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# Novel Hyper-Breeder Nuclear Reactor Concept

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Department of NUCLEAR ENGINEERING

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# All calculations done using MCNP™

MCNP6

Schwarz Software & Consulting, LLC

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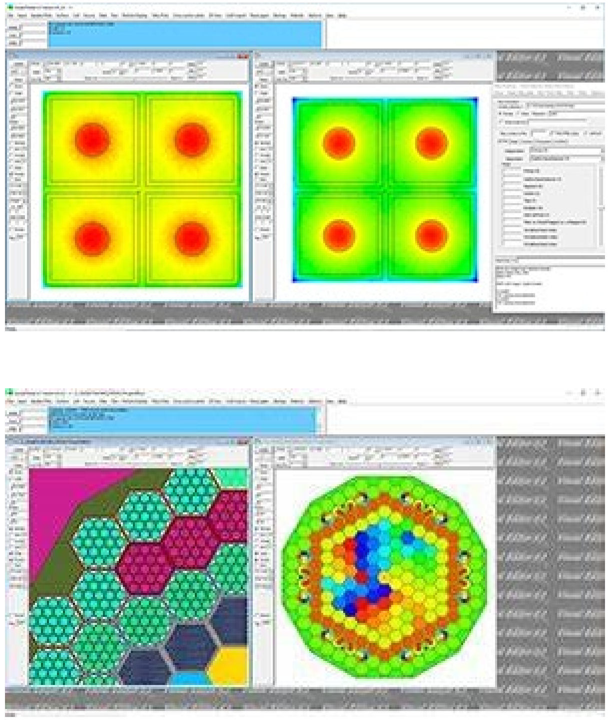
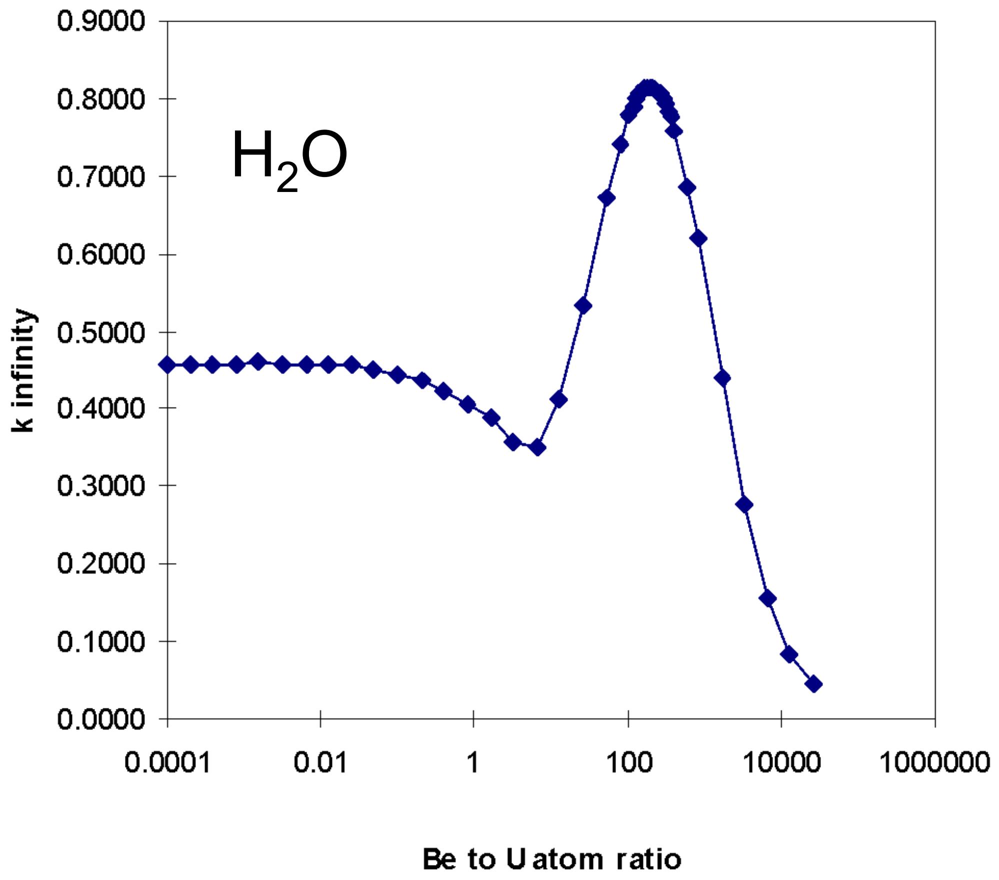
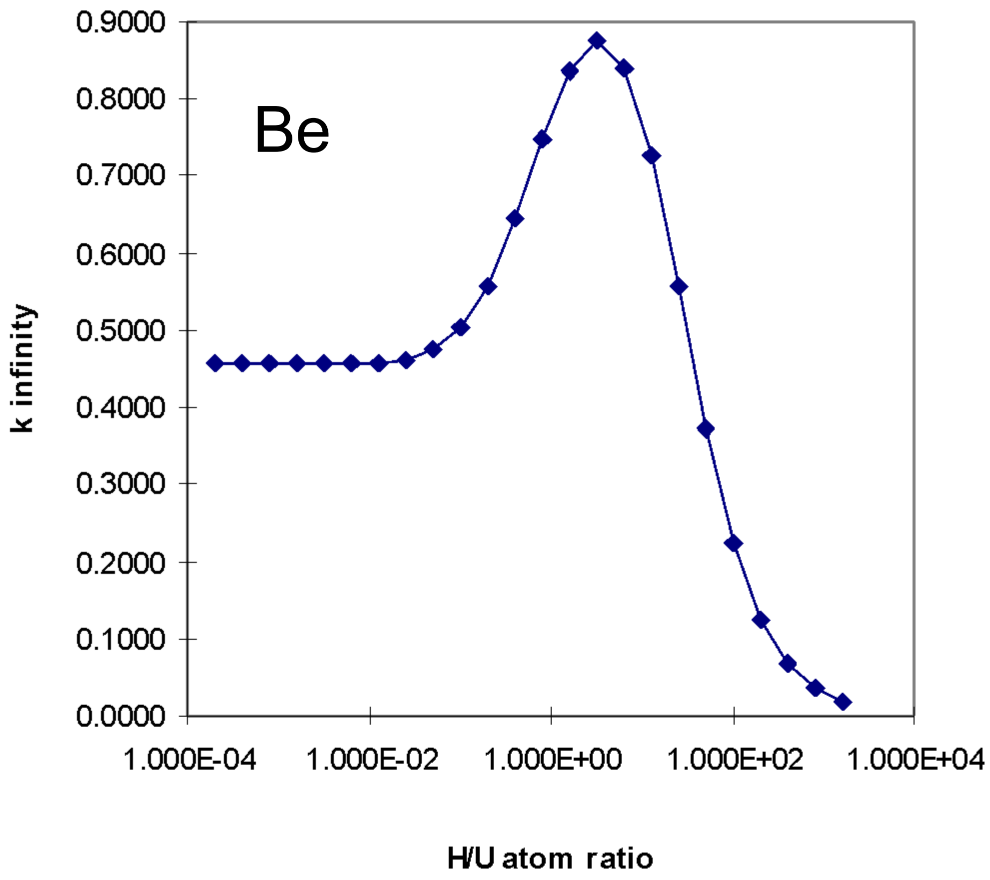


Graphs by R. B. Hayes using National Nuclear Data Center at https://www.nndc.bnl.gov/

# Neither natural uranium (NU) and Be nor NU and light water can be critical in any homogenous mix

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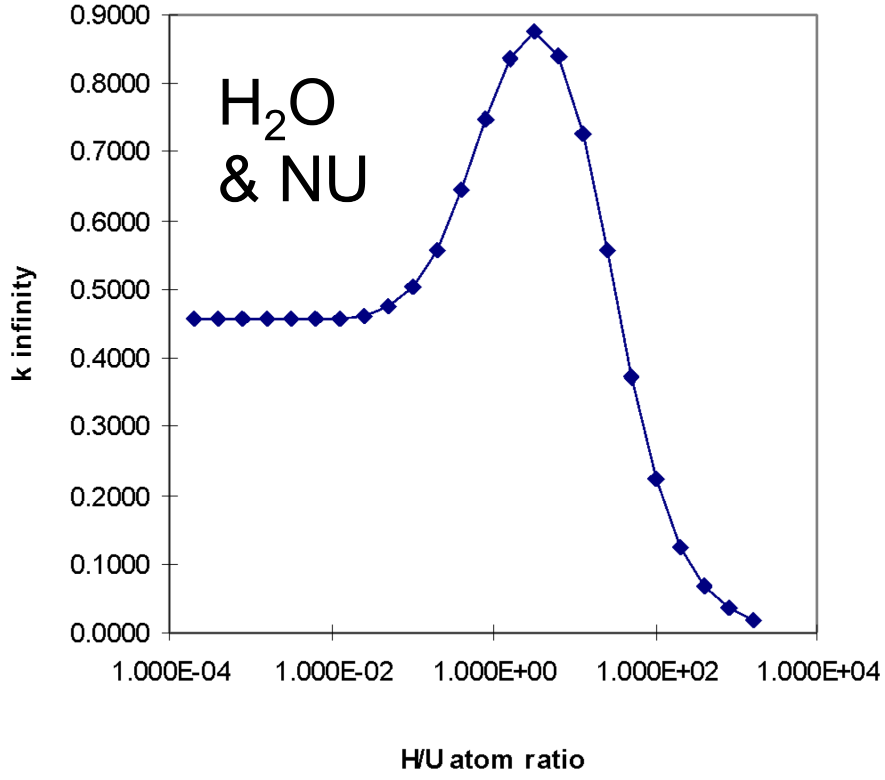
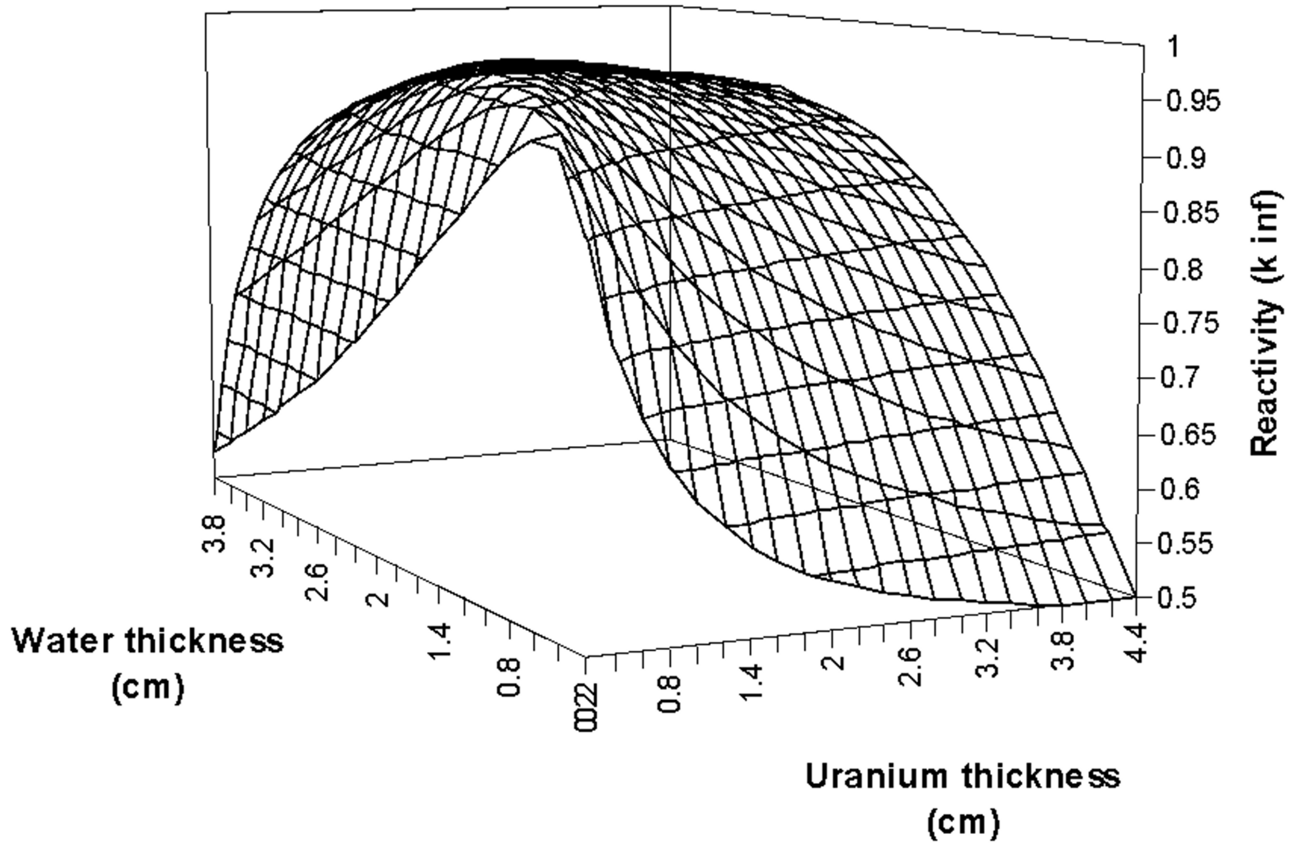
# Slab layers of LW and NU can attain slightly higher reactivity

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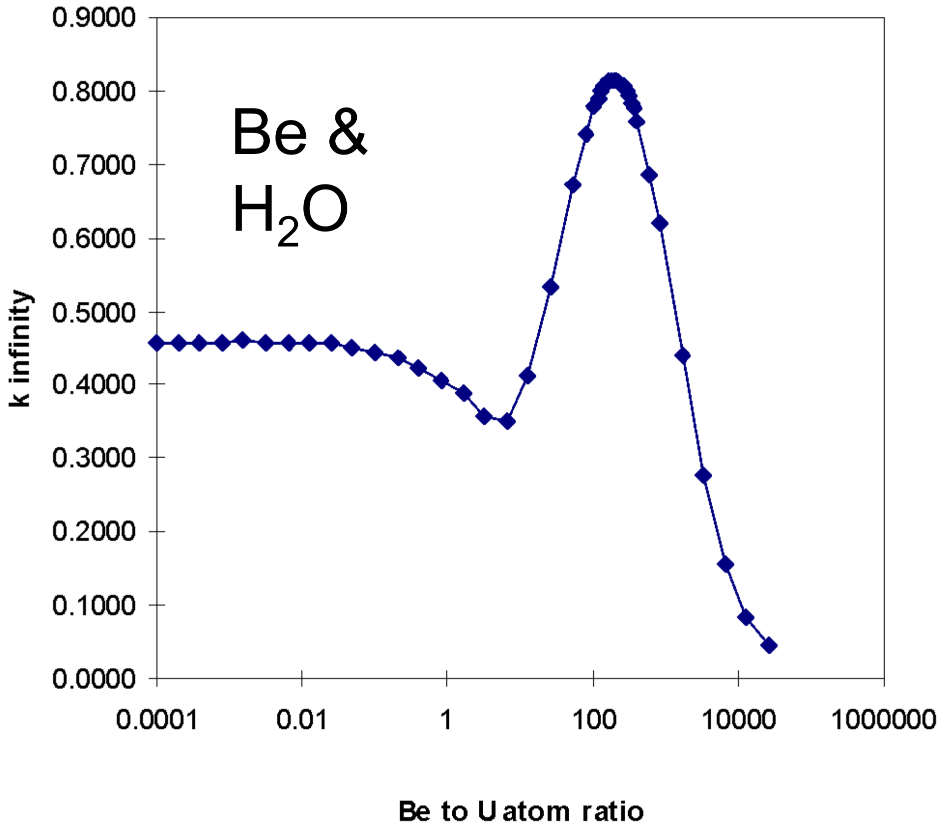
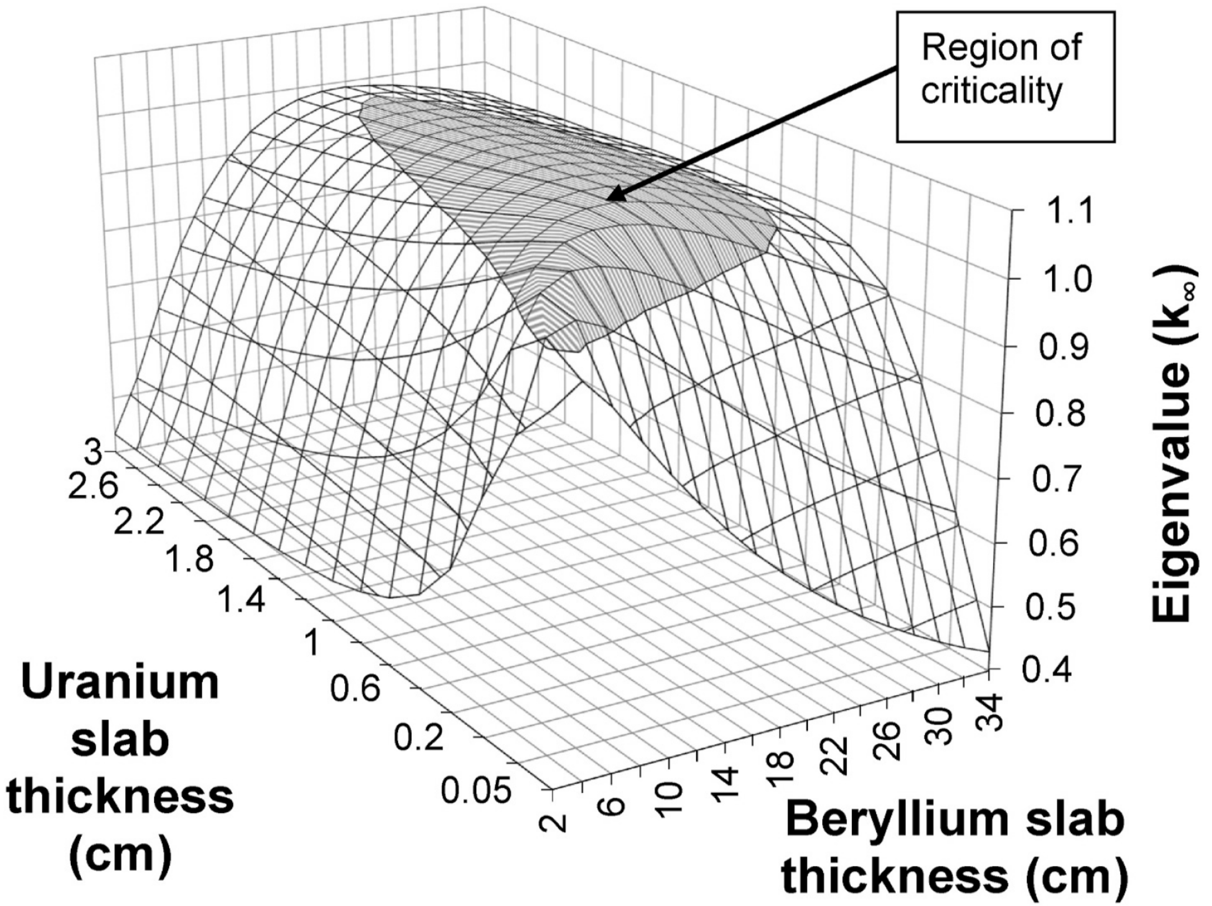
# Slab layers of LW and Be can be prompt critical!

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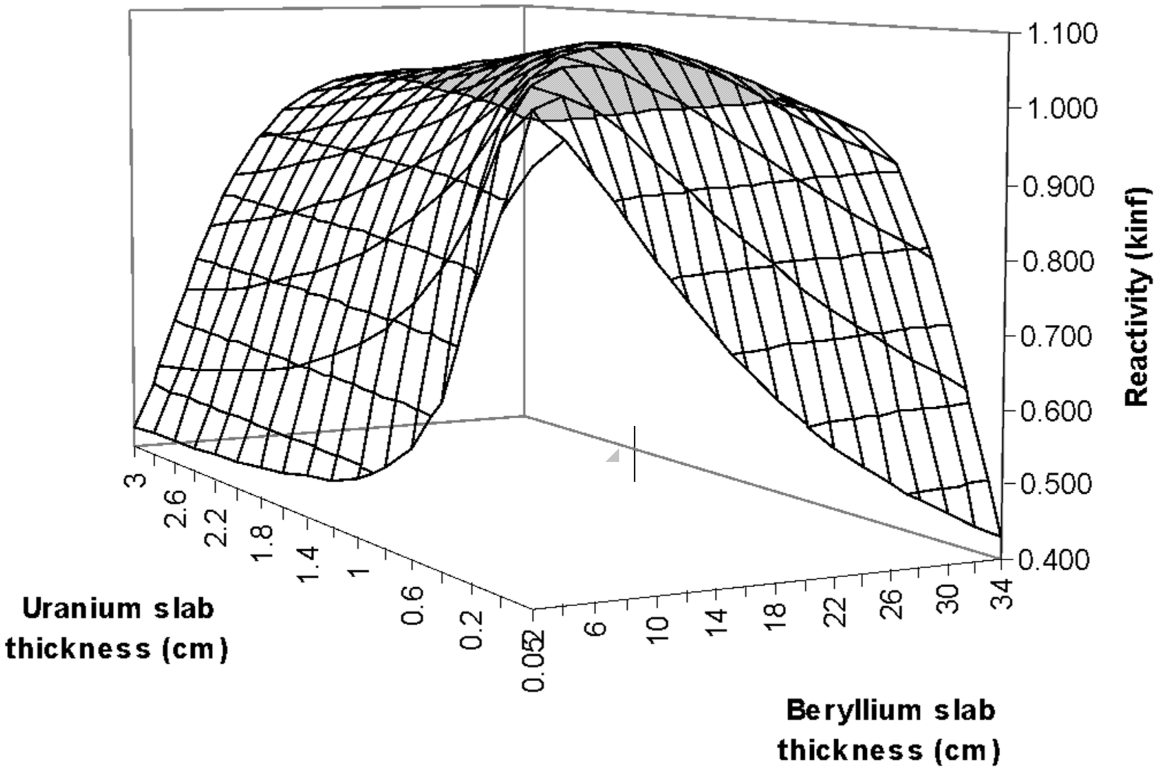
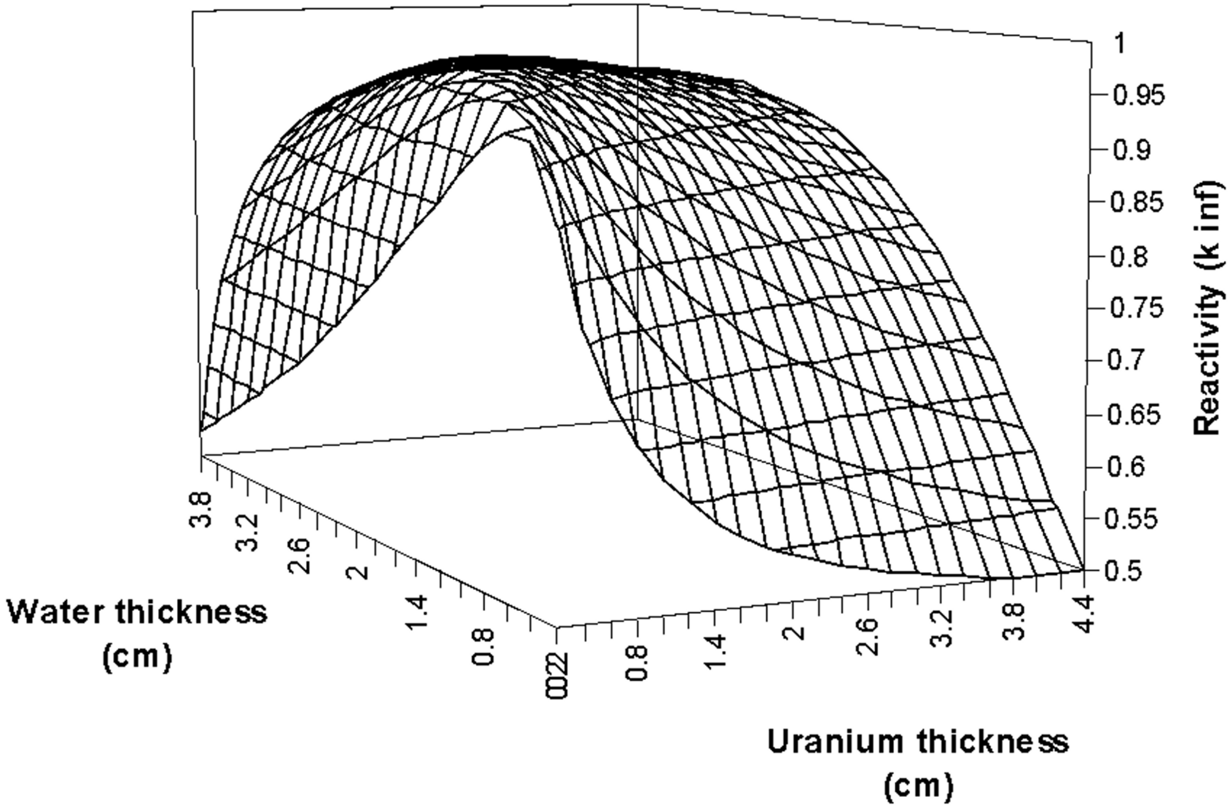
# Can these be combined?

The optimum NU is very similar

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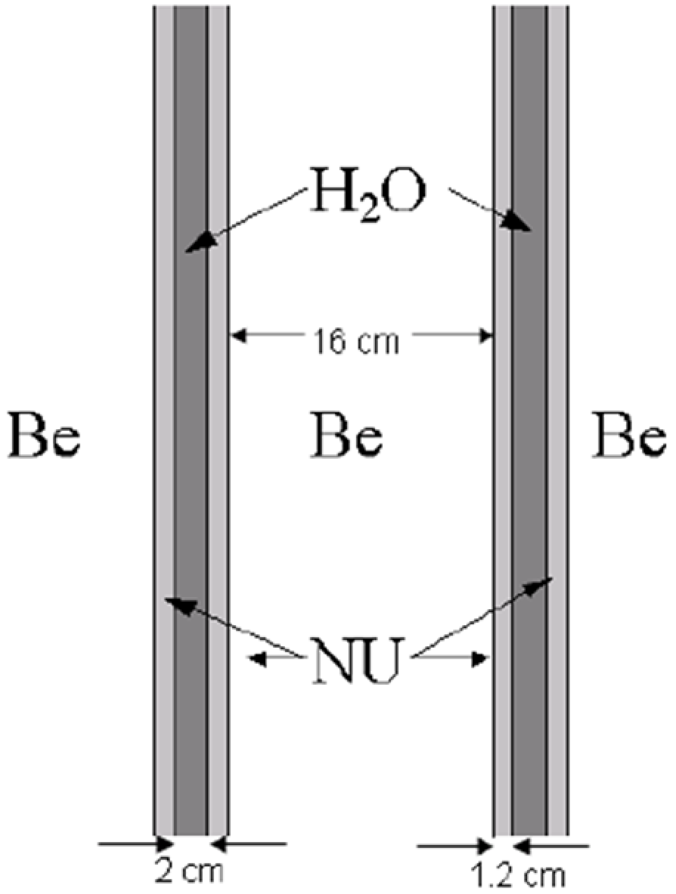
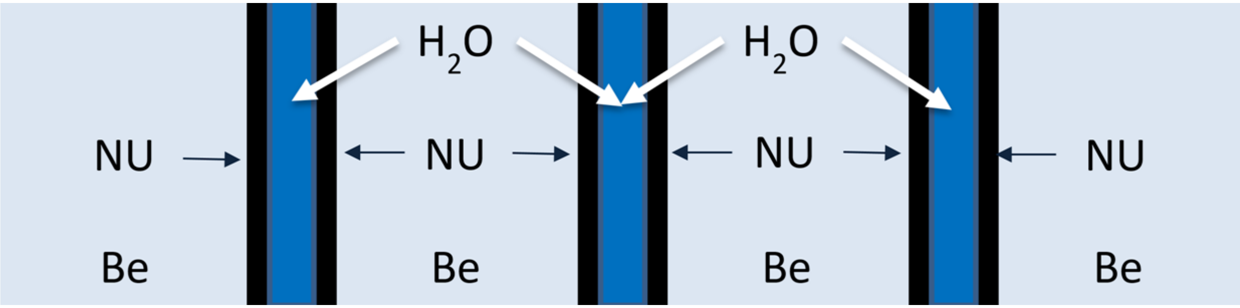
Maximum reactivity Be-NU straddling maximum $H_2O$-NU means the subcritical $H_2O$-NU provides neutronic isolation from having a double NU thickness between the Be layers




Hayes, R.B., Sawyers, M.J., (2023) A thermal natural uranium breeder reactor for large and small applications with passive safeguard designs. *Progress in Nuclear Energy* **163** 104804.

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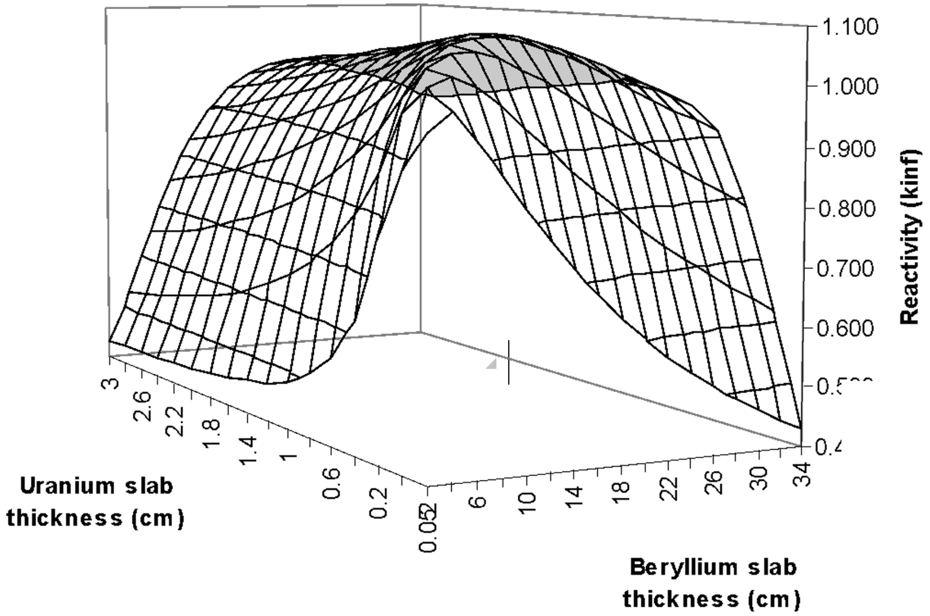
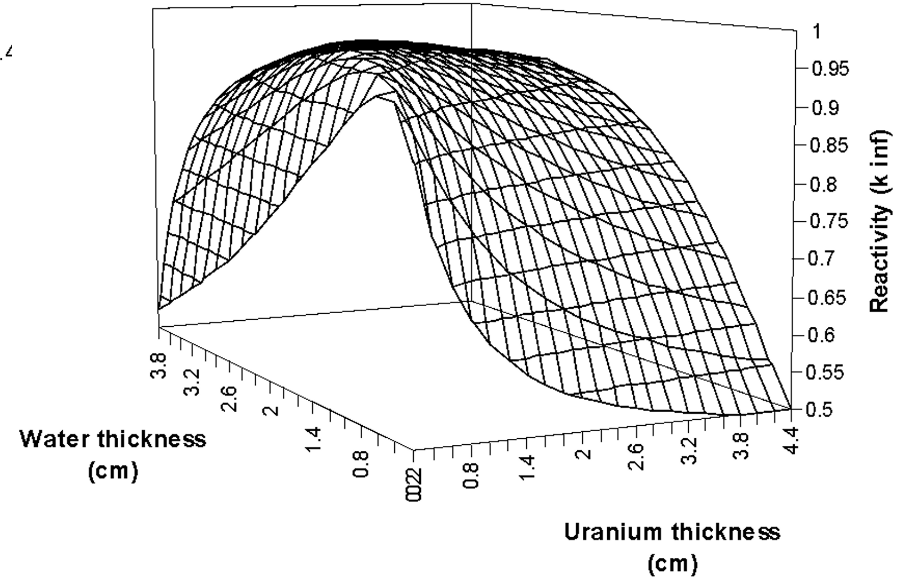
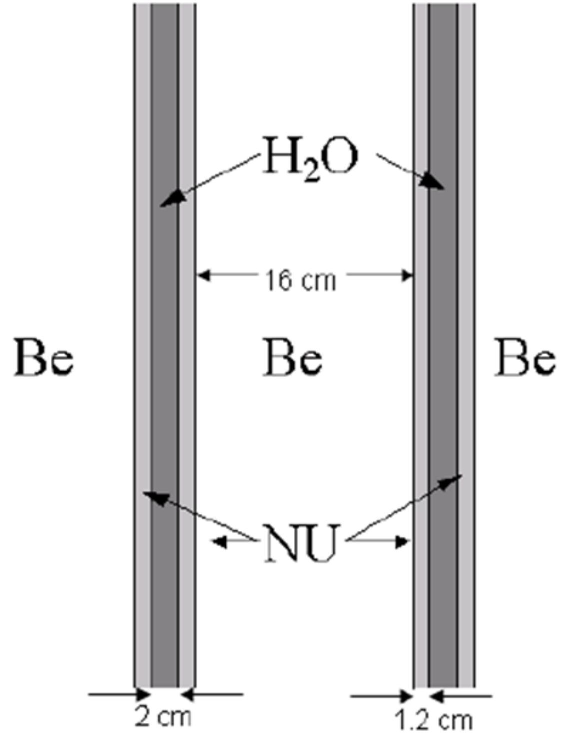
# A LOCA results in doubling the NU thickness giving a subcritical configuration




Hayes R. B. (2006) A light-water-cooled nuclear reactor of natural uranium and beryllium. *J. ASTM Int.* **3** (8), 1-11.

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# Multiplication factor and criticality at criticality, $k_{eff}$=1

$$k_{eff} = \frac{\text{no. neuts. at some point in the cycle}}{\text{no. neuts. at \textit{same} point in previous generation}}$$

$$= \frac{\varepsilon p \eta f \, P^{f}_{NL} P^{t}_{NL} n}{n} = \varepsilon p \eta f \, P^{f}_{NL} P^{t}_{NL}$$

$$k_{eff} = \varepsilon p \eta f \, P^{f}_{NL} P^{t}_{NL}$$

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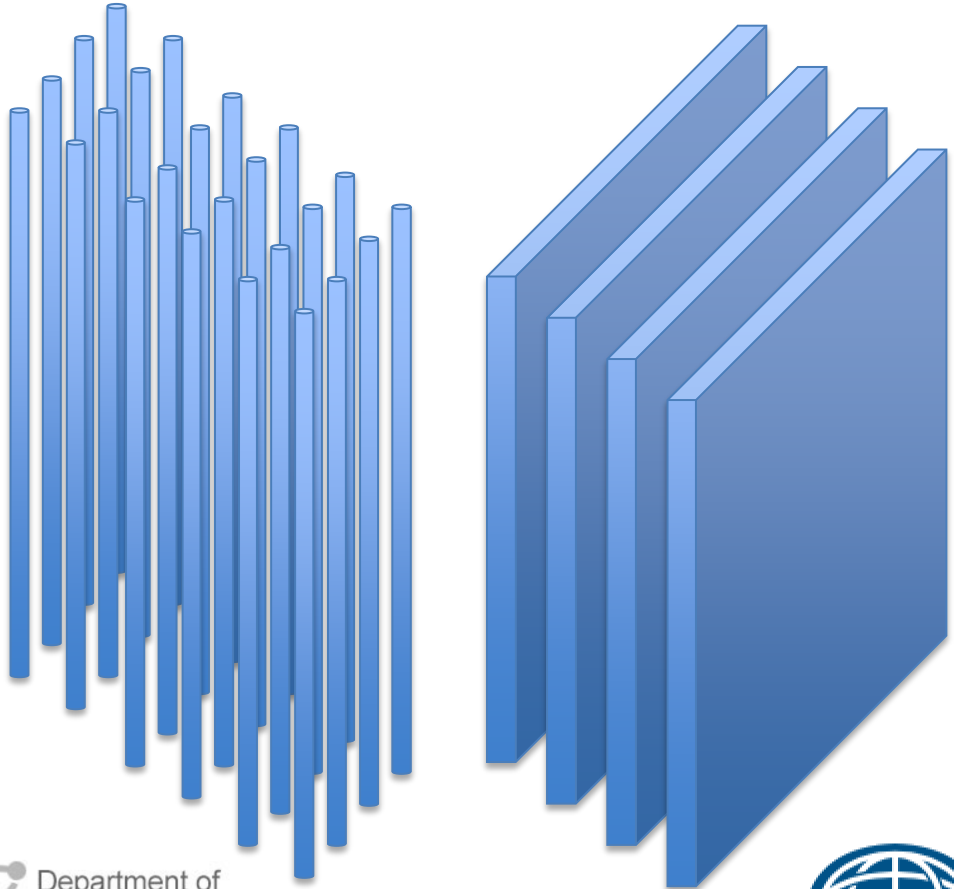
# Fuel solid angle effects on $\varepsilon$

- Large slab metallic fuel increases fast fission factor $\varepsilon$ relative to $UO_2$ pin (thin cylinder) configuration due to subtended solid angle.

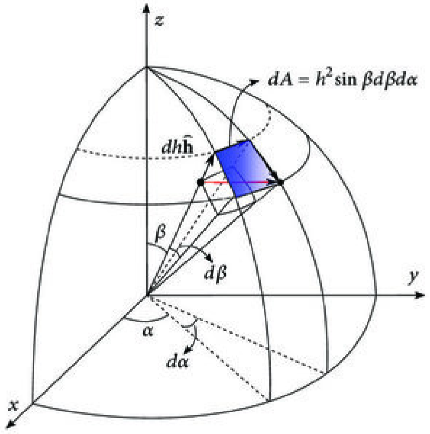


$$\varepsilon = \frac{\text{no. neuts. from thermal + fast fission}}{\text{no. neuts. from thermal fission alone}}$$

$$k_{eff} = \varepsilon p \eta f \, P_{NL}^{f} P_{NL}^{t}$$

$$\varepsilon = 1.093$$

Instead of 1.04
or 50k mpc

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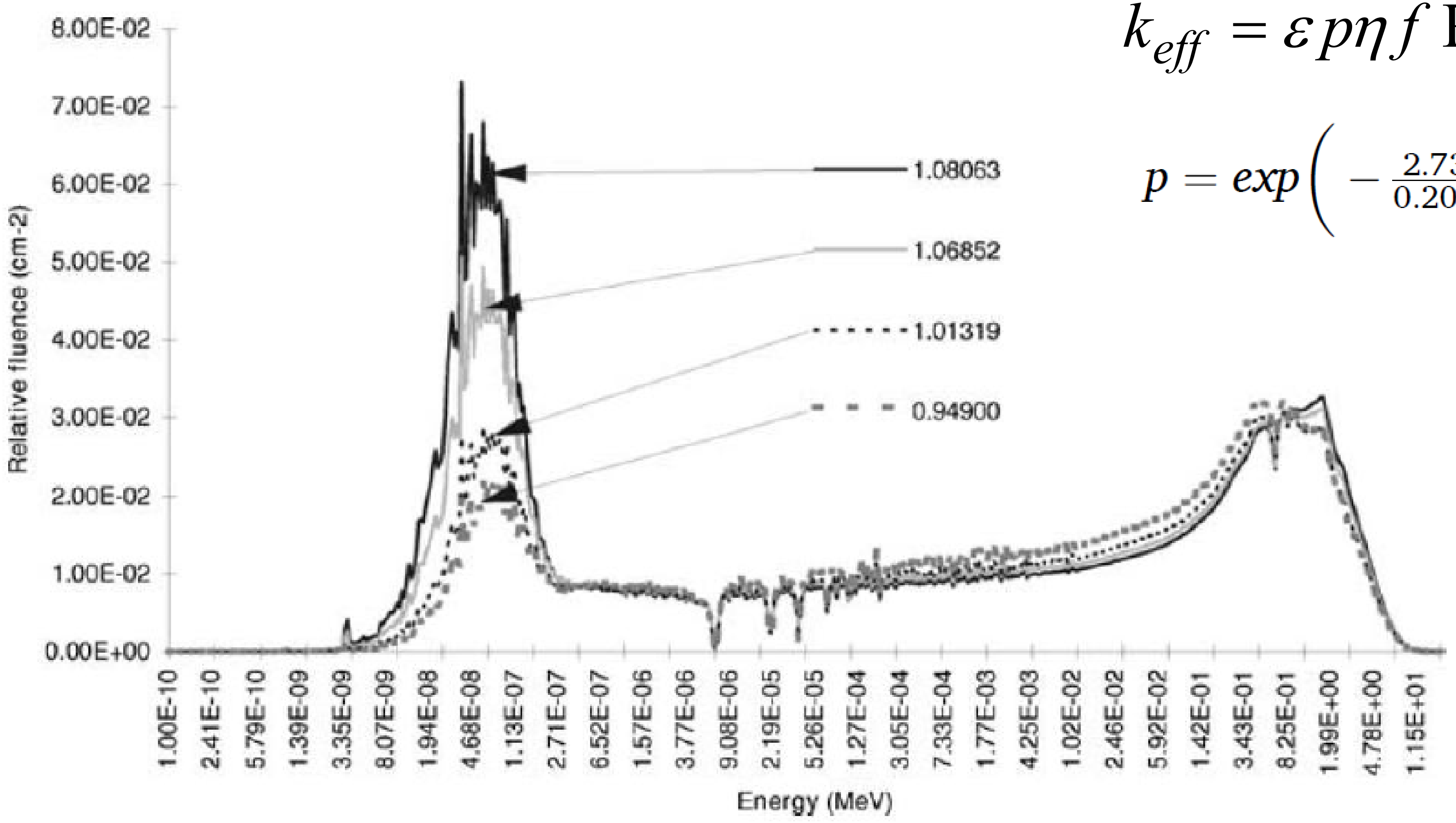
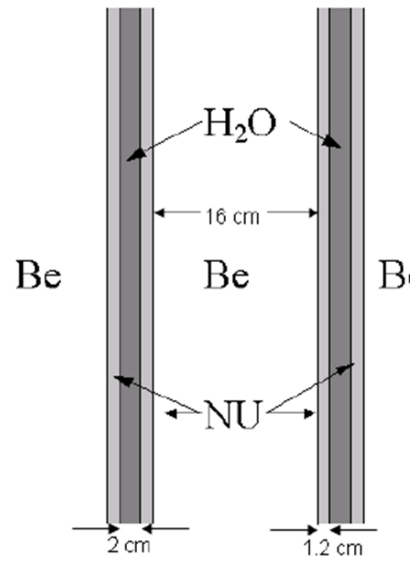
# Resonance escape probability *p*

$$k_{eff} = \varepsilon p \eta f \, P_{NL}^{f} P_{NL}^{t}$$

$$p = exp\left( -\frac{2.73}{0.207}\left(\frac{N_A/N_M}{6.1\times10^{24}}\right)^{0.747}\right)$$




Graphs by R. B. Hayes using National Nuclear Data Center at https://www.nndc.bnl.gov/

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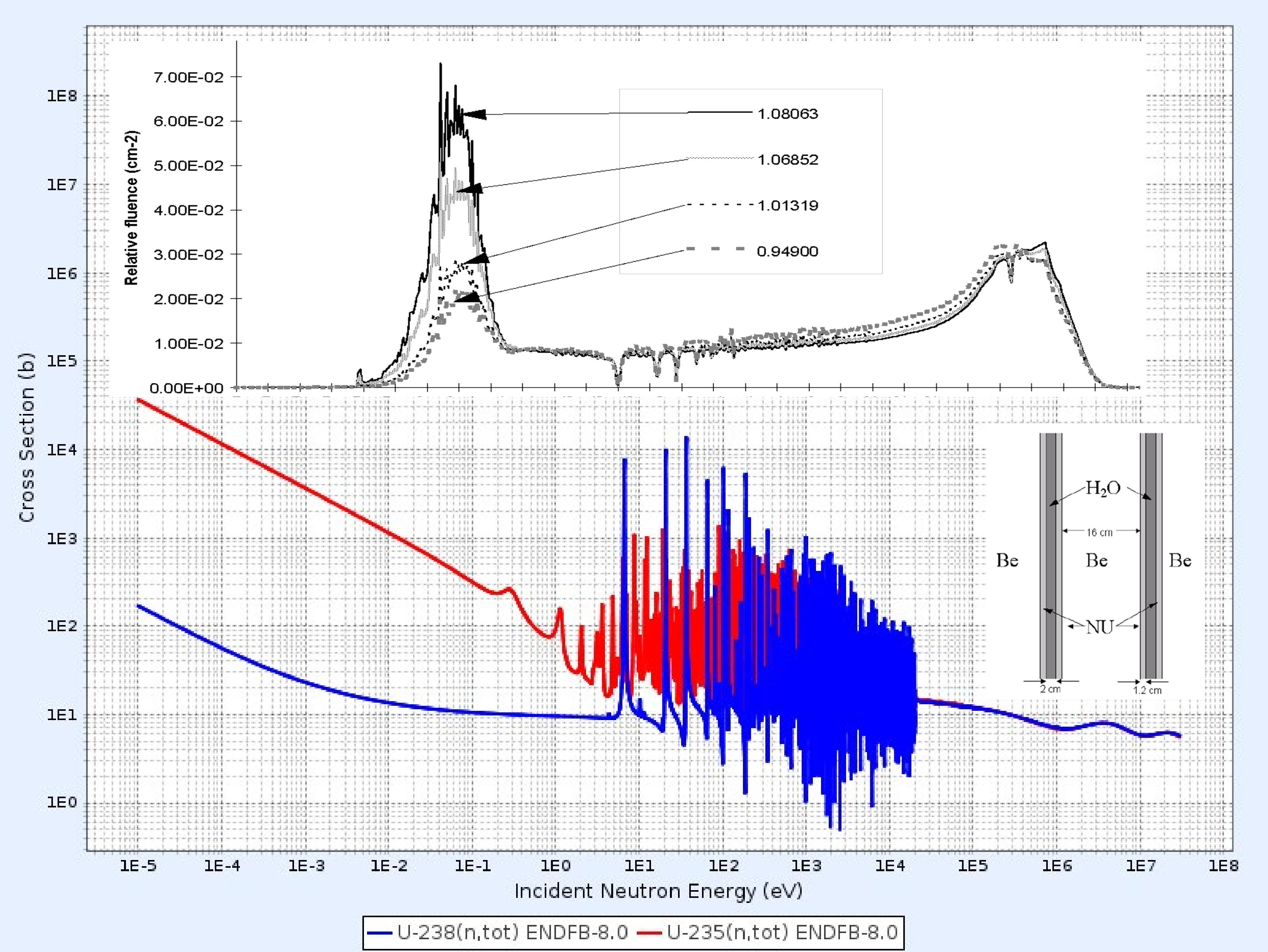
# Bypass the U238 absorption in the Be

- Red is U235 total
- Blue is U238 total
- Inset is fluence as a function of keff
- Resonances of the U238 are seen in dips of the neutron fluence at all keff values
- Resonance escape probability in action



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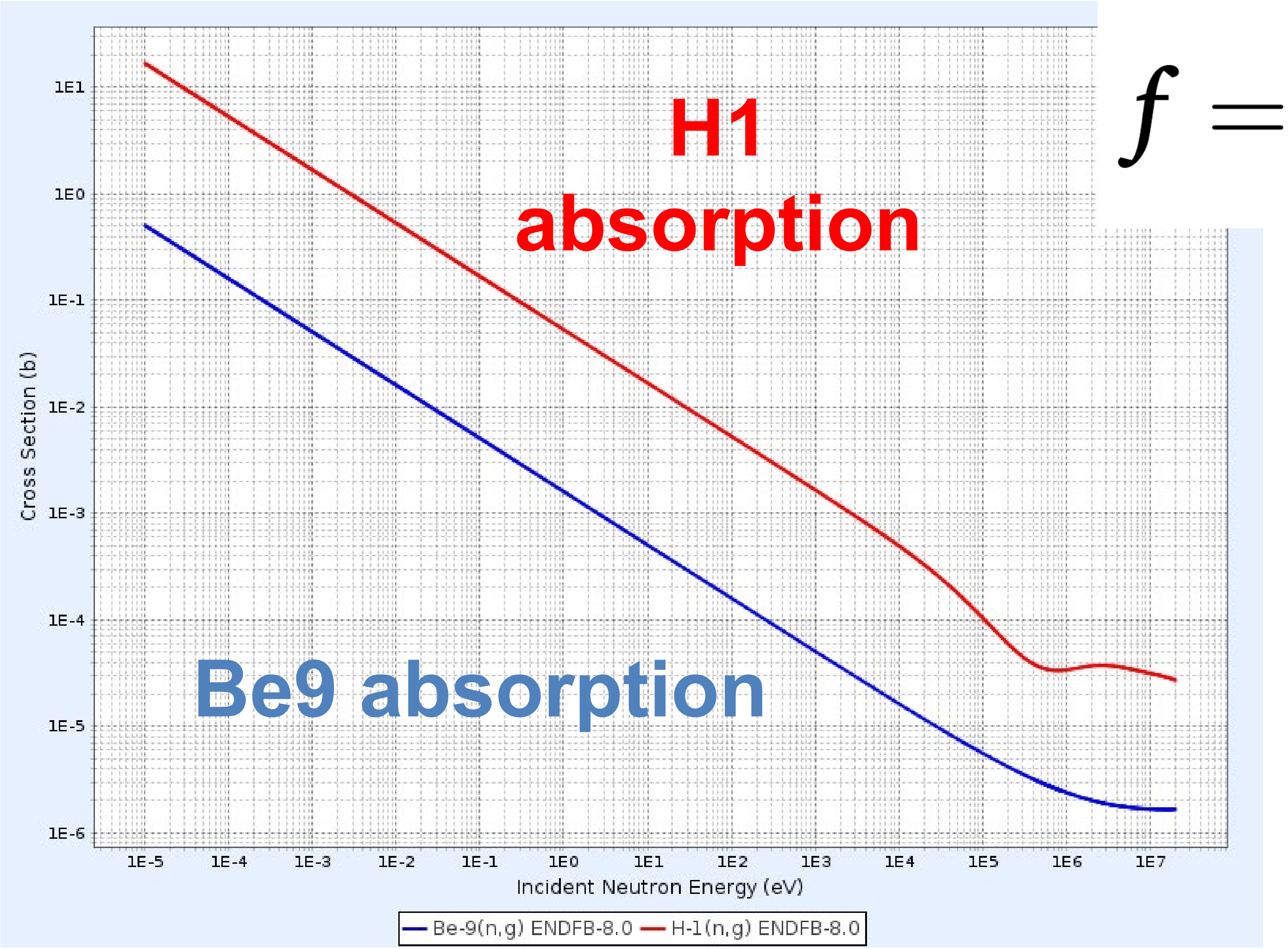
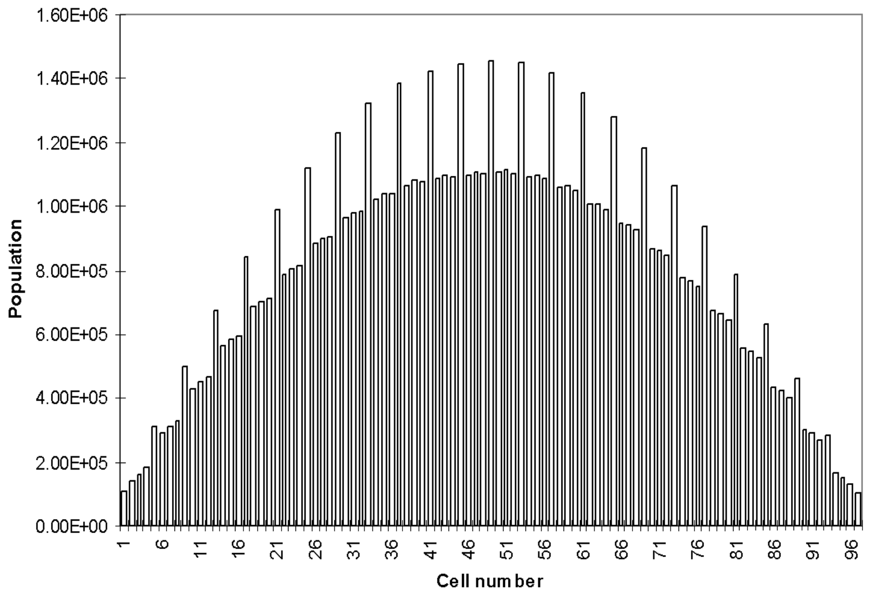
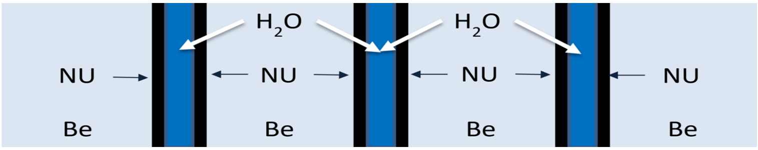
# **Thermal utilization** (nominal effect)




$$f = \frac{\Sigma_a^F}{\Sigma_a^F + \Sigma_a^{NF} (V^{NF}/V^F)(\varphi^{NF}/\varphi^F)}$$




Graphs by R. B. Hayes using National Nuclear Data Center at https://www.nndc.bnl.gov/

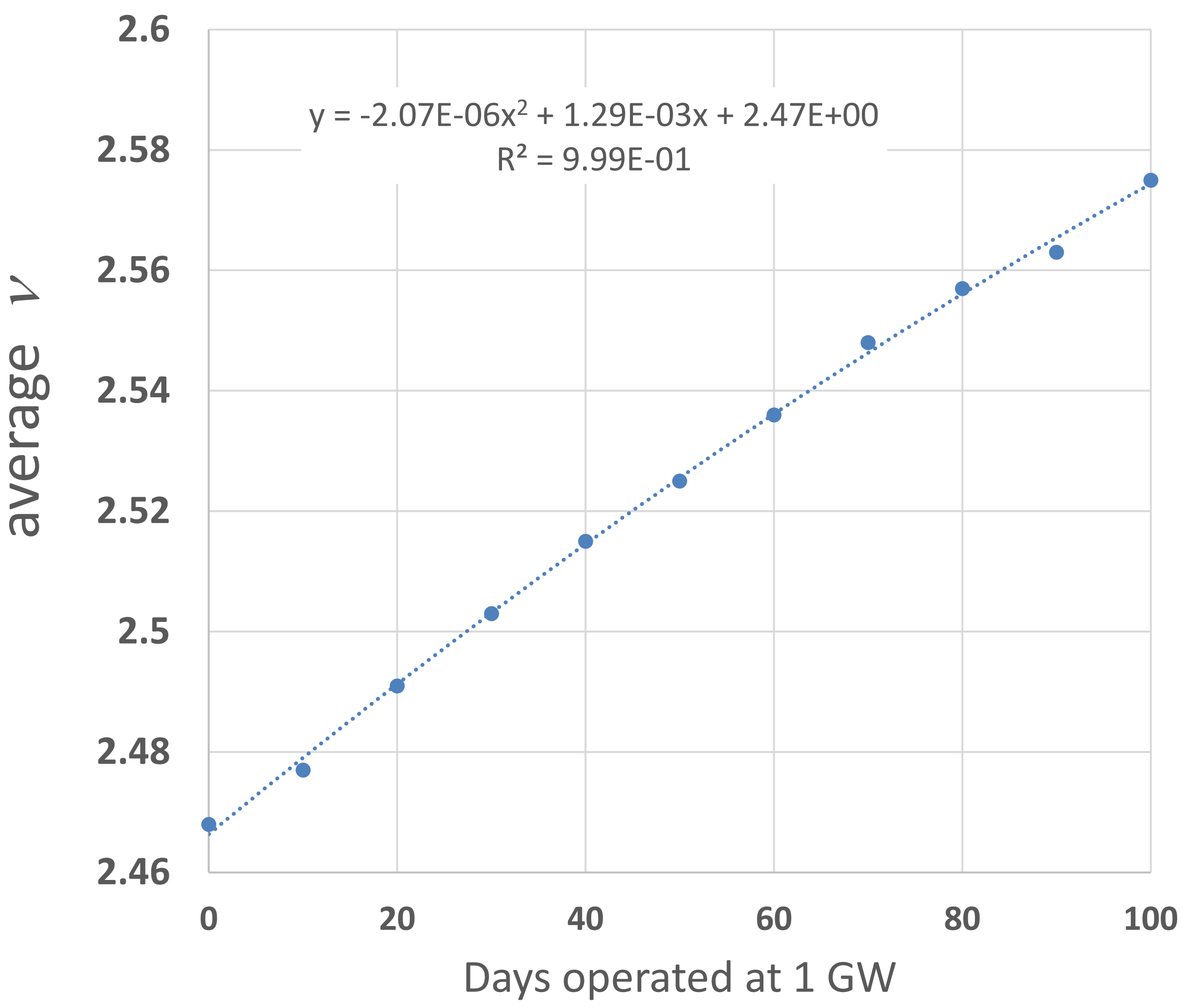
# Configuration effects on thermal fission factor eta $\eta$

$\eta =$ no. fission neuts. produced per thermal neutron absorbed in fuel

$$= \nu \frac{\Sigma_f^F}{\Sigma_a^F} = \nu \frac{\sigma_f^F}{\sigma_a^F} = \nu \frac{\sigma_f^F}{\sigma_\gamma^F + \sigma_f^F}$$

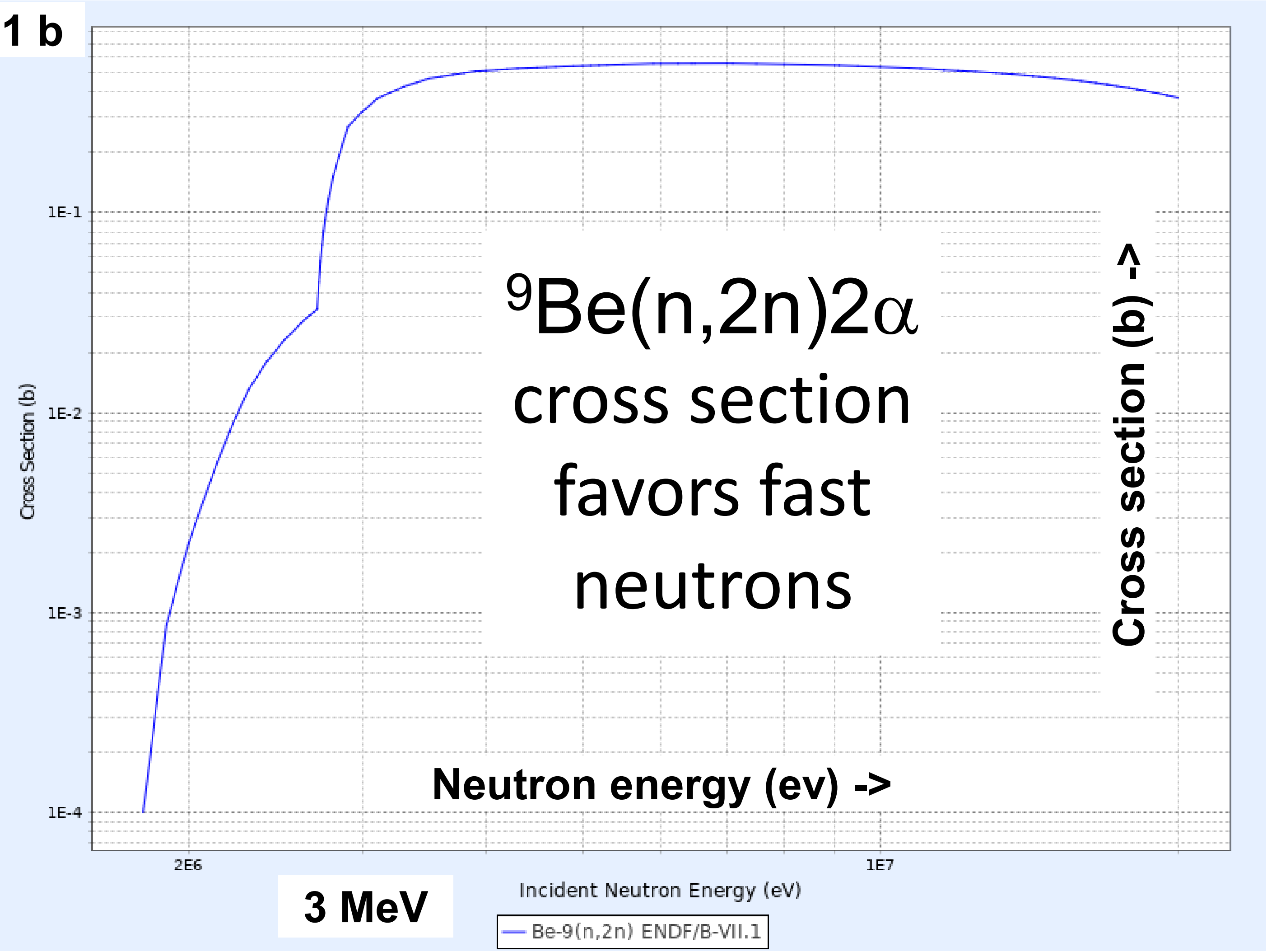
*NOTE :* $\eta > 1$

$$k_{eff} = \varepsilon p \eta f \, P_{NL}^{f} P_{NL}^{t}$$




Graphs by R. B. Hayes using National Nuclear Data Center at https://www.nndc.bnl.gov/

# The α,n reaction in Be effectively increases $\eta$

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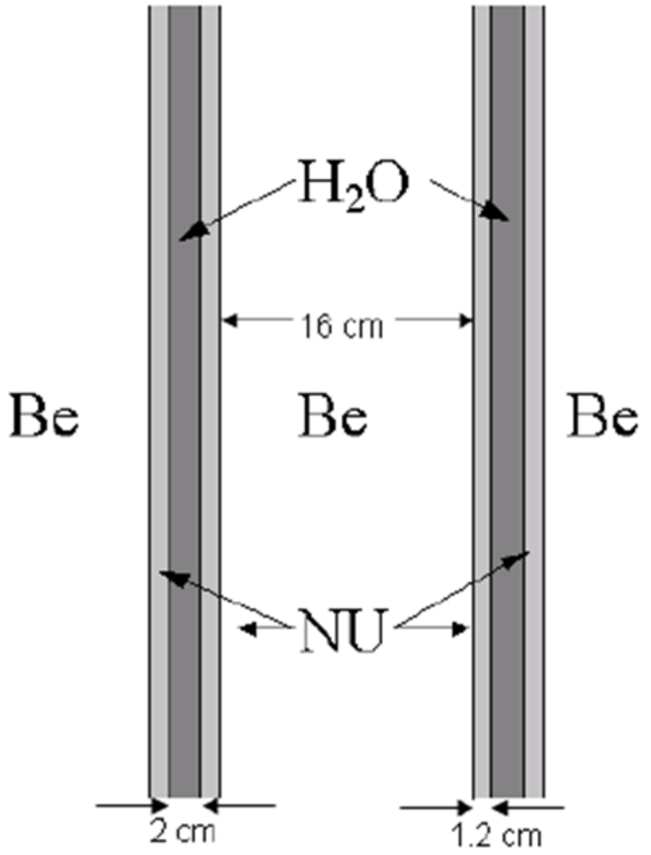
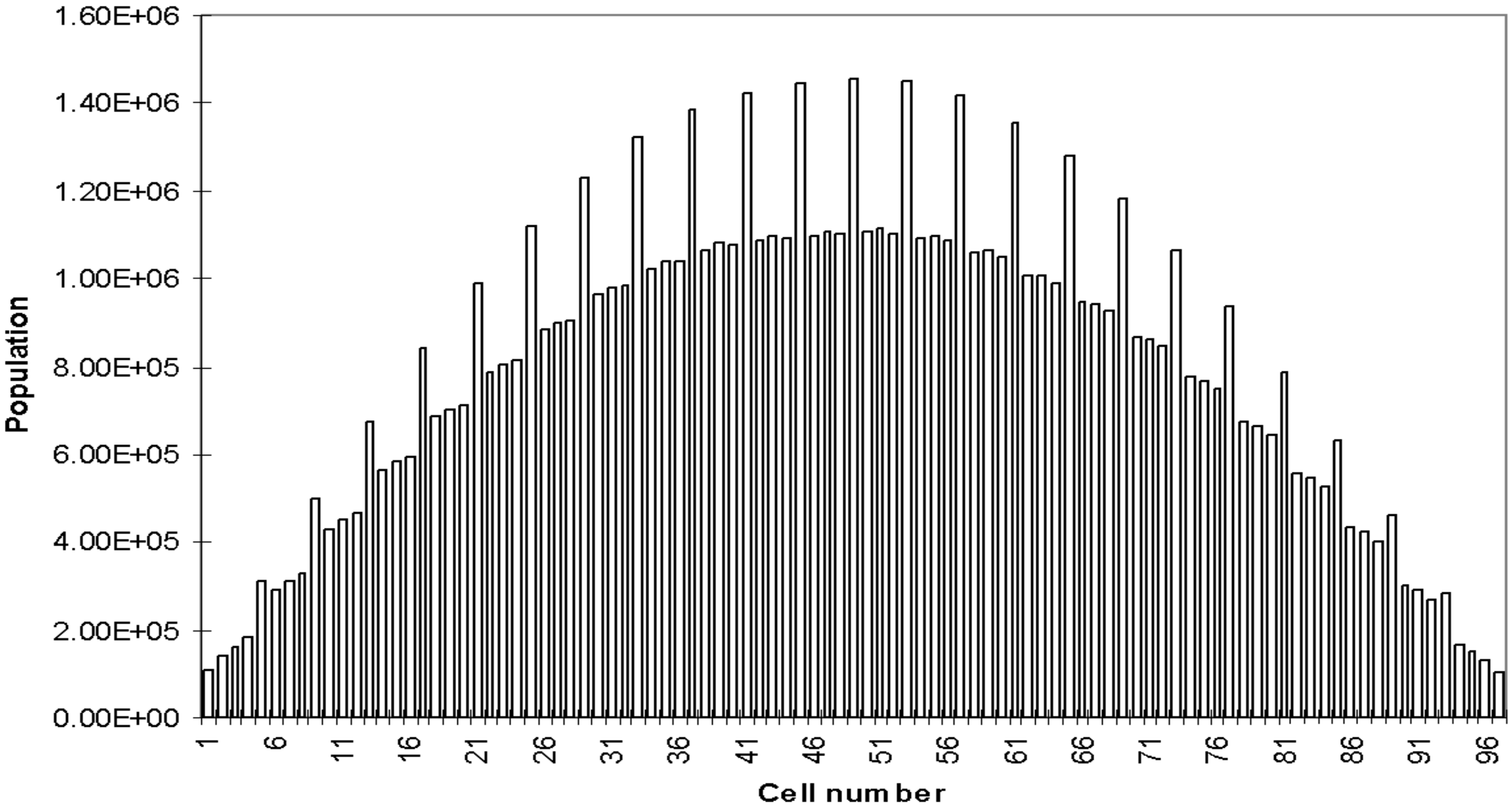
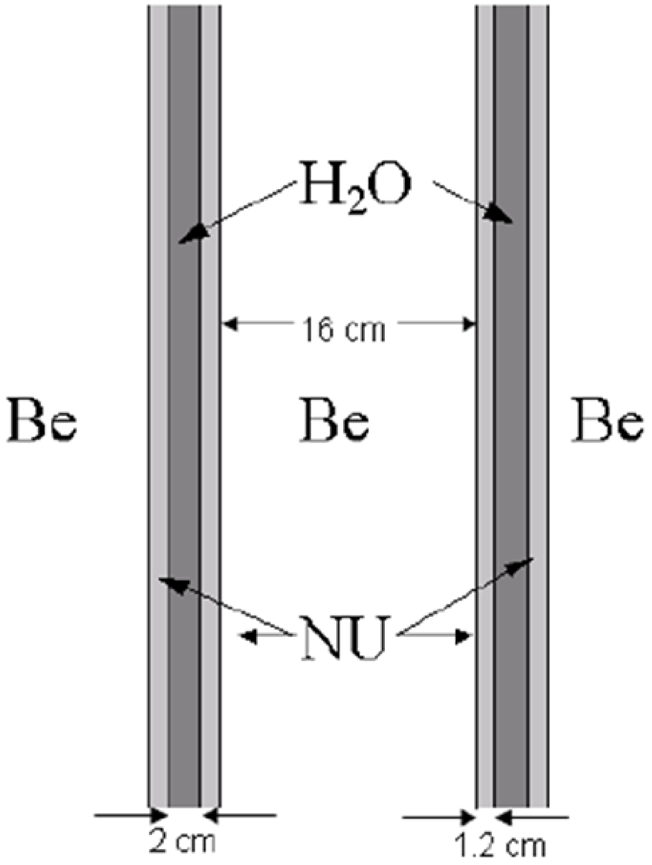
$$k_{eff} = \varepsilon p \eta f \, P_{NL}^{f} P_{NL}^{t}$$



# Thermal and fast non-leakage escape probabilities $P_{NL}^{th}, P_{NL}^{f}$




Hayes R. B. (2007) Burn-up characteristics of a light-water-cooled nuclear reactor of natural uranium and beryllium. ISSN 1936-6256, *J. Physical & Natural Sci.* **1** (2). 1-11.

# Reactor breeding estimates

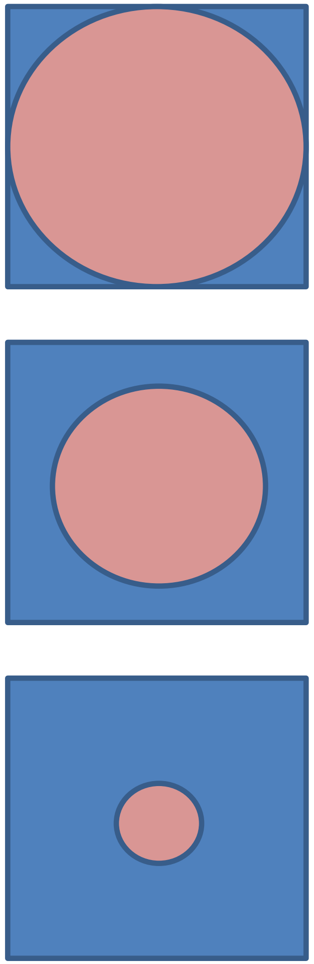
- Values shown are the ratio of tallied (nonfission) absorptions in NU to the total fissions in the same.
- Full edge effects ignored

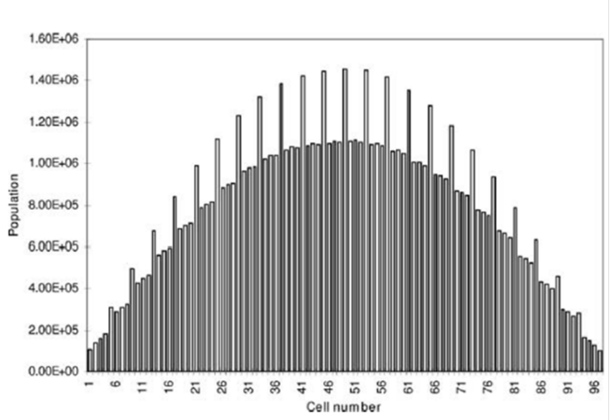
TABLE 4—*Reactor breeding estimates. Values shown are the ratio of tallied (nonfission) absorptions in NU to the total fissions in the same. Water densities are the same as those used in Table 3. Errors are from first-order error propagation on the tally error estimators. Note that the column headers of middle, quarter, and edge refer to the location of the uranium slab in the core.*

| Temp., °C | Middle | Quarter | Edge |
|---|---|---|---|
| 27 | 1.295±0.005 | 1.286±0.006 | 1.352±0.015 |
| 127 | 1.309±0.005 | 1.305±0.005 | 1.358±0.015 |
| 227 | 1.352±0.005 | 1.342±0.006 | 1.384±0.014 |
| 327 | 1.403±0.005 | 1.396±0.006 | 1.450±0.015 |
| 527 | 1.551±0.005 | 1.547±0.006 | 1.553±0.014 |

# Individual region modeling required detailed geometries

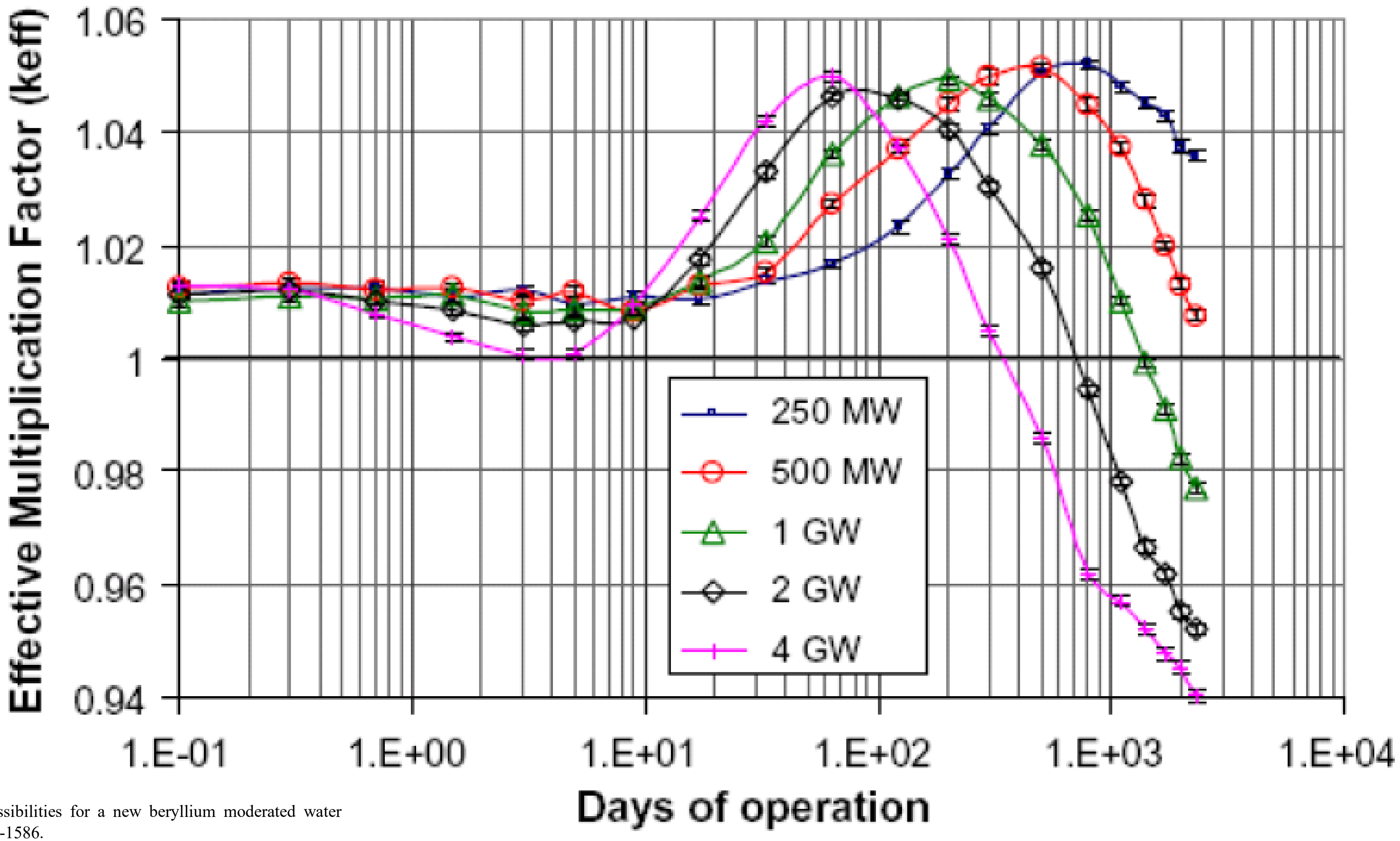
- Each plate is composed of two pieces
  - The plate has a disk cut out with the disk being one piece and the remainder being the other.
- Each plate is individually modeled as an independent material for activation, fission and fission product buildup
- Reactor symmetry credited by modeling only a quarter of the reactor.
- Early results were poor without this





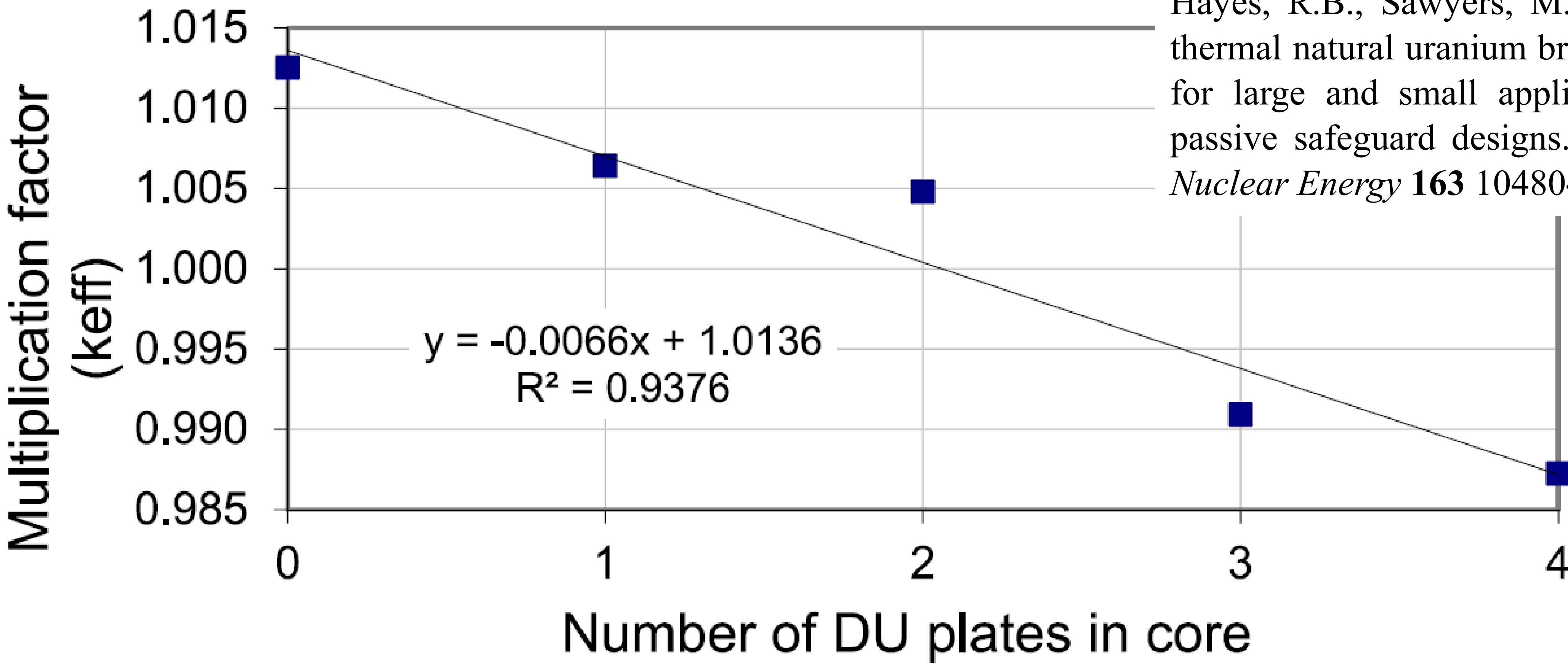

Hayes R. B. (2007) Burn-up characteristics of a light-water-cooled nuclear reactor of natural uranium and beryllium. ISSN 1936-6256, *J. Physical & Natural Sci.* **1** (2). 1-11.

# > 1000 GWd operation capability!



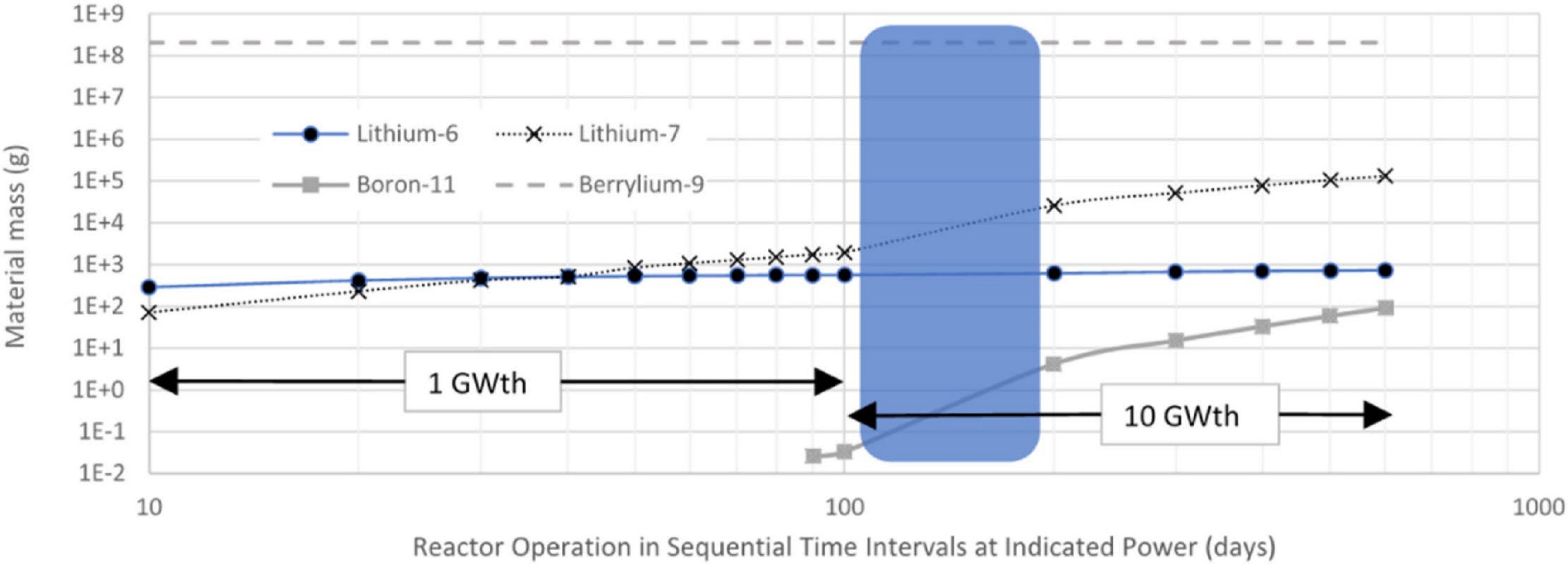

Hayes R. B (2008) High burn-up capability possibilities for a new beryllium moderated water cooled nuclear reactor. *Ann. Nuc. Energy* **35**, 1584-1586.

# Use of depleted uranium in the core!




Hayes, R.B., Sawyers, M.J., (2023) A thermal natural uranium breeder reactor for large and small applications with passive safeguard designs. *Progress in Nuclear Energy* **163** 104804.

# Moderator material considerations

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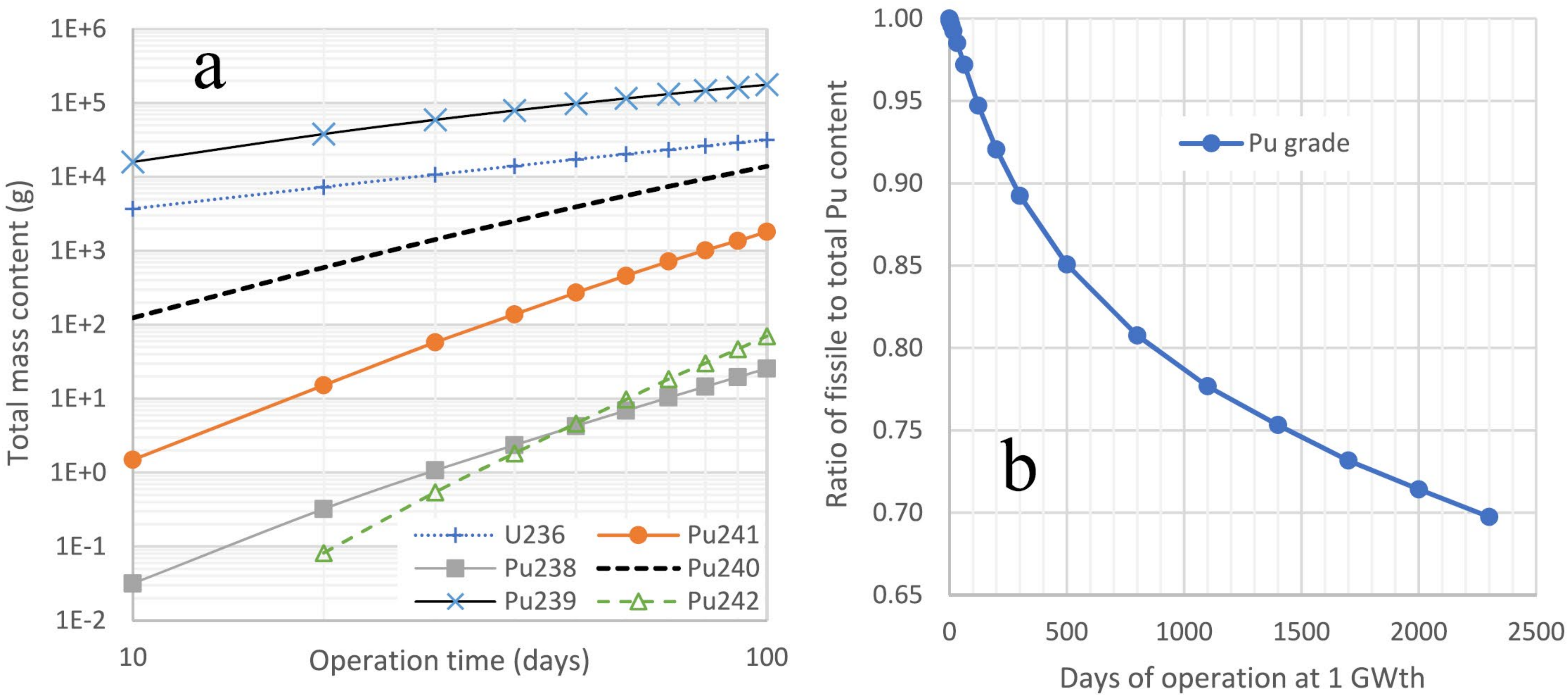
# Non-proliferation considerations

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# Nonprolification research


1. Tchouaso MT.  Coon N, Hayes RB. A Nondestructive Method for Accidental Dose Assessment from Electronic Devices *Radiat. Meas.* **148**, 106648, 2021
2. O'Mara RP, Hayes RB. Three-dimensional positional analysis of weapons grade plutonium using gridded arrays of dosimeters. *ESARDA Bulletin*, **61**, December 2020
3. Hayes RB, O'Mara RP. (2020) Retrospective characterization of special nuclear material in time and space. *Radiat. Meas.* **133**, 106301.
4. Hayes RB, O'Mara RP, Abdelrahman F. (2019) Nuclear forensics via the electronic properties of particulate and samples. *ESARDA Bull.* **59**, 21- 28, December 2019
5. Hayes RB. (2019) Retrospective uranium enrichment potential using solid state dosimetry techniques on ubiquitous building materials *J Nuc Mat Mgmt.* **47**(2), 4-12.
6. Hayes RB, O'Mara RP. (2019) Retrospective dosimetry at the natural background level with commercial surface mount resistors. *Radiat. Meas.* **121**, 42-48. doi:10.1016/j.radmeas.2018.12.007
7. O'Mara RB, Hayes RB. (2018) Dose deposition profiles in untreated brick material. *Health Phys.* **114**(4), 414-420.

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# Current design directions

- Modifications for an SMR or even a microreactor using these concepts is being pursued.
- Nonproliferation technology allowing ubiquitous detection to sternly discourage clandestine activities
- Passive safety to insure walk away capability.
- Materials incapable of phase change under all credible operational scenarios

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# Pros and Cons(iderations)

- Nuclear security friendly design
  - Hyper breeder configuration that makes it difficult to generate large quantities of WGPu
  - No enriched uranium required
  - Refueling with DU is an option during high $k_{eff}$
- Material degradation and thermal hydraulics not conducted.
- Loosely coupled and only metallic materials

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