead to nuclear threats, so many countries are keeping a close eye on their nuclear activities.
- Xenon isotopes and their isomers are the most likely observable radioactive signatures of nuclear test.
- They are collected in the atmosphere from control stations deployed through the International Monitoring System (IMS) established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).

[Fig. 1. IMS Station map established by CTBTO]

1. Introduction

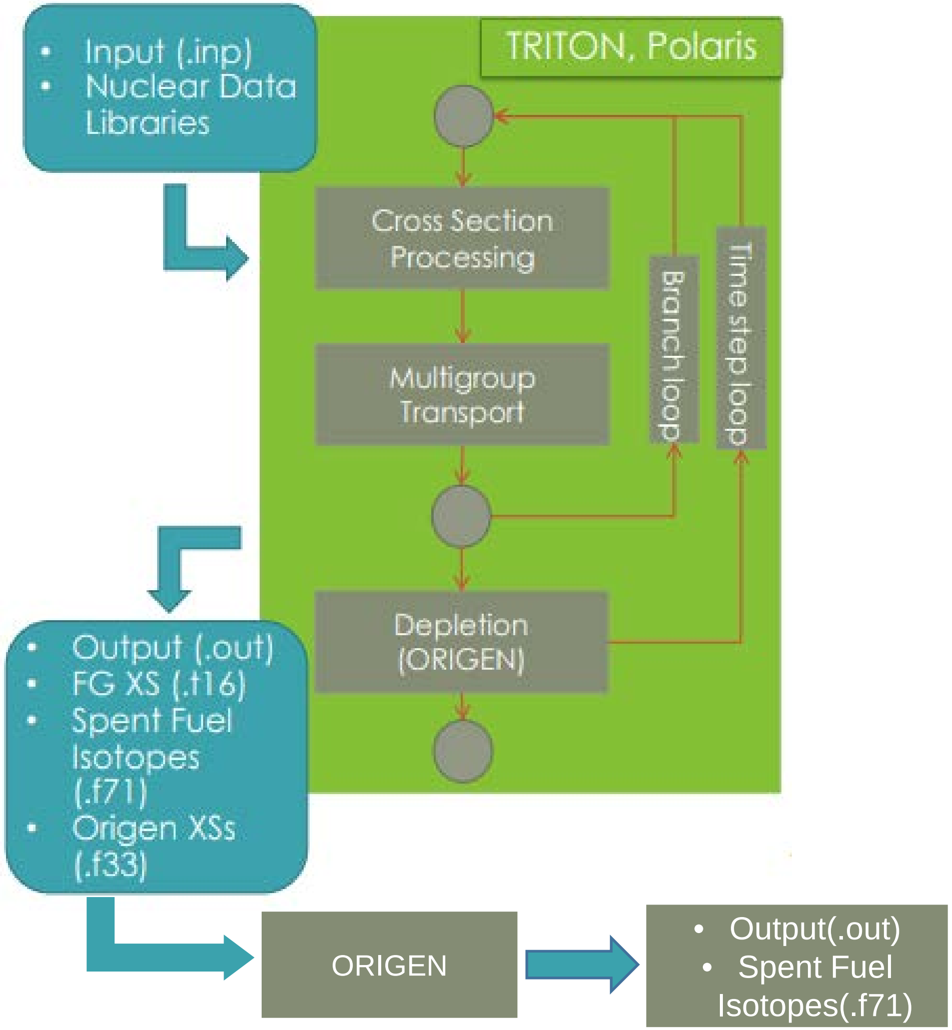
- **There are many possible facilities generating xenon isotopes such as different types of reactors and nuclear tests, which makes it difficult to identify the source of the xenon isotopic detection.**
- **Therefore, it is very important to devise a reliable indicator which can discriminate the source of xenon detection.**
- **Although there have been lots of researches in analyzing xenon isotopic characteristics, there are no comprehensive works on the xenon isotopic characteristics for various facilities in neighboring countries.**
- **The nuclear facilities operating in neighboring countries include IRT research reactor, nuclear fuel reprocessing facilities, uranium enrichment facilities, and 5MWe graphite reactor(MAGNOX) in Yongbyon.**
- **In this work, the characteristics of xenon isotopic activity ratios are analyzed and discussed in detail for the various reactors including PWR, CANDU, IRT-2000, and MAGNOX reactors.**



[Fig. 2. Various nuclear reactor]

2. Computational Method

- **In this work, TRITON and ORIGEN modules in SCALE6.2 were used to analyze the xenon isotopic characteristics for various reactor types.**
- **Several codes included in SCALE can be represented through a platform called Fulcrum.**
- **In this study, ORIGEN and TRITON codes were performed (Fig. 3)**
  - **TRITON generates one-group effective cross sections as a function of burnup, uranium enrichment, and so on through depletion calculation coupled with transport calculation.**
  - **ARP interpolates the effective one-group cross sections for a given parameter set.**
  - **ORIGEN performs the point depletion and decay calculations with the prepared one-group effective cross section.**



- Input (.inp)
- Nuclear Data Libraries

TRITON, Polaris

Cross Section Processing

Multigroup Transport

Branch loop

Time step loop

Depletion (ORIGEN)

- Output (.out)
- FG XS (.f16)
- Spent Fuel Isotopes (.f71)
- Origen XSs (.f33)

ORIGEN

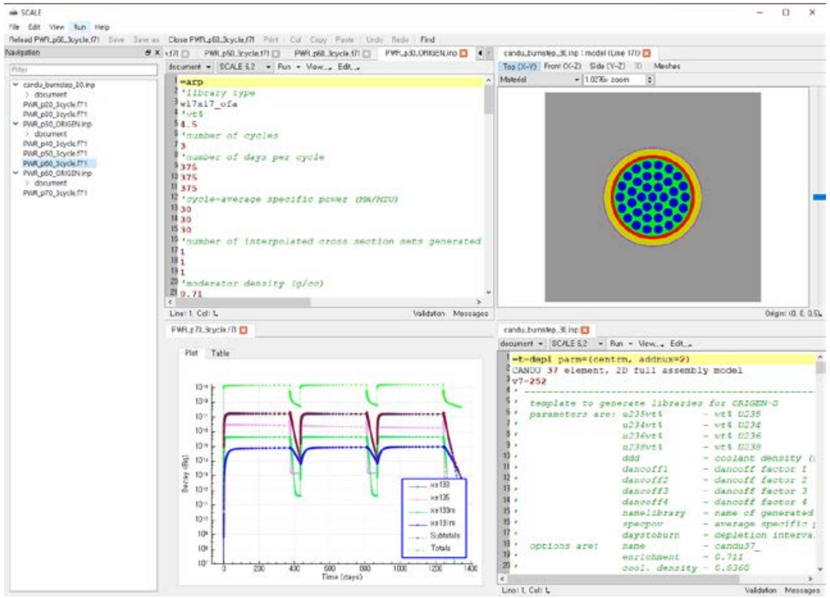
- Output(.out)
- Spent Fuel Isotopes(.f71)

[Fig. 3. TRITON calculation sequence and follow- on ORIGEN calculation]

2. Computational Method

Scale: A Comprehensive Modeling and Simulation Suite for Nuclear Safety Analysis and Design

[Fig. 4. SCALE]



```
=arp
'library type
w17x17_ofa
'wt%
4.5
'number of cycles
3
'number of days per cycle
375
375
375
'cycle-average specific power (MW/MTU)
30
30
30
'number of interpolated cross section sets generated
1
1
1
'moderator density (g/cc)
0.71
```

```
=t-depl parm=(centrm, addnux=2)
CANDU 37 element, 2D full assembly model
v7-252
' -------------------------------------------------------------
'  template to generate libraries for ORIGEN-S
'  parameters are: u235wt%       - wt% U235
'                  u234wt%       - wt% U234
'                  u236wt%       - wt% U236
'                  u238wt%       - wt% U238
'                  ddd           - coolant density (
'                  dancoff1      - dancoff factor 1
'                  dancoff2      - dancoff factor 2
'                  dancoff3      - dancoff factor 3
'                  dancoff4      - dancoff factor 4
'                  namelibrary   - name of generated
'                  specpow       - average specific p
'                  daystoburn    - depletion interva
'  options are:    name          - candu37_
'                  enrichment    - 0.711
'                  cool. density - 0.8360
```

[Fig. 5. SCALE Graphical User Interface – Fulcrum]

❖ **SCALE 6.2 provides a user-friendly GUIs designed to create, modify, view and visualize input, output, and files.**

- **Geometry models can be visualized for sequences that use KENO V, KENO-VI, Monaco, and NEWT**
- **ORIGEN concentration file (f71) with integrated unit conversion (OPUS capability)**

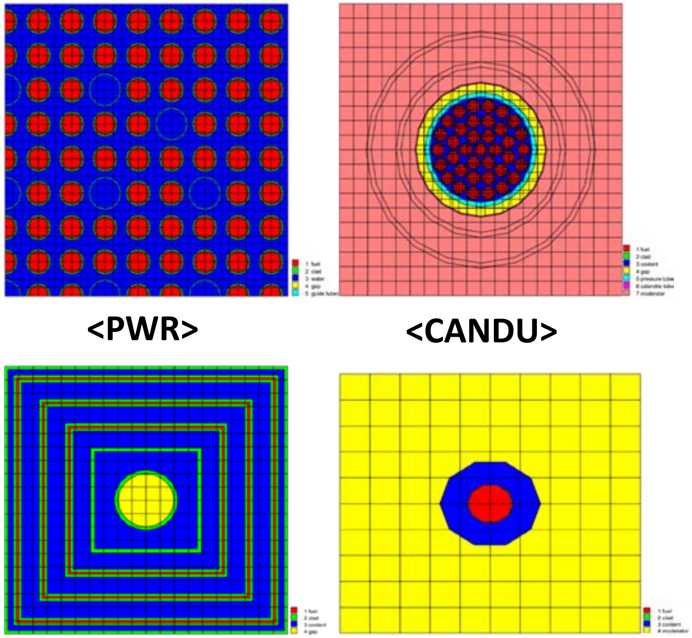
3. Modeling of Reactors

[Table 1. Specification of each reactor assembly]

Parameter	PWR	CANDU	IRT-2000	MAGNOX
Fuel assembly type	W17x17_ofa	Candu37	IRT-2M 3tube	MAGNOX
Number of Fuel pin	264	37	-	-
Fuel	1.5~6.0 wt% UO_2	0.711 wt% UO_2	36.15 wt% UO_2	0.711 wt% U + 0.5 wt% Al
Cladding	Zircaloy-2	Zircaloy-2	Al	Mg - Al(0.8 wt%) + Be(0.03 wt%)
Moderator	H_2O	D_2O	H_2O	Graphite
Fuel pin diameter(cm)	0.7844	1.215	0.064	2.5
Clad thickness(cm)	0.05715	0.0465	0.064	0.05
Fuel density(g/cm^3)	10.516	10.6	2.63	18.17
Moderator density(g/cm^3)	0.71	0.836	1.0	1.628

❖ **In this work, we considered the following reactors :**

- **PWR (WH 17x17)**
- **CANDU**
- **IRT-2000**
- **MAGNOX (Yongbyon 5MWe graphite moderated reactor)**



<PWR> **<CANDU>**

<IRT-2000> **<MAGNOX>**

[Fig. 6. The reactors modeled with SCALE 6.2]

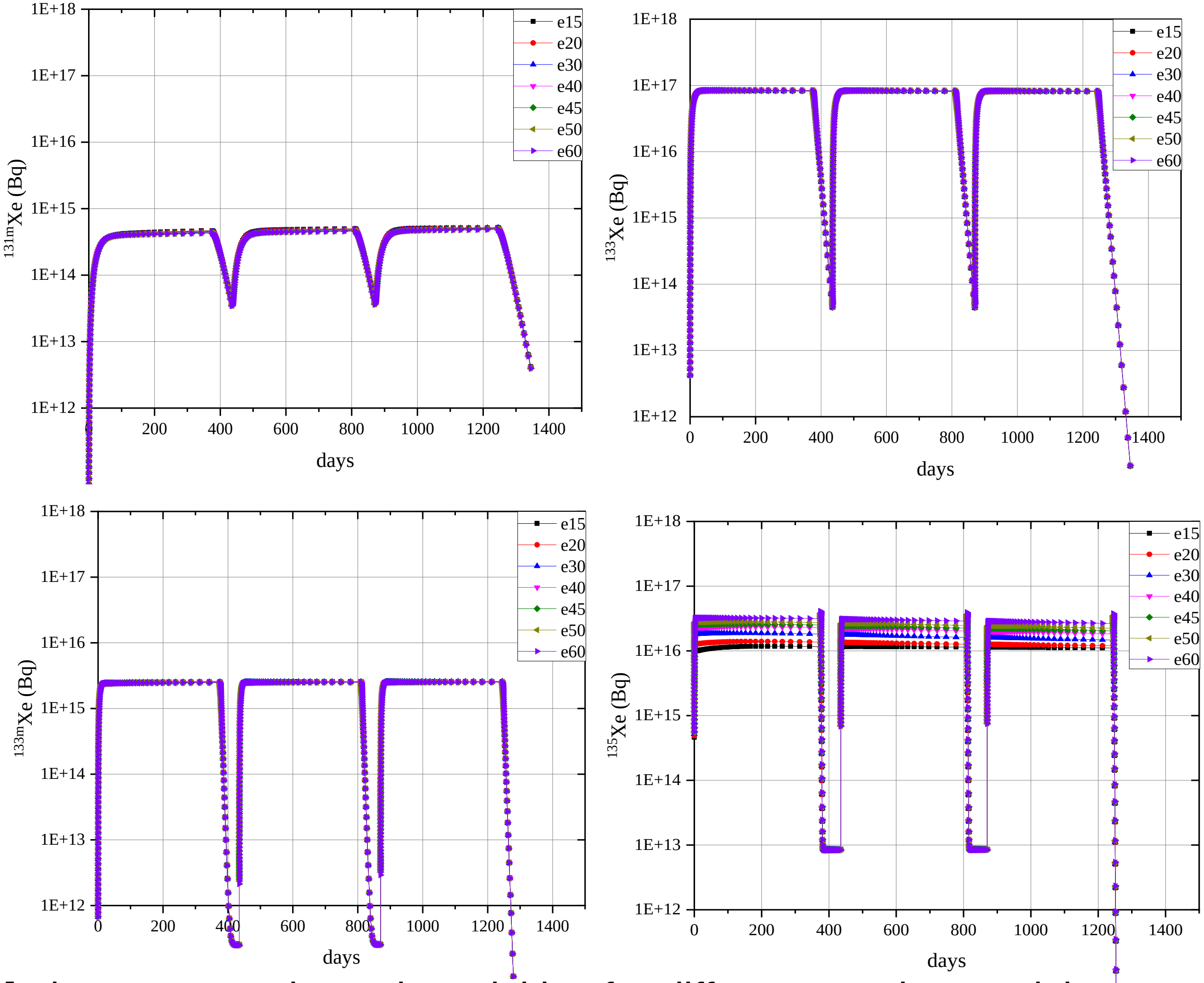
3. Modeling of Reactors

[Table 2. Burn data of each reactor in ORIGEN Calculation]

	PWR	CANDU	IRT-2000	MAGNOX
Burn Time (day)	375/60	700	350	4000
Number of Cycle	3	1	1	1
Specific power (MW/t)	40/0.004	19.5	557.1	0.502622
Burnup (MWd/t)	45,000	13,650	195,000	2,010
Cooling time after shutdown (day)	100			

- ❖ **Table 2 summarizes the conditions for depletion calculation including decay.**
- ❖ **The depletion calculation was performed using ORIGEN with the CRAM (Chebyshev rational approximation method) solver option.**
- ❖ **Initial the masses of uranium in all cases are normalized to 1 ton.**
- ❖ **The number of depletion calculation time steps including decay calculation : 600**
- ❖ **The decay calculation after shutdown was performed up to cooling period of 100 days.**

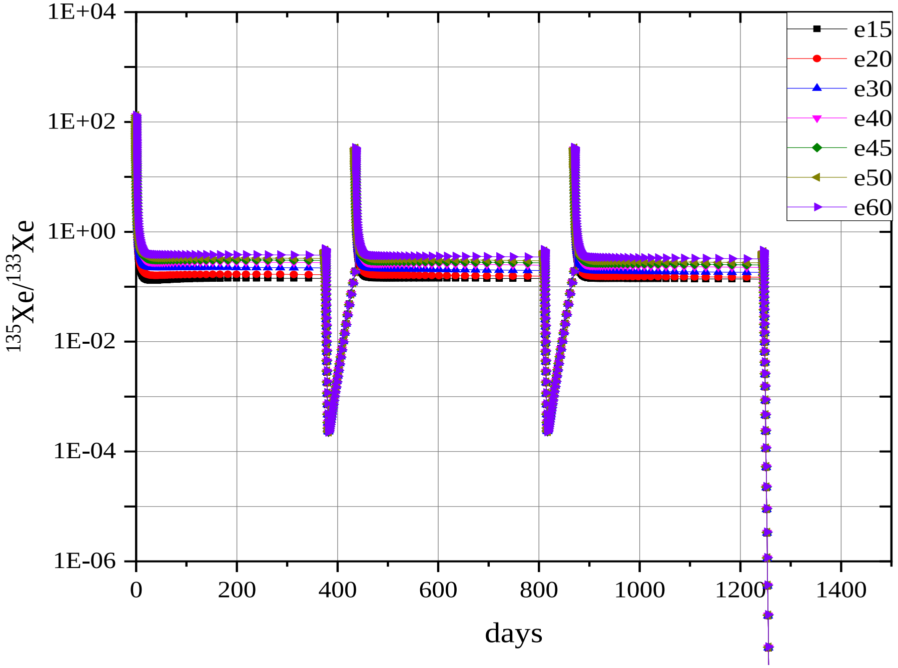
4. Calculation Results (PWR, Xenon Isotope Radioactivity)



[Fig. 7. Xenon isotopic activities for different uranium enrichments]

- ❖ ^{135}Xe radioactivity increases as uranium enrichment while the others' radioactivities do not change so much :
  - Higher enrichment ➔ lower thermal flux ➔ lower thermal neutron absorption by ^{135}Xe ➔ higher ^{135}Xe concentration.
- ❖ After shutdown, ^{135}Xe increases for ~10 hours due to the decay of I-135.

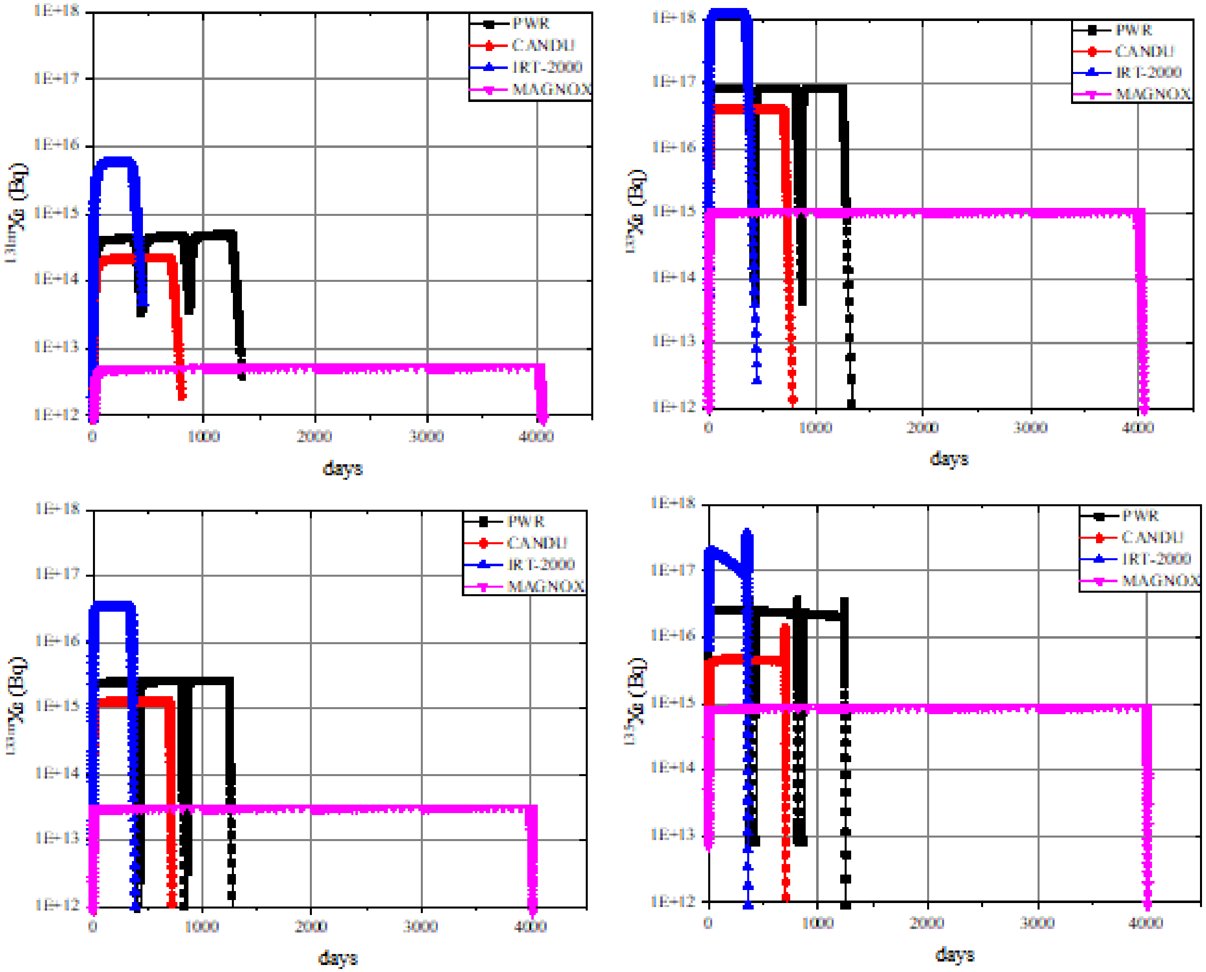
4. Calculation Results (PWR, Xenon Isotope Radioactivity Ratios)



[Fig. 8. ^{135}Xe/^{133}Xe activity ratio for different uranium enrichments]

- ❖ **We used isotopic activity ratio because collected isotopic activity can be changed depending on nuclear fuel mass and burnup.**
- ❖ **During reactor operation, xenon isotopic activity ratios reach equilibrium after a certain period.**
- ❖ **The equilibrium of ^{135}Xe/ ^{133}Xe ratio increases as uranium enrichment.**
- ❖ **For example, the equilibrium ^{135}Xe/ ^{133}Xe ratio for 6.0 wt% uranium enrichment is higher by ~2.8 times than the one for 1.5 wt% uranium enrichment.**

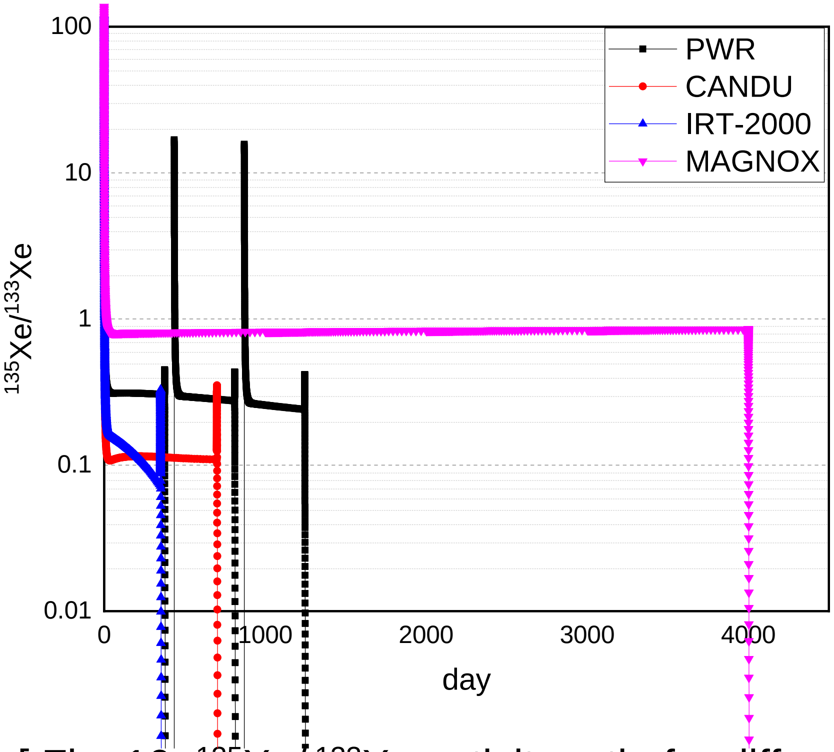
4. Calculation Results (Reactor Types, Xenon Isotope Radioactivity)



[Fig. 9. Xenon isotopic activities for different reactor types]

- ❖ **IRT-2000 shows the highest radioactivity for all the nuclides due to high specific power and uranium enrichment.**
- ❖ **For all the nuclides, the equilibrium isotope radioactivity increases as specific power.**
- ❖ **MAGNOX having lowest specific power has the lowest equilibrium isotopic radioactivity.**

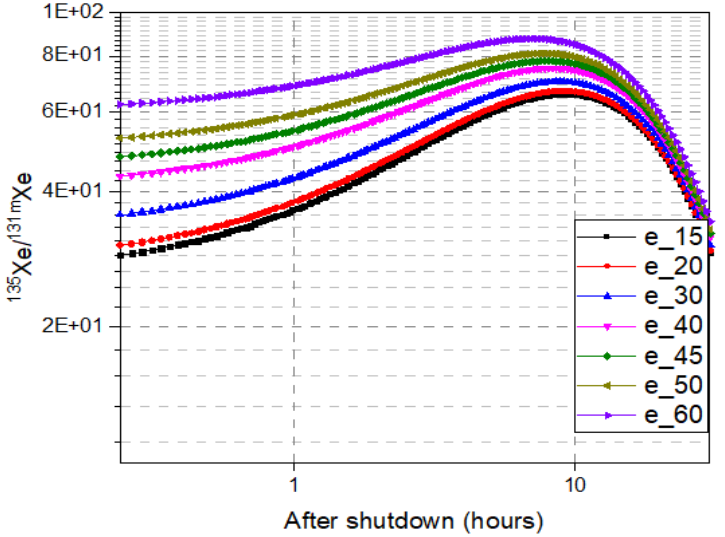
4. Calculation Results (Reactor Types, Xenon Isotope Radioactivity Ratio)



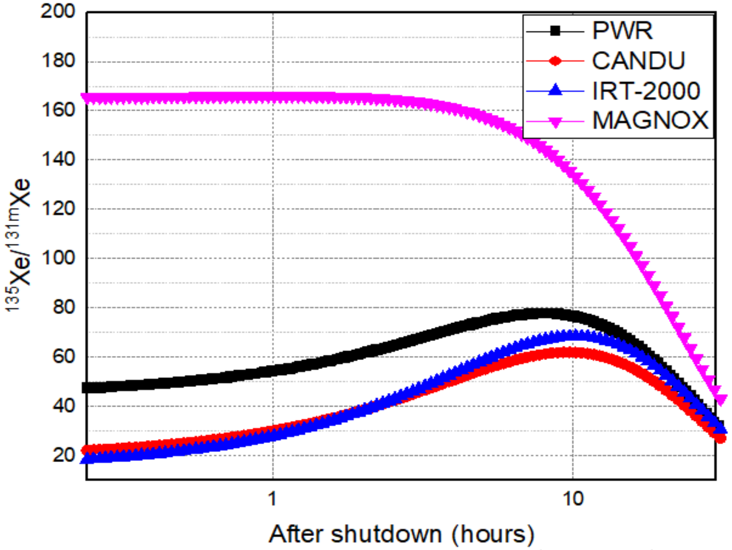
[Fig. 10. $^{135}Xe/^{133}Xe$ activity ratio for different reactor types]

- ❖ **CANDU shows high increase of $^{135}Xe/^{133}Xe$ after shutdown even though its specific power is lower than PWR.**
- ❖ **The equilibrium $^{135}Xe/^{133}Xe$ ratio can be used as an indicator for discrimination of the reactor types even if there are some overlaps between IRT-2000 and CANDU.**

4. Calculation Results (Reactor Types, Xenon Isotope Radioactivity Ratio, After Shutdown)



[Fig. 11. Comparison of the ^{135}Xe/ ^{131m}Xe isotopic ratio evolutions for PWRs with different uranium enrichments]



[Fig. 12. Comparison of the ^{135}Xe/^{131m}Xe isotopic ratio evolutions for different reactors (PWR with 4.5wt% uranium enriched fuel)]

- **The uranium enrichment gives a significant effect on the ^{135}Xe/ ^{131m}Xe isotopic ratio. (Fig. 11)**
  - **The initial value : 20~60**
- **It is possible to discriminate MAGNOX reactor from the other reactors and to discriminate IRT-2000 and CANDU from the other reactors except for the PWRs having very low uranium enrichments less than ~1.0wt% within several hours after shutdown. (Fig. 12)**

5. Conclusion

- In this study, we analyzed the xenon isotopic activities generated by nuclear activity in neighboring countries to find the source of nuclear activity.

- The activity of xenon isotopes was identified and their ratios were evaluated through SCALE simulation for the four possibly operable reactors (PWR, CANDU, IRT-2000, MAGNOX).

- In particular, ^{135}Xe was remarkable isotope, which was more affected by neutron flux than other xenon isotopes and showed significant changes by three factors (uranium enrichment, specific power, and moderator).
  - Under a same specific power, higher uranium enrichment of nuclear fuel leads to the low neutron flux, which reduces neutron absorption of ^{135}Xe and so gives higher equilibrium concentration.
  - High specific power produces a large amount of xenon isotopes.
  - Higher increase of ^{135}Xe after shutdown was observed for CANDU due to lower thermal neutron absorption by good moderating ratio of D_2O.

- Finally, it was shown that the MAGNOX reactor can be discriminated from the other reactors using ^{135}Xe/ ^{133}Xe ratio at the equilibrium state, and that CANDU and IRT-2000 reactor can be discriminated using this xenon isotopic ratio from PWRs having conventional uranium enrichments of 3.0~5.0wt%.

Thank you for listening

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