# Reactor Physics Design Criteria

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**Objective** – Understand how design criteria (e.g., NRC's General Design Criteria in Appendix A of 10CFR50 and other issues) limit physics design of core to assure integrity of clad, pressure vessel and containment, and how these limits combine with other objectives to yield core (especially PWR) designs.

## *RELATIONSHIP OF SAFETY ANALYSES TO LICENSING AND TECH SPECS*

START HERE

The risk to public health and safety is

Radioactive material

Whose release is prevented by

Clad, pressure vessel & containment

Whose integrity is assured by

Adherence to GDC of 10CFR50, App A

Which is checked by

Analyses of credible transients and accidents

Which give acceptable results for

A range of plant and core characteristics

To which range, operation is restricted by

Technical specifications

# For LWRs in US (more general to more specific)

- General Design Criteria (GDC in 10CFR50)
- Standard Review Plan (NUREG-0800)
- Tech Specs
- Core Operating Limits Report (COLR)

# GOAL – design a core that:

- Is safe and licensable
- Operates for desired time between refuelings
- Is “economic”
- Meets operations constraints
- Does whatever else it is supposed to (make Btu at some T & P, neutrons, isotopes, be non-proliferative …

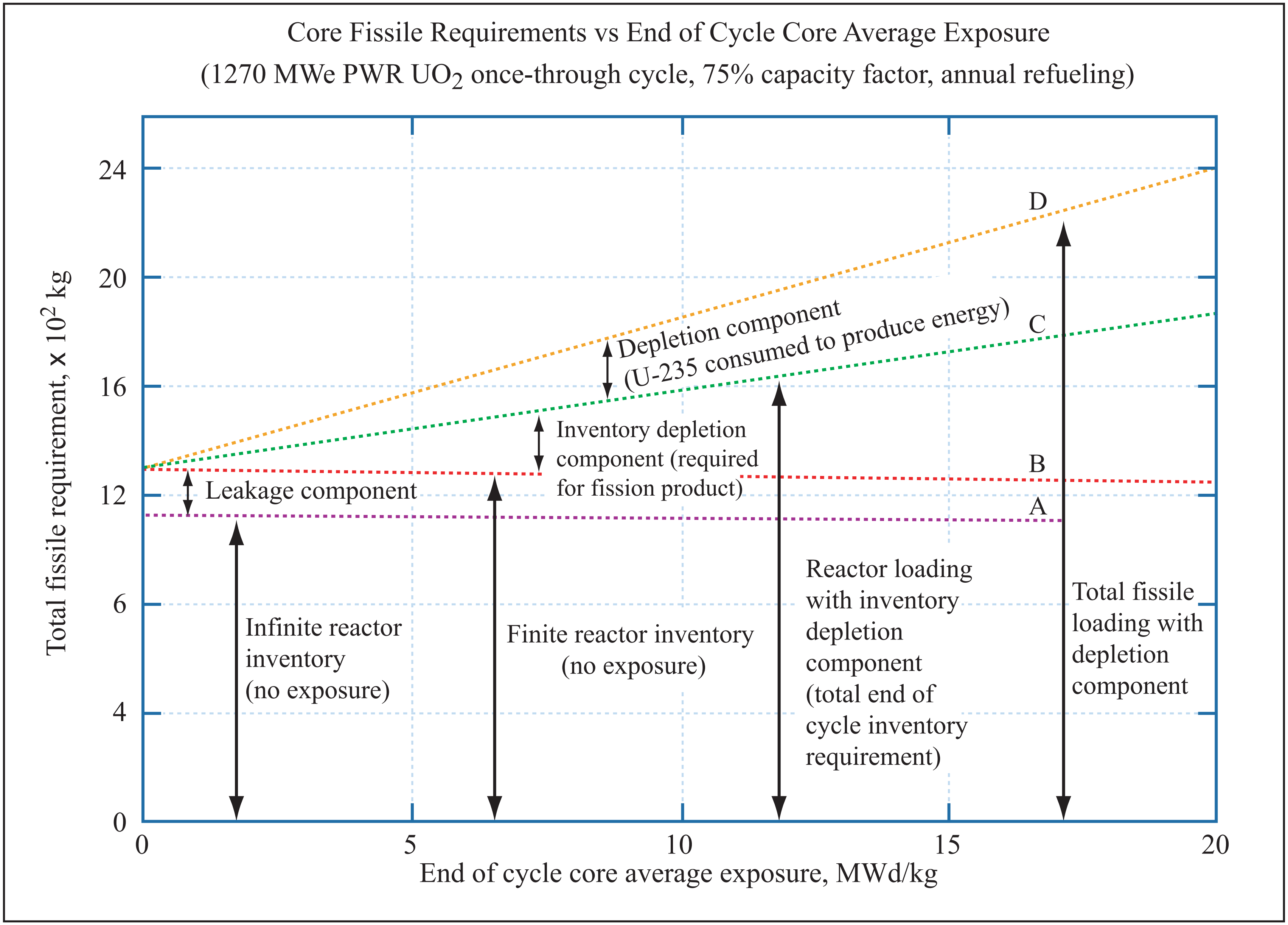
# Safety/licensing constraints

- Limit power peaking
- Limit total reactivity, reactivity coefficients
- Limit ejected control rod worth
- Provide shutdown margin
- Limit delayed neutron fraction
- Maintain fuel integrity

# The Language

- Fuel mass – actinides only, Kg or MT
- Burnup, cycle burnup, discharge burnup
- $F_Q$, $F_{\Delta h}$, $F_Z$, $F_{loc}$, – normalize each to unity
- Heat flux, LHGR – absolute units
- Fuel batch, number of fuel batches
- Power density – thermal power/core volume
- Specific power – thermal power/core mass

# Getting the right cycle lifetime

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# What transients are considered?

- Type I Normal operation (start up, shut down, change power level, etc.)
- Type II transients (scram, dropped control rod, unintended dilution, control rod banks out of sequence, etc) = AOO
- Type III unlikely but $p > 0$
- Type IV whoops! (LOCA, main steam line break)

# Response to transients is combination of:

- Transient response of core
- Transient response of primary and secondary coolant systems
- Automatic controls
- Trip system (reactor and coolant/secondary)

# Think & usually use point kinetics

$$\frac{dP}{dt} = \frac{(\rho - \beta)}{l}P + \sum \lambda_i C_i$$

$$\frac{dC_i}{dt} = \beta_i P - \lambda_i C_i$$

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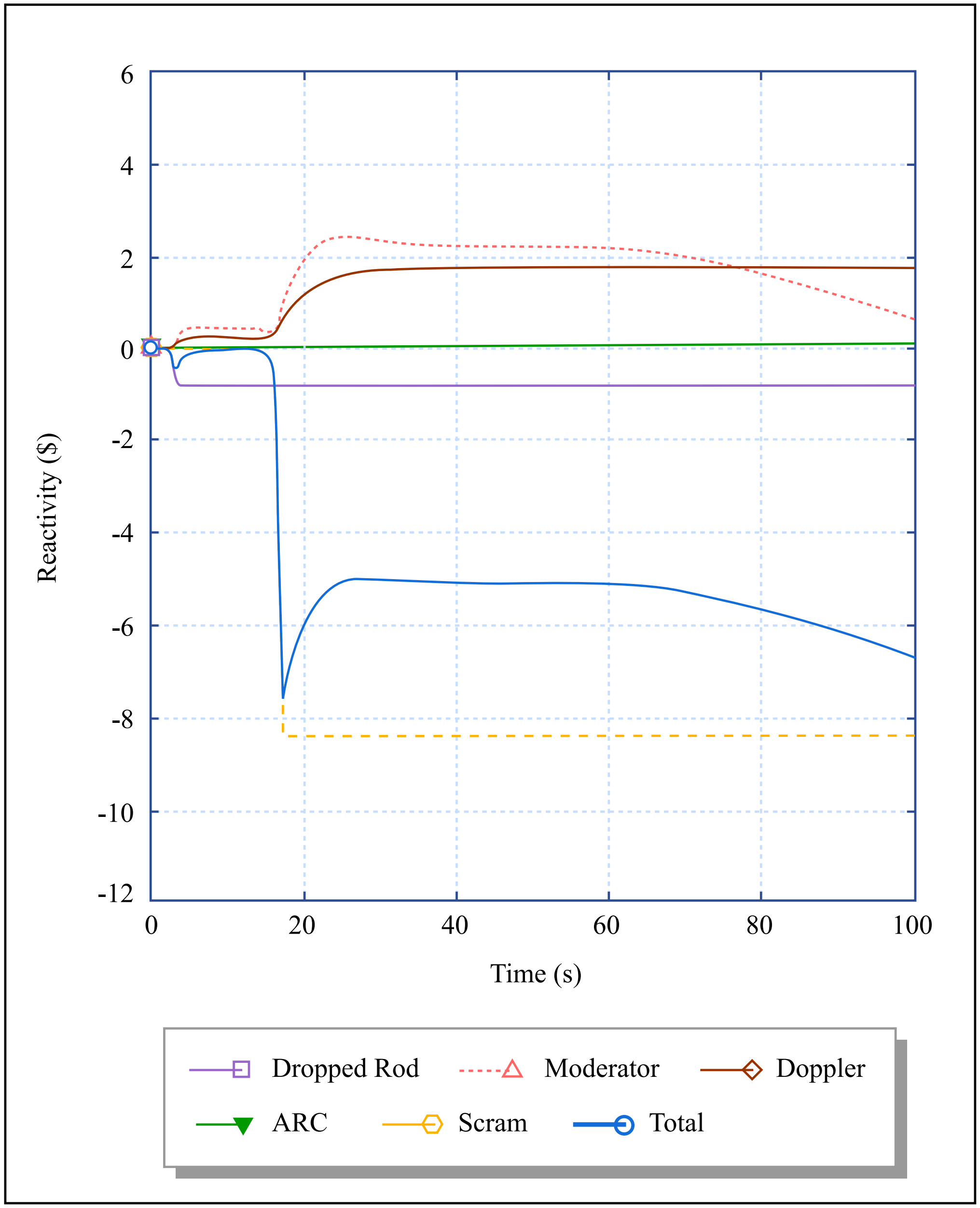
Actually 6 groups of delayed neutrons

# Usually use point kinetics

- $\rho = \rho_{doppler} + \rho_{mod\ temp} + \rho_{void} + \rho_{Xe} + \rho_{control\ rods} + \rho_{soluble\ boron} + \rho_{etc}$
- Calculate individual reactivities
- But each depends on core conditions

# Example: Rod drop in US EPR

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From Tier 2 Revision 0 Page 15.4-64

# What does a core look like

- Try to maintain 1/8 or 1/4 core symmetry
- Modern loading patterns are “in-out”
- Core map conventionally shows:
  – Assembly power (relative to core ave assy = 1)
  – Max pin power within assembly (relative to core ave pin = 1)
  – Sometimes assy absolute burnup
  – Sometimes assy ID or fuel type

# What Does a Core Look Like ?

| | H | G | F | E | D | C | B | A |
|---|---|---|---|---|---|---|---|---|
| 8 | 0.921 | 1.298 | 1.161 | 1.041 | 1.055 | 1.095 | 1.017 | 0.603 |
| 9 | 1.298 | 1.052 | 1.283 | 1.000 | 1.252 | 1.078 | 1.187 | 0.625 |
| 10 | 1.161 | 1.287 | 1.045 | 1.301 | 1.123 | 1.153 | 1.200 | 0.621 |
| 11 | 1.041 | 1.000 | 1.302 | 1.065 | 1.318 | 1.161 | 1.039 | 0.326 |
| 12 | 1.055 | 1.253 | 1.125 | 1.320 | 1.140 | 1.210 | 0.556 | |
| 13 | 1.095 | 1.080 | 1.155 | 1.161 | 1.209 | 0.951 | 0.307 | |
| 14 | 1.017 | 1.193 | 1.203 | 1.040 | 0.555 | 0.298 | | |
| 15 | 0.603 | 0.628 | 0.623 | 0.326 | | | | |

Value represents assembly relative power

# What Does a Core Look Like?

| | | | | |
|---|---|---|---|---|
| 1.279 | | | | |
| 1.154 | 1.273 | | | |
| 1.268 | 1.142 | 1.250 | | |
| 1.137 | 1.250 | 1.111 | 1.193 | |
| 1.254 | 1.113 | 1.203 | 1.033 | 0.859 |
| 1.161 | 1.168 | 1.026 | 1.041 | 0.630 |
| 0.975 | 0.913 | 0.851 | 0.561 | |
| 0.541 | 0.436 | | | |

Calculated F-Delta-H = 1.406

Key: Value represents assembly
Relative power

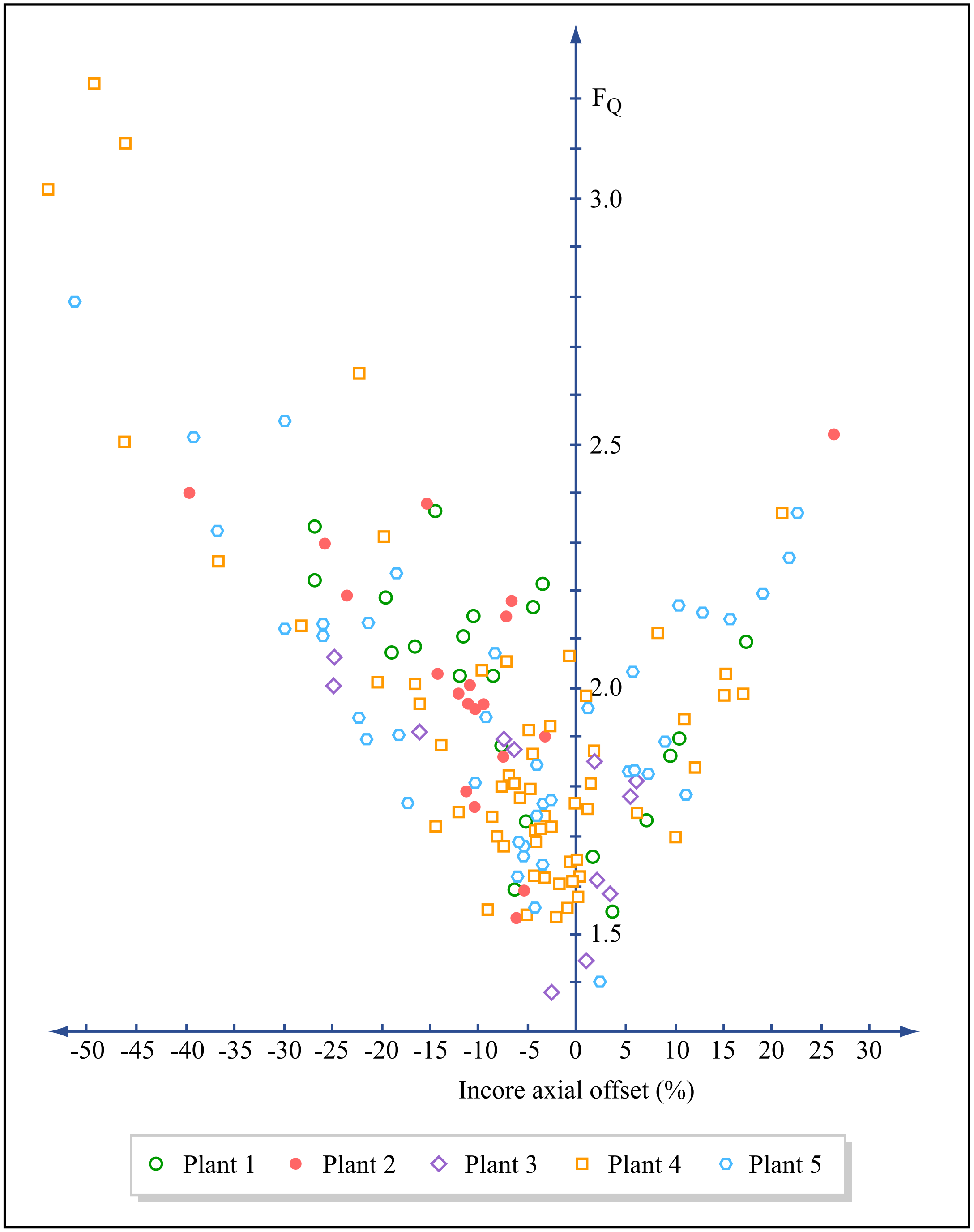
# Reactivity Control

| | **Peaking** | **Time Constant** |
|---|---|---|
| Control rods | Somewhat high | Short – seconds |
| Soluble boron | Negligible | Hours |

# Types of BP

- Pyrex glass ($^{10}B$) in rods separate from fuel
- WABA ($^{10}B$) in rods separate from fuel
- $B_4C$ in alumina ($^{10}B$) in rods separate from fuel
- Erbia - mixed with $UO_2$
- Gadolinia - mixed with $UO_2$ ($^{155}Gd$, $^{157}Gd$)
- IFBA ($^{10}B$) -on pellet surface

# How W controls axial power peaking

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# General Design Criterion 10

- margin to assure that specified acceptable fuel design limits are not exceeded during any condition of normal operation, including the effects of anticipated operational occurrences

# General Design Criterion 11

- in the power operating range the net effect of the prompt inherent nuclear feedback characteristics tends to compensate for a rapid increase in reactivity

# General Design Criterion 12

- assure that power oscillations which can result in conditions exceeding <u>specified acceptable fuel design limits</u> are not possible or can be reliably and readily detected and suppressed

# General Design Criterion 13

- <u>Instrumentation shall be provided</u> to monitor variables and systems over their anticipated ranges for normal operation, for anticipated operational occurrences, and for accident conditions as appropriate to assure adequate safety

# General Design Criterion 20

- protection system shall be designed (1) to initiate automatically the operation of appropriate systems including the reactivity control systems, to assure that <u>specified acceptable fuel design limits</u> are not exceeded as a result of <u>anticipated operational occurrences</u>

# General Design Criterion 25

- The protection system shall be designed to assure that specified acceptable fuel design limits are not exceeded for any single malfunction of the reactivity control systems, such as accidental withdrawal (not ejection or dropout) of control rods

# General Design Criterion 26

- Two independent reactivity control systems
- One ... shall use control rods…[for] ... <u>controlling reactivity changes to assure that under conditions of normal operation, including anticipated operational occurrences, and with appropriate margin for malfunctions such as stuck rods</u>, <u>specified acceptable fuel design limits</u> are not exceeded

# General Design Criterion 26

- The second ... shall be capable of reliably controlling the rate of reactivity changes resulting from planned, normal power changes (including xenon burnout) to assure <u>acceptable fuel design limits</u> are not exceeded

# General Design Criterion 27

- reliably controlling reactivity changes to assure that under postulated accident conditions and <u>with appropriate margin for stuck rods the capability to cool the core is maintained</u>.

# General Design Criterion 28

- <u>limits on the potential amount and rate of reactivity increase</u> to assure that the effects of postulated reactivity accidents can neither (1) result in damage to the reactor coolant pressure boundary nor (2) impair significantly the capability to cool the core.

# Linear Reactivity

- Simple core model relating enrichment and core average burnup at EOFPL
- Useful for broad scoping analyses covering large range and for small changes
- Works best when normalized
- Can be constructed solely from operating data

# Apparent Assumptions

- Slope of reactivity vs burnup is linear
- All batches have same (core average) power
- Separation of reactivity curves for different enrichment fuel is uniform vs enrichment

# Equilibrium Only

- $B_d$ = discharge burnup of a batch of fuel assemblies
- n = number of equal size batches
  (typically 2 to 4 in LWRs)
- S = specific power
- T = calendar length of every cycle
- L = capacity factor

THEN at equilibrium, $B_d = n\ S\ T\ L$

1. **Plot reactivity of a given fuel type vs burnup**

2. **Draw a horizontal line at $\rho = 1/NLP$ where NLP is the non-leakage probability at EOFPL (end of full power life)**

3. **IF you had several batches of this kind of fuel at different burnup levels in the core –**

4. **AND IF the power distribution were flat – the same everywhere –**

5. **THEN the core reactivity would be the average of the individual "batch reactivities" read from this line –**

6. **AND IF the reactivity curve were linear with burnup –**

7. **THEN the <u>core average reactivity</u> would occur at the <u>core average burnup</u>**

8. **SO the core would reach EOFPL where the curve crosses the $\rho = 1/NLP$ line**

# At Equilibrium

$$B_d = \frac{2n}{(n+1)} B_1$$

$$B_1 = B_d/2 + B_c/2$$

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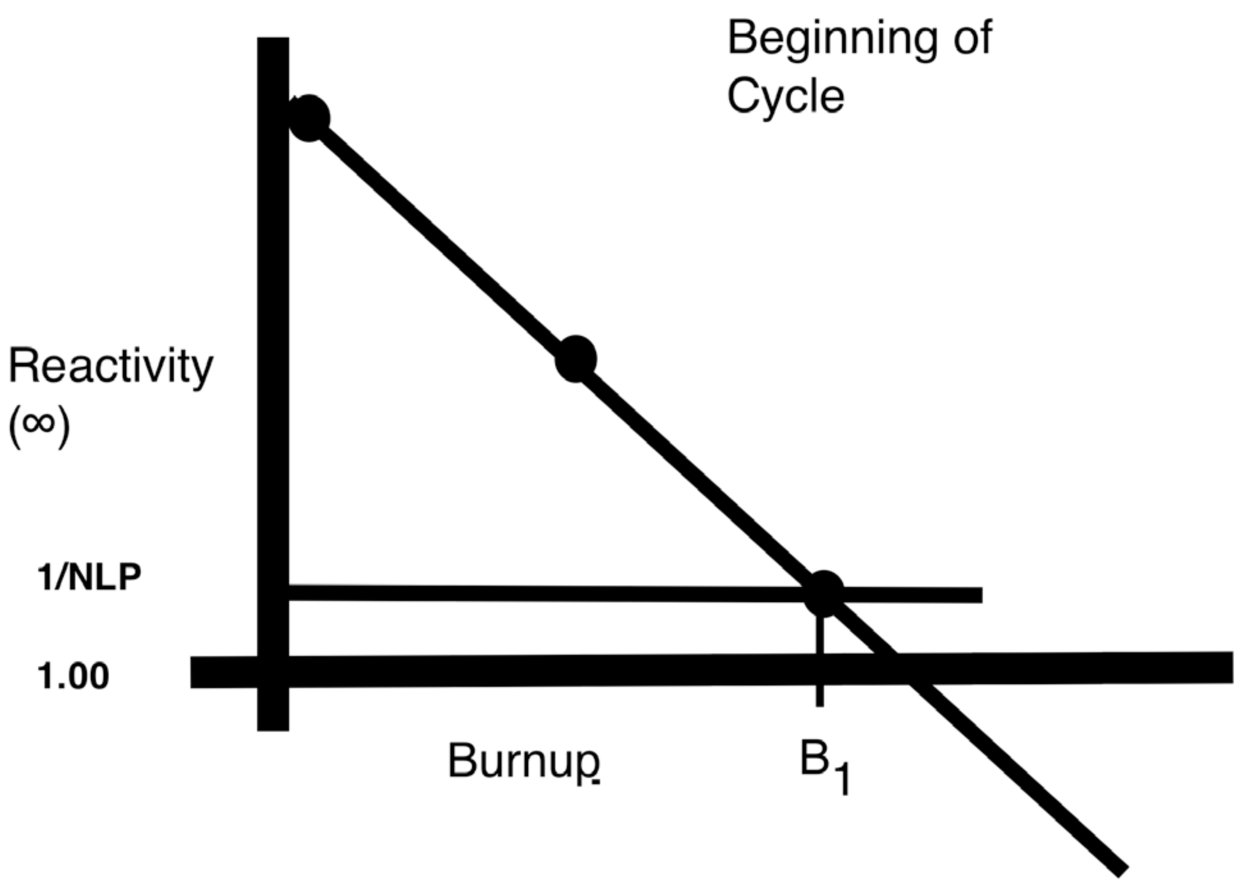
# For One Enrichment



# Linear Reactivity – Batches with Different Enrichments

1. **Plot reactivity vs burnup for several enrichments**

2. **IF reactivity is linear with burnup**

3. **IF reactivity curves for different enrichments are parallel**

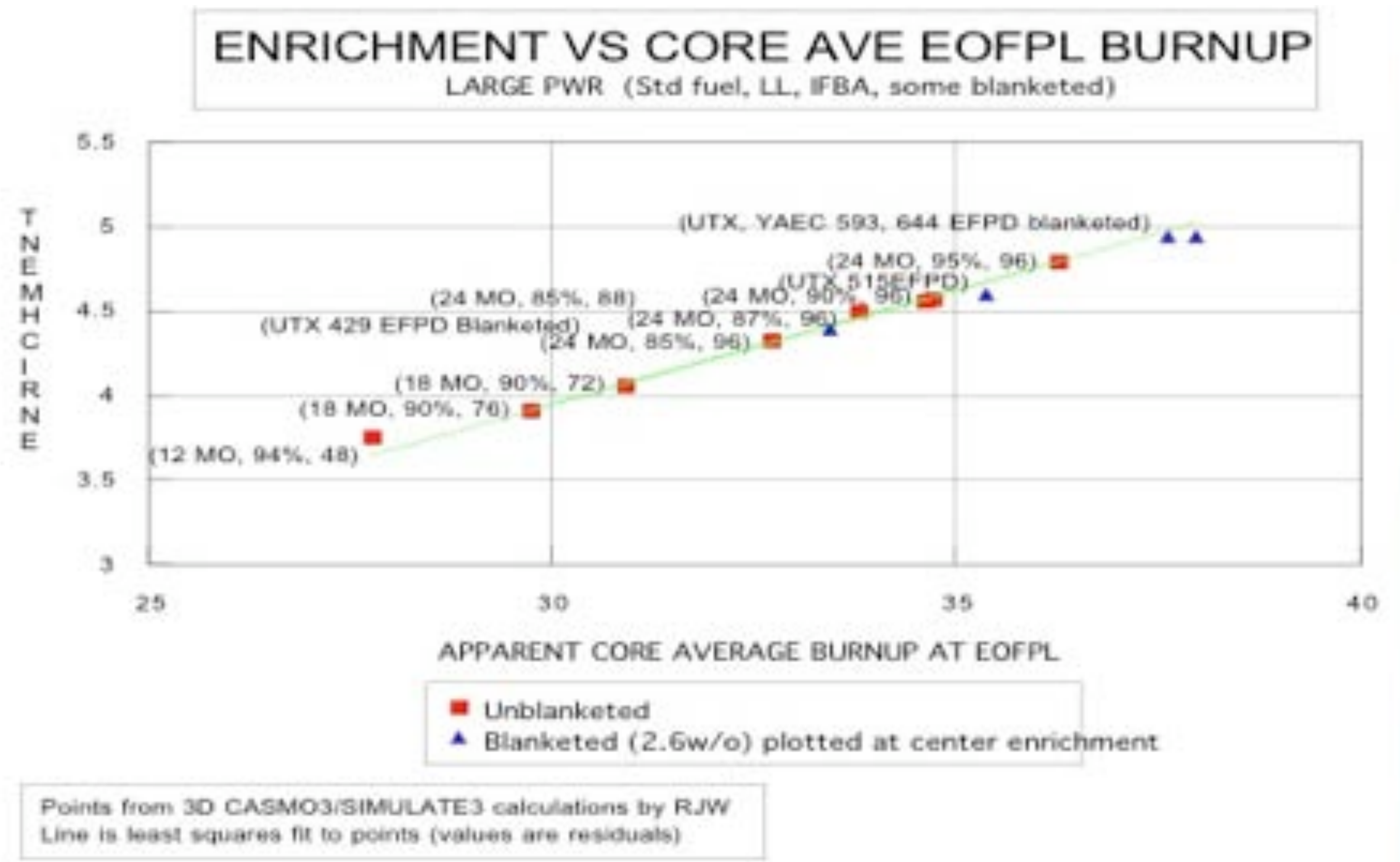
4. **Draw a horizontal line at $\rho = 1/NLP$ where NLP is the non-leakage probability at EOFPL**

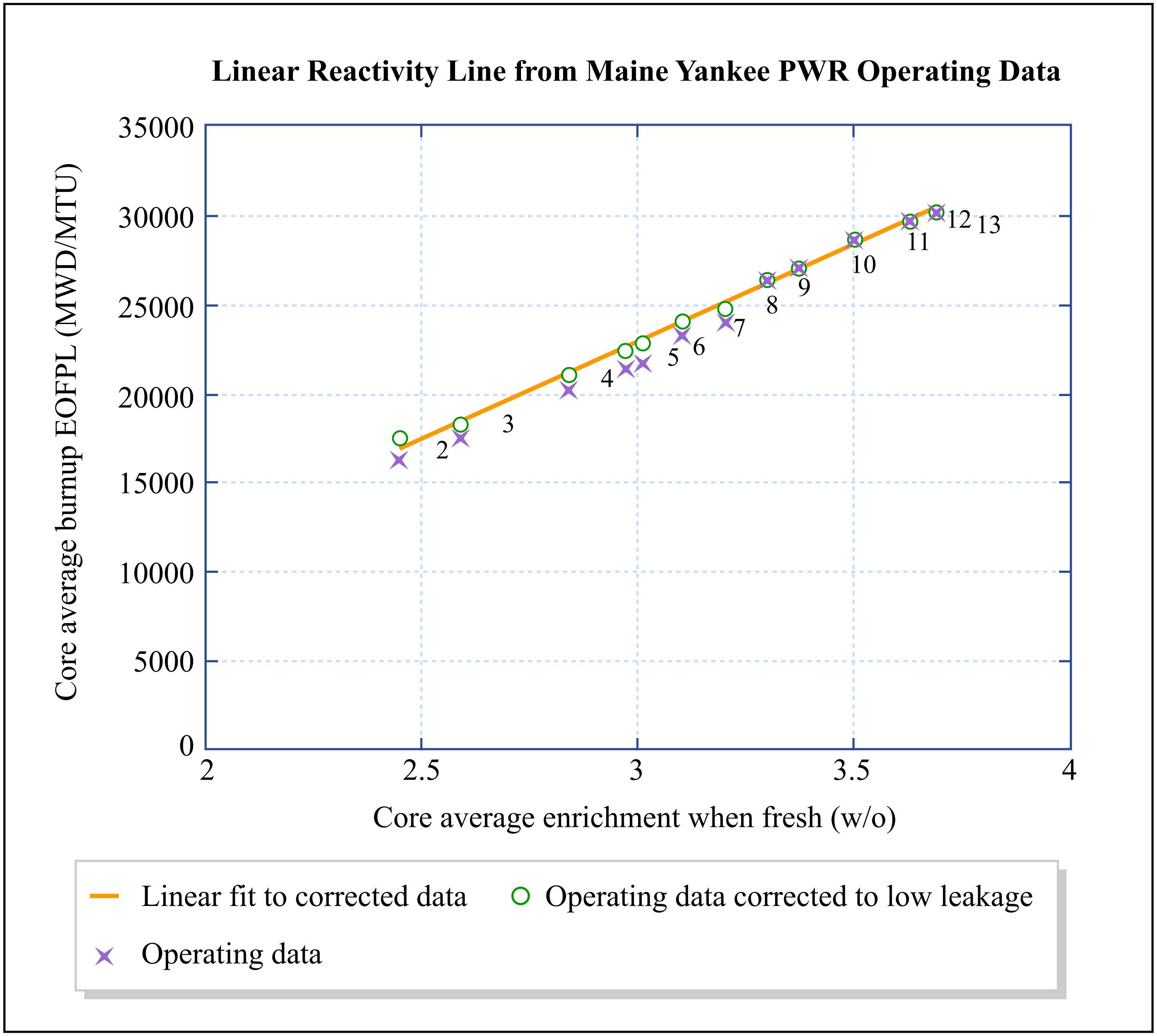
5. **Make a plot showing the enrichment of each curve vs the burnup where it crosses the $\rho = 1/NLP$ line**

6. **The locus of these points is the LRM line, which reads:**

$$e = e_0 + e_1 * B_1$$

# From Good Calculations



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