Fast Reactor Designing Study for Proliferation Resistance and Physical Protection Enhancement

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Research Plan and Objectives

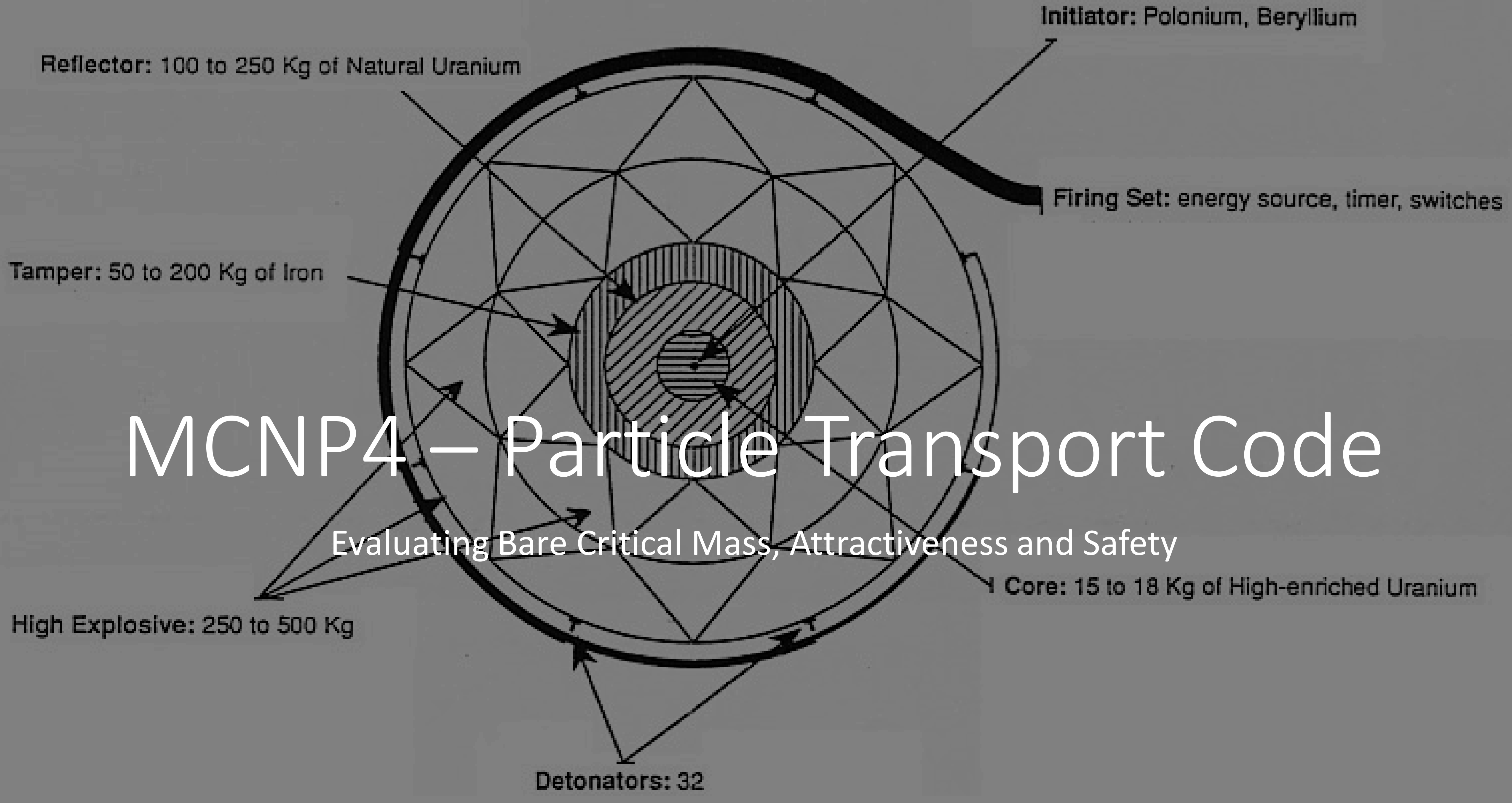
- MCNP4 particle transport code
  - Critical mass and heat content calculations
  - Neutron transport calculations
  - Nuclear material attractiveness methodology
- Research on fast spectrum reactor designing for Minor Actinides (MA) transmutation and for High Proliferation Resistance.
- Neutronics analysis of a Fast Spectrum Reactor core design:
  - Reactivity and burnup calculation by the combination of a 2-D deterministic code, SLAROM-JOINT-CITATION, for full scale fast spectrum core designing and performance evaluation
- Learning of the Plutonium (Pu) fuel cycle in Japan. This will include the research of the underlying physics of the Pu fuel cycle.

Important Definitions:

- Proliferation Resistance
  - is that characteristic of an NES that impedes the diversion or undeclared production of nuclear material or misuse of technology by the Host State seeking to acquire nuclear weapons or other nuclear explosive devices.
- Physical Protection
  - is that characteristic of an NES that impedes the theft of materials suitable for nuclear explosives or radiation dispersal devices (RDDs) and the sabotage of facilities and transportation by sub-national entities and other non-Host State adversaries.

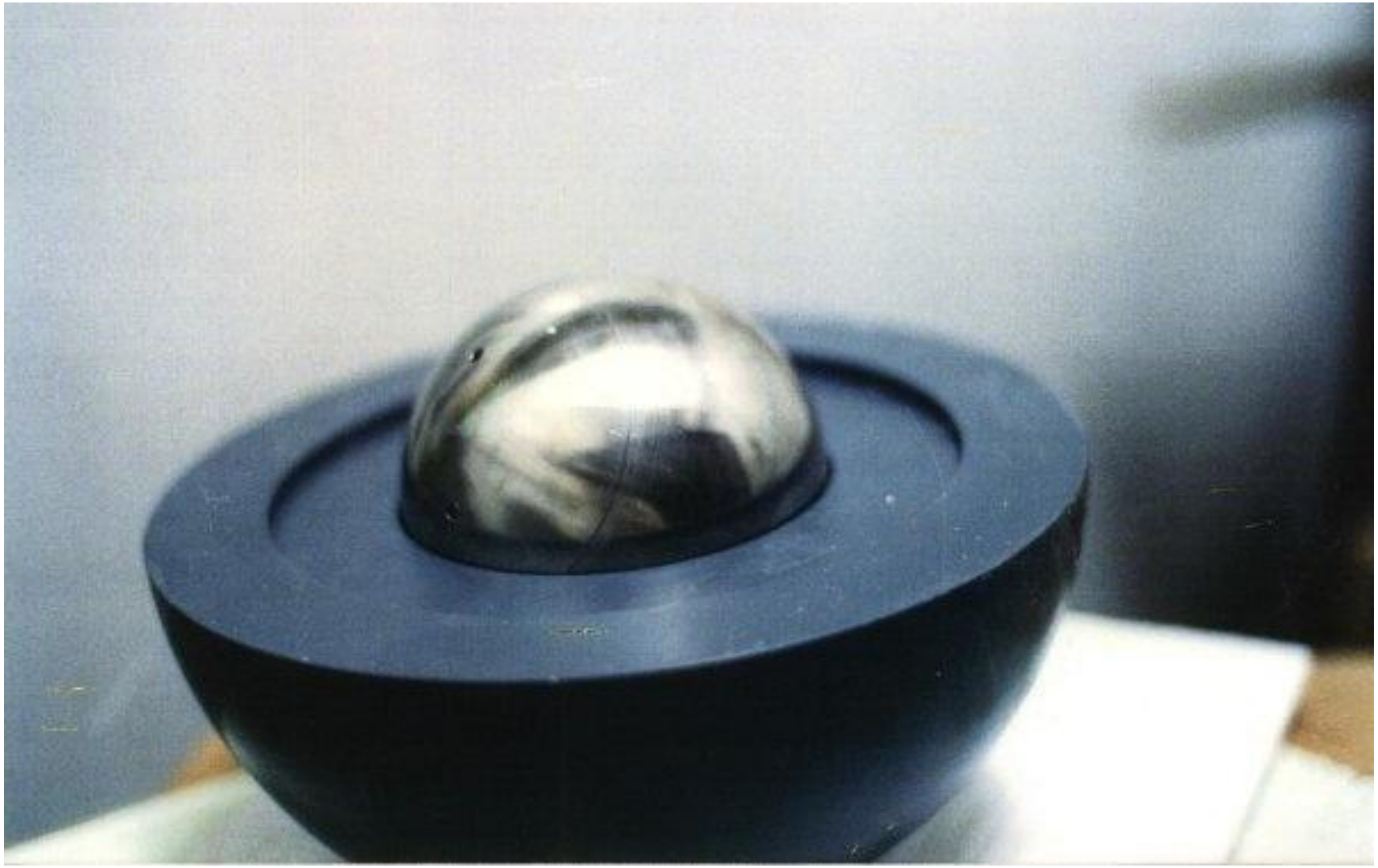
MCNP4 – Particle Transport Code

Evaluating Bare Critical Mass, Attractiveness and Safety



Schematic diagram of an implosion bomb similar to the one designed by Iraq

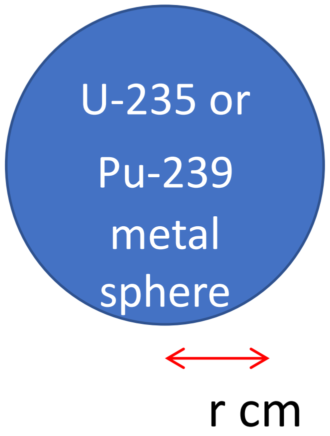
Bare Critical Mass

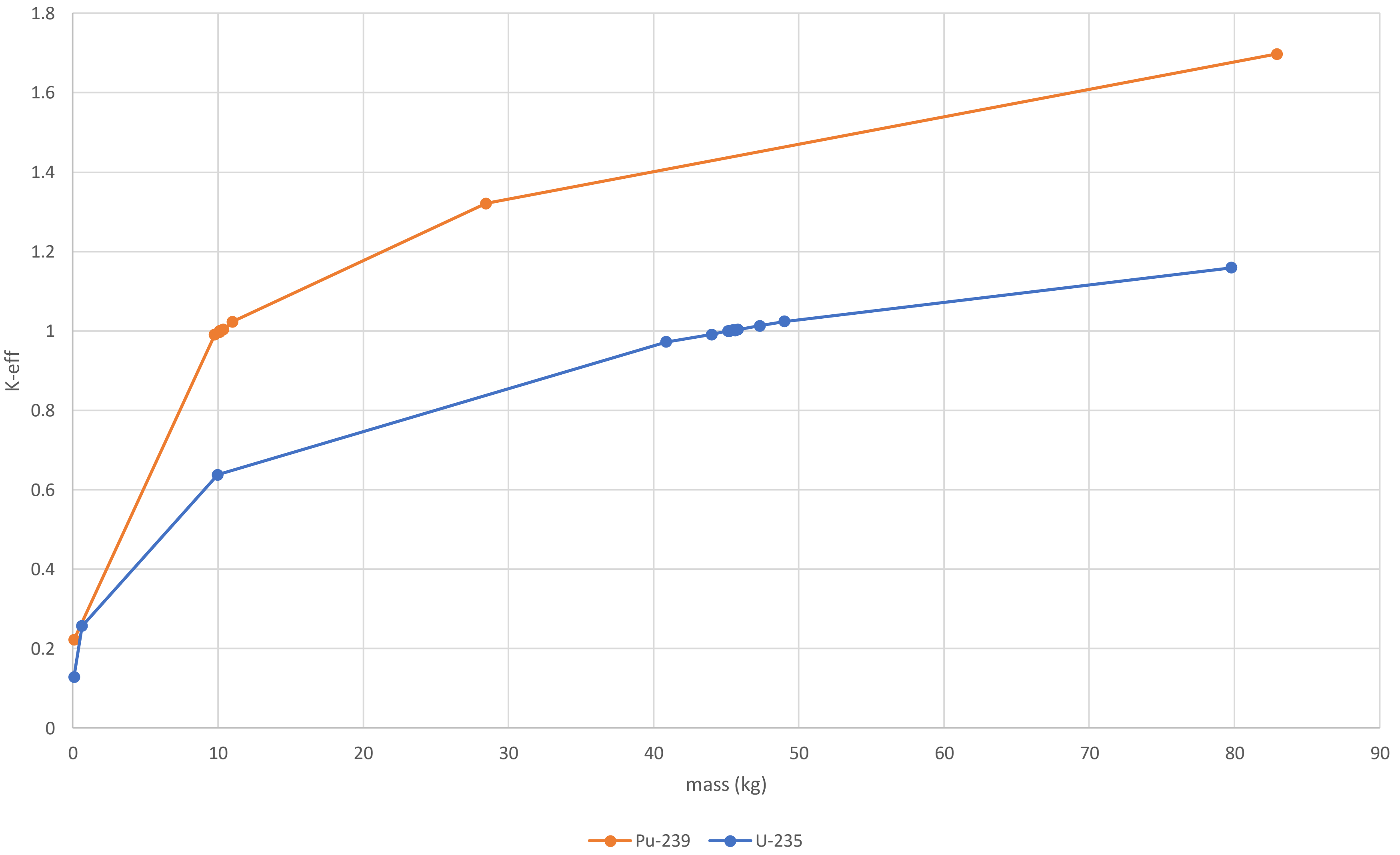


Exercise 1: BCM of U-235 and Pu-239

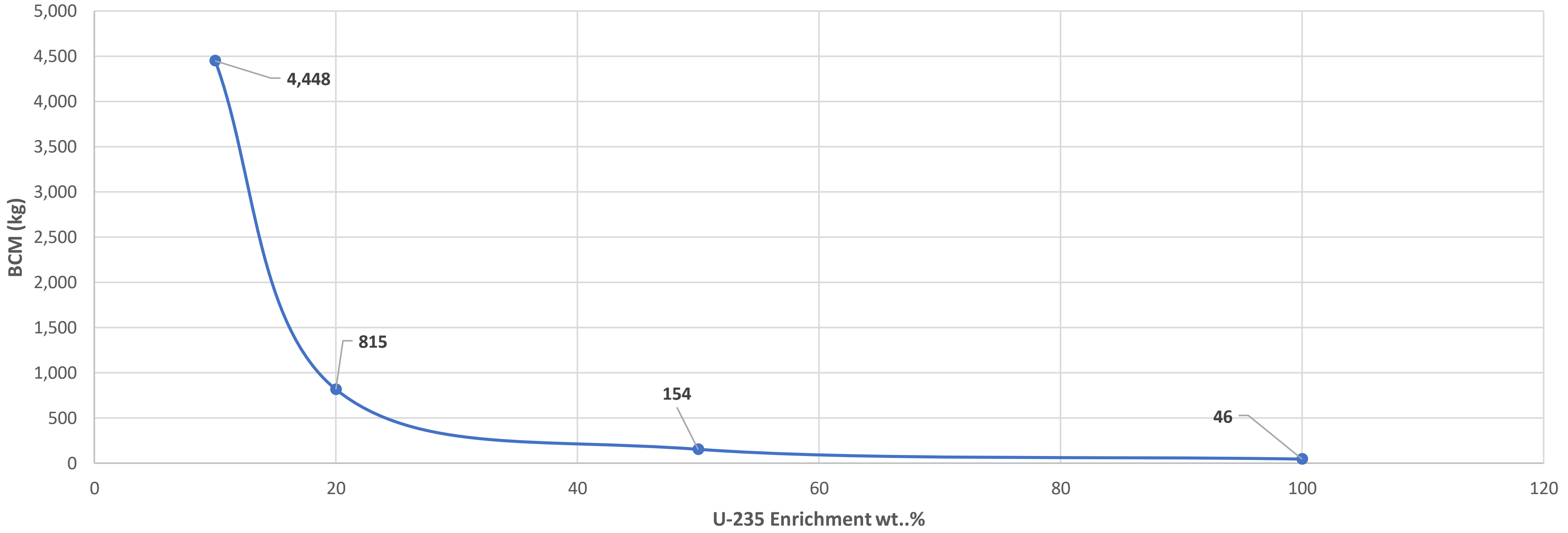
Isotope	radius (cm)	k-eff
U-235	8.28	1.00054
Pu-239	4.96	1.00018

BCM U-235 = **45.29 kg**
BCM Pu-239 = **10.12 kg**





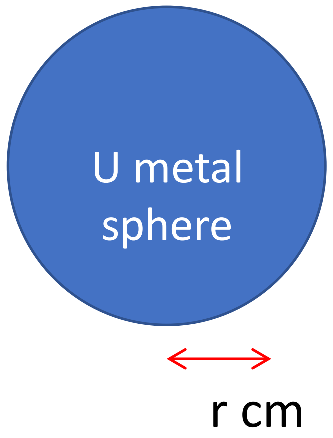
Exercise 2: BCM of different U-enrichment



Mass density:

U-metal 19.05 g/cc

Enrichment (wt..%)	BCM (kg)	k-eff	radius (cm)
0.72	-	0.43197	-
5	-	0.94089	-
10	4448	1.00092	38.2
20	815	0.99948	21.7
50	154	0.99907	12.45
100	46	1.00042	8.3

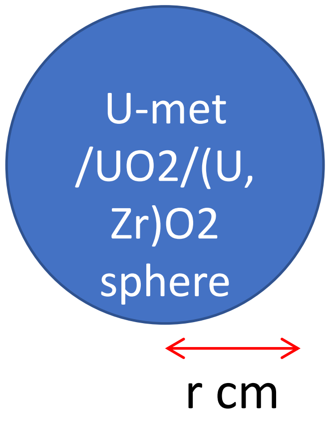


Exercise 3: BCM of different material forms of Uranium

Nuclide: U-235

Material form: U-Metal, UO2, (U,Zr)O2

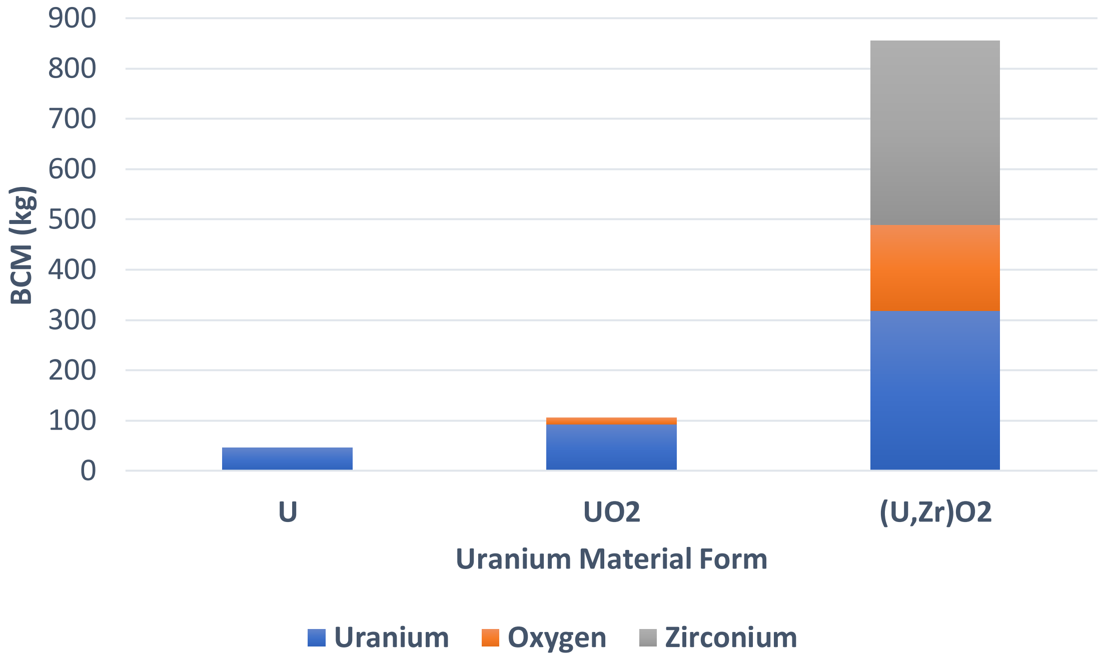
Mass density: U-metal 19.05 g/cc, UO2 10.96gcc,
(U,Zr)O2 6.0g/cc, U:Zr=1:3 in atom



BCM U-Metal = **45.63 kg-U**, 45.63 kg-total

BCM UO2 = **92.44 kg-U**, 104.87 kg-total

BCM (U,Zr)O2 = **318.08 kg-U**, 854.82 kg-total

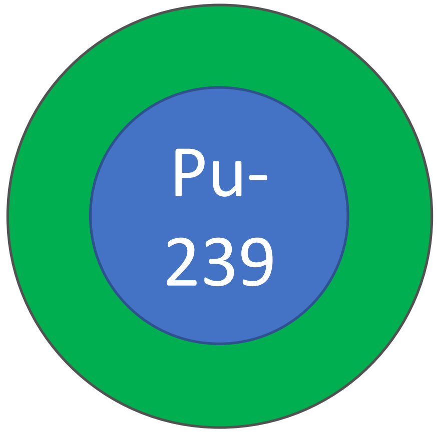


Exercise 4: CM with reflector

Material : Pu239-Metal with reflector

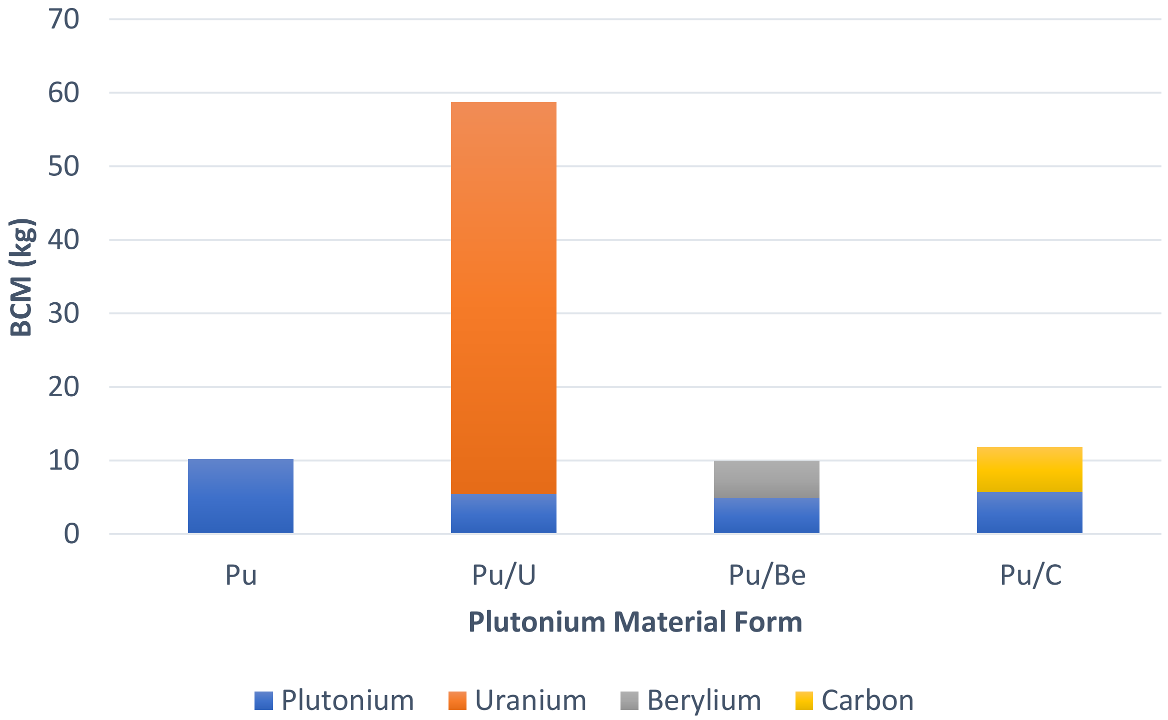
Mass density: Pu-metal 19.80g/cc

Reflector : U-metal 19.05g/cc, Be-metal 1.85g/cc, Graphite 2.10g/cc



CM Bare Pu = **10.12 kg-Pu**, 10.12 kg-total
CM Pu/U= 5.39 kg-Pu, 58.76 kg-total
CM Pu/Be= 4.92 kg-Pu, 9.92 kg-total
CM Pu/C= 5.72 kg-Pu, 11.74 kg-total

	Pu	Pu/U	Pu/Be	Pu/C
Radius	4.96	4.02/9.02	3.9/8.9	4.1/9.1
Capture CS	-	2.683	0.008603	0.0035



Exercise 5: Attractiveness

Material : bare Pu-Metal, Pu-239, Pu238

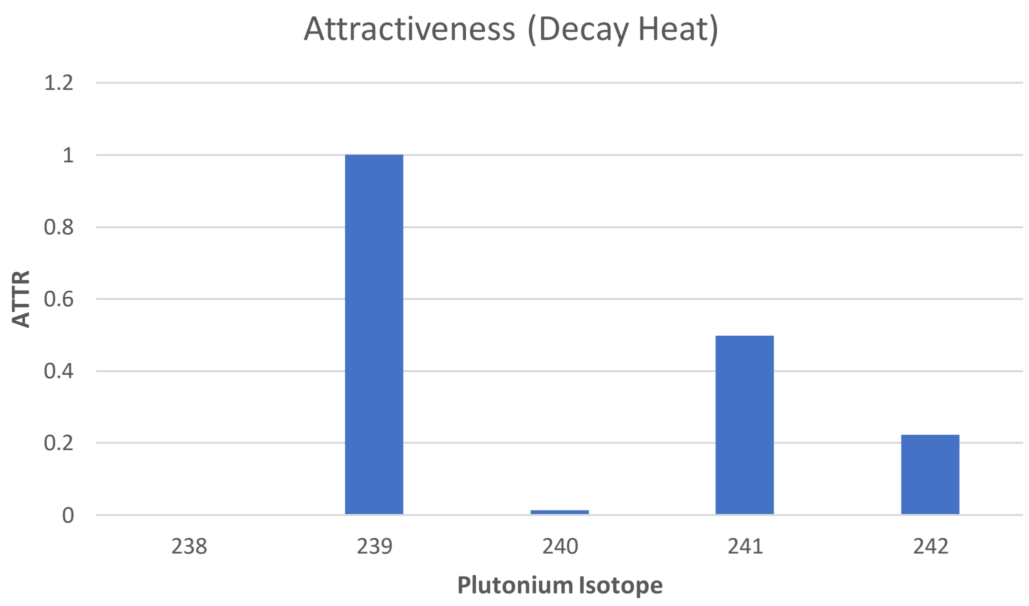
Mass density: Pu-metal 15.80g/cc

with delta-phase

Rossi-alpha:

$$\alpha = \frac{k-1}{l}$$

$$ATTR = \frac{\left(\dfrac{\alpha(\infty,1)}{\alpha^{239}(\infty,1)}\right)^{n=1,2,3}}{\dfrac{DH_{CM}}{DH_{CM}^{238}} + \cancel{\dfrac{SN_{CM}}{SN_{CM}^{238}} + \dfrac{RD_{CM}}{RD_{CM}^{238}}}}$$



Isotope	Decay heat (W/kg)	SN (n/g/s)
^{238}Pu	567	2660
^{239}Pu	1.93	0.0226
^{240}Pu	7.06	1030
^{241}Pu	3.4	0.0493
^{242}Pu	0.12	1720

Isotope	radius (cm)	mass (kg)	k-inf	l (abs)	alphaN	decayN	ATTR	**ATTR(N)**
238	5.96	14.01	2.81324	1.27E-08	0.96	1.00000	0.9627619	**0**
239	6.22	15.93	2.95061	1.31E-08	1.00	0.00387	258.4596560	**1**
240	9.02	48.57	2.23078	4.57E-08	0.18	0.04316	4.1926093	**0.012543**
241	6.58	18.85	2.90547	1.23E-08	1.04	0.00807	129.1969948	**0.498003**
242	11.3	95.50	1.9642	7.68E-08	0.08	0.00144	58.5002960	**0.223449**

Exercise 6: Criticality Safety of Chemical Process in Pulse column

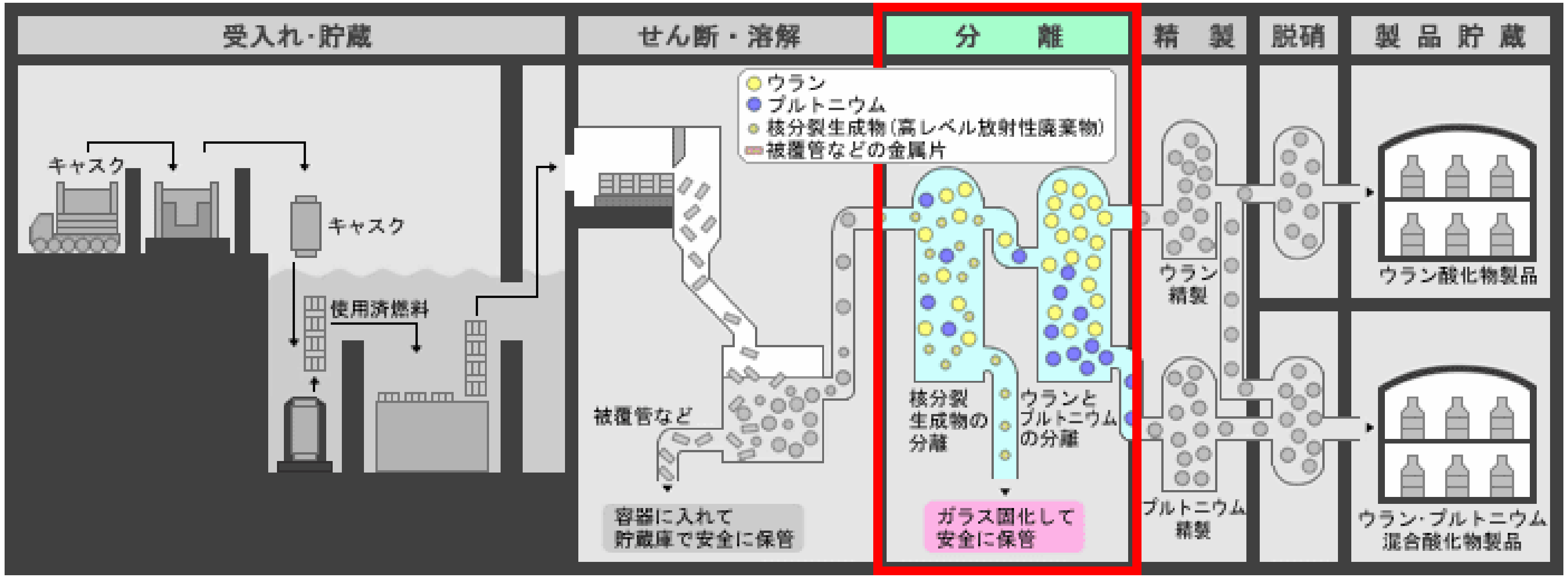
Material : Pu and U in solution

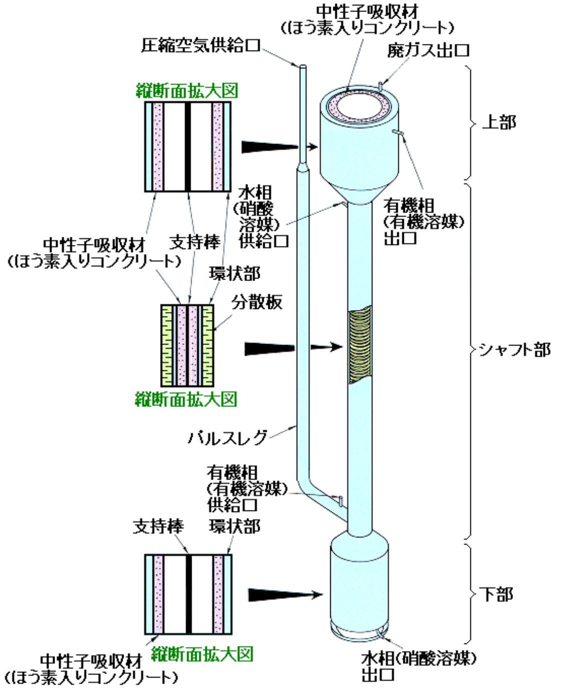
Mass density: Water solution, fix with 1.0g/cc

Pulse Column: Variable Diameter (cm), infinite column

Parameters: Pu density, U-Pu composition

Material Form	radius (cm)	k-eff
Pu(-0.2)	27.8	1.00095
Pu(-1.0)	13.4	0.99959
PuU (0.72/7.2)	21.44	0.99954
PuU (0.36/7.2)	28.75	1.00049
PuU (0.5/8)	25.18	1.00018

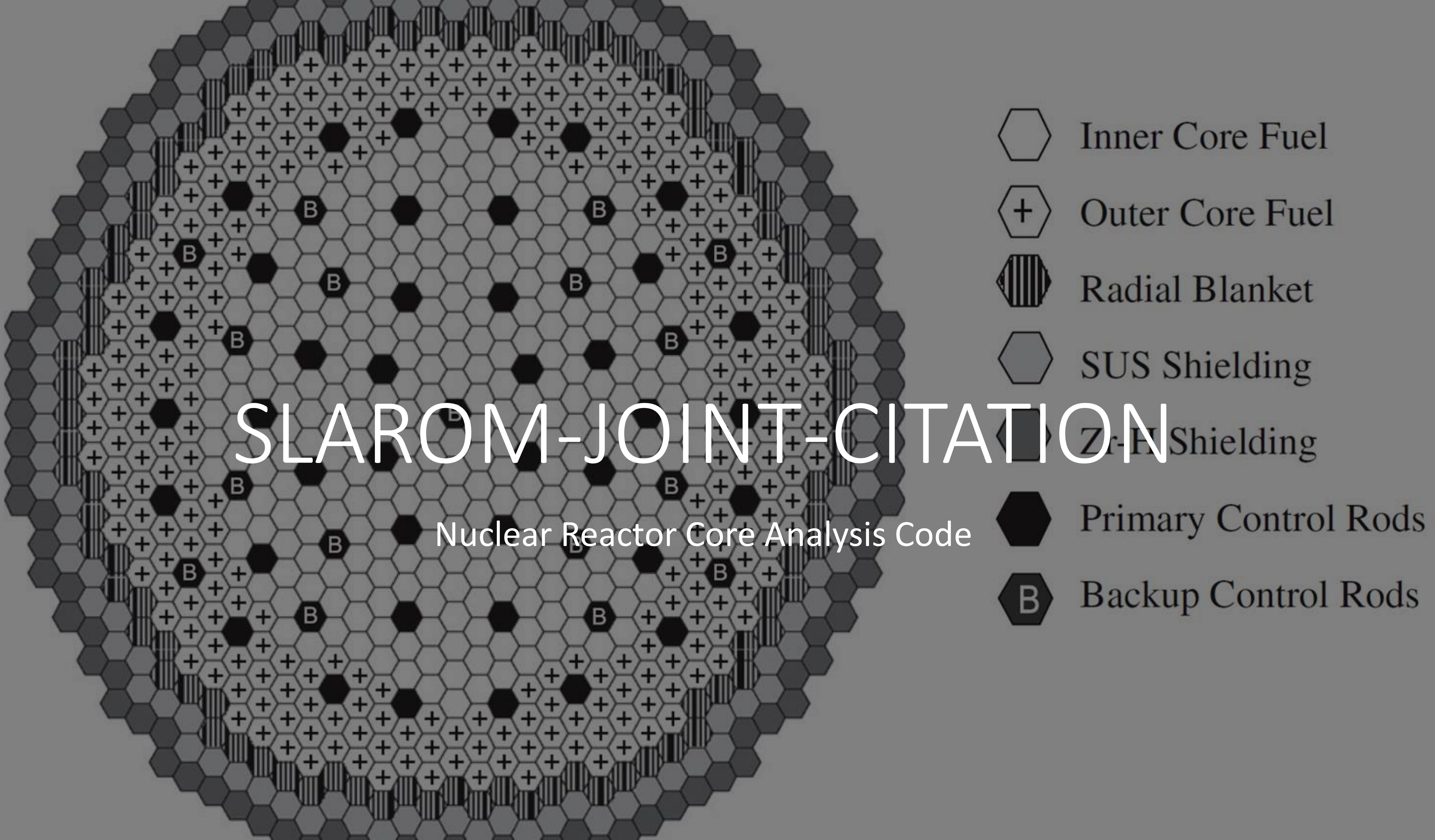




パルスカラムでは、シャフト部の上部から水相(硝酸溶液)を、下部から有機相(有機溶媒)を供給し、パルスレグから圧縮空気により脈動を与えながら両相を向流接触させる。脈動とシャフト部の分散板によって連続相中に分散相(液滴)を形成させ、両相間の物質移動の効率をよりよくする。「抽出塔」を例にすると、上部から溶解液(硝酸溶液：水相)を供給し、下部から有機溶媒(有機相)を供給して、両相を向流接触させることによって溶解液中のウランとプルトニウムをほぼ全量有機溶媒中に抽出させることができる。

図８　六ヶ所再処理工場の環状型パルスカラム概要図

[出展]日本原燃（株）：パンフレット「六ヶ所再処理工場の概要」、（2000年6月）p.14



SLAROM-JOINT-CITATION

Nuclear Reactor Core Analysis Code

Japan Sodium-cooled Fast Reactor (JSFR)

Item	Unit	Specification
a. Plant		
Reactor thermal power	MW_{th}	3570
Coolant temperature (inlet/outlet)	℃	395/550
Fuel/colant/structure	vt.%	43.9/30.3/25.8
Subassembly pitch	mm	206.0
b. Fuel		
Fuel material		$TRUO_2$-UO_2
Pu enrichment in HM (inner core/outer core)	wt.%	18.3/20.9
^{235}U enrichment	wt.%	0.2
Refueling patern		four-batch
Irradiation time per one batch	day	800
Core diameter/core height	m	5.38/1.0
c. Blanket		
Blanket fuel material		UO_2
^{235}U enrichment	wt.%	0.2
Pattern of fuel exchange		four-batch
Thickness of axial blanket (upper/lower)	m	0.2/0.2

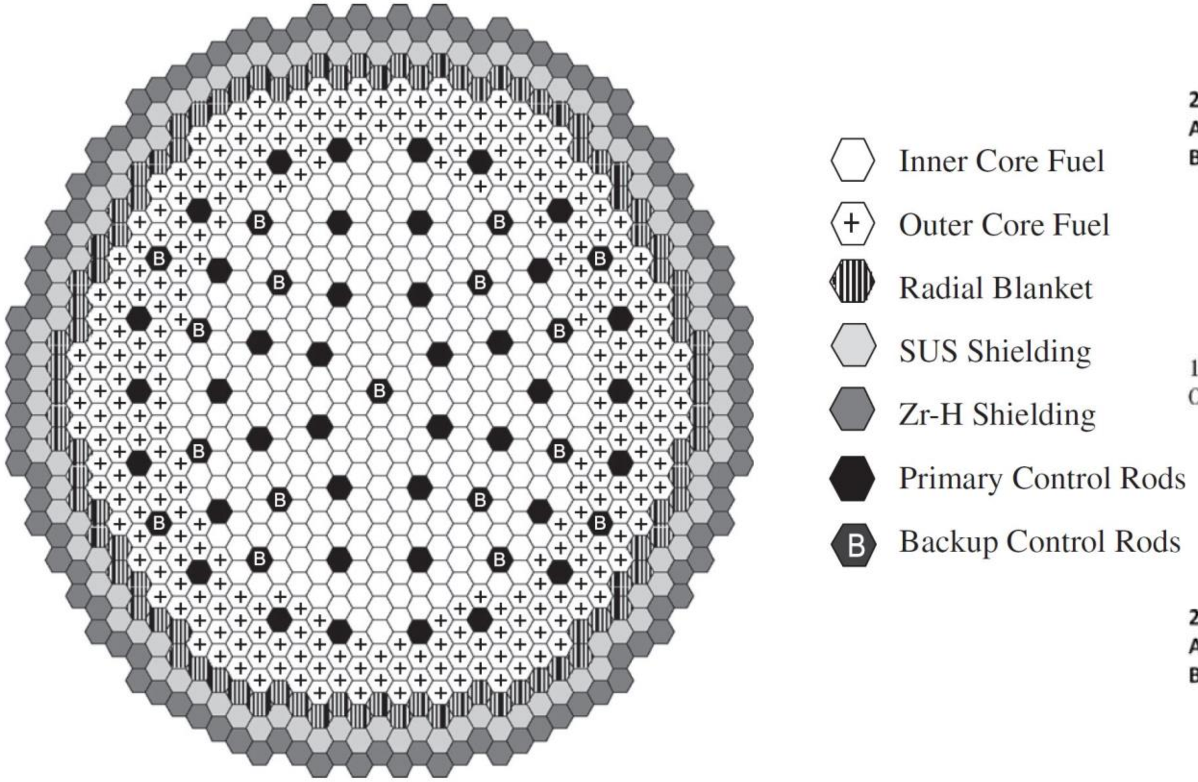
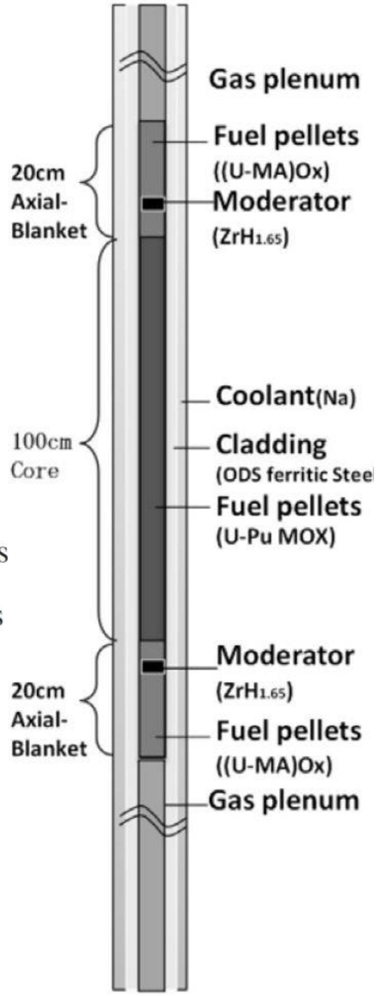


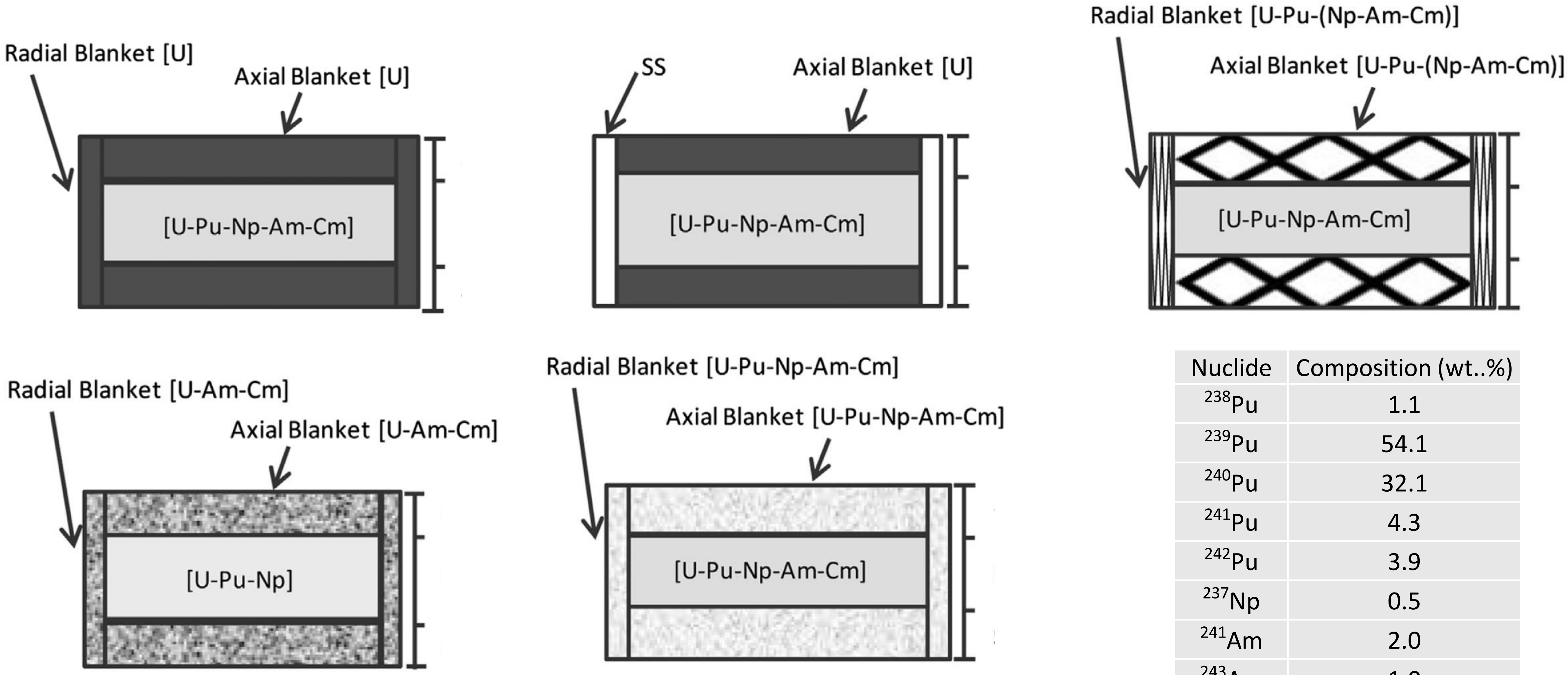
Fig. 1a. Core layout (horizontal view).



(Sagara et al., 2005).

(Meiliza et al., 2014)

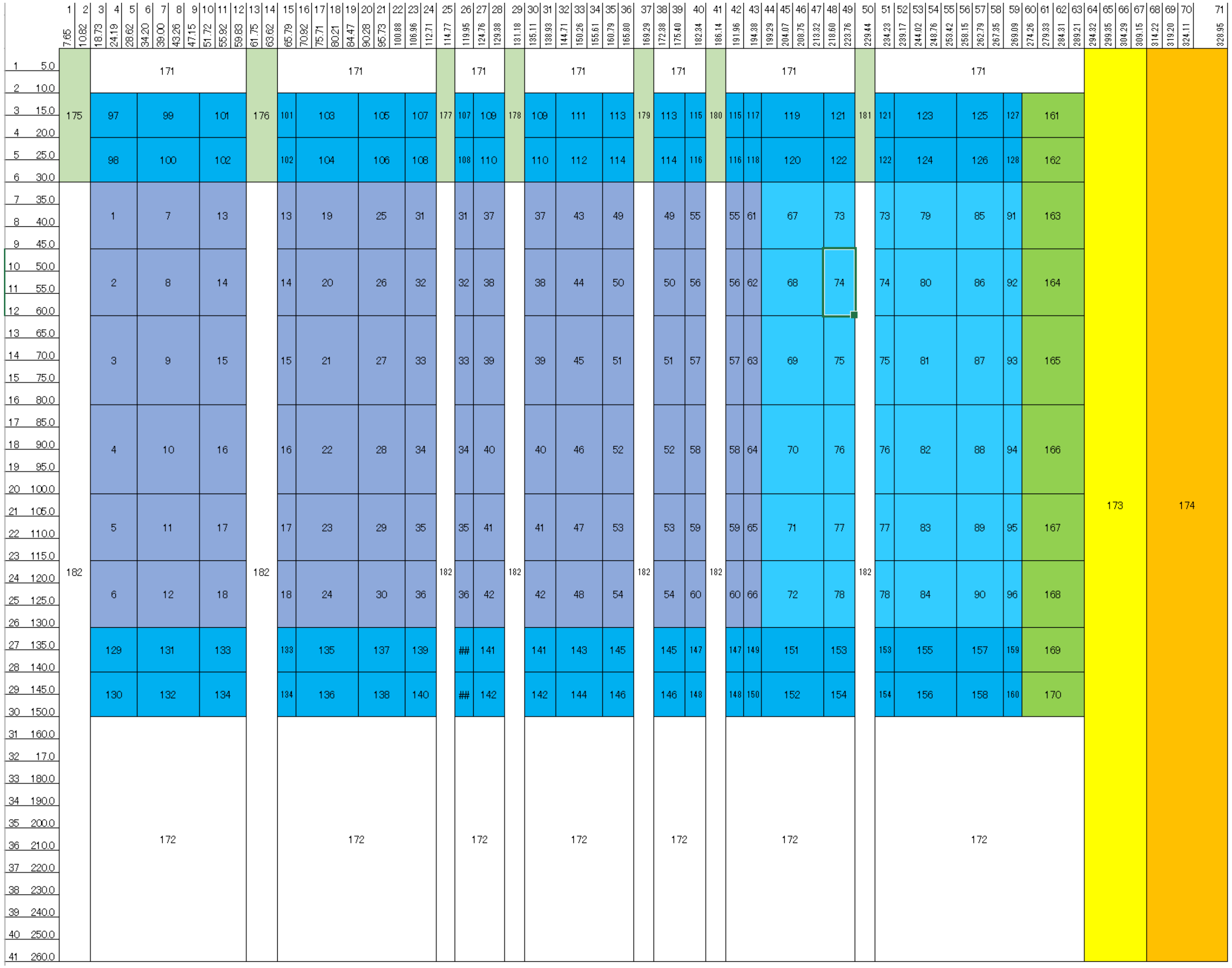
Core design approaches



Nuclide	Composition (wt..%)
^{238}Pu	1.1
^{239}Pu	54.1
^{240}Pu	32.1
^{241}Pu	4.3
^{242}Pu	3.9
^{237}Np	0.5
^{241}Am	2.0
^{243}Am	1.0
^{244}Cm	1.0

SLAROM-JOINT-CITATION

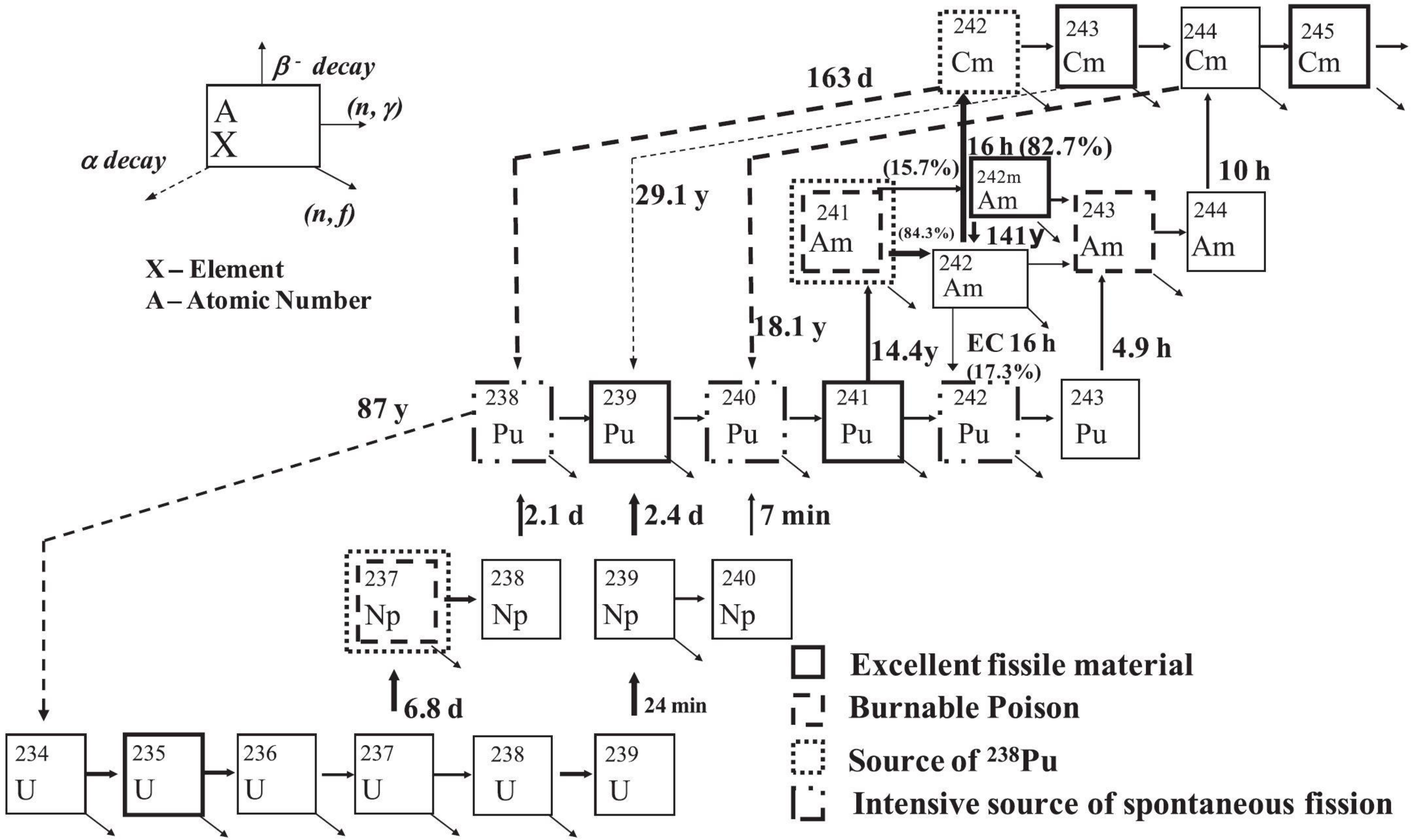
- SLAROM-UF
    - Cell homogenization calculation
    - Fast power reactor
    - Fast critical assembly
    - Using the Japanese Evaluated Nuclear Data Library (JENDL-3.2)
- JOINT-FR
- CITATION
    - Nuclear reactor core analysis code system
    - Neutron diffusion theory
    - Two-dimensional RZ diffusion theory
    - Depletion Chain
    - Multi-cycle analysis



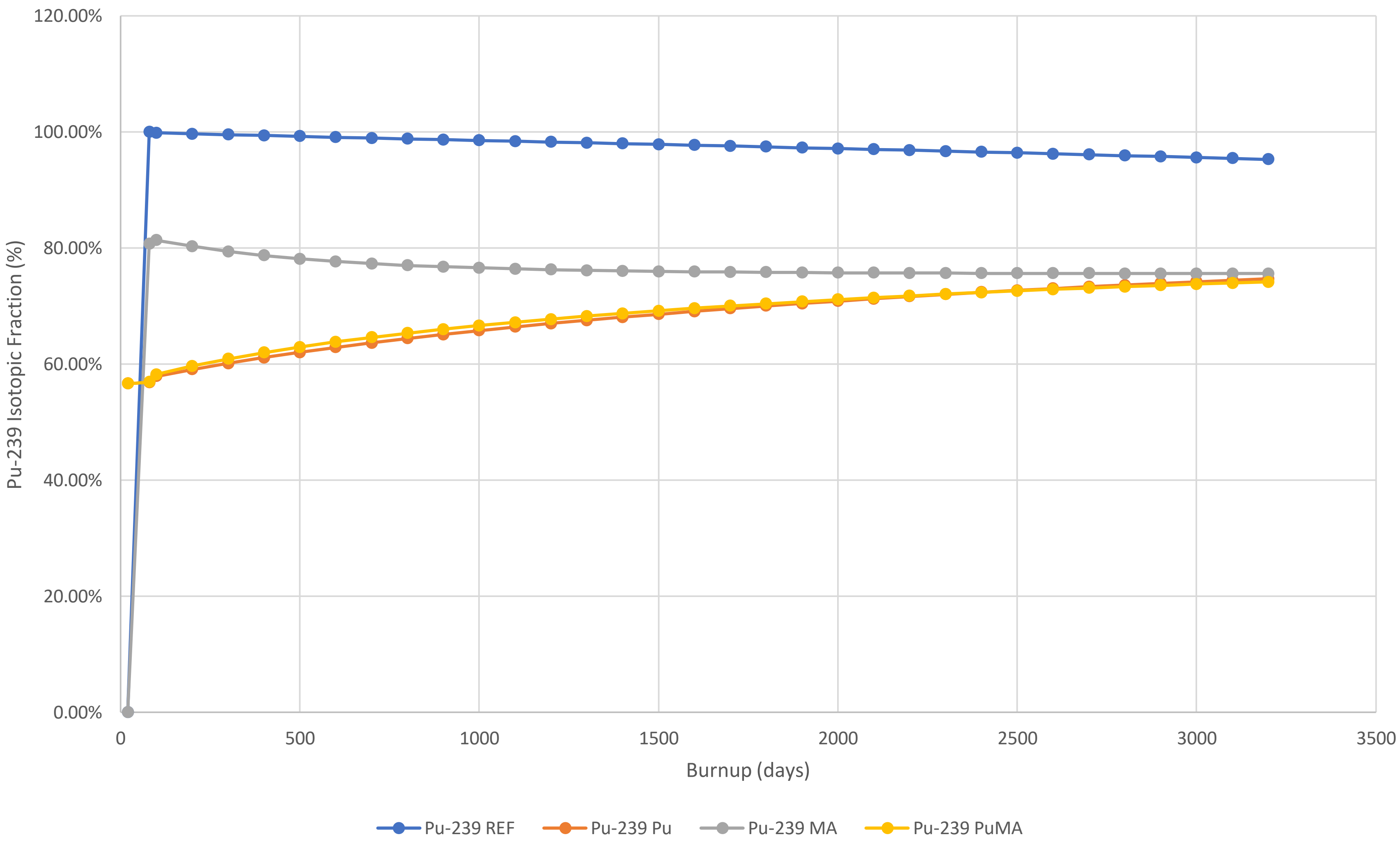
(Naganuma et al., 2005).

(Meiliza et al., 2008)

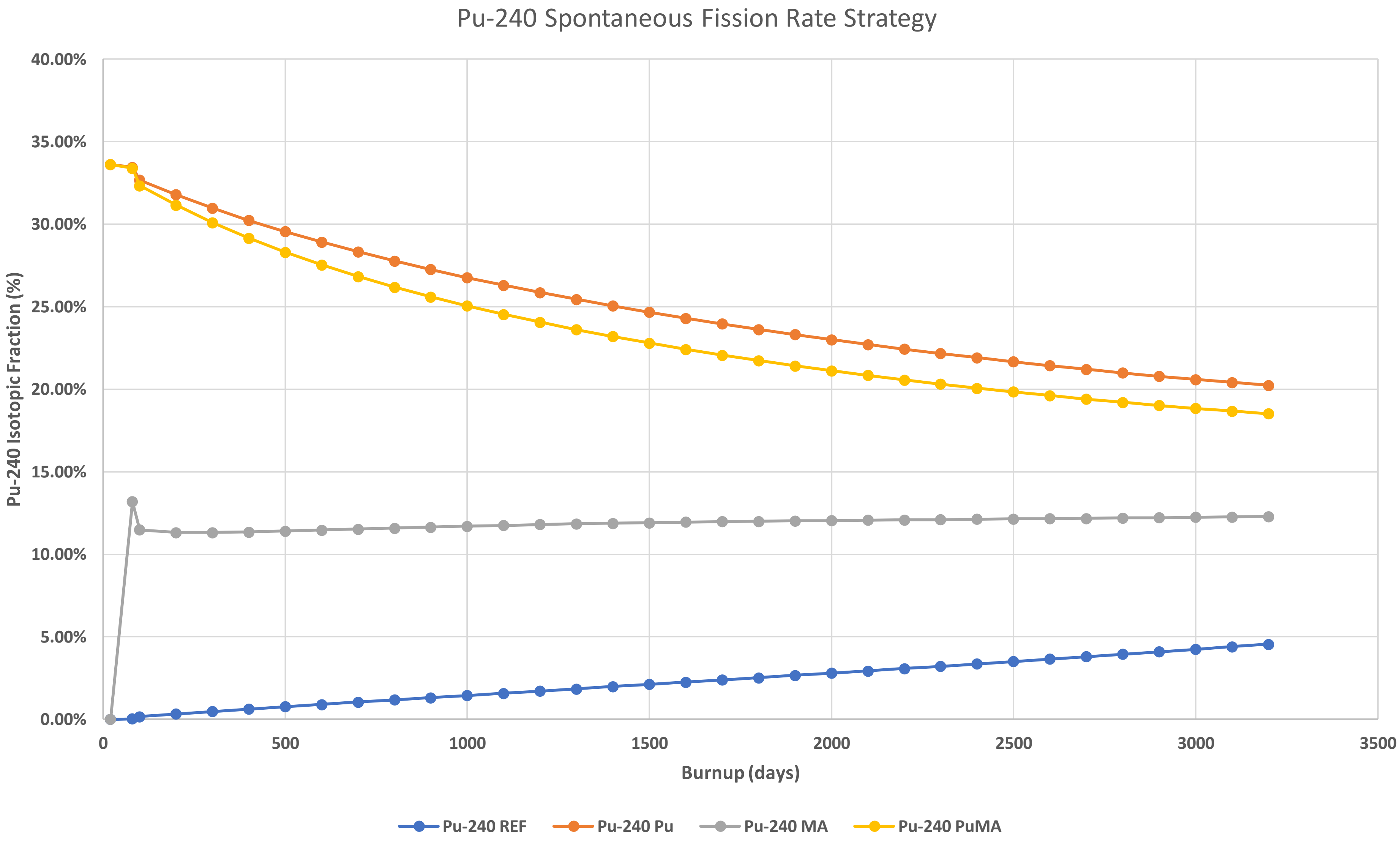
Decay Chain



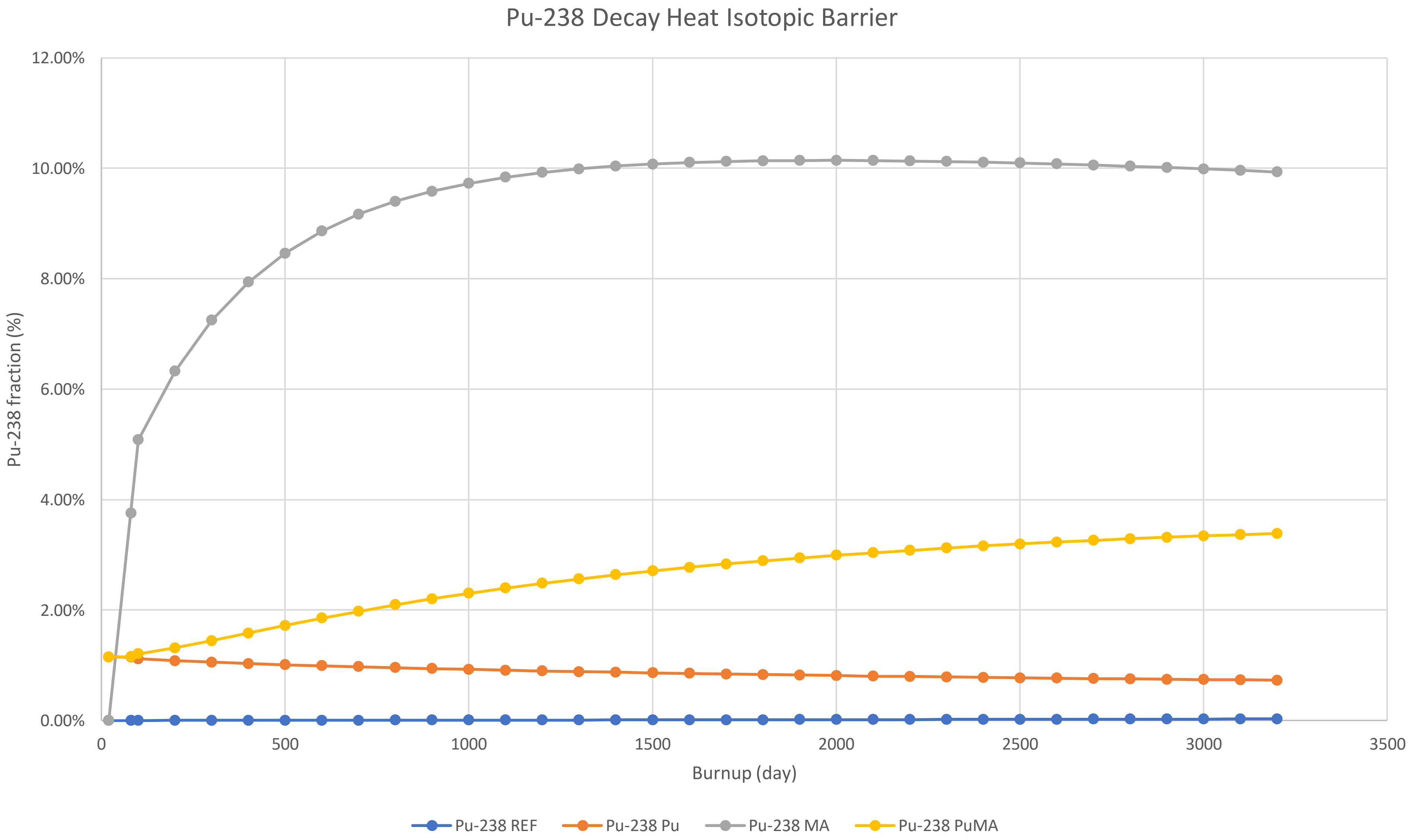
Pu-239 Isotopic Fraction remains high throughout cycle



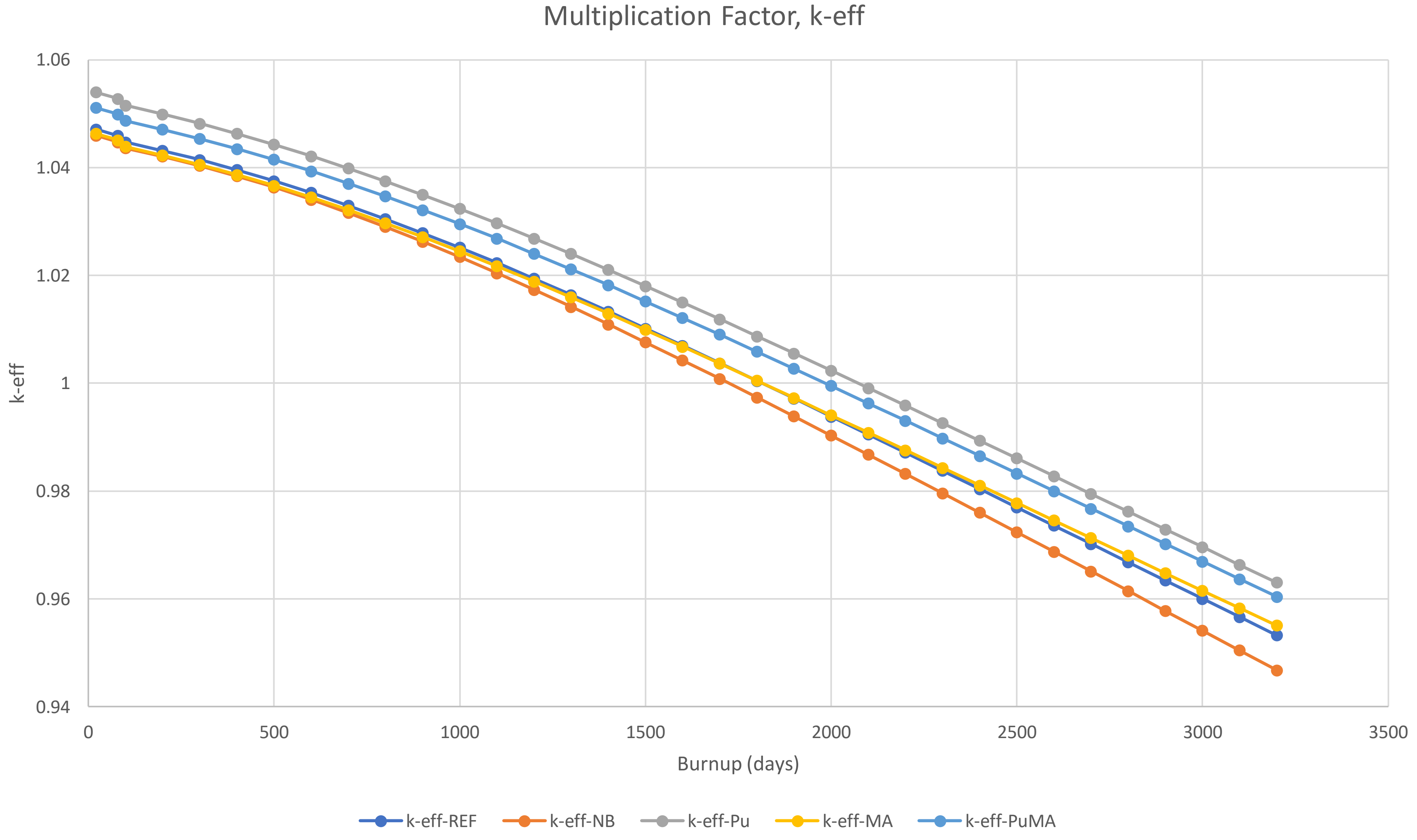
Spontaneous Fission Rate Strategy (Pu-240)



Decay Heat Isotopic Barrier Strategy (Pu-238)



Initial Reactivity is mostly unchanged



Case	Initial K-eff	Change (%)
REF	1.0471084	-
No Blanket	1.0459388	0.11
Pu loading	1.0539622	-0.77
MA loading	1.0463084	0.73
PuMA loading	1.0510942	-0.46

Case	VRC	Change (%)
REF	0.00022537	-
No Blanket	0.00021632	-4.02
Pu loading	0.00023405	8.20
MA loading	0.00022602	-3.43
PuMA loading	0.00023156	2.45

Specifications and core characteristics

Item	Unit	HBC	Blanket Free	Pu Loading	Am/Cm Loading	Pu/MA Loading
a) Plant						
Axial Blanket Thickness (upper/lower)	cm	20/20	20/20	20/20	20/20	20/20
Breeding Ratio		1.12	1.04	1.07	1.09	1.08
Transmutation Rate	%	-	-	-	17.00	16.02
Initial Pu Fissile Inventory	[t/GWe]	9.395	9.395	10.446	9.392	10.095
Pu Reduction Ratio		-0.0874	-0.0393	-0.0565	-0.1027	-0.0720
Discharge Burnup						
Core	GWd/t	139.6	87.4	83.3	84.2	83.7
Total	GWd/t	52.0	59.2	52.0	52.0	52.0
Void Reactivity Coefficient		1.83E-04	1.67E-04	0.00E+00	1.87E-04	1.91E-04
Blanket TRU enrichment	[wt.%]	-	-	3	-	2
Blanket MA fraction	[wt.%]	-	-	-	5	2

Isotopic composition in discharged fuel

Item	HBC		Blanket Free		Pu Loading		Am/Cm Loading		Pu/MA Loading	
	Core + AB	RB	Core + AB	RB	Core + AB	RB	Core + AB	RB	Core + AB	RB
Pu isotopic composition (wt%)										
^{238}Pu	1.36	0.03	1.35	-	1.40	0.73	2.46	9.93	1.81	3.39
^{239}Pu	57.95	95.27	57.96	-	57.27	74.68	56.64	75.58	57.00	74.16
^{240}Pu	32.16	4.55	32.17	-	32.68	20.23	32.24	12.28	32.53	18.52
^{241}Pu	4.67	0.00	4.67	-	4.72	0.02	4.62	0.00	4.68	0.02
^{242}Pu	3.86	0.00	3.86	-	3.94	0.02	4.04	0.02	3.98	0.02
MA isotopic composition (wt%)										
^{237}Np	8.79	59.4	8.8	-	8.73	12.22	9.75	11.54	9.31	11.45
^{238}Np	0.01	0.0	0.0	-	0.01	0.00	0.01	0.00	0.01	0.00
^{239}Np	1.54	36.9	1.6	-	1.39	2.44	0.57	0.09	0.90	0.24
^{241}Am	38.52	3.5	38.5	-	39.63	50.68	38.19	42.12	38.70	42.31
^{242m}Am	2.36	0.0	2.3	-	2.35	1.30	2.09	1.20	2.21	1.30
^{242}Am	0.01	0.0	0.0	-	0.01	0.00	0.01	0.00	0.01	0.00
^{243}Am	22.04	0.0	22.0	-	21.83	17.54	21.20	22.04	21.42	21.58
^{242}Cm	1.82	0.1	1.8	-	1.76	0.76	1.24	0.55	1.45	0.61
^{243}Cm	0.32	0.0	0.3	-	0.30	0.05	0.21	0.04	0.25	0.05
^{244}Cm	20.68	0.0	20.7	-	20.26	13.77	23.16	20.85	22.05	20.71
^{245}Cm	3.40	0.0	3.4	-	3.27	1.18	3.24	1.52	3.31	1.68
^{246}Cm	0.51	0.0	0.5	-	0.46	0.04	0.34	0.05	0.40	0.06

Research Laboratory Visit

Tsuruga, Fukui Prefecture

Monju Japanese Sodium-Cooled Fast Reactor

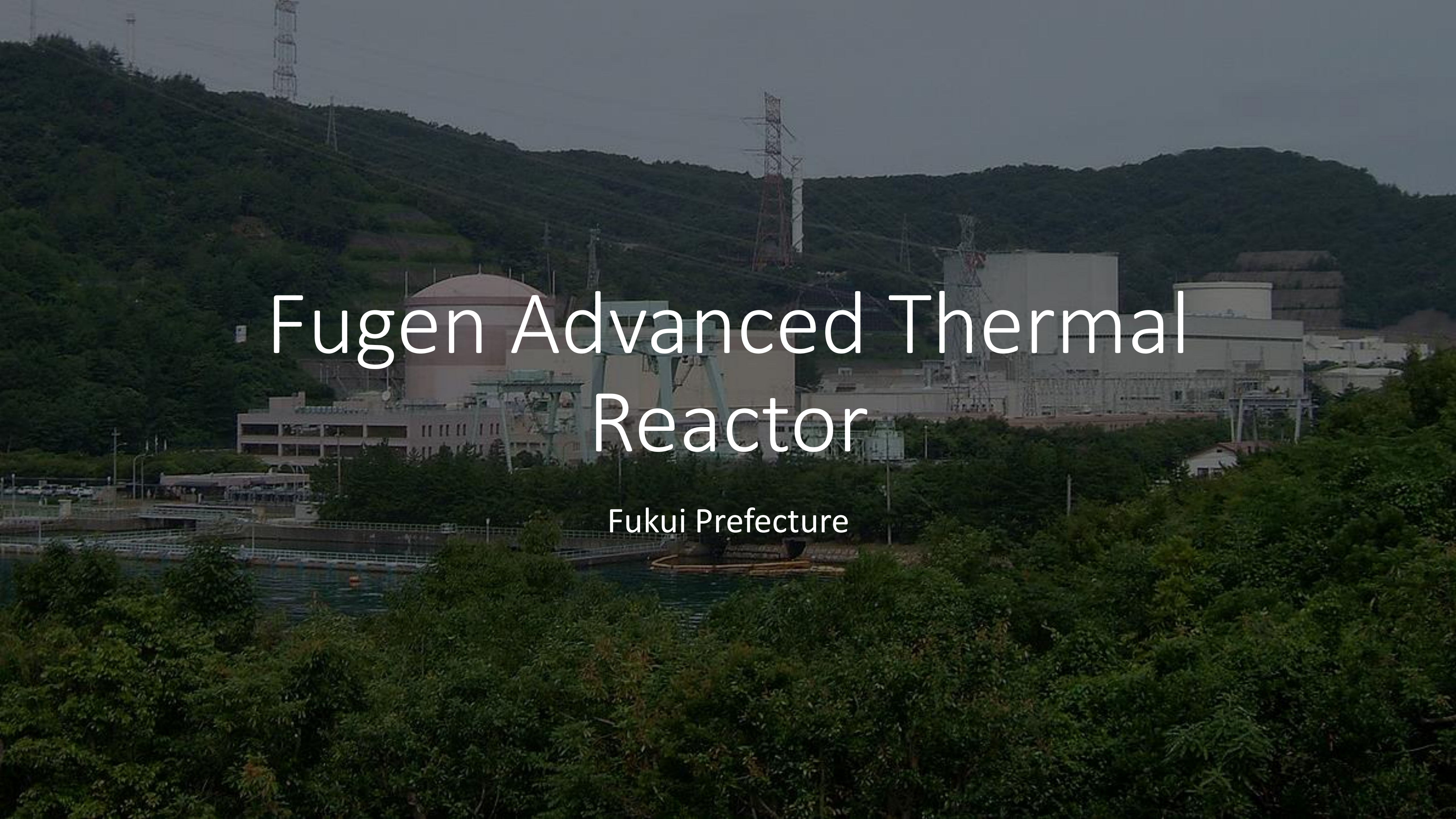
Fukui Prefecture

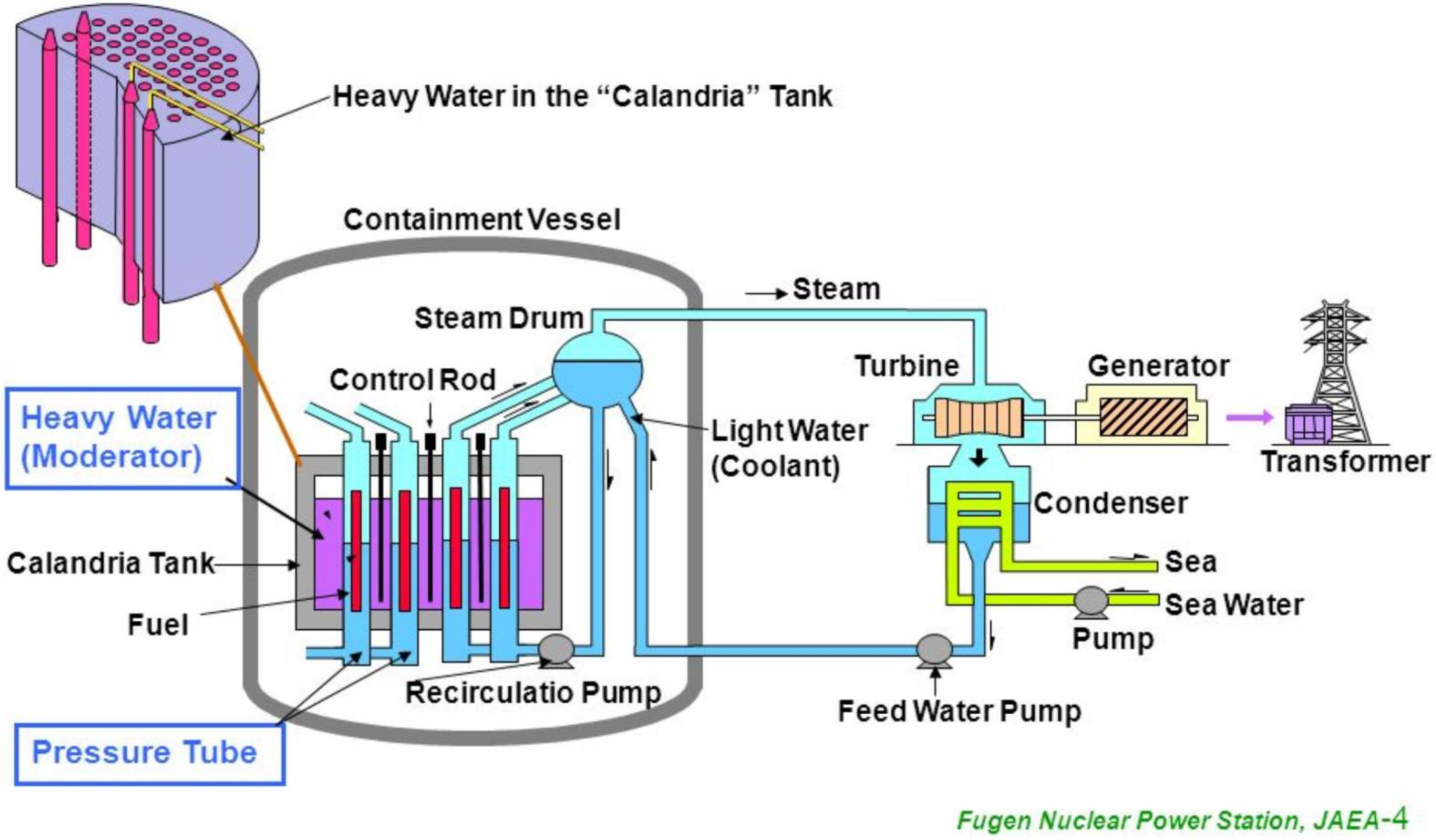
Fast-Spectrum Reactor Characteristics

- Sodium Cooled
- MOX-fueled
- Loop-type
- 280 MWe and 714 MWt
- Breeding ratio of 1.2
- Currently undergoing decommissioning process

Fugen Advanced Thermal Reactor

Fukui Prefecture





Advanced Thermal Reactor

- 165 MWe (557 MWt)
- Demonstration reactor
- Pressure Tube Type Core
- Heavy Water Moderator
- Boiling Light Water Coolant

World Politics and Nonproliferation in the Nuclear Age


Questions?

Acknowledgements

Professor Hiroshi SAGARA

Tokyo Tech summer program staff

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