

# **Enhancing VVER Annular Proliferation Resistance Fuel with Minor Actinide**

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# INTRODUCTION

- **Key aspects of the Global Nuclear Energy Partnership (GNEP) are to significantly advance the science and technology of nuclear energy systems and the Advanced Fuel Cycle (AFC) program.**
- **Planned efforts involve near-term and intermediate-term improvements in fuel utilization and recycling in current LWR as well as the longer-term development of new nuclear energy systems that offer much improved fuel utilization and proliferation resistance.**
- **The challenges are solving the energy needs of the world, protection against nuclear proliferation, the problem of nuclear waste, and the global environmental problem.**

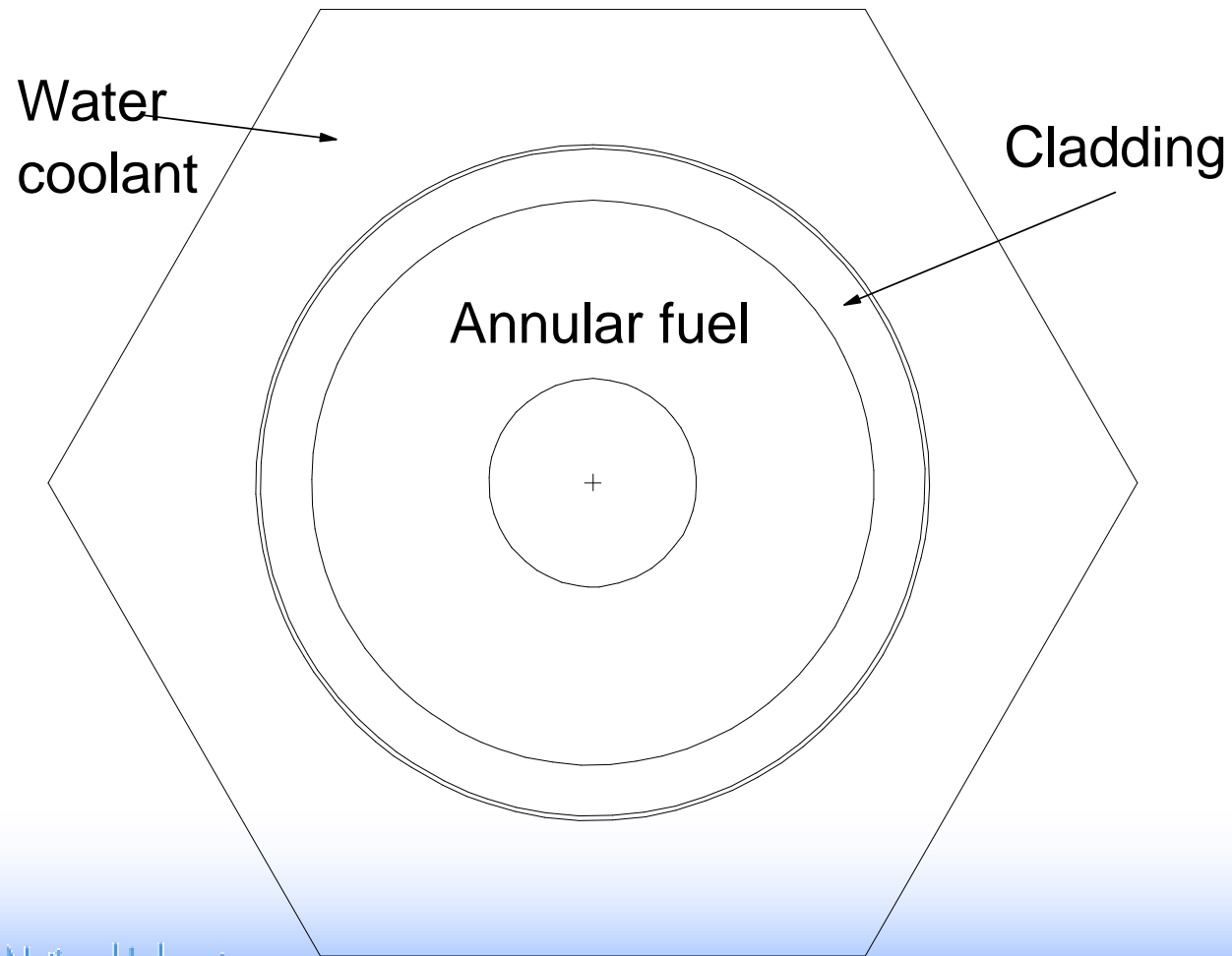
# Objectives

- To reduce the spent fuel for storage and enhance the proliferation resistance for the intermediate-term of LWR fuel cycle.
- There are two major approaches (a) increase the discharged spent fuel burnup in the advanced LWR (Gen-III Plus), which not only can reduce the spent fuel for storage, but also increase the  $^{238}\text{Pu}$  and  $^{240}\text{Pu}$  isotopes ratio to enhance the proliferation resistance, (b) use of transuranic nuclides ( $^{237}\text{Np}$  and  $^{241}\text{Am}$ ) in the high burnup fuel, which can drastically increase the proliferation resistance isotope  $^{238}\text{Pu}$  /Pu ratio.

# MINOR ACTINIDES (MA) REDUCTION APPROACH IN LWR

- MA are viewed more as a resource to be recycled, or transmuted to less hazardous and possibly more useful forms, rather than simply as a waste stream to be disposed of in expensive repository facilities.
- As a result, they play a much larger part in the design of advanced systems and fuel cycles, not only as additional sources of useful energy, but also as direct contributors to the reactivity control of the systems into which they are incorporated.
- A typical pressurized water reactor (PWR) VVER-1000 annular fuel unit lattice cell model with  $\text{UO}_2$  fuel pins will be used to investigate the effectiveness of MARA for enhancing proliferation resistance and improving the fuel cycle performance in the intermediate term goal for future nuclear energy systems.

Typical VVER lattice unit cell model with a pin pitch of 1.275 cm.



## VVER-1000 unit lattice cell parameters

Lattice pitch	1.275 cm
Fuel pin outer radius	0.455 cm
Cladding thickness	0.069 cm
Pellet outer radius	0.38 cm
Pellet central hole radius	0.14 cm

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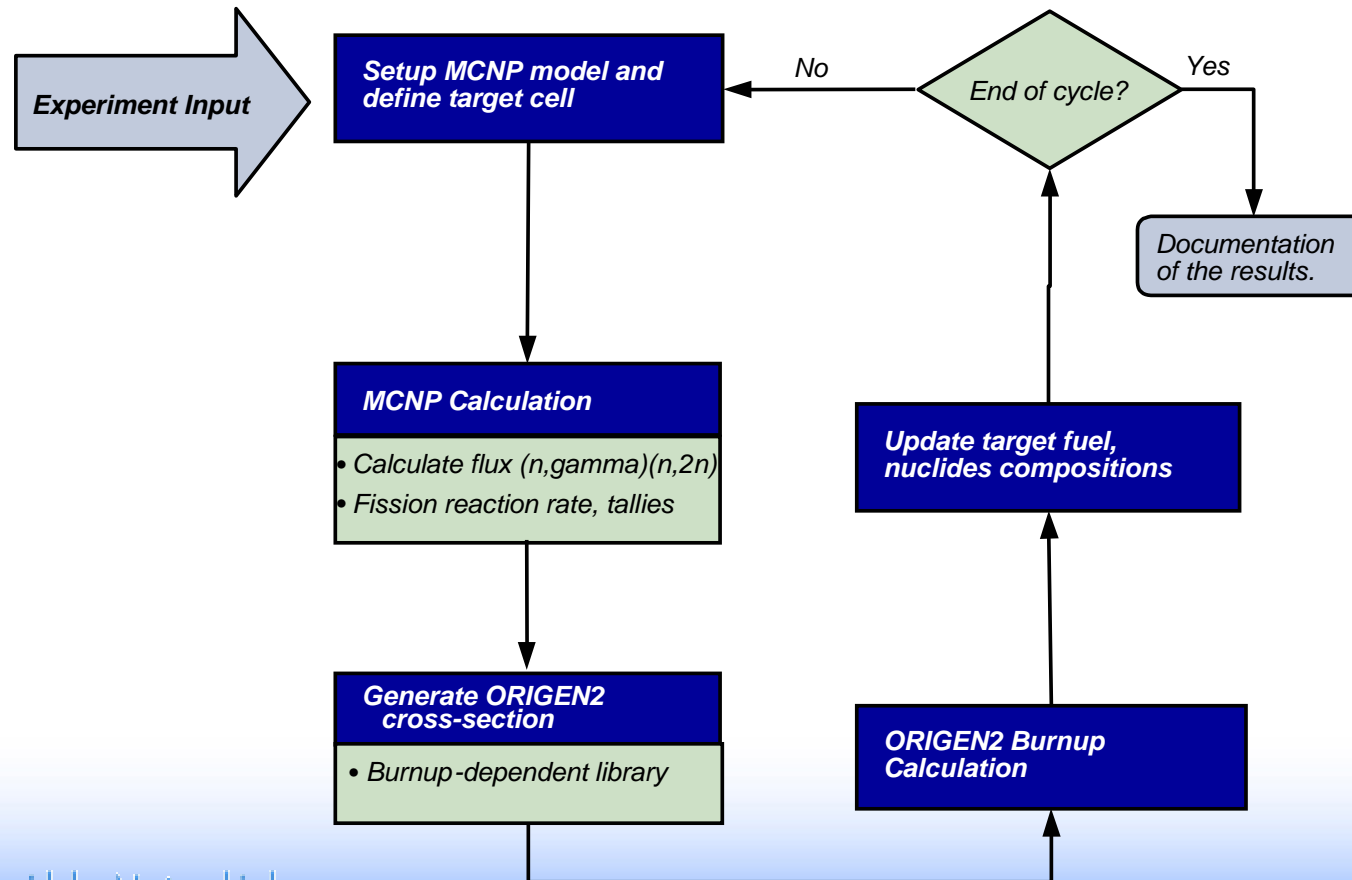
# Methodology - MCWO

- **MCNP coupled With ORIGEN2, or MCWO is a fuel burnup analysis tool developed and used at the INL. This fully automated analysis tool consists of a UNIX BASH (Bourne Again Shell) script which couples the Monte Carlo transport code MCNP with the radioactive decay and burnup code ORIGEN2.**
- **MCWO is capable of handling a large number of fuel burnup and material loading specifications, powers, and irradiation time intervals.**

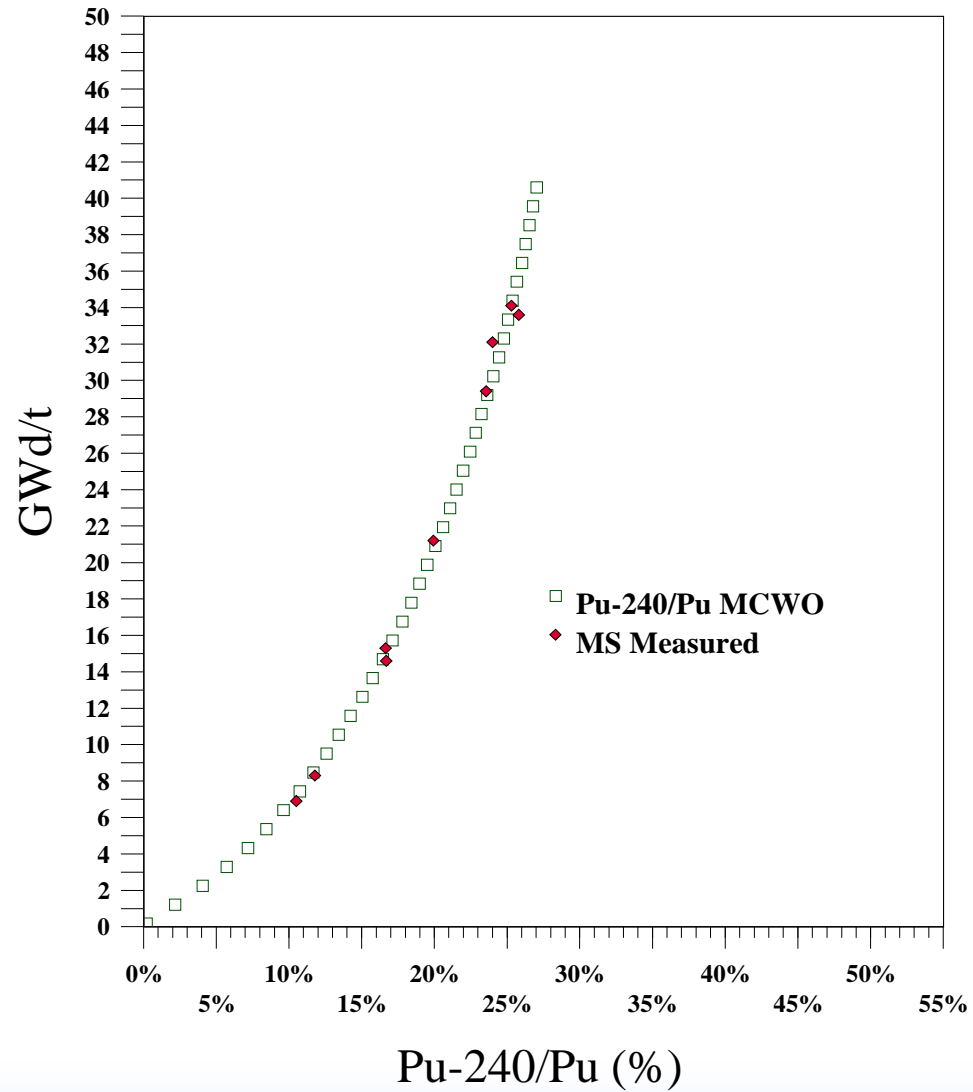
The isotopic depletion and buildup are functions of the energy-dependent neutron flux, the total neutron flux, and the neutron-spectrum-averaged neutron interaction cross sections (XS) as shown in the following equation.

$$\text{Fission XS} = \frac{\int_0^{20\text{MeV}} \sigma(E) \phi(E) dE}{\int_0^{20\text{MeV}} \phi(E) dE}$$

# Schematic of MCWO Methodology (MCNP and ORIGEN2 calculations)



# MCWO-Calculated and JAERI Mass- Spectrometer- Measured $^{240}\text{Pu}/\text{Pu}$ Ratio Versus Burnup

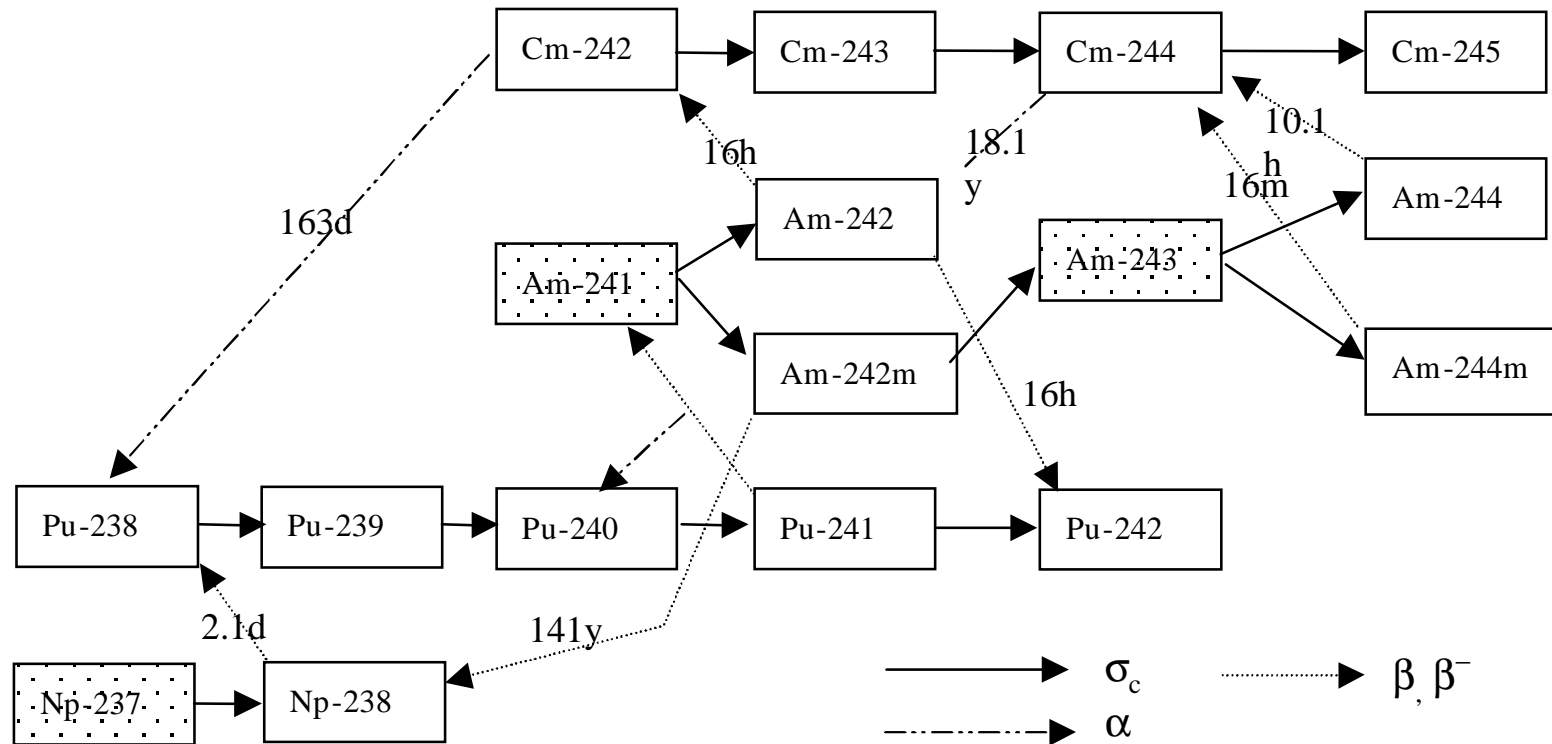


## Plutonium isotope properties important to proliferation resistance

	Half-life (yrs)	Spontaneous fission neutrons (n/kg/sec)	Decay heat (W/kg)	Bare critical mass (kg)
Pu-238	87.7	2,600,000	560	10
Pu-239	24,100	22	1.9	10
Pu-240	6,560	910,000	6.8	40
Pu-241	14.4	49	4.2	10
Pu-242	376,000	1,700,000	0.1	100

- **G. Kessler pointed it out for  $^{238}\text{Pu}/\text{Pu}$  above 6%, can be considered it's proliferation resistant as effective as  $^{235}\text{U} < 20\%$  or  $^{233}\text{U} < 12\%$ .**
- **G. Kessler, "Plutonium Denaturing by  $^{238}\text{Pu}$ ," Nucl. Sci. & Eng.: 155, 53-73 (2007).**
- **M. SAITO, "Advanced Core Concepts with Enhanced Proliferation Resistance by Transmutation of Minor Actinides," Proceedings of GLOBAL 2005 Tsukuba, Japan, Oct 9-13, 2005 Paper No. 172.**

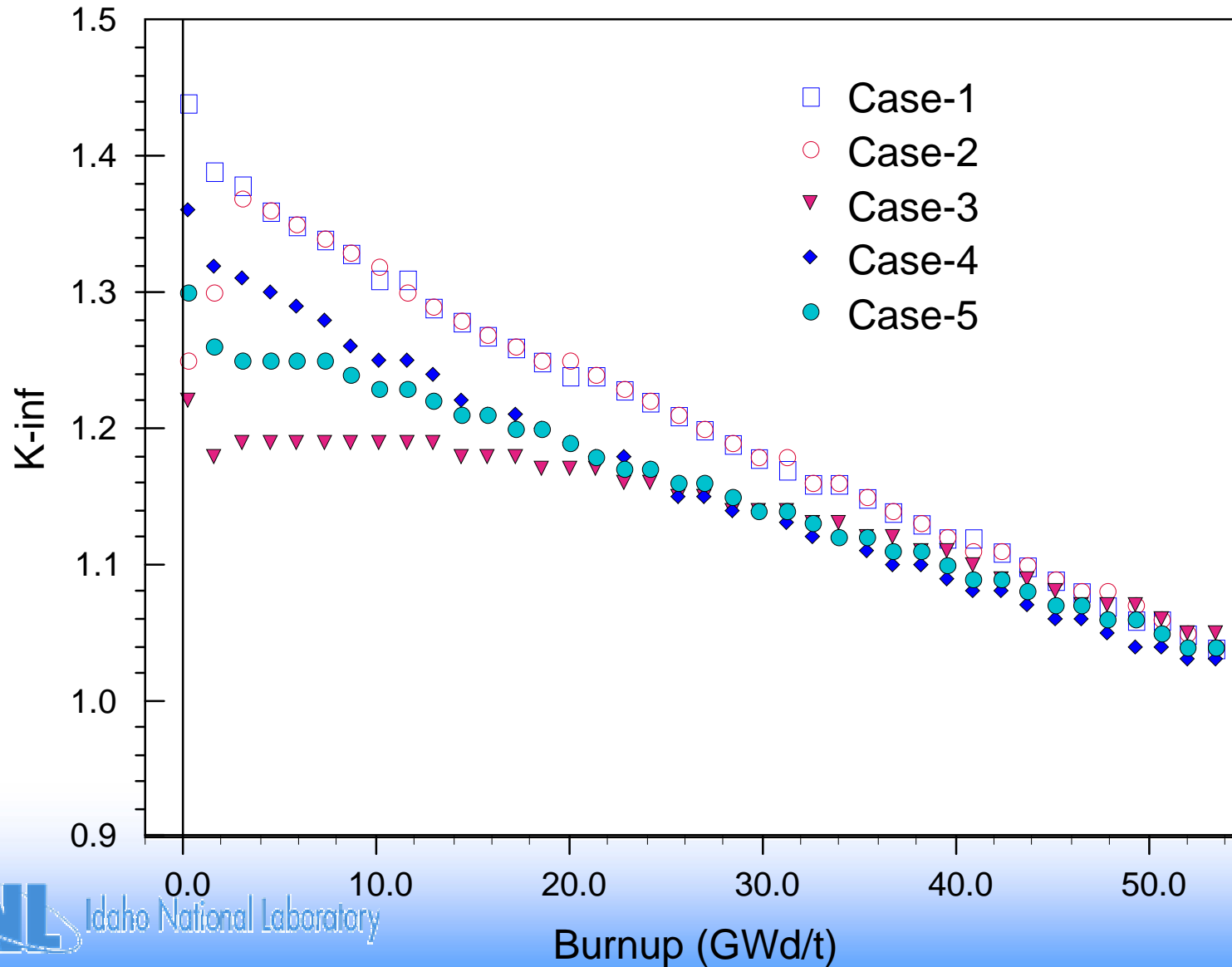
# Buildup and decay chains for the MAs.



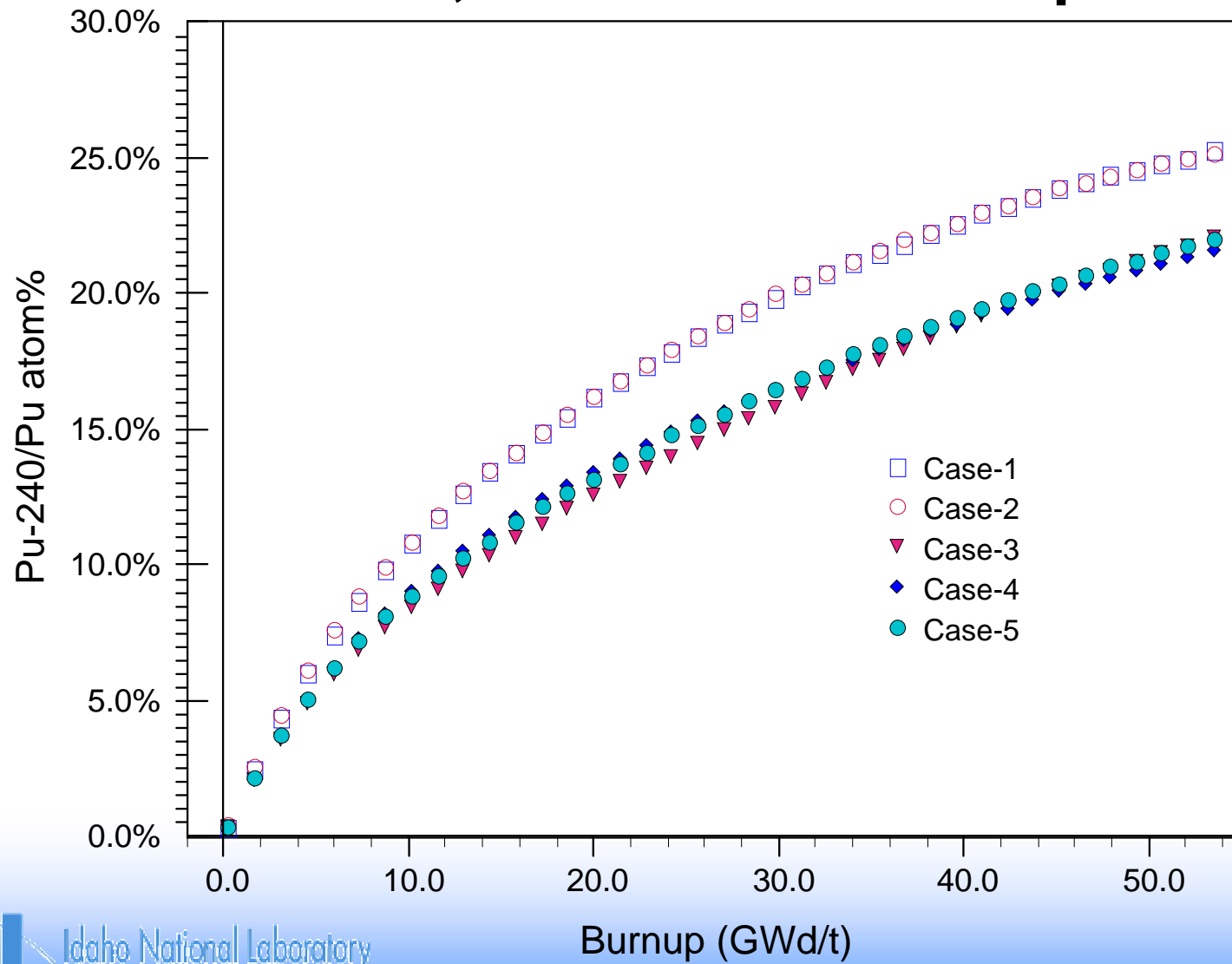
# UO<sub>2</sub> - <sup>235</sup>U enrichment (4.4 wt%), Gd<sub>2</sub>O<sub>3</sub>, NpO<sub>2</sub>, and AmO<sub>2</sub> composition of the 5 study cases

ID	Gd <sub>2</sub> O <sub>3</sub> (wt%)	NpO <sub>2</sub> (wt%)	AmO <sub>2</sub> (wt%)
Case-1	--	--	--
Case-2	0.028	--	--
Case-3	--	0.45	--
Case-4	--	--	0.45
Case-5	--	0.2	0.2

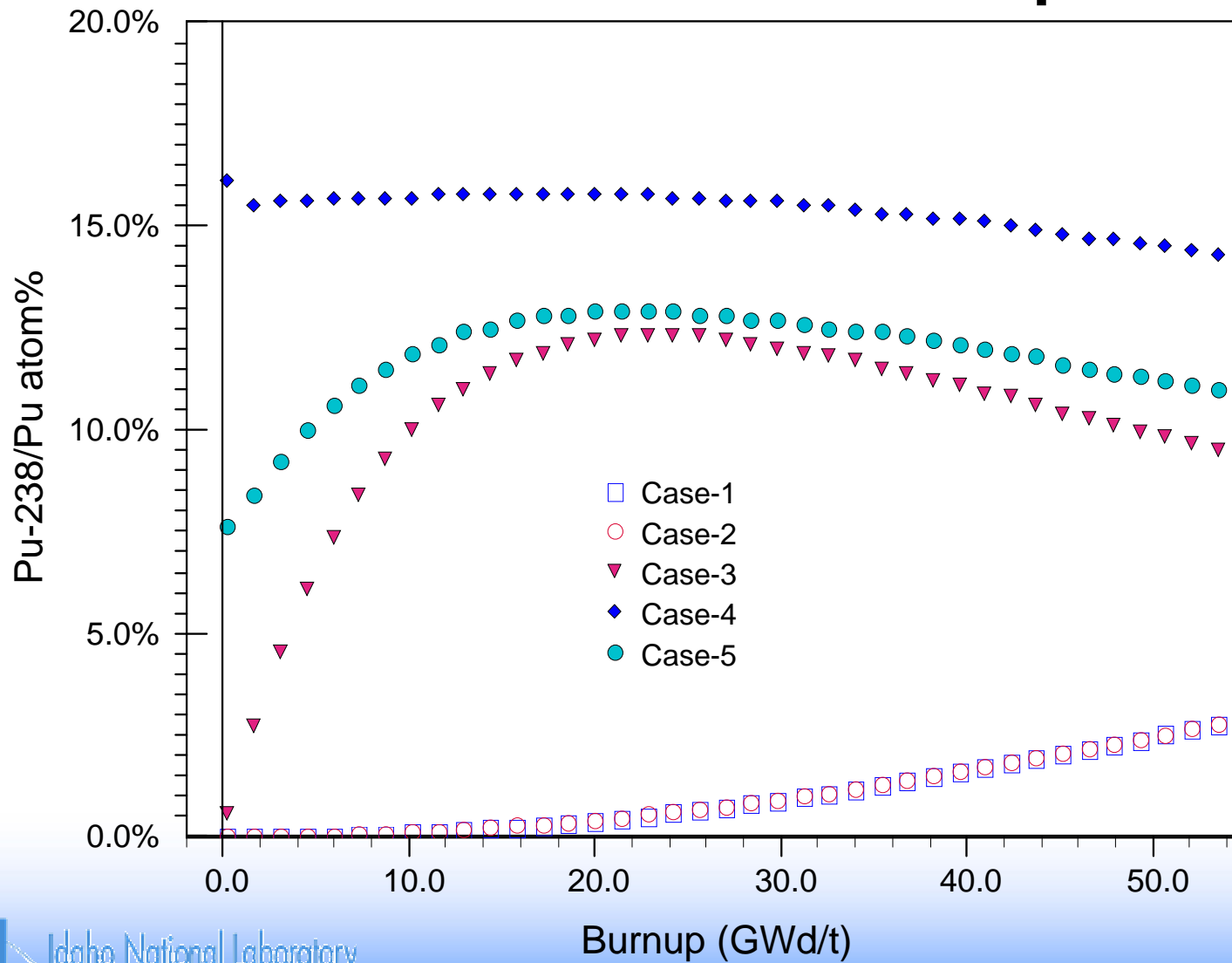
# K-inf comparison of VVER-1000 lattice unit cell Cases-1 to -5 versus burnup



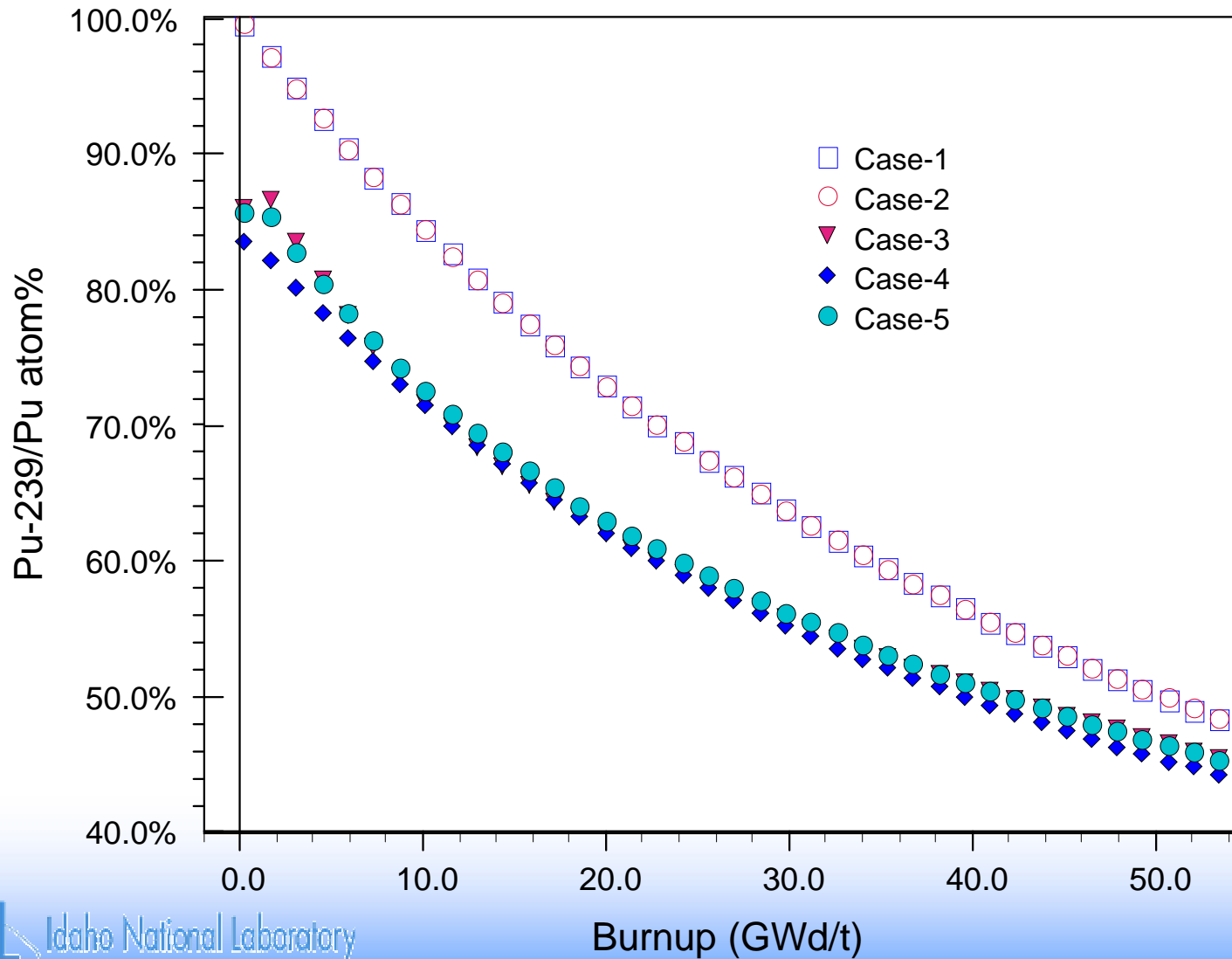
# $^{240}\text{Pu}/\text{Pu}$ ratio profiles comparison of Cases-1, to -5 versus burnup



# $^{238}\text{Pu}/\text{Pu}$ ratio profiles comparison of Cases-1 to -5 versus burnup



# 239Pu/Pu ratio profiles comparison of Cases-1 to -5 versus burnup



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# The known disadvantages of MARA

- $^{237}\text{Np}$  and  $^{241}\text{Am}$  in the fuel will generate more  $^4\text{He}$ , which will affect the fission gas release performance.
- The need to have improved transuranic cross-section library data.
- The  $^{237}\text{Np}$  is a controlled nuclear sensitive material.

# The encouraging advantages of MARA

- The high burnup of the spent fuel ( $^{235}\text{U}$  4.4-wt %) is well developed and becoming a standard for LWR fuel reloading, which can effectively reduce the spent fuel storage volume.
- $^{237}\text{Np}$  and/or  $^{241}\text{Am}$  can drastically increase the fraction of  $^{238}\text{Pu}$  to enhance the proliferation resistance.
- $^{241}\text{Am}$  not only can increase the fraction of  $^{238}\text{Pu}$ , but also can be used as a burnable absorber to reduce the initial excess reactivity.
- $^{237}\text{Np}$  can be transmuted quickly with  $\beta$ -decay (half-life 2.1 days) to a high fraction of  $^{238}\text{Pu}$ , which can effectively enhance the proliferation resistance for early removal of low burnup fuel.

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# Conclusions

- The concept of MARA involves the use of transuranic nuclides ( $^{237}\text{Np}$  and/or  $^{241}\text{Am}$ ), can not only drastically increase the  $^{238}\text{Pu}/\text{Pu}$  ratio for proliferation resistance, but also can serve as a burnable absorber to hold-down the initial excess reactivity.
- It is believed that MARA can play an important role in atoms for peace and the intermediate term of nuclear energy reconnaissance.