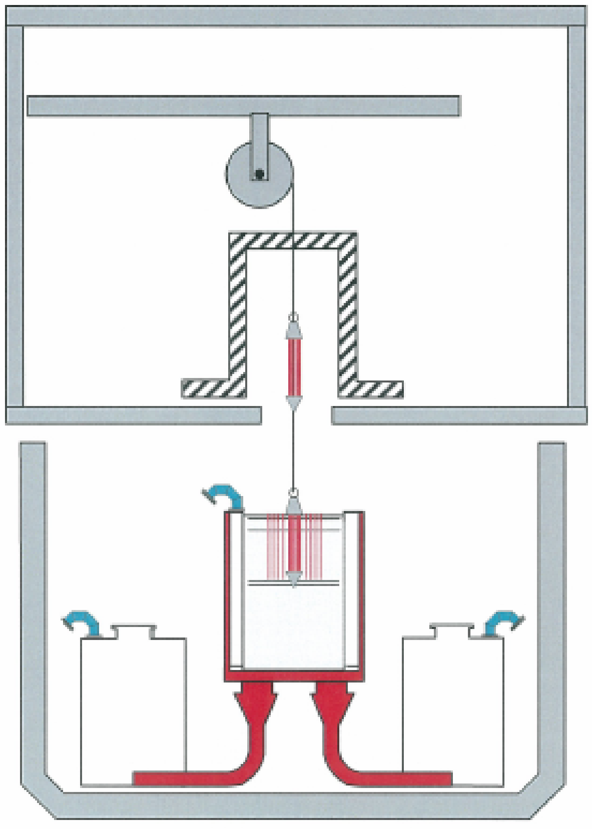
Study of Burnup Reactivity and Isotopic Inventories in REBUS Program

T. Yamamoto[1], Y. Ando[1],
K. Sakurada[2], Y. Hayashi[2], and
K. Azekura[3]
[1]Japan Nuclear Energy Safety Organization (JNES)
[2]Toshiba Corporation
[3]NAIS Co., Inc.

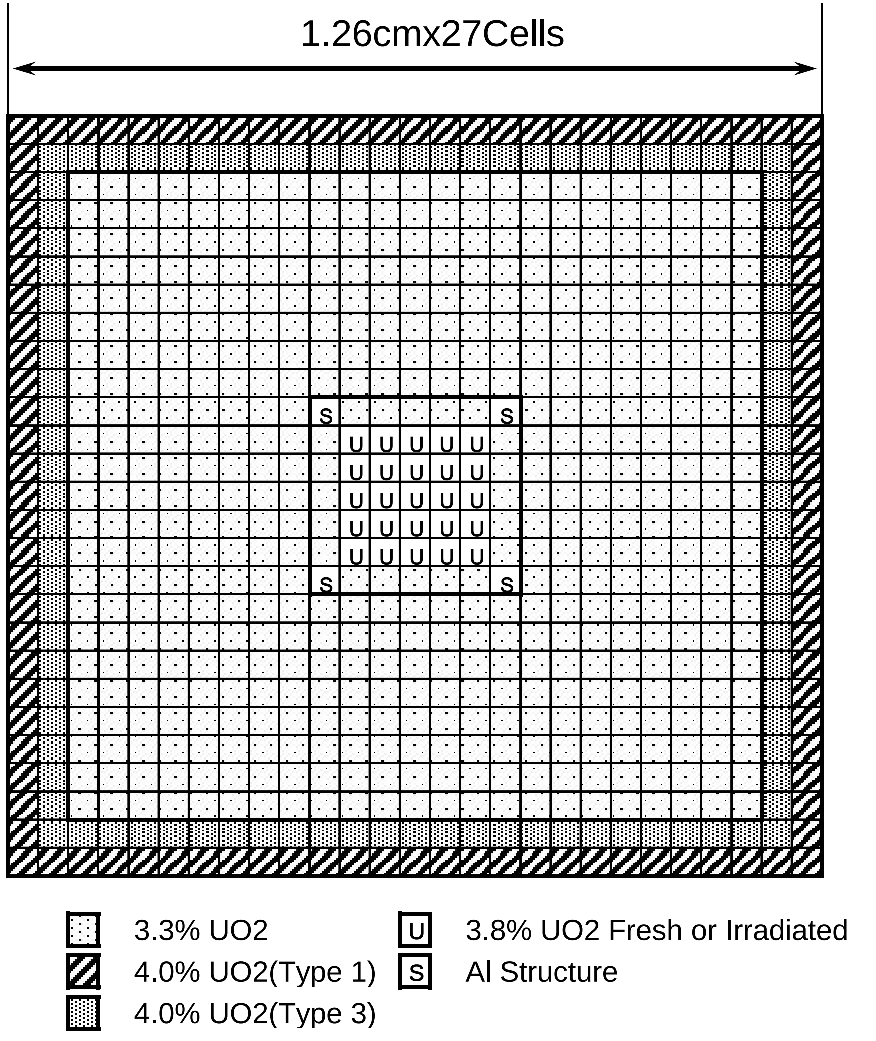
Contents

1. REBUS Program
2. Determination of Burnup Reactivity in Critical Experiment
3. Analysis of Burnup Reactivity
   - 3.1 Calculated Isotopic Inventories
   - 3.2 Corrected Isotopic Inventories with Measured Data
4. Discussion on Bias of Inventory and Reactivity Calculations

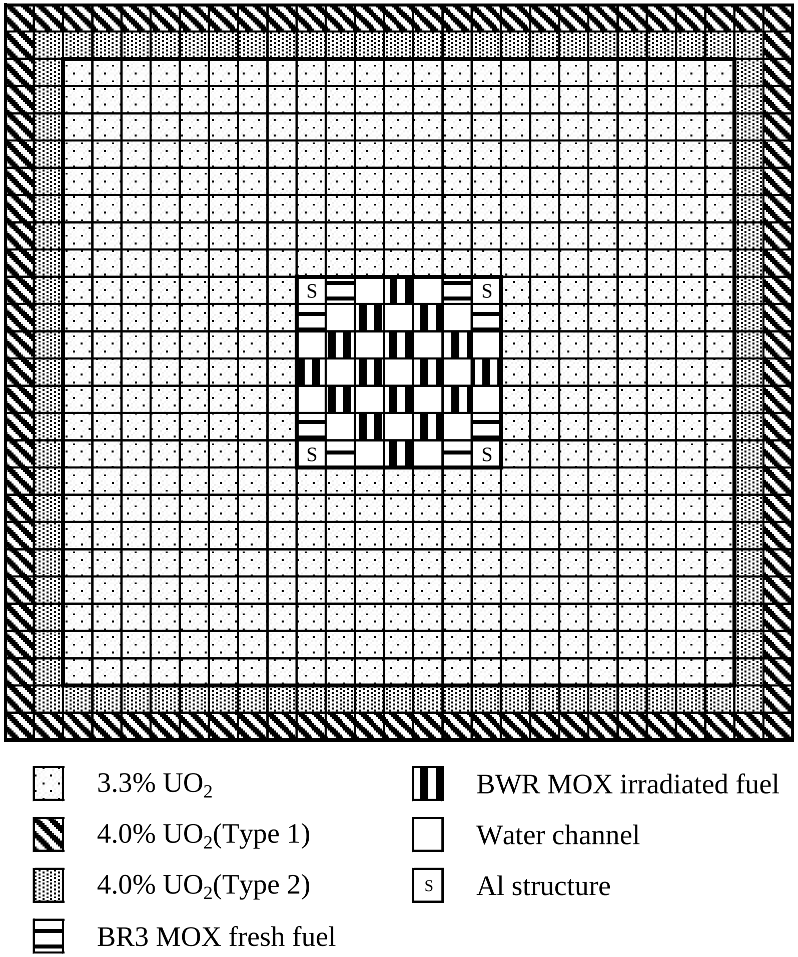


1. REBUS Program

- PWR 3.8wt% UO2
  - Fresh bundle
  - Irradiated fuel bundle
    - GKN II, 4 cycles
    - Average 54.5 GWd/t

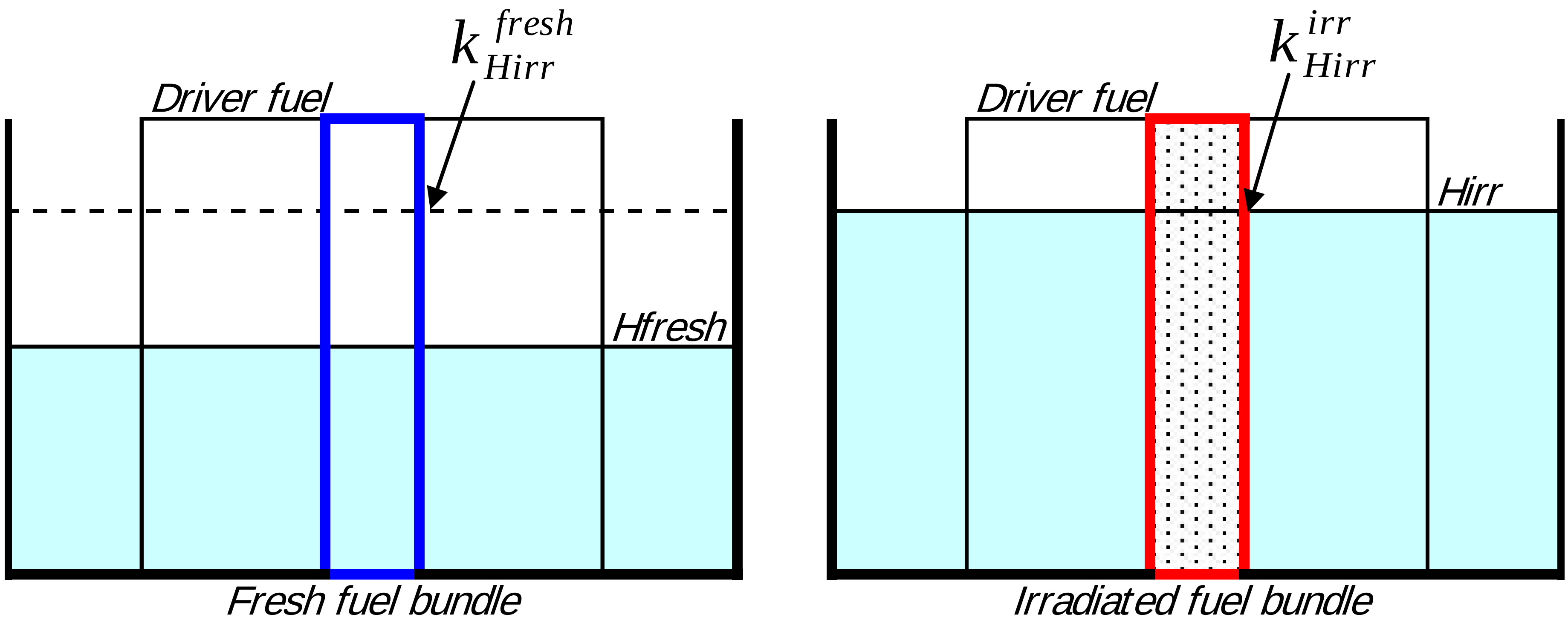


- BWR MOX
  - Fresh bundle (BR3 MOX Puf 6.8 wt%)
  - Irradiated BWR MOX fuel (Puf 5.5 wt%) bundle
    - Gundremmingen, 4, 5, 6 cycles
    - Average 60.6 GWd/t



- VENUS
  - Critical water level
    - About 60 cm for fresh and about 80 cm for irradiated fuel bundle
  - Water level reactivity
  - Fission rate distribution (^{140}La , 1.59 MeV)
  - Flux distribution (Sc or Co wire activation)
- Hot Lab.
  - Burn-up distribution determination (all test rods)
    - Gross gamma-ray and Cs-137 Spectrometry
  - Fuel sample radiochemical analysis
    - U, Pu, Am, Cm (19 Actinides)
    - 19 FP and BU indicator FP

2. Determination of Burnup Reactivity in Critical Experiment



$$\rho = \left\{1 - \left(1 / k_{Hirr}^{irr}\right)\right\} - \left\{1 - \left(1 / k_{Hirr}^{fresh}\right)\right\}$$

In experiment $k_{Hirr}^{irr} = 1.0$

$$\rho = -\left\{1 - \left(1 / k_{Hirr}^{fresh}\right)\right\}$$

$$\rho = -\int_{Hfresh}^{Hirr} \left(\partial \rho / \partial h\right) dh$$

$\left(\partial \rho / \partial h\right)$: Measurements at *Hfresh* and *Hirr*

With one group diffusion theory

$$\rho = 1 - \left\{1 + M^2 B_{rad}^2 + M^2 \pi^2 / \left(h + \delta_z\right)^2\right\} / k_\infty$$

$$\left(\partial \rho / \partial h\right) = 2\pi^2 M^2 / k_\infty \left(h + \delta_z\right)^3 = \alpha / \left(h + \delta_z\right)^3$$

Measured burnup reactivity

Fuel bundle	PWR UO2		BWR MOX	
	Fresh	Irradiated	Fresh	Irradiated
Critical water level (cm)	59.05	81.38	61.10	84.84
Water level reactivity coefficient ($/cm)	0.186	0.0924	0.191	0.0887
Reflector saving (cm)	12.60	13.23	12.81	14.91
Averaged reflector saving (cm)	12.92		13.86	
α (pcm cm^2)	5.65×10^7	6.26×10^7	6.08×10^7	6.42×10^7
Burnup reactivity (%dk/kk')	-2.28	-2.52	-2.29	-2.42
Averaged burnup reactivity and error (%dk/kk') (relative error)	-2.40 $\pm$ 0.17 (7%)		-2.36 $\pm$ 0.09 (4%) -2.48 $\pm$ 0.10 (4%)*	

*Corrected for reactivity difference between fresh BR3 and BWR MOX fuel

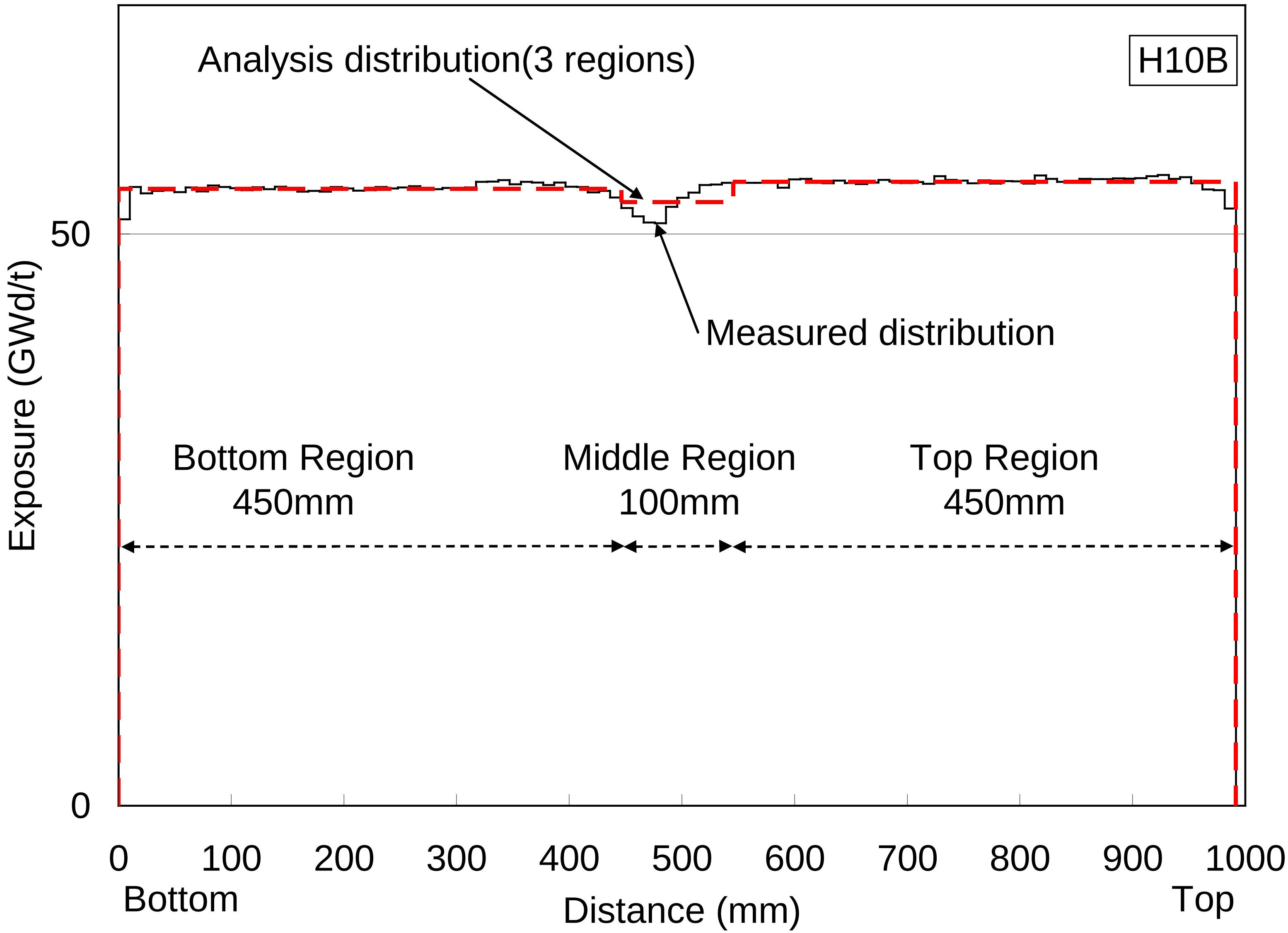
3. Analysis of Burnup Reactivity

$$\rho = \left\{1-\left(1/k_{Hirr}^{irr}\right)\right\} - \left\{1-\left(1/k_{Hirr}^{fresh}\right)\right\}$$

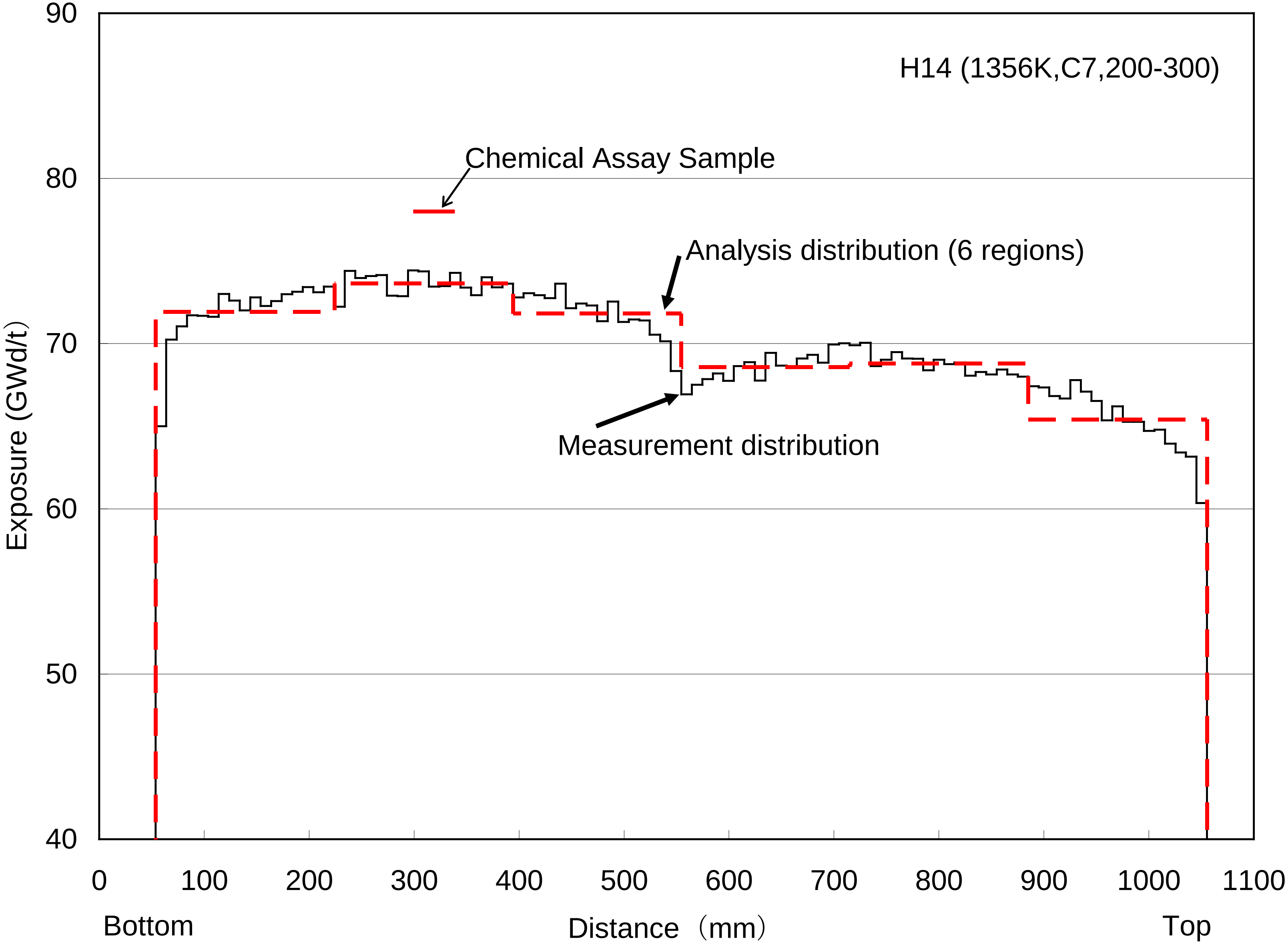
3.1 Calculated Isotopic Inventories

- Inventory calculation of PWR UO2 and BWR MOX Fuels for core calculation loaded with irradiated fuel bundle
  - Pin cell model (assembly mock-up) for PWR UO2 and assembly model for BWR MOX
  - 107 group energy spectrum (Pij) and burnup calculation by SRAC code
  - Resonance cross sections with hyper-fine energy group (PEACO)
  - JENDL-3.2 nuclear data library
  - Tracking irradiation history (rod power, boron, in-channel void)
- Target burnups: Measurements by gross gamma-ray and Cs-137 Spectrometry

– PWR UO2: Axial 3 regions x 25 rods



– BWR MOX: Axial 6 regions x 16 rods



– Core Calculation

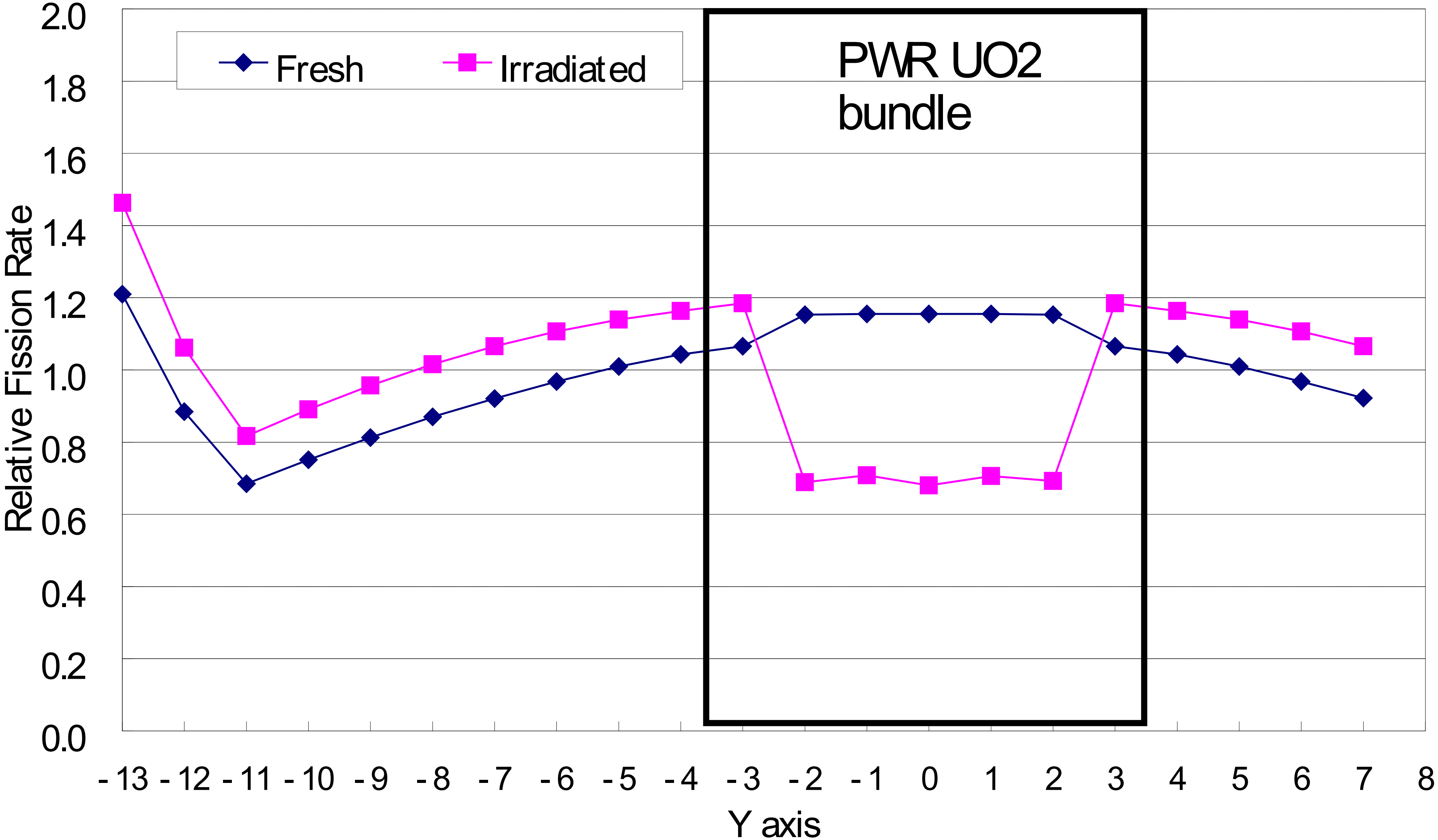
- Lattice calculation
  - Pin cell model
  - 107 energy-group
  - SRAC Pij module with resonance cross sections PEACO
  - JENDL-3.3
- Core calculation
  - Transport calculation THREEDANT
  - Collapsed 16-energy group cross sections
  - XYZ three-dimensional model

Calculated burnup reactivity with calculated inventories

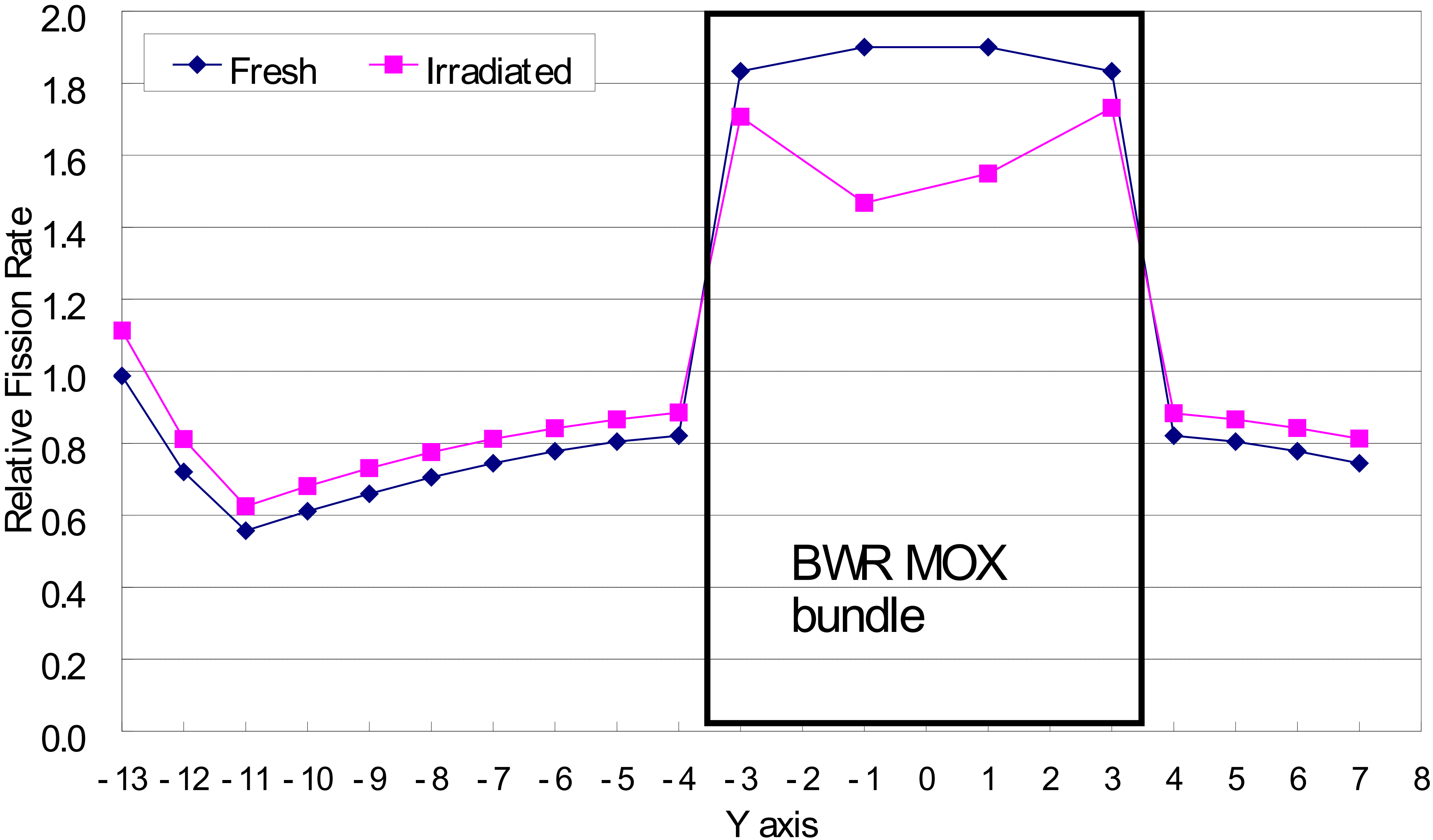
Fuel bundle	PWR UO2		BWR MOX	
k-effective	k_{Hirr}^{irr}	k_{Hirr}^{fresh}	k_{Hirr}^{irr}	k_{Hirr}^{fresh}
	0.99445	1.02004	0.99721	1.02205
Burnup reactivity (%dk/kk')	-2.522		-2.437	
Bias of burnup reactivity (Calculated - measured) (%dk/kk')	-0.1227		+0.0438	
C/E	1.051		0.982	

Biases of burnup reactivity (UO2 and MOX): -0.12 and +0.04 %dk/kk' and comparable to measurement errors ±0.17 and 0.10 %dk/kk'

Calculated radial fission rate distribution



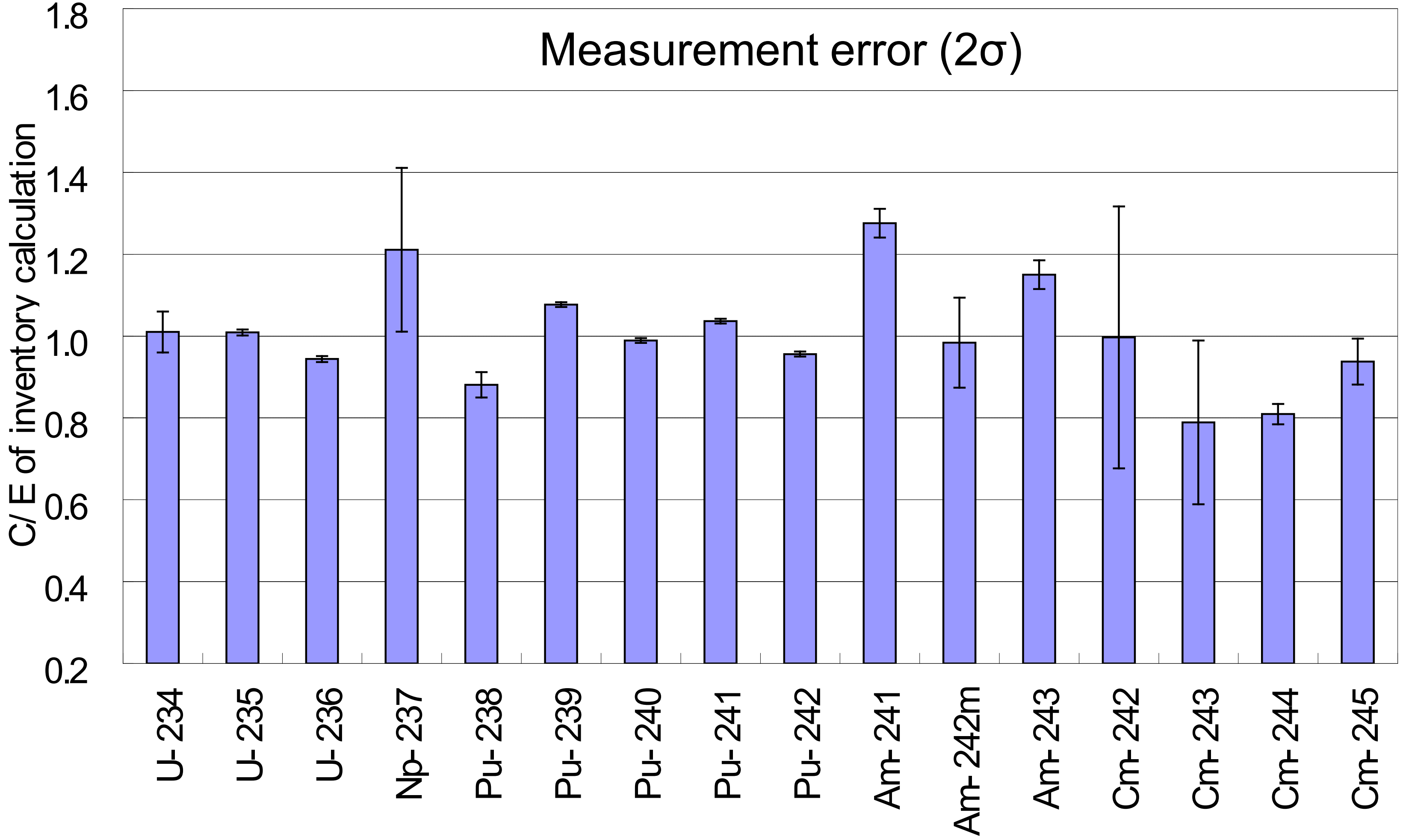
Calculated radial fission rate distribution



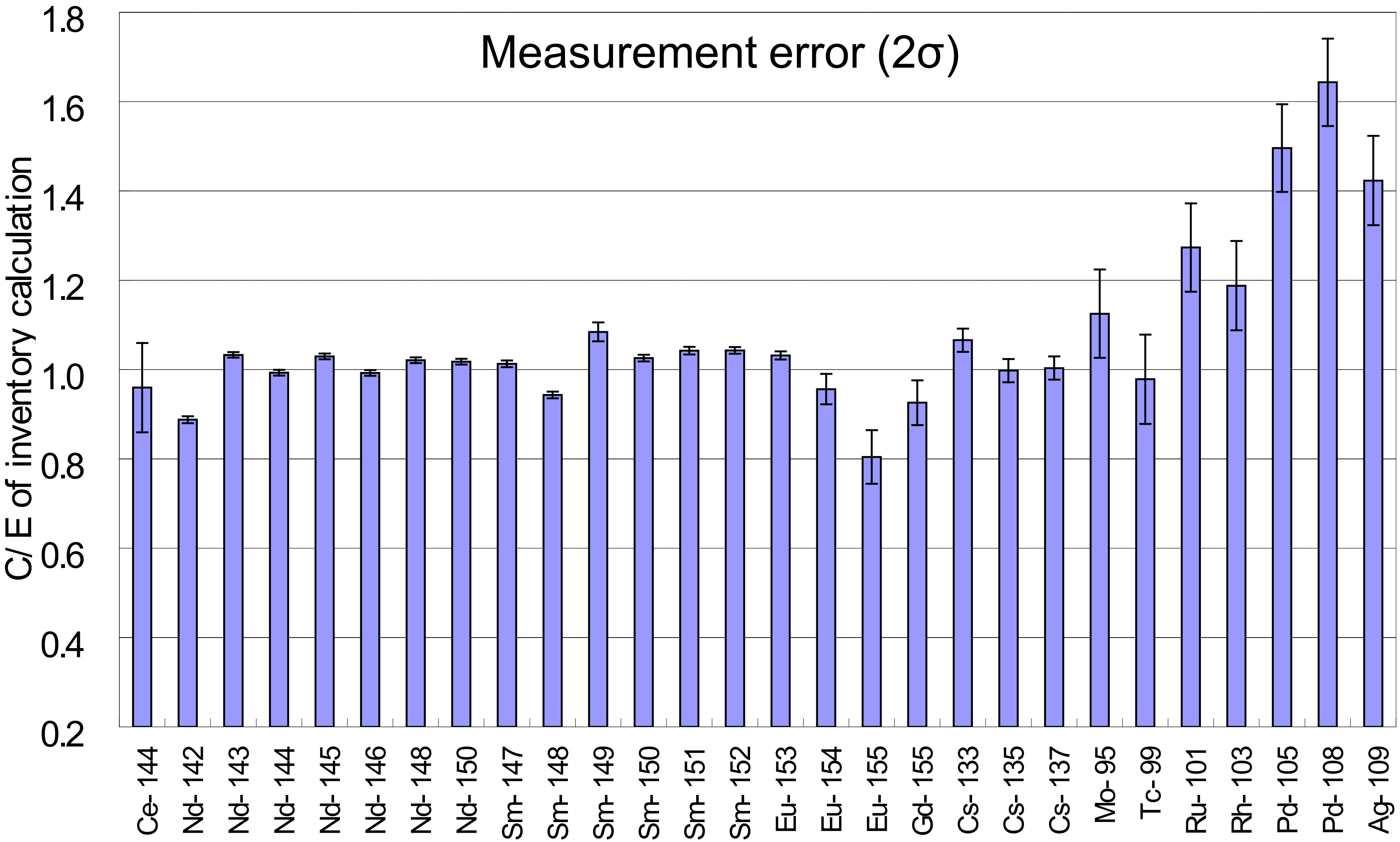
3.2 Corrected Isotopic Inventories with Measured Data

- Comparison was made for a chemical sample between
  - Calculated inventory with burnup determined by “gamma spectrometry”
    - 54.4 GWd/t for PWR UO2 and
    - 73.6 GWd/t for BWR MOX
  - Measured inventory by radio chemical analysis
- Deviation caused by
  - Burnup (determined by gamma-ray spectroscopy)
  - Calculation model including nuclear data library

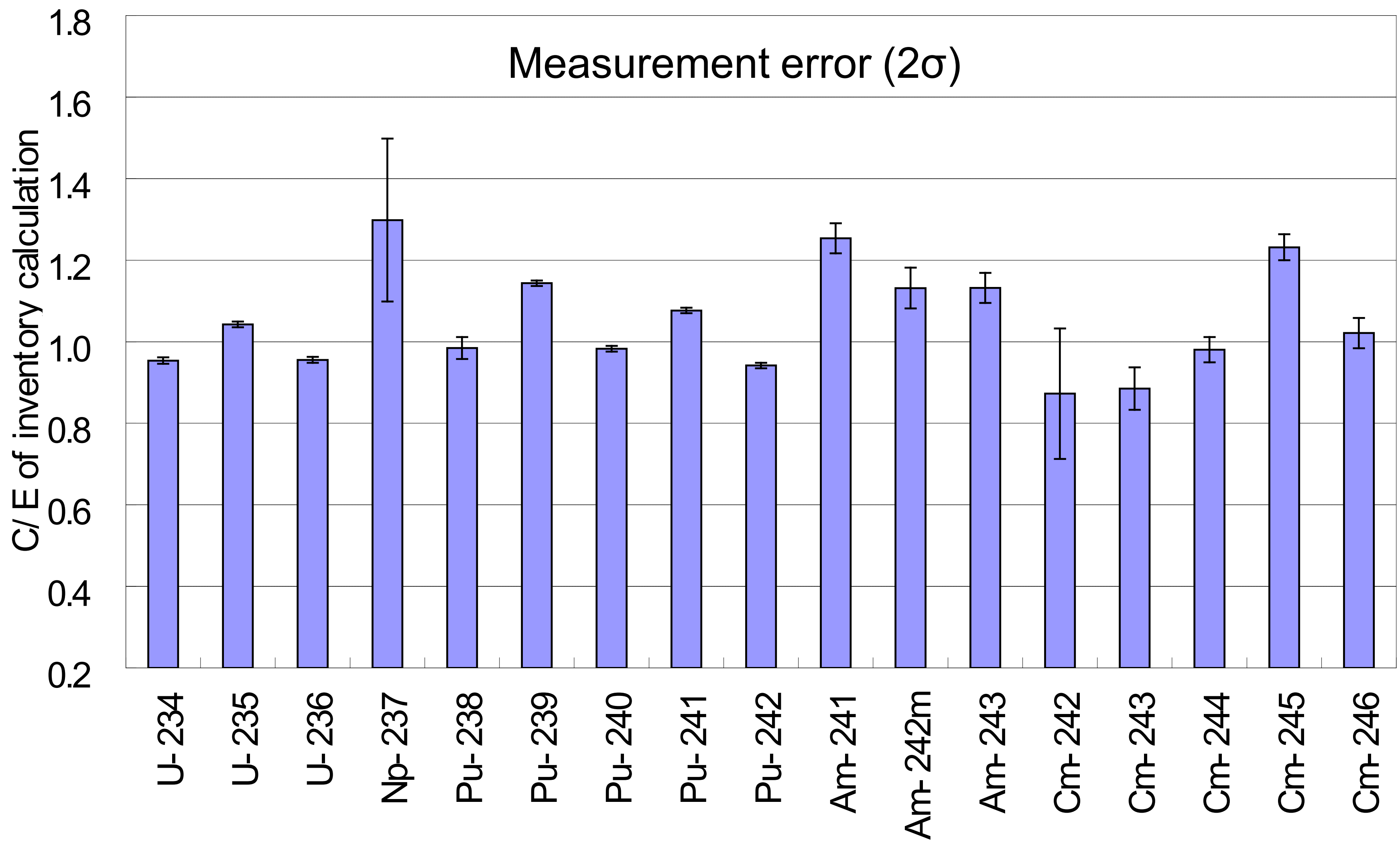
PWR UO2 sample: marked overestimation is observed for Np-237, Am-241, Am-243 and overestimation is observed for Pu-239 and 241



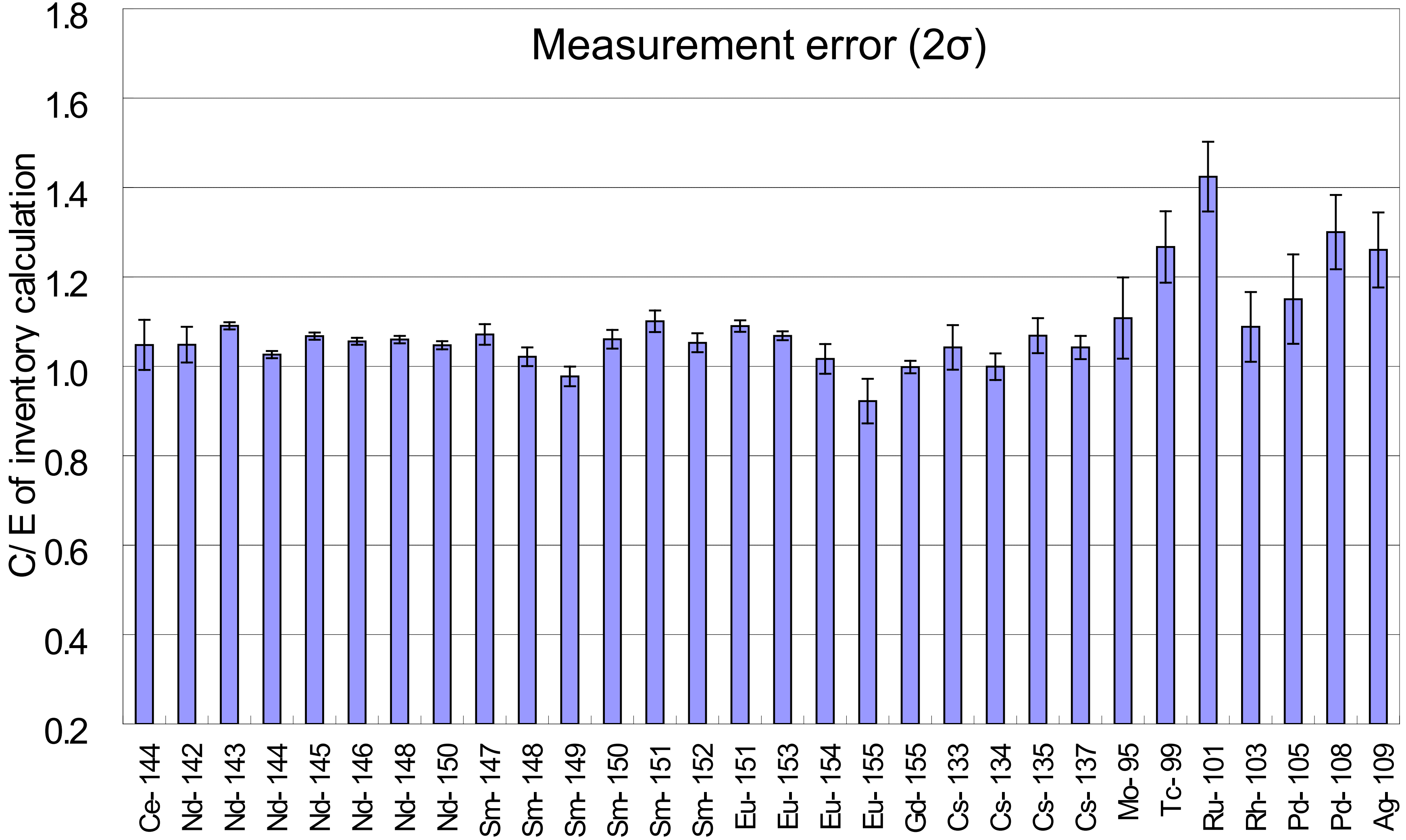
PWR UO2 sample: marked overestimation for FP nuclides (Ru-101, Rh-103, Pd-105, -108 and Ag-109)



BWR MOX sample: marked overestimation appears in Np-237, Pu-239, -241, Am-241, -242m, -243, Cm-245



BWR MOX sample: overestimation appears for Nd isotopes (= overestimation of burnup) and marked overestimation for metallic FP nuclides



Correction of Isotopic Inventories by using C/E for the analysis sample with assumption: C/Es are 1.0 at the burnup=0 and proportional to the burnup

$$E_i^j = C_i^j \left[\left\{ \left(E_i / C_i \right) - 1 \right\} \left(B^j / B \right) + 1 \right]$$

E_i^j : corrected inventory for nuclide *i* in a segment of rod *j*

C_i^j : calculated inventory

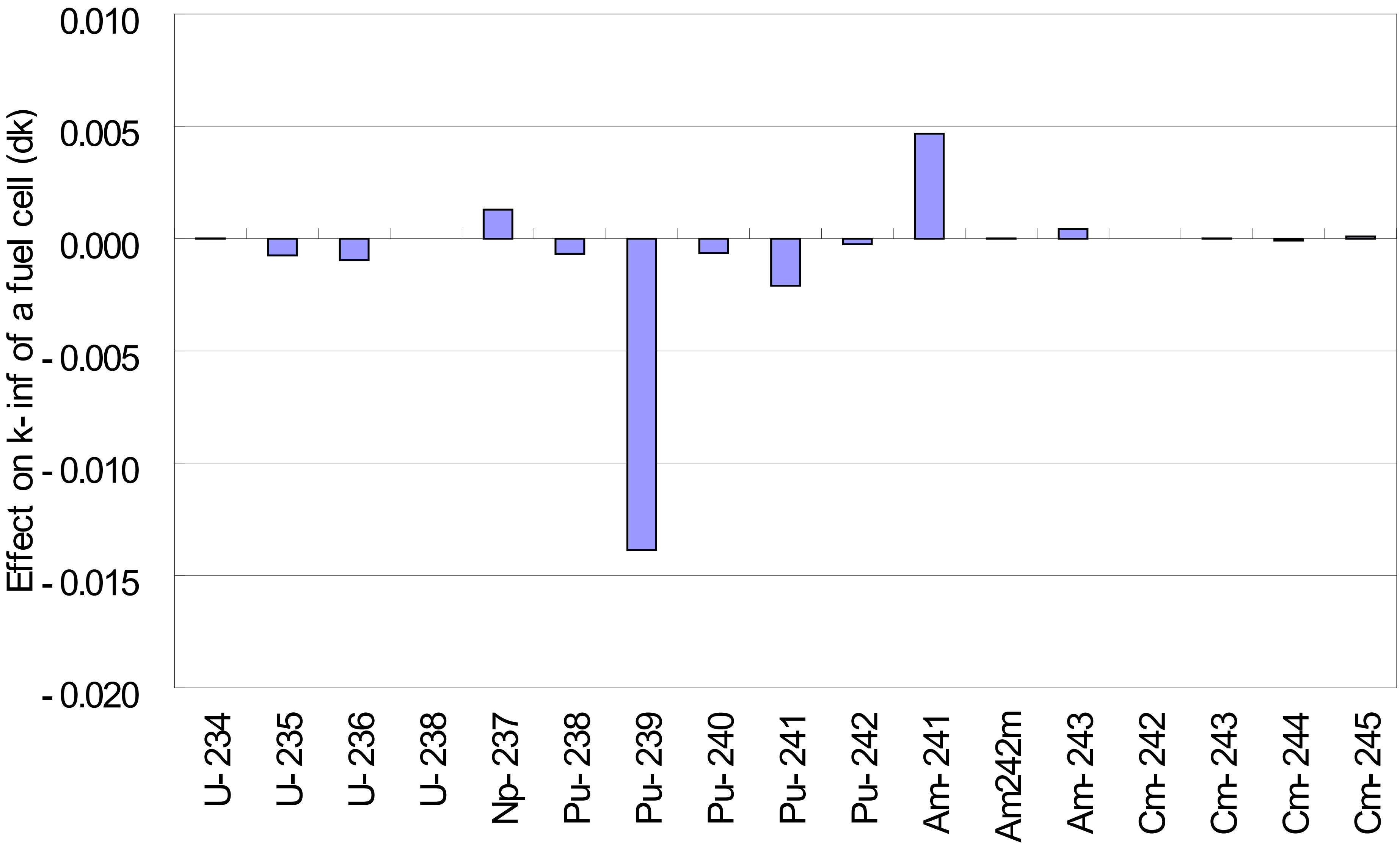
E_i / C_i: inverse of the C/E for the nuclide *i* for the sample of the radiochemical analysis

B^j : burnup of the segment *j* by gamma-ray spectroscopy

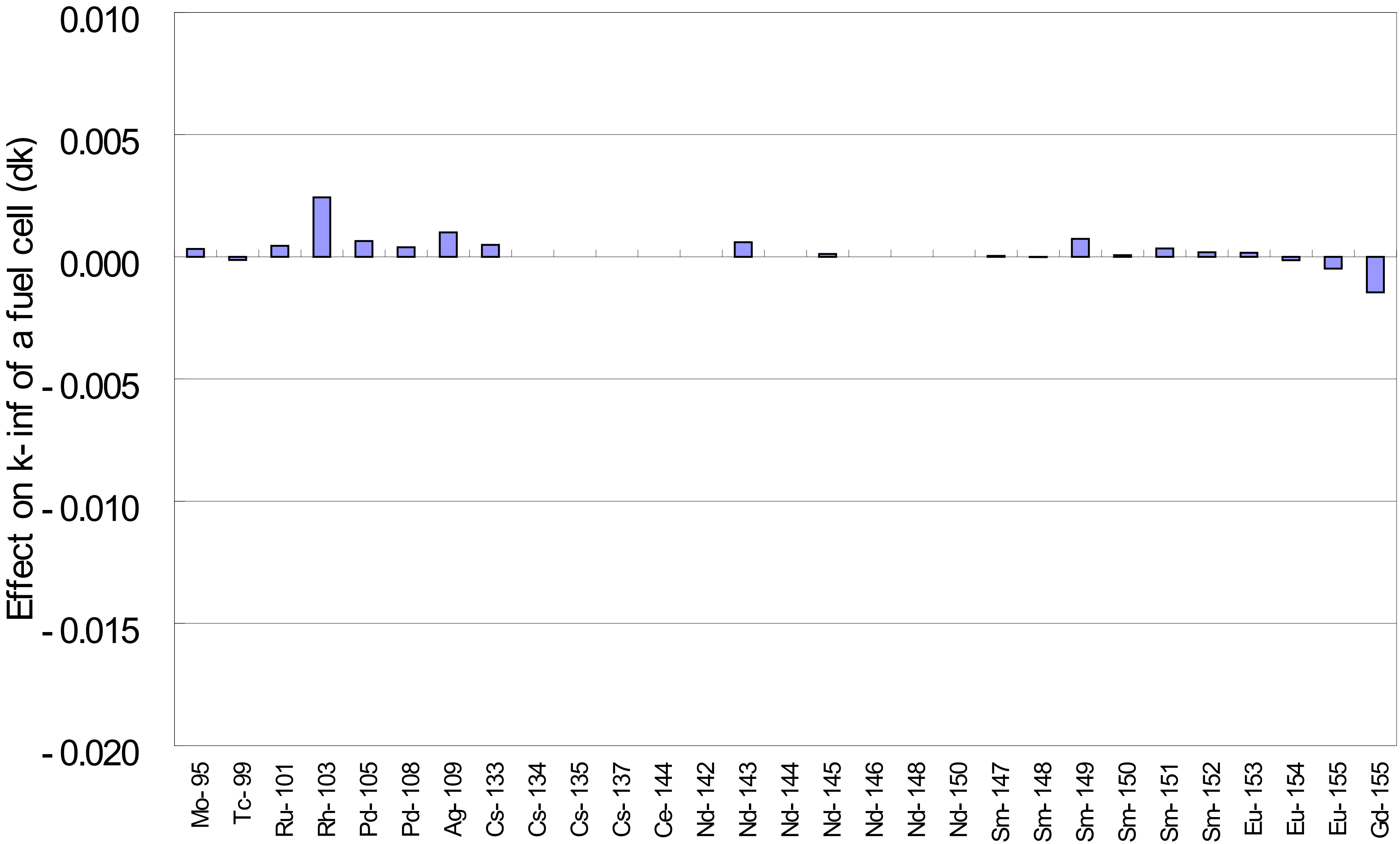
B : burnup value measured by gamma-ray spectroscopy for the sample

k_{Hirr}^{irr} Calculated with the corrected isotopic inventories

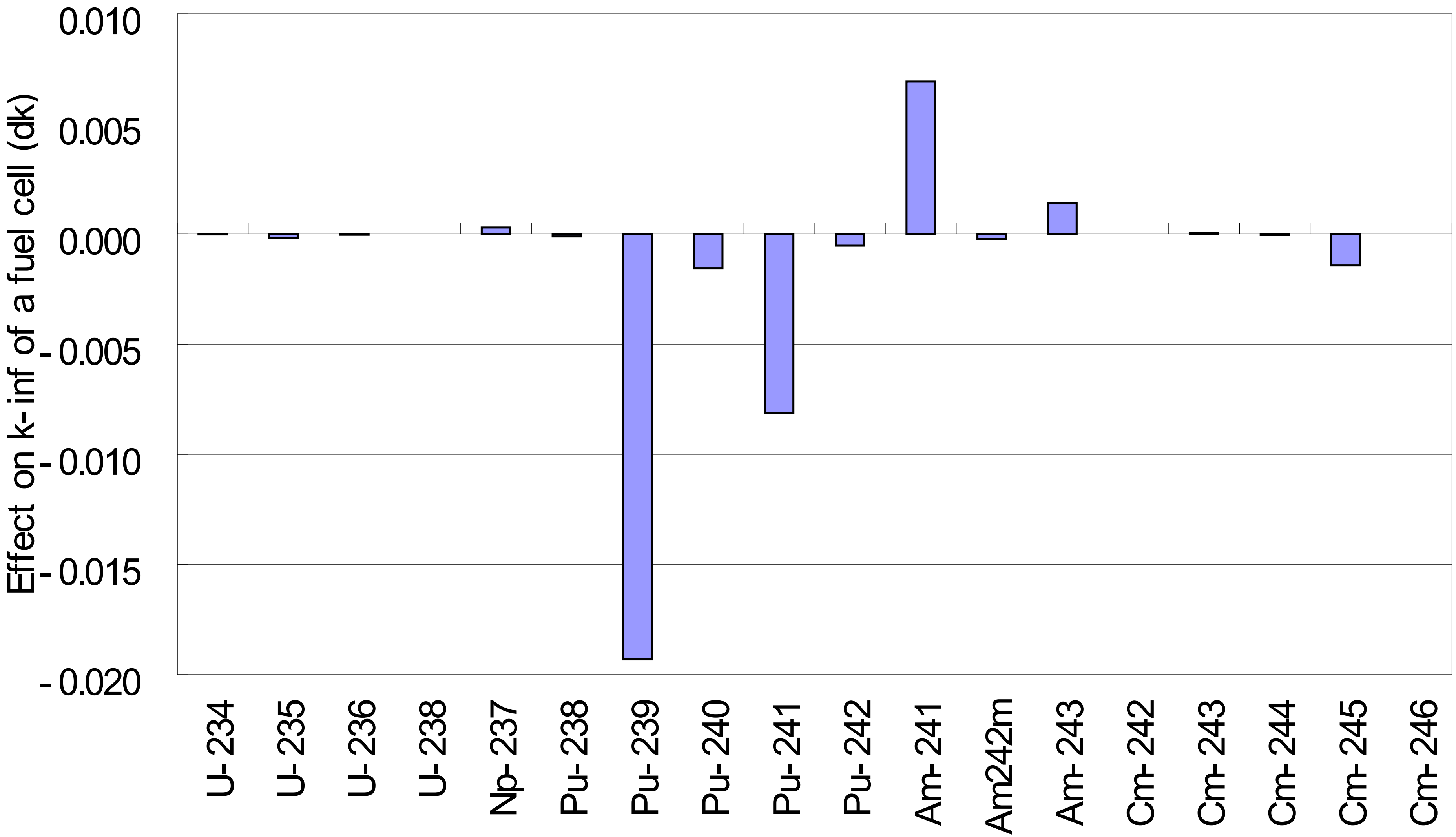
PWR UO2 cell: Δk-inf caused by correction for actinide nuclides



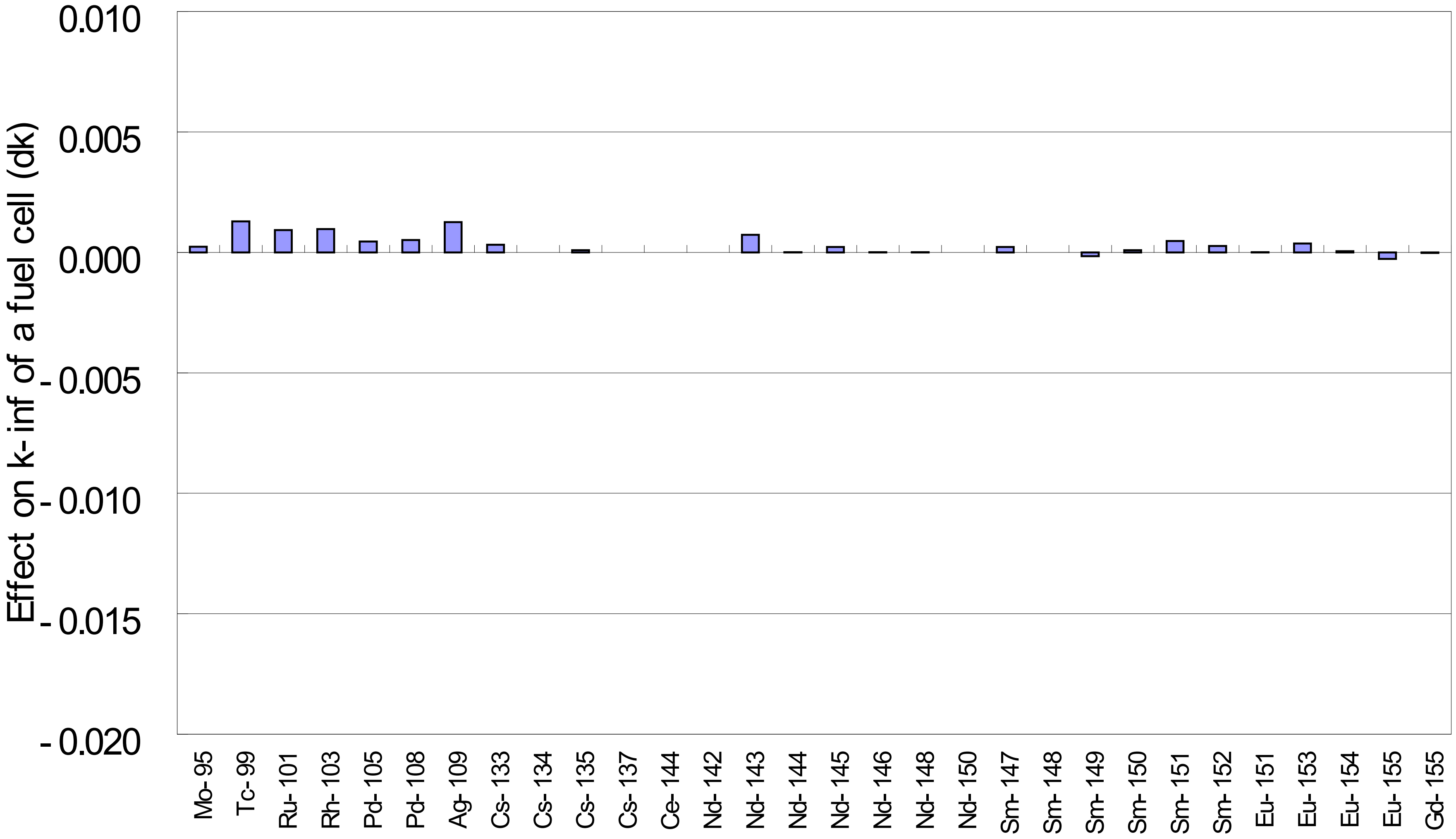
PWR UO2 cell: Δk-inf caused by correction for FP nuclides



BWR MOX cell: Δk-inf caused by correction for actinide nuclides



BWR UO2 cell: Δk-inf caused by correction for FP nuclides

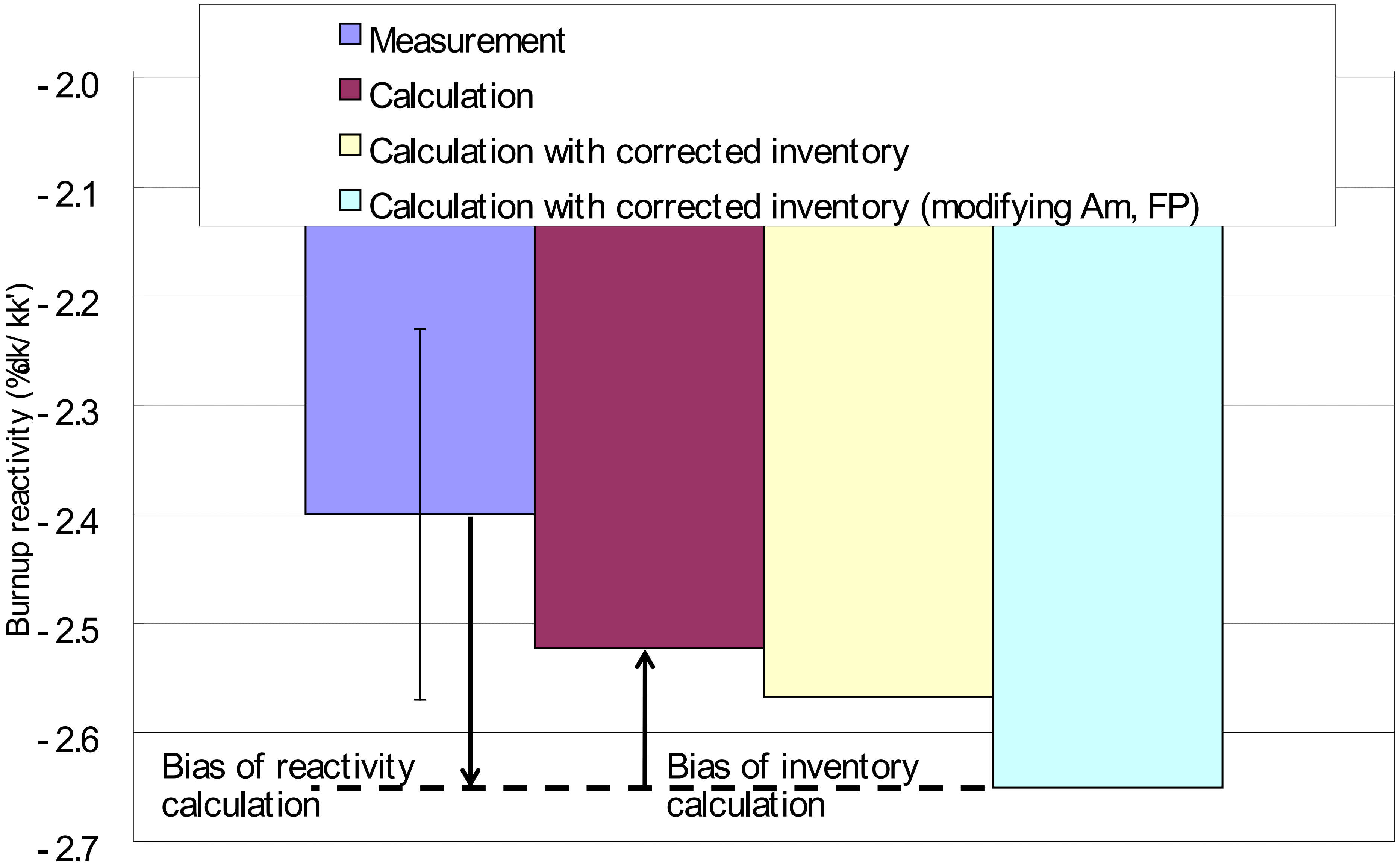


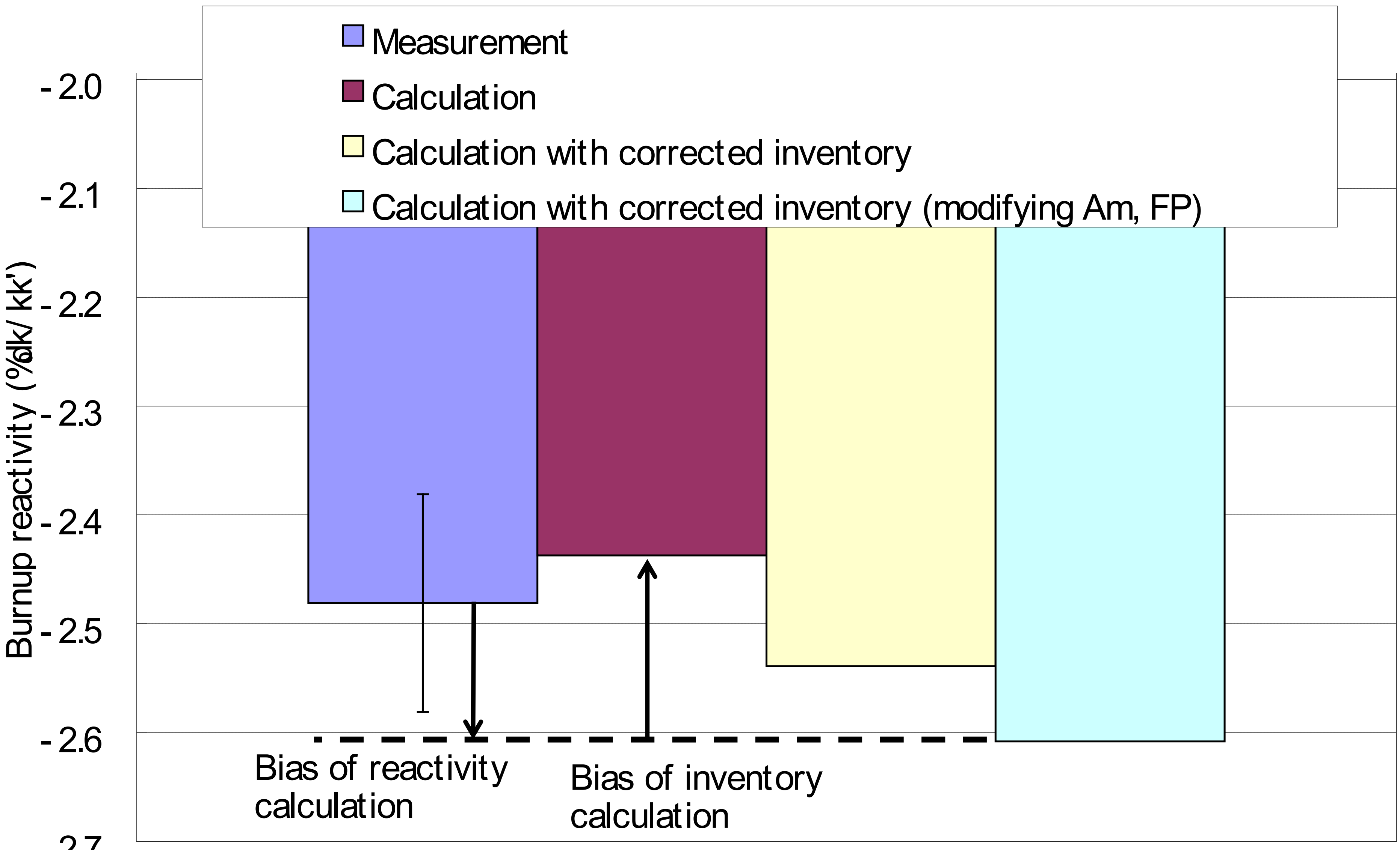
- Americium-241 and metallic FP nuclides are the nuclides showing prominent trend in C/Es and relatively large contribution to the reactivity change of typical infinite fuel cells
- The major inventory of Am-241 caused by decay of Pu-241, since the ratios of Pu-241 to Am-241 at the discharge of the fuel assembly are 30.17 and 8.07 for the PWR UO2 and BWR MOX fuel, and the cooling times for the isotopic inventory measurement are 7.2 and 4.7 years, respectively
- The values of C/Es for Am-241 are fairly larger than those of Pu-241, which indicate that systematic errors in the measurements of Am-241 are large
- The values of C/Es for some of metallic FP nuclides seem to be too large to accept as they are
- Therefore, as an alternative inventory correction, it is assumed that the C/E of Am-241 equal to that of Pu-241 and the C/Es of the metallic FP nuclides are 1.0

Calculated burnup reactivity with corrected inventories

Correction case/Fuel bundle	PWR UO2*	BWR MOX
(a) Burnup reactivity with corrected inventories (Difference from that with calculated inventories)	-2.567 (-0.045)	-2.539 (-0.102)
(b) Burnup reactivity with corrected inventories -modifying Am and metallic FP- (Difference from that with calculated inventories)	-2.651 (-0.128)	-2.608 (-0.171)

*Neutron balance only in the region of the irradiated fuel bundle was considered for the change in k_{Hirr}^{irr} caused by the corrected inventory for the PWR UO2 fuel bundle


Measurement
Calculation
Calculation with corrected inventory
Calculation with corrected inventory (modifying Am, FP)
Burnup reactivity (%dk/kk')
-2.0
-2.1
-2.2
-2.3
-2.4
-2.5
-2.6
-2.7
Bias of reactivity calculation
Bias of inventory calculation


Measurement
Calculation
Calculation with corrected inventory
Calculation with corrected inventory (modifying Am, FP)
-2.0
-2.1
-2.2
-2.3
-2.4
-2.5
-2.6
-2.7
Burnup reactivity (%dk/ kk')
Bias of reactivity calculation
Bias of inventory calculation

4. Discussion on Bias of Inventory and Reactivity Calculations

- The burnup reactivity of irradiated PWR UO2 (average burnup: 54.5GWd/t) and BWR MOX (average burnup: 60.6GWd/t) fuel bundles in the REBUS program was obtained using the measured critical water levels and water level reactivity coefficients Those are -2.40 and -2.48%dk/kk' for the PWR UO2 fuel and BWR MOX fuel bundles, respectively
- The study for splitting calculation biases of the burnup reactivity into inventory and reactivity calculations was performed with measured isotopic analysis data

- The calculation biases for the PWR UO2 fuel bundle are +0.13 %dk/kk' for inventory calculation and -0.25 %dk/kk' for reactivity calculation, which makes total bias -0.12 %dk/kk'. Those for the BWR MOX fuel bundle are +0.17%dk/kk' for inventory calculation and -0.13 %dk/kk' for reactivity calculation, which makes total bias +0.04 %dk/kk'
- The study shows that the calculation biases of the inventory and reactivity are in inverse relation to make the total biases smaller
- The obtained information is useful to improve the analysis tools and models for further reduction of the calculation biases in the burnup reactivity