On Accounting the Materials in the PB-HTR Spent Fuels Based on the Random Fuel Shuffling Algorithm

XIA Bing, WU Hongwei, ZHANG Ziwen, SHE Ding, LI Fu

Institute of Nuclear and New Energy Technology (INET),
Tsinghua University, Beijing 100084, China

Email: xiabing@tsinghua.edu.cn

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Outline

- Introduction
- Considerations on PB-HTR’s Accountancy
- Determining the Spent Fuel Material Amount
- Conclusions

Introduction

- **Pebble bed high temperature reactor (PB-HTR) is a promising type of reactor with excellent features:**
  - ✓ Inherent safety with definitely passive decay heat removal;
  - ✓ High temperature process heat application;
  - ✓ Potential co-generation of heat and electricity;
  - ✓ Modularity……
- **PB-HTR has been studied, constructed and operated in countries for many years, and firstly deployed commercially in China.**

Introduction

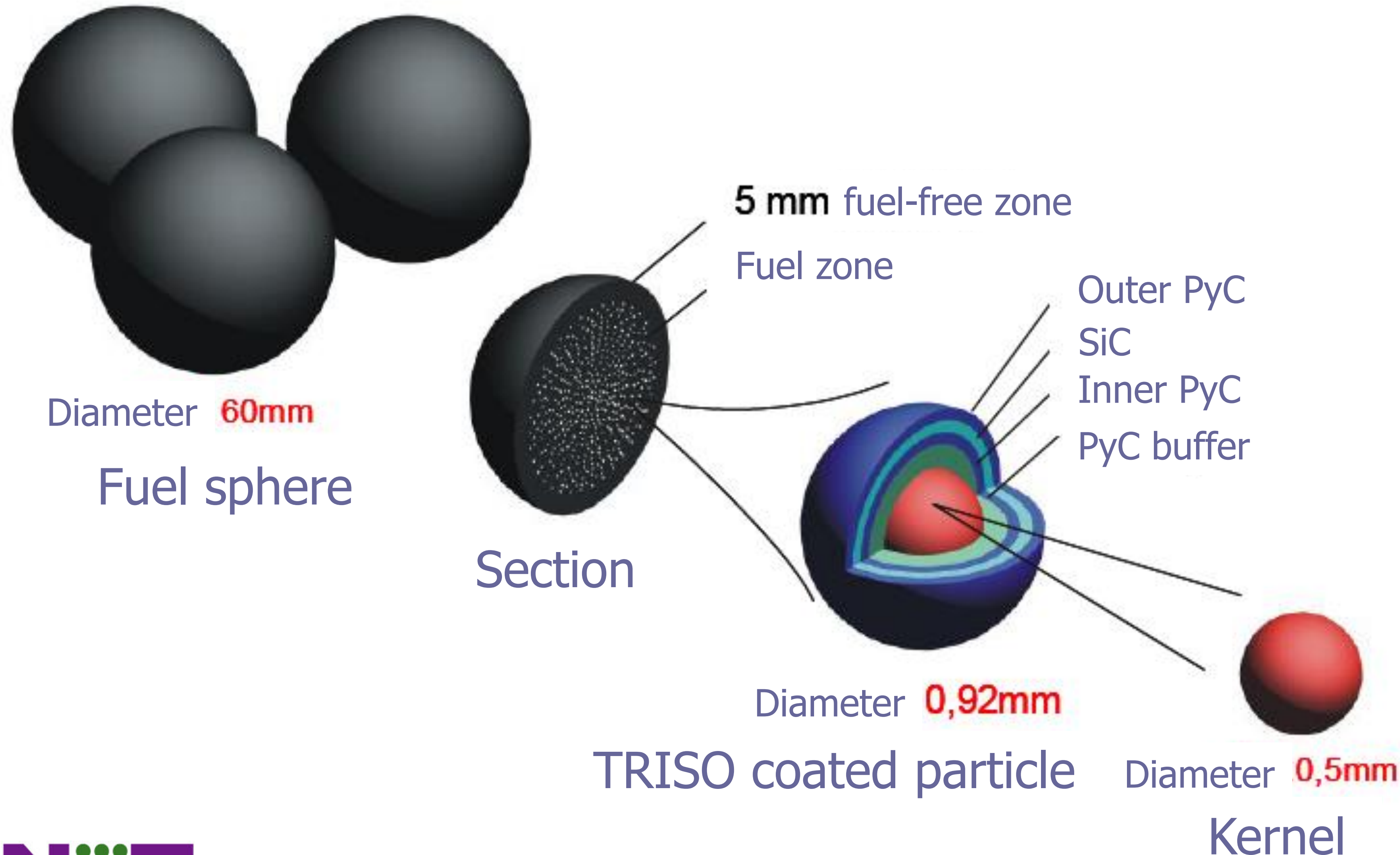
☐ PB-HTR:

- ✓ Quite different from the conventional PWRs in many aspects:
  - ✓ Large amount of fuel pebbles;
  - ✓ Continuous on-line refueling;
  - ✓ Low heavy metal density in fuels.

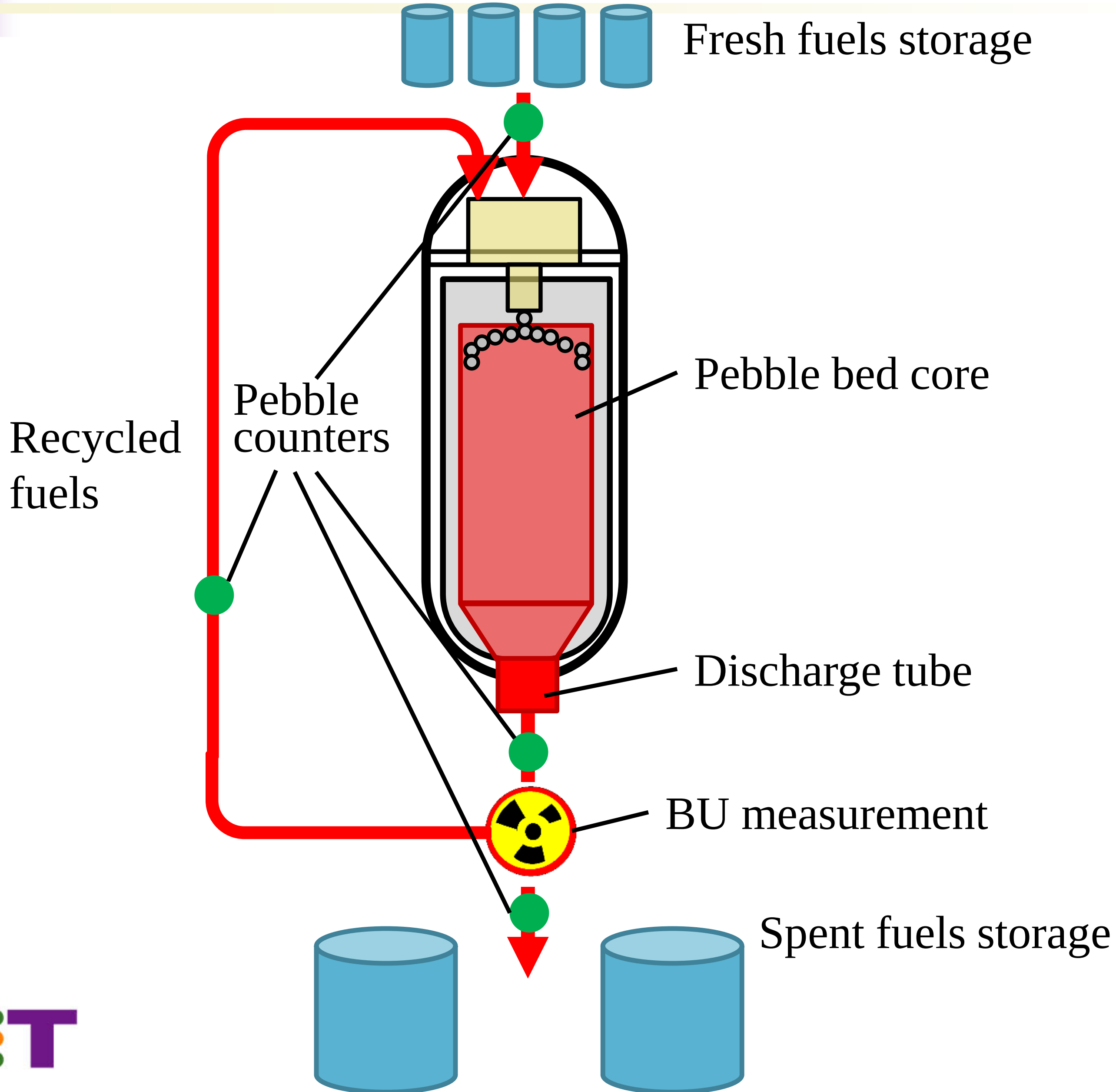
- ✓ The **spent fuel storage** of PB-HTR is also different from those of PWRs:
  - ✓ Containers with tens of thousand fuel pebbles;
  - ✓ Cooled by air, in the storage silos.

- ✓ Spent fuel accountancy: **a challenge**.
  - ✓ To control all the spent fuels;
  - ✓ To account the materials;

PB-HTR Graphite Fuel



Fueling Process of PB-HTR



Consideration on Spent Fuel Accountancy

☐ Accountancy regime of PB-HTR:

- ✓ Not items:
  - ✓ Fuel elements cannot be identified;
  - ✓ Fuel elements are difficult to trace precisely within the core;
- ✓ Not bulk:
  - ✓ Uncertainties of pebble mass and volume;
  - ✓ Friction of pebbles within the core: mass loss.

☐ Mixed accountancy regime: a novel concept

- ✓ Pebbles in fresh fuel storage and the spent fuel storage can be identified and traced **in the unit of containers**;
- ✓ Items: the containers filled with fresh and spent fuel pebbles in the fresh and spent fuel storages;
- ✓ Bulk: in-core fuels, but **in the unit of pebbles**, not mass or volume.

MBAs and KMPs

- **MBAs: material balance areas**
- **KMPs: key measurement points**
  - ✓ **Inventory KMPs: A, B, C……**
  - ✓ **Flow KMPs: 1, 2, 3……**

1: **receipts** of fresh fuels;

2: return of **unqualified** fuels;

3: **transfer** of fresh fuels;

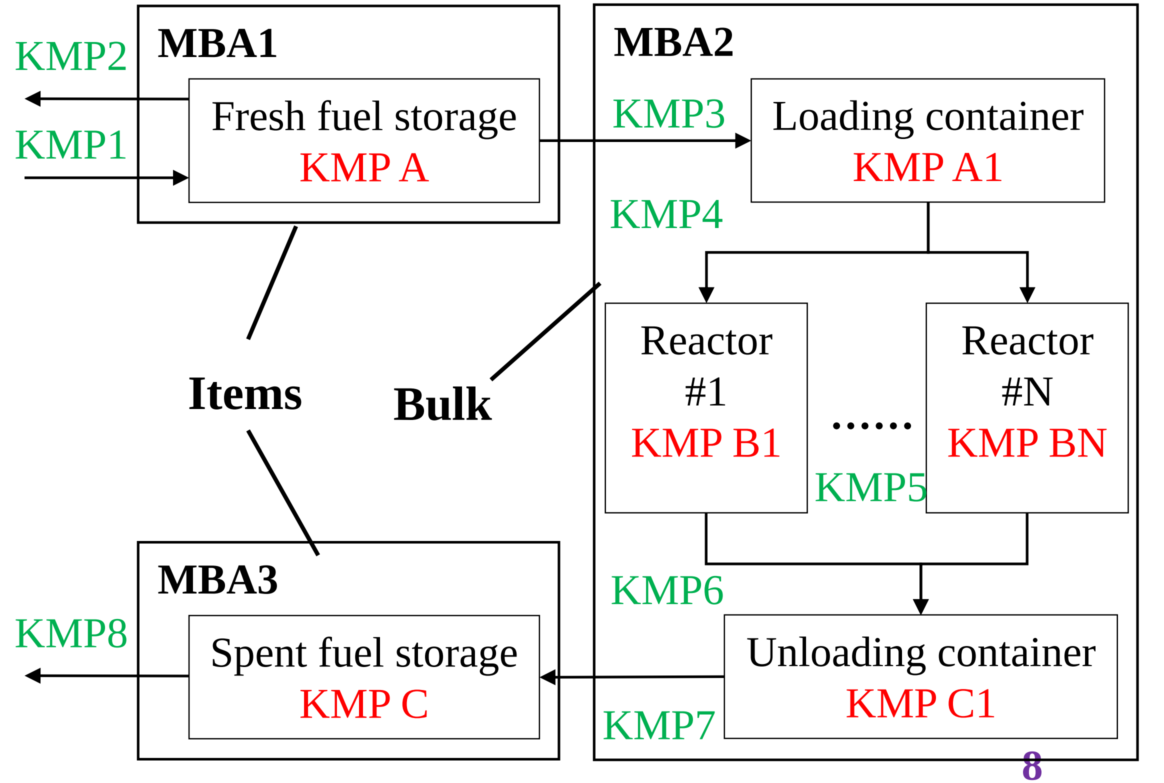
4: **loading** fresh fuels;

5: nuclear **production and loss**;

6: **unloading** spent fuels;

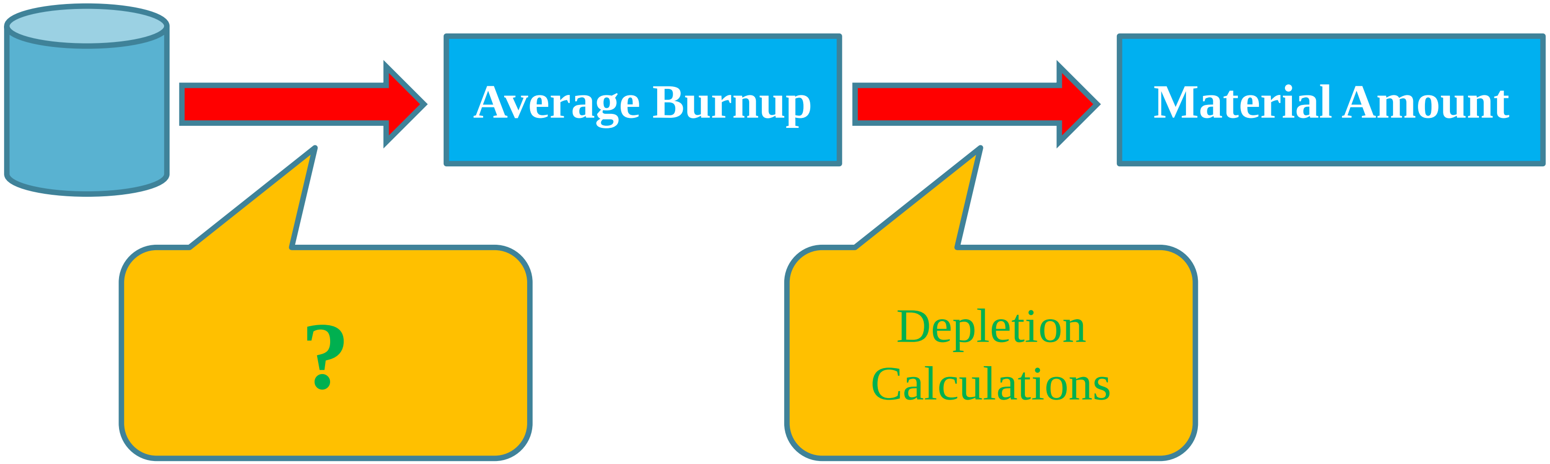
7: **transfer** of spent fuels;

8: **shipment** of spent fuels.

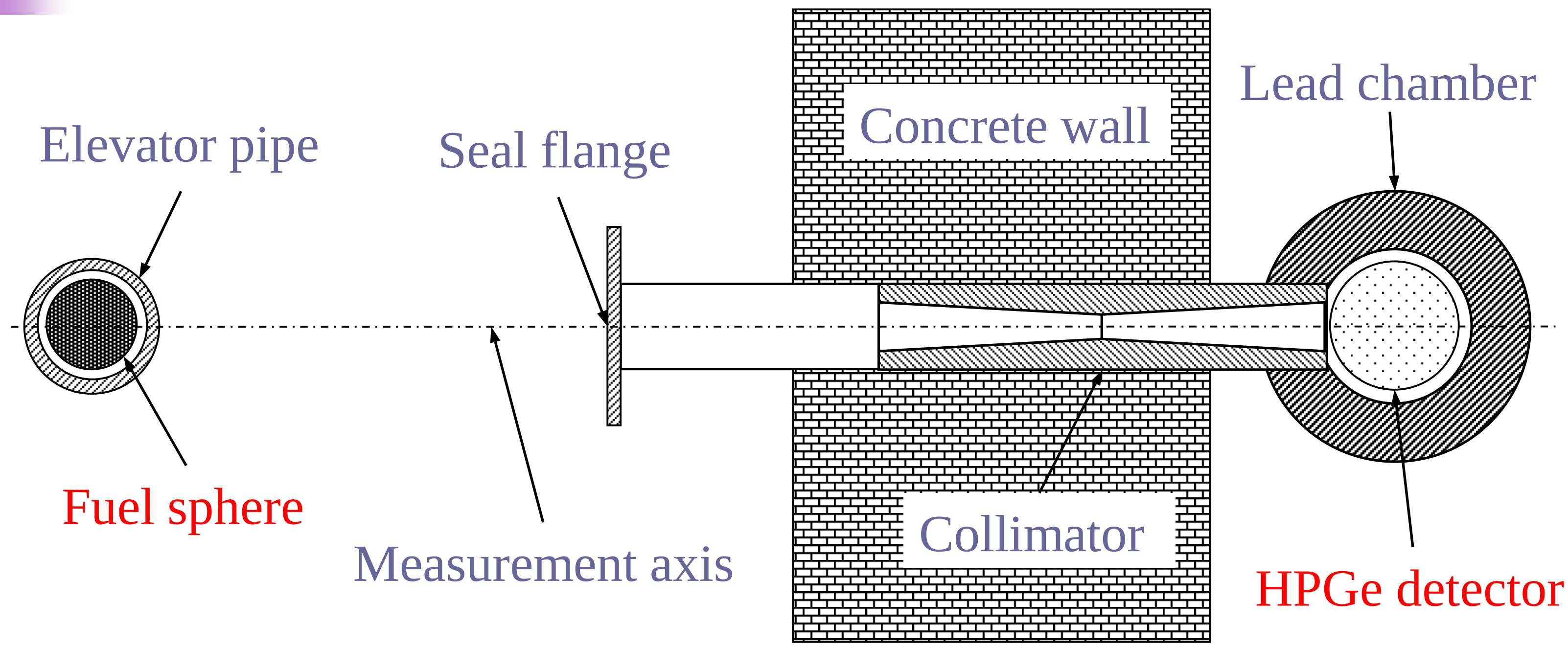


Aims of Spent Fuel Accountancy

- **Control all the items -- the containers:**
  - ✓ Identifications;
  - ✓ Locations;
  - ✓ **Amount of nuclear materials**, including ^{235}U, ^{239}Pu, ^{241}Pu……



Burnup Measurement of PB-HTR



$$BU = \frac{10^6 E_f}{G_b Y_7 \lambda_7} C(t) A_7$$

Average fission energy (MWD)

Correction term of decay

Activity of ^{137}Cs (s^{-1})

Mass of heavy metal (g)

Cumulative fission yield

Decay constant of ^{137}Cs(s^{-1})

Estimate the Nuclear Material Amount

□ Based on the burnup value:

- ✓ This step has to be implemented by using the depletion calculations;
- ✓ The depletion calculations is carried out to reveal **the dependency of the nuclear material amount on the fuel burnup**;

□ Complications:

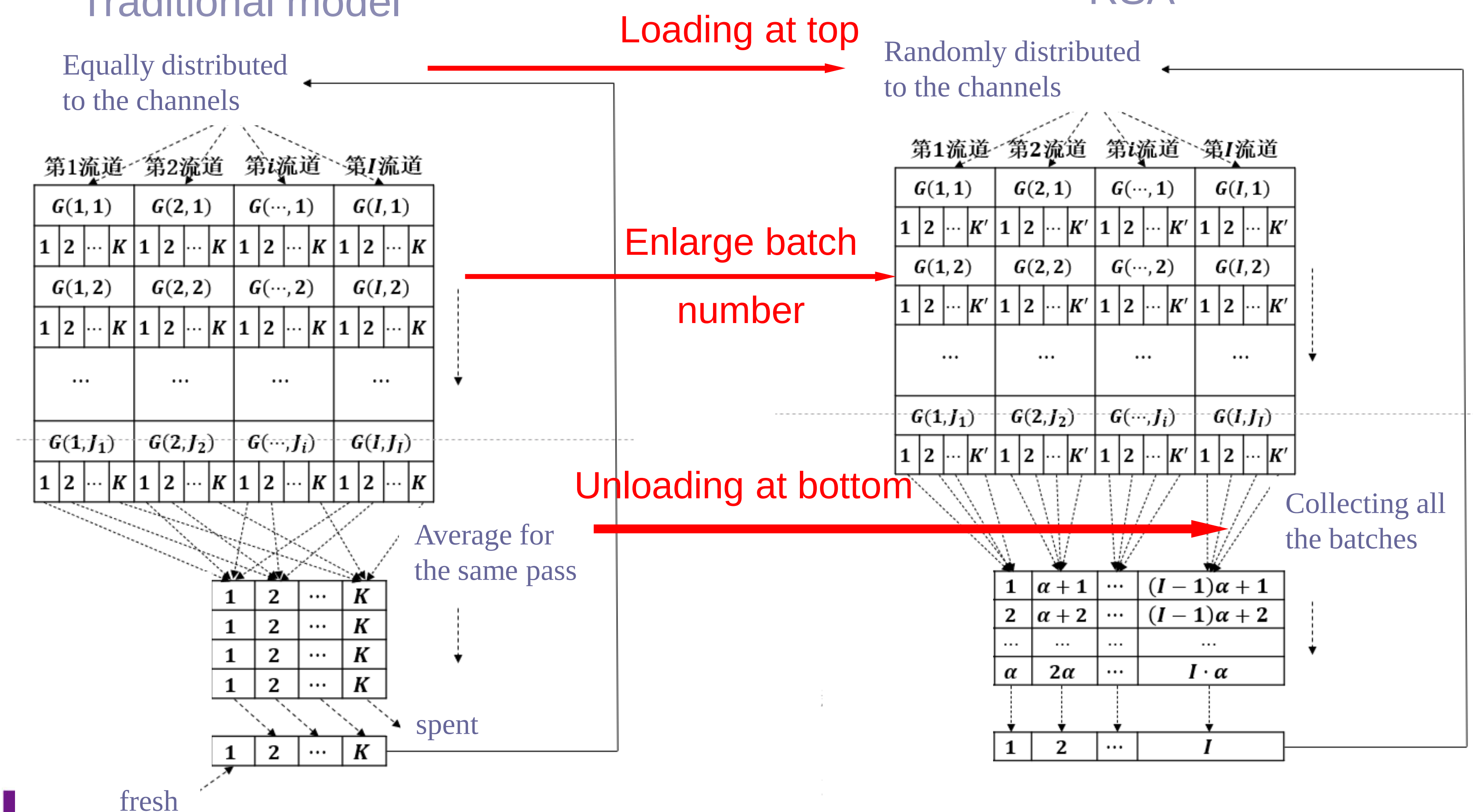
- ✓ Randomness of entering radial position each time the pebble enters the core top;
- ✓ Probability distributions of both burnup values and nuclear density values.

□ How to establish the dependency between BUs and MAs, especially with random probabilities?

Random Shuffling Algorithm (RSA)

VSOP
Traditional model

New-developed code: PANGU
RSA

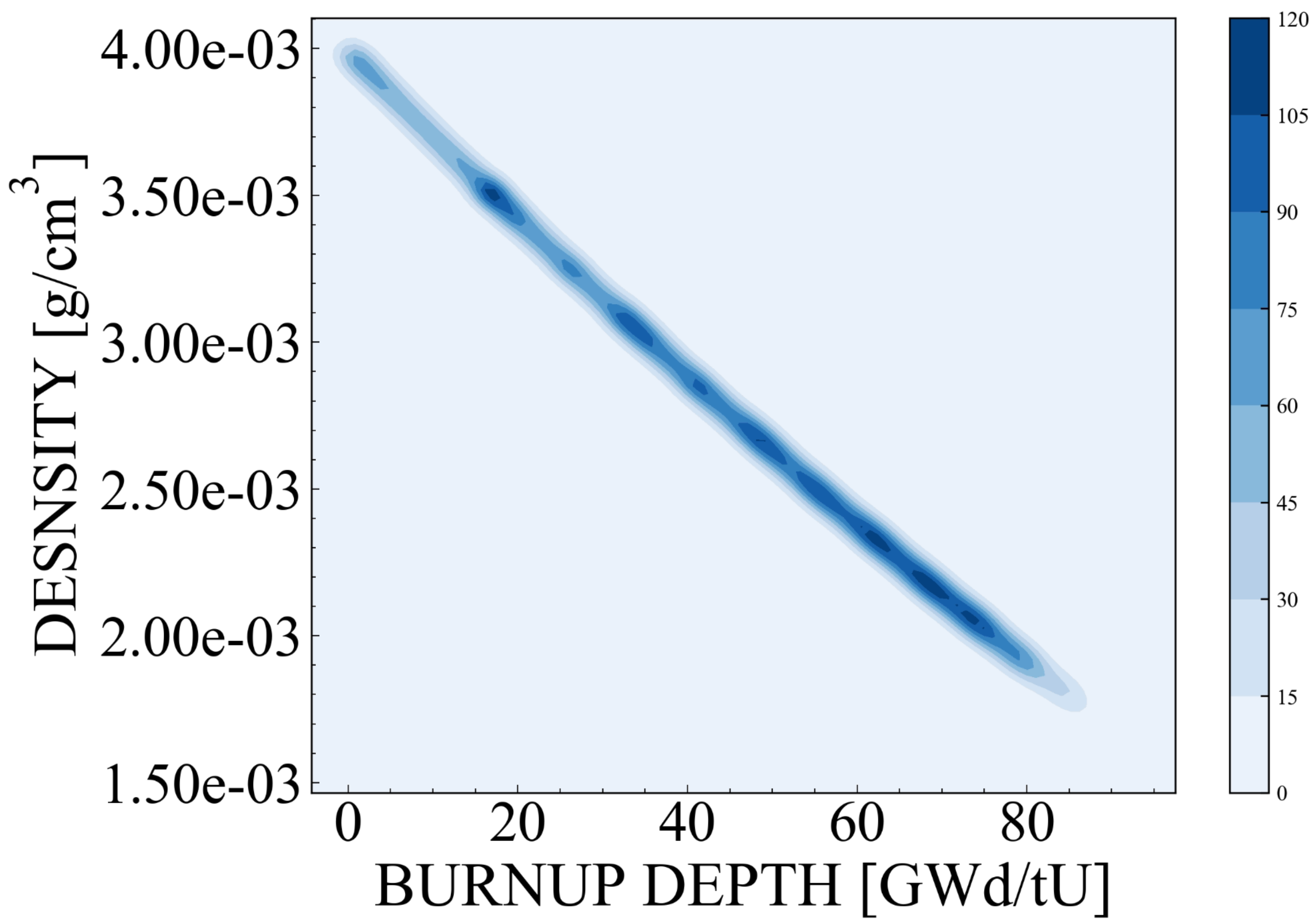


RSA

	VSOP Traditional models		RSA
Refinement of depletion model	BATCHES = PASSES		BATCHES ≥ PASSES
Burnup history possibilities	= Channel number	Exponential →	= CN ^ Passes e.g. 5^15 ~ 3E+10

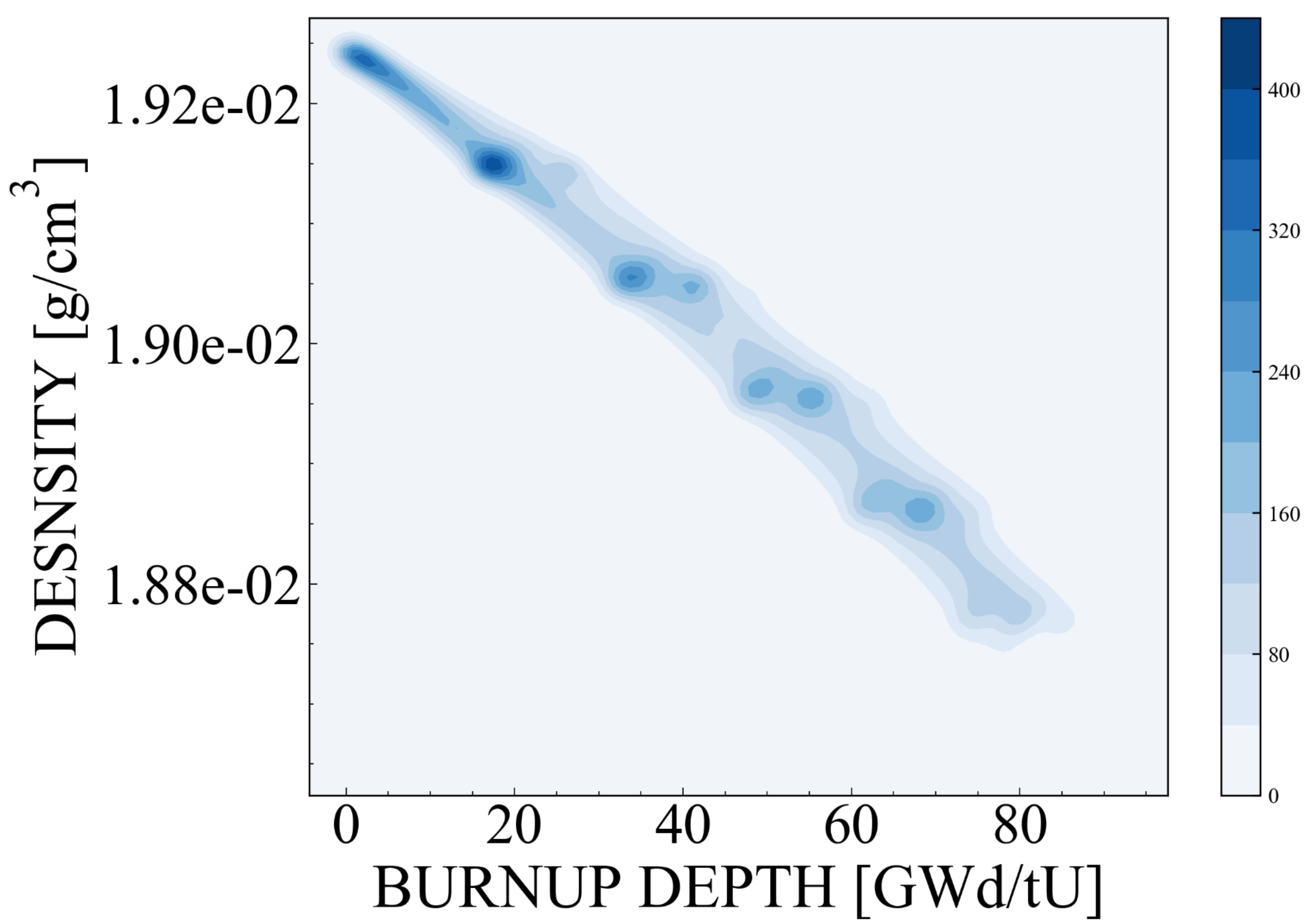
RSA results for the HTR-10: 5x Passes

❖ Joint probability of BU and material density: ^{235}U



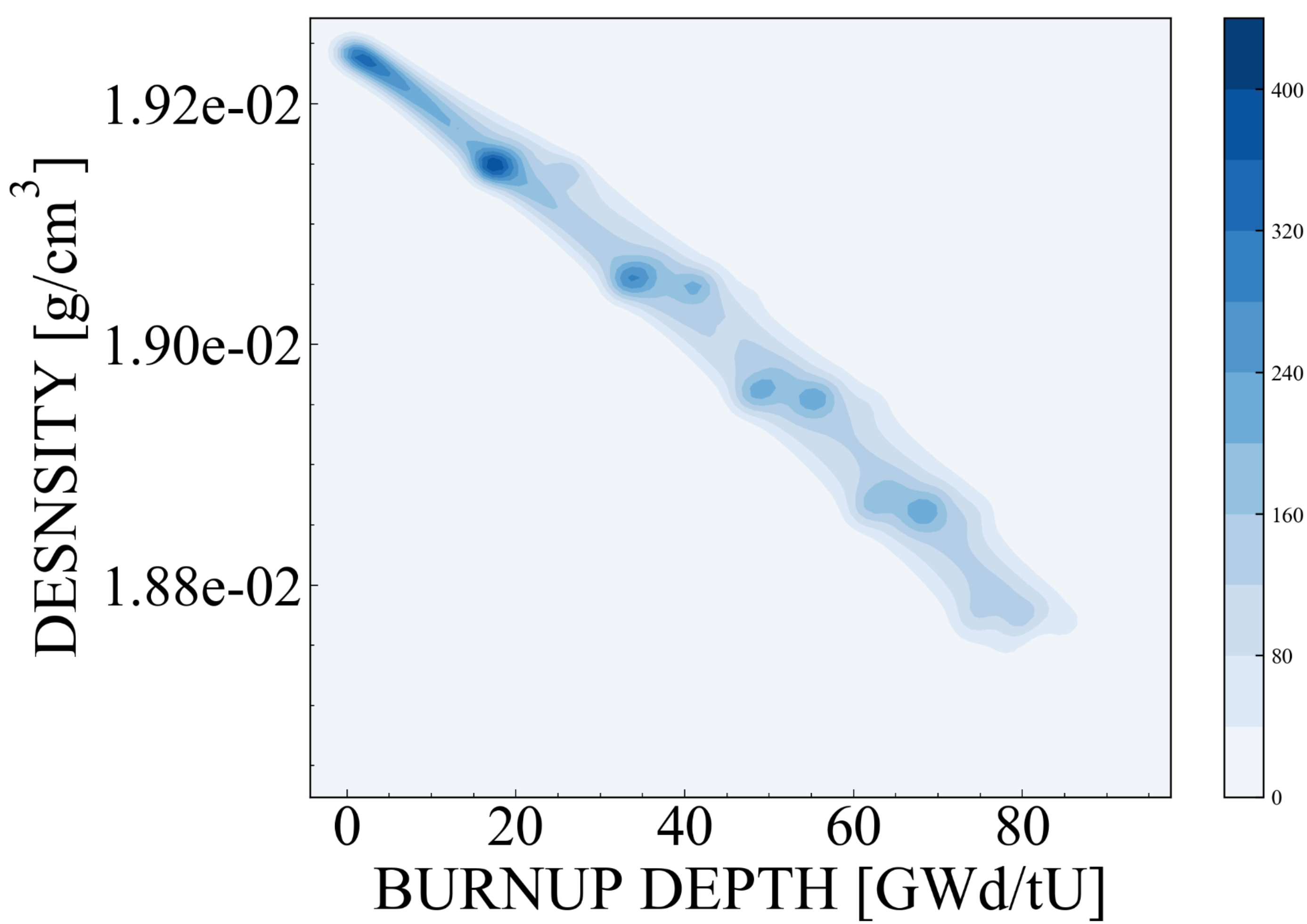
RSA results for the HTR-10: 5x Passes

❖ **Joint probability of BU and material density: ^{238}U**



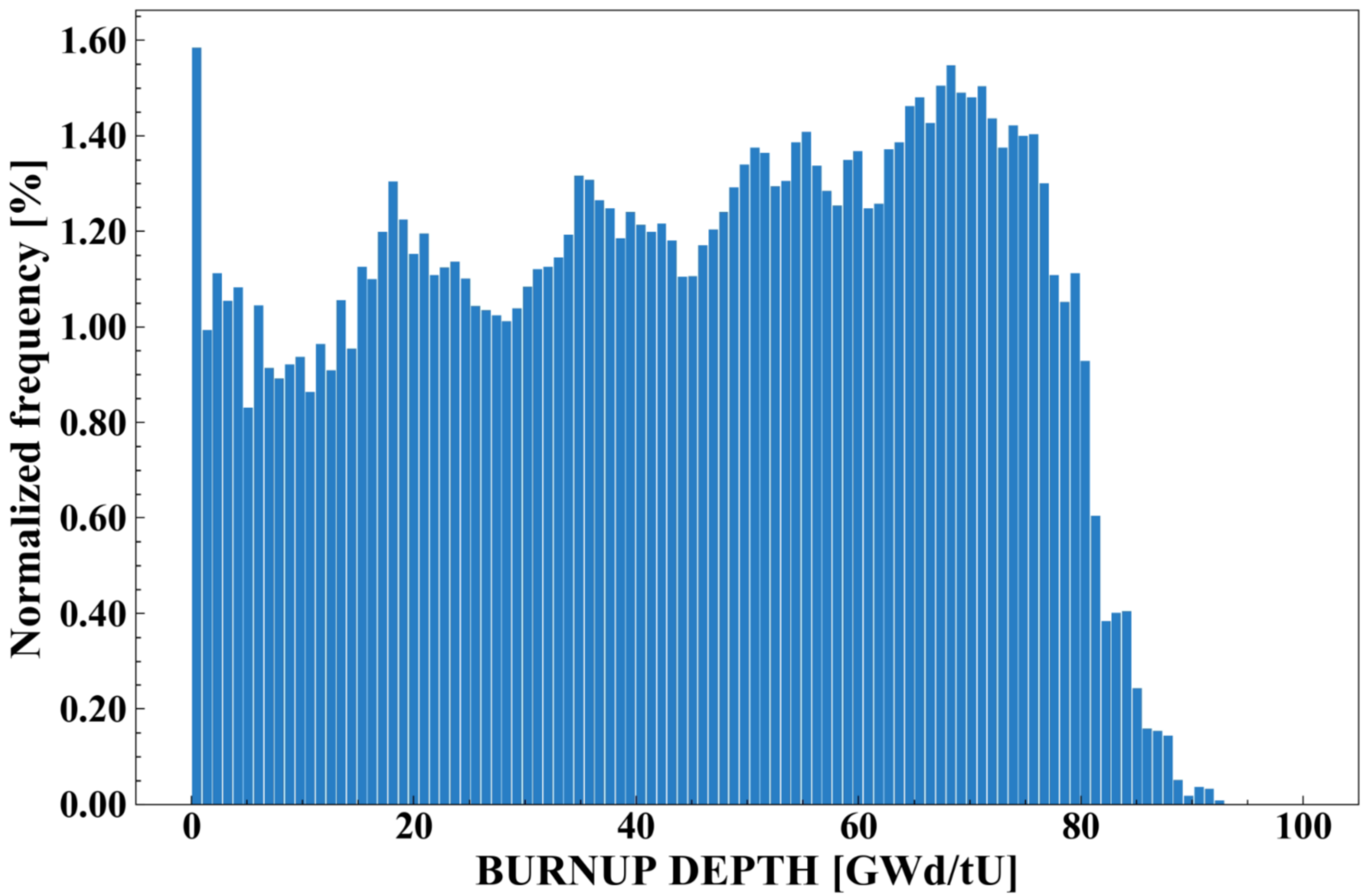
RSA results for the HTR-10: 5x Passes

❖ **Joint probability of BU and material density: ^{238}U**



Prior Probability of BU

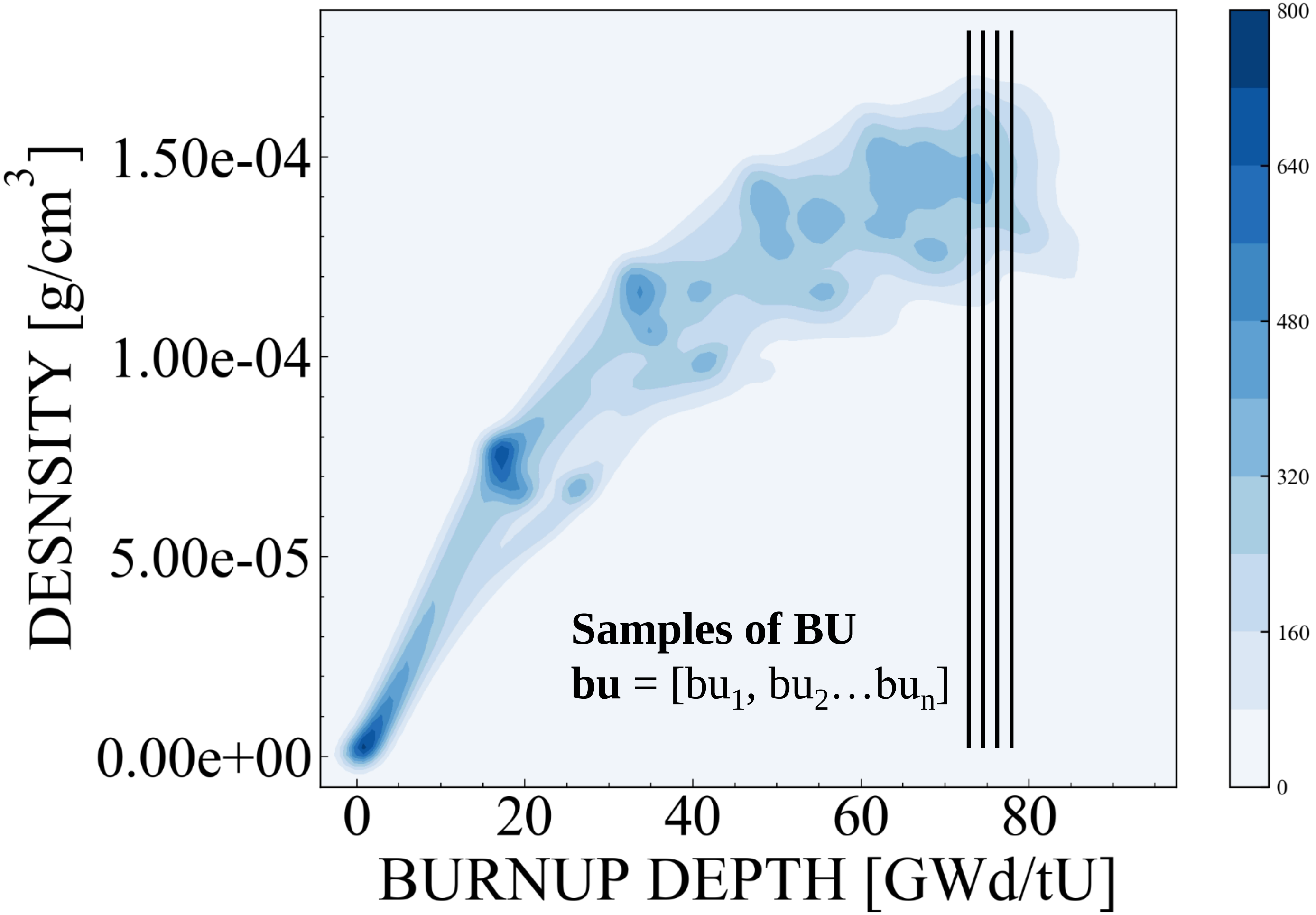
❖ $g(BU)$



Bayesian Estimate for BU and N

- ☐ **RSA gives the joint probability distribution *f*(BU, *N*):**

^{239}Pu



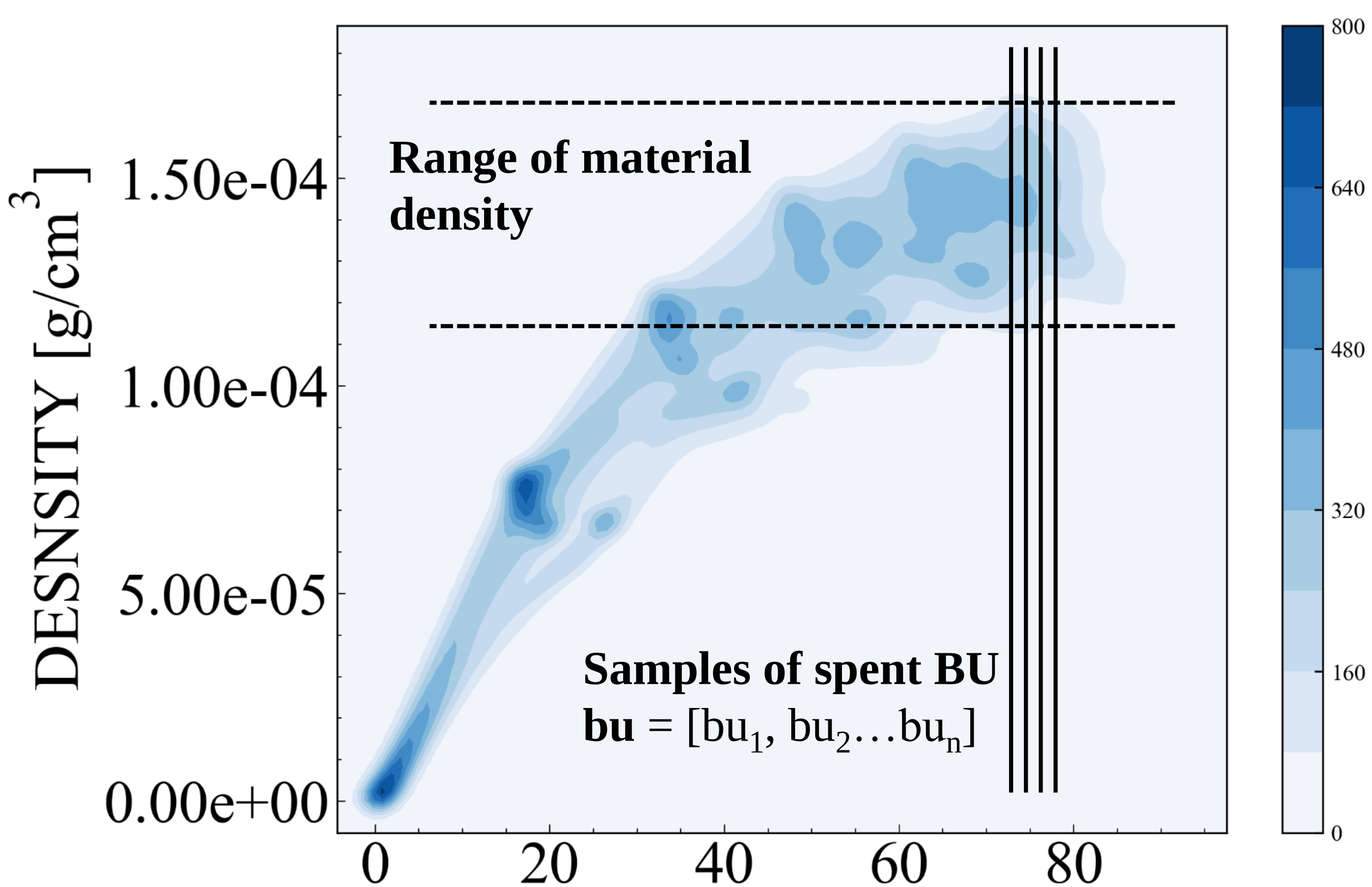
Bayesian Estimate for BU and N

☐ The conditional probability $p(N|\text{bu})$:

Posterior probability: $p(N|\mathbf{bu}) \propto \sum_{i=1}^{n} f(bu_i, N)/h(N)$

—prior probability

^{239}Pu

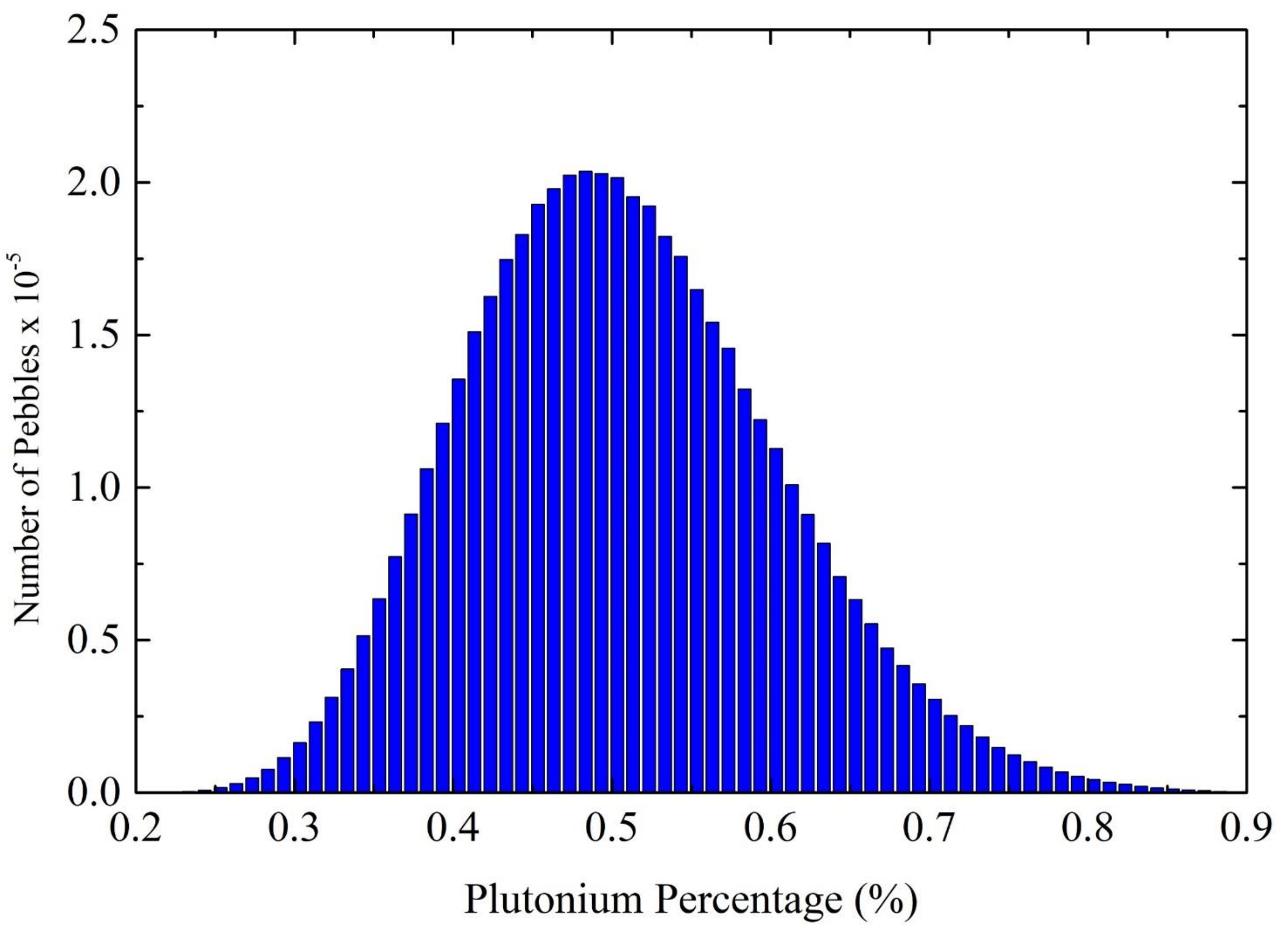


Bayesian Estimate for BU and N

□ The posterior probability $p(N|\mathrm{bu})$:

- **The mean value and variance can be obtained by statistics**

^{239}Pu



Advantages of RSA

- ✓ Direct solution of Monte Carlo type depletion history sampling problem by using just a deterministic code.
- ✓ No pre-defined neutron flux profile needed.
- ✓ Actual operation conditions of HTRs can be handled.
- ✓ During the operation of HTRs, each burnup value of pebbles is recorded to implement the Bayesian estimate, to obtain the specific material amount both for the mean value and variance.

Conclusions

- ✓ The PB-HTRs' material accountancy is different from the conventional LWRs.
- ✓ An accountancy scheme **mixed by item and bulk regimes** is proposed in this work, in which the fuels in the fresh and spent fuel storages in the containers are considered as items and the fuel pebbles within the reactor core are considered as bulk.
- ✓ The **on-line burnup measurement** can be employed to obtain burnup values of spent fuel containers, especially for the running-in phase before equilibrium state.
- ✓ The random shuffling algorithm (RSA) realizes the random sampling of the fuel pebble recycling history by much refined batch-wise approximation in a deterministic code.
- ✓ The dependency of nuclear material amount on the average burnup of a batch of fuel pebbles can be obtained via a Bayesian estimate upon the joint probability of BU and MA from the RSA analysis.

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Thanks for your attention