Small Sized High Temperature Gas-Cooled Reactors with Innovative Nuclear Burning

Peng Hong LIEM, ISMAIL and Hiroshi Sekimoto

Research Laboratory for Nuclear Reactors,

Tokyo Institute of Technology

The 2nd COE-INES International Symposium on
Innovative Nuclear Energy Systems (INES-2)
Yokohama, November 26-30, 2006

CONTENTS

- Background and Motivation (Case Study of Indonesia)
- Introduction of Innovative CANDLE Burning Scheme
- Proposed Small Sized, Long Life HTGR design (for the Indonesian case)
- Burn-up Performance of Small Sized, Long Life HTGR with CANDLE scheme (compared with Multipass, OTTO and Peu-A-Peu Burning Schemes)
- Concluding Remarks

Background and Motivation

- The needs for small (very small), medium sized reactors – SMR- (IAEA 1985; 1996; 2000; Kuznetzov 2005)
- SMR user countries dominated by developing countries facing large growth of its domestic energy demand (constraints: small grid, dispersed/remote area, low population, less developed infrastructure, lack of skilled human resources, capital investment capability etc.)
- SMR vendor countries offer LWRs, HWRs, GCRs (none offers small power/unit) and LMRs (wide spectrum of design phase/maturity and deployment schedule)
- Potential contribution of small, very small sized HTGRs for heat applications as well as electricity generation (half of the word primary energy is used for heat generation)

An Example of Design Requirements of Small Sized Reactors

Ref. Subki (1992), Arbie (1998)

Eastern Region

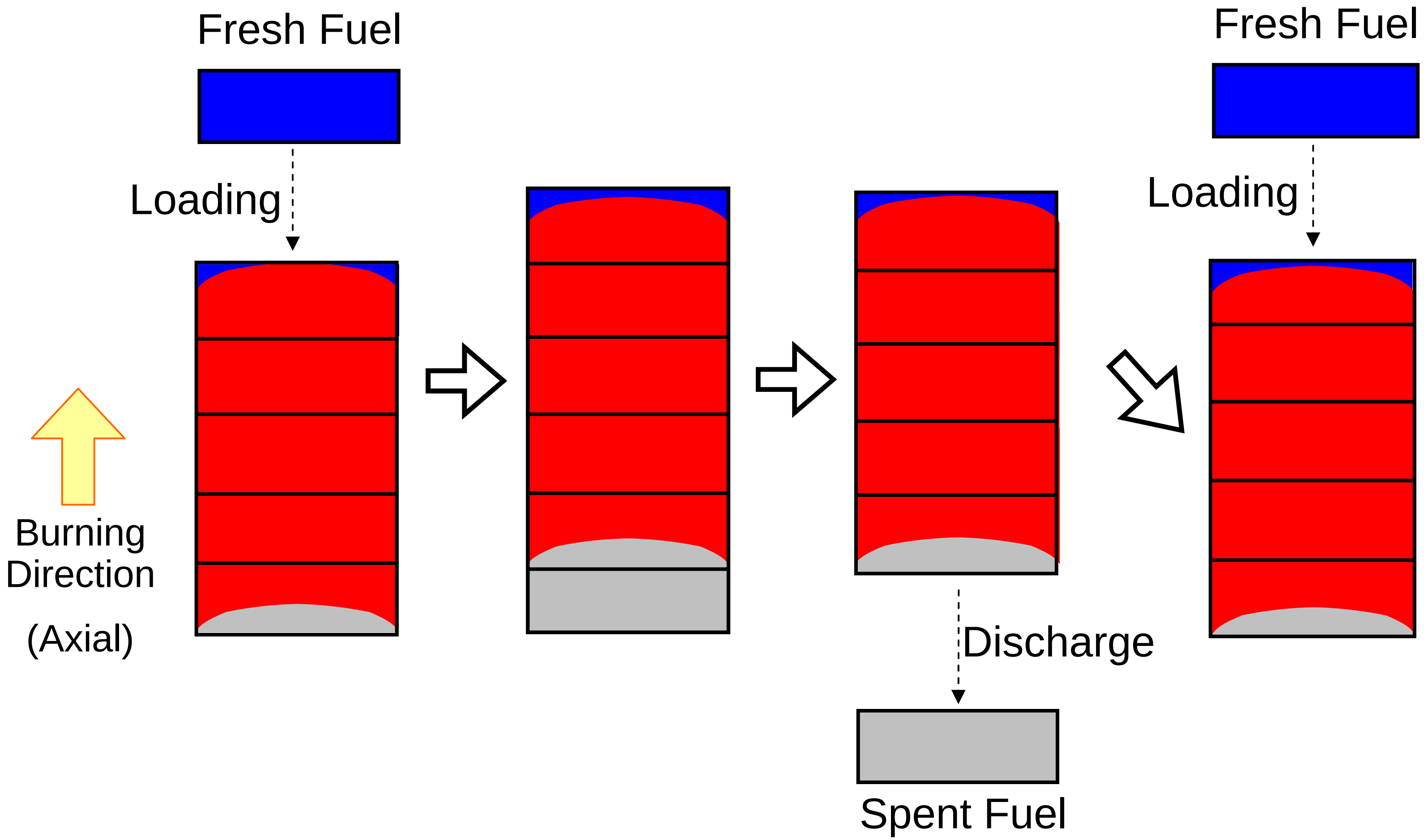
Marine resources based industrial centers, agro-industries

- Siting
    - Power level (small)
    - Seismic (0.05-0.25g)
- Licensibility in the country of origin
    - Inherent &Passive safety
    - Simplified design
- Economic Criteria
    - Large social gain
    - Zero or least government subsidy
    - Cost to remove “remoteness”
    - Low capital cost
- Domestic Participation
- International Acceptance

Recent Trends in HTGR Design

- Proposed Designs of HTGR
  - HTR-M 200 (200 MWth, Siemens/Interatom, Germany)
  - PBMR (110 MWe, ESCOM, South Africa)
  - HTR-PM (160 MWe, Tsinghua University, China)
  - GT-MHR (600 MWth, General Atomic, USA)
  - GTHTR300 (600 MWth, JAERI-TEPCO, Japan)
- Innovative Burning schemes
  - Multipass, OTTO, Peu-A-Peu (Pebble type fuel)
  - Sandwich Method, CANDLE (Block/Prismatic type fuel)

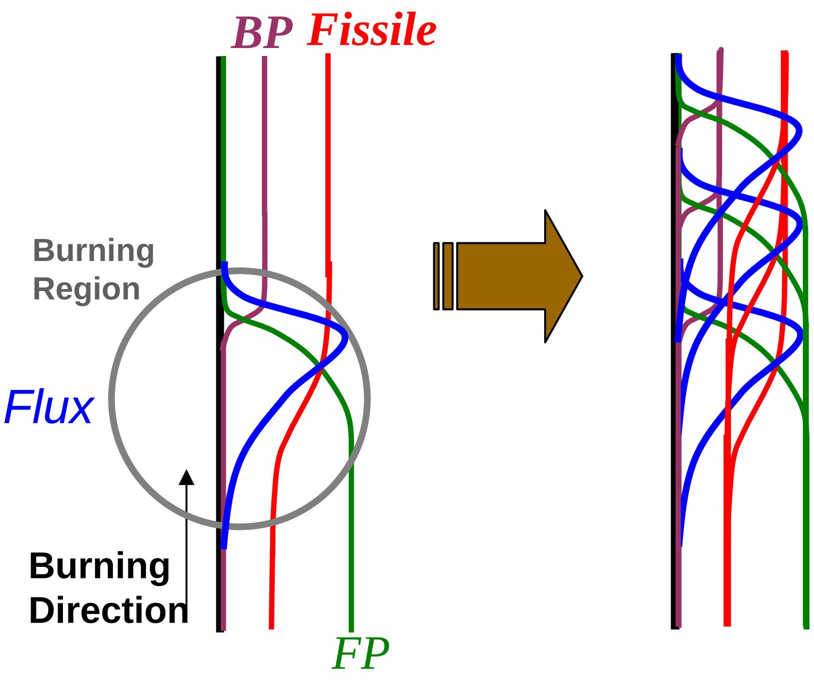
CANDLE Burning Scheme (1/2)
(Applied to Block-type HTGR)



Sekimoto (2001)

CANDLE Burning Scheme (2/2)
(Necessary Conditions for HTGR)

- Fresh Fuel Region (k<1)
  - Enriched Uranium & BP
  - BP is burnt slowly by neutrons leaked from the burning region
- Burning Region (k>1)
  - BP is almost completely burnt
  - Fissile material is depleted for producing energy and neutrons
  - Fertile material is converted to fissile material
- Spent Fuel Region (k<1)
  - Fission products are accumulated
  - Depleted fuel



Steady-State (Equilibrium)

BP：Burnable Poison
FP：Fission Products

Advantages of Small Sized HTGR with CANDLE Burning Scheme

- Constant reactor parameters
- No requirement for burn-up reactivity control
- No requirement for on-line fuel loading mechanism

Simple O & M

- Favorable axial power profile
- Easy optimization for radial power profile

Thermal Design

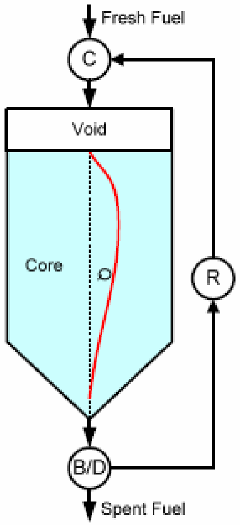
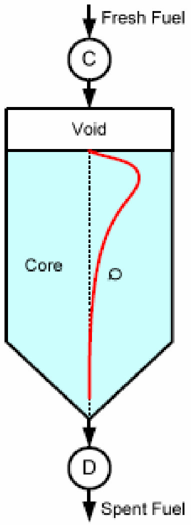
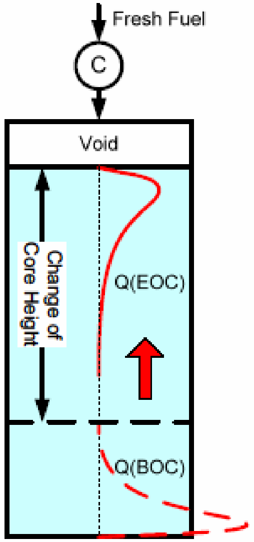
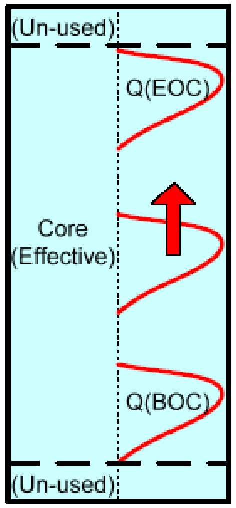
- Proportionality of core height to core lifetime

Long Life Core

- Subcriticality of fresh fuel

Criticaltiy Safety

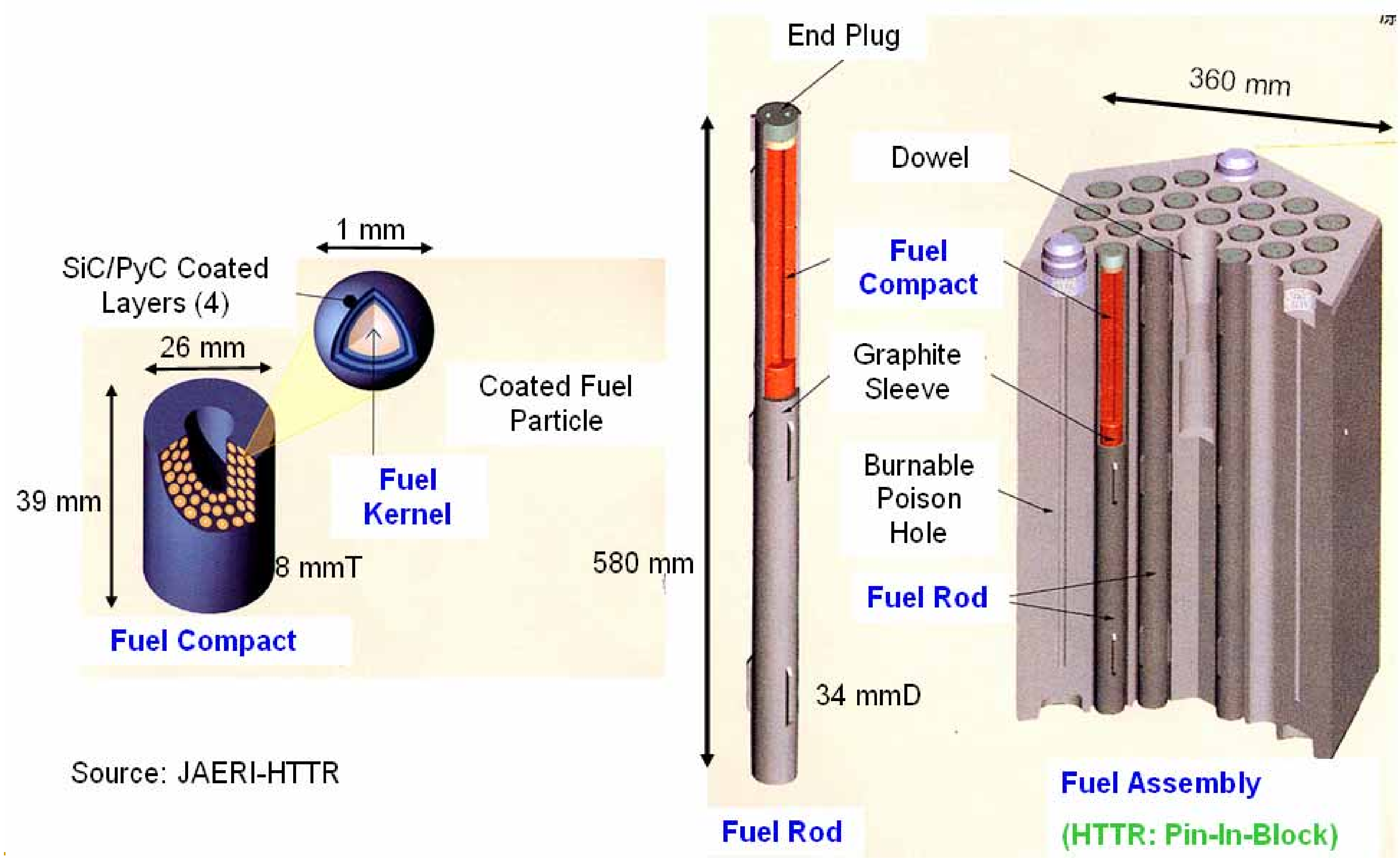
COMPLEX → **SIMPLER**

Fuel Element Type and Burning Scheme	Fuel element	Pebble-type			Block-type
	Burning scheme	Multipass	OTTO	Peu A Peu	CANDLE
	Illustration C: fresh fuel charging mechanism D: burnt fuel discharging mechanism B: burnt fuel burn-up measuring mechanism R: burnt fuel reloading mechanism Q: axial power distribution BOC: beginning of cycle EOC: end of cycle				
	Fresh fuel loading mech.	Yes	Yes	Yes	No
	Burn-up measuring mech.	Yes	No	No	No
	Fuel reloading mech.	Yes	No	No	No
	Fuel discharging mech.	Yes	Yes	No	No
	Core life (theoretical)	Infinite	Infinite	Prop. to core height	Prop. to core height
	Burnable poison	No	No	Yes or No	Yes
	Neutron economy (burn-up level, conversion ratio)	Best	Better	Good (some neutrons leak, BOC)	Good (some neutrons absorbed by BP)
Thermal/ Safety	Power peaking (axial)	Low	Moderate	High (esp. at BOC)	High
	Core pressure drop	Constant	Constant	Change considerably	Constant

Main Design Parameters of Small Sized, Long Life HTGRs

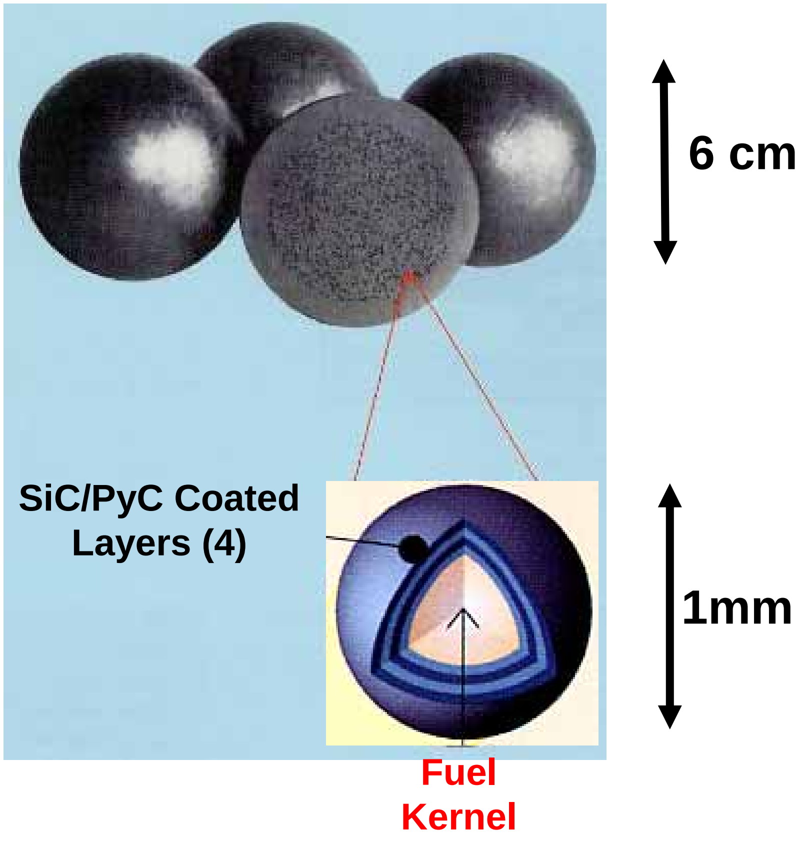
- Power: 25 MWth/Unit
- Core Lifetime: 10 Years
- Fuel (Current Fuel Technology):
  - TRISO
  - Fissile Enrichment 8 % (ref. HTR-M 200)
  - Uranium and Thorium Fuel
  - Burnable Poison (CANDLE): Gd (smeared in kernel)
  - Fast Neutron Fluence Limit $< 3 \times 10^{22}$ n/cm^2
- Burning Scheme (Innovative):
  - Block-type: CANDLE (ref. HTTR), PF=30 %
  - Pebble-type: Multipass, OTTO, Peu-A-Peu (ref. HTR-M 200), MR=537 (7 g HM/pebble)
- Core Dimension:
  - Core Radius: 1.5 m (ref. HTR-M 200)
- Thermal Design (Conservative):
  - He Inlet/Outlet Temperature: 250/750 ^{o}C (ref. HTR-M 200)
  - He Pressure: 4 MPa (< HTR-M 200)

Block Type Fuel Element

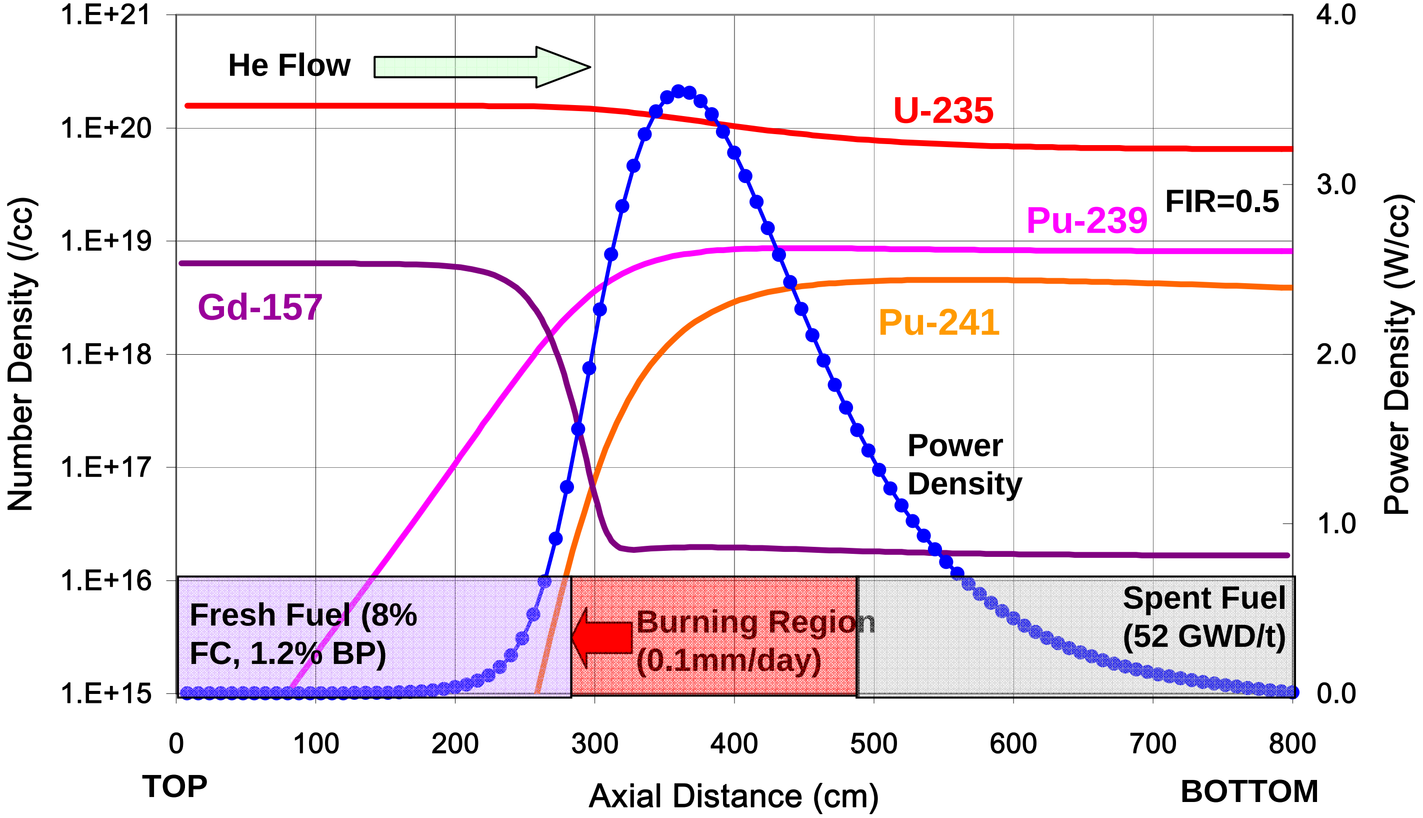


Source: JAERI-HTTR

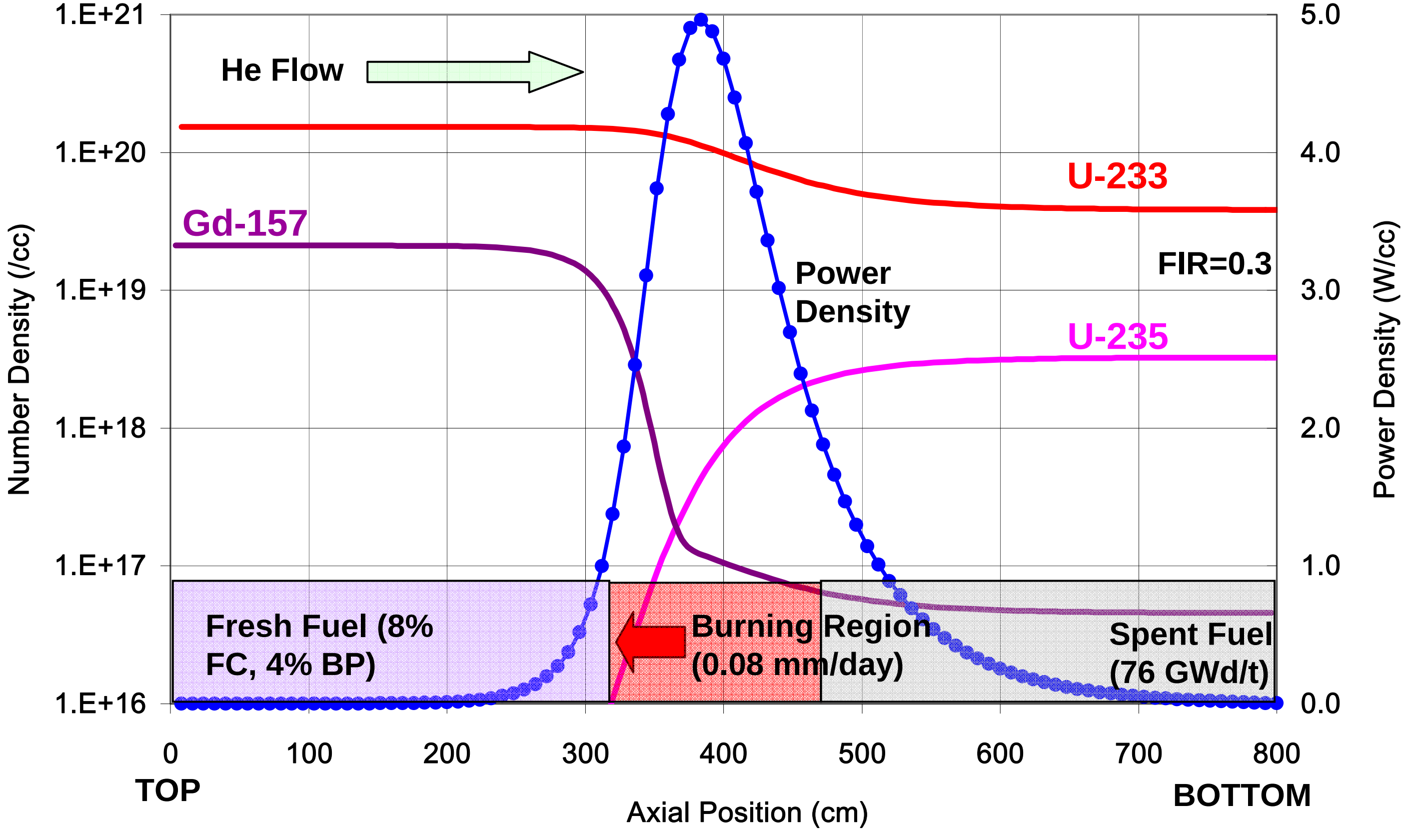
Pebble Type Fuel Element



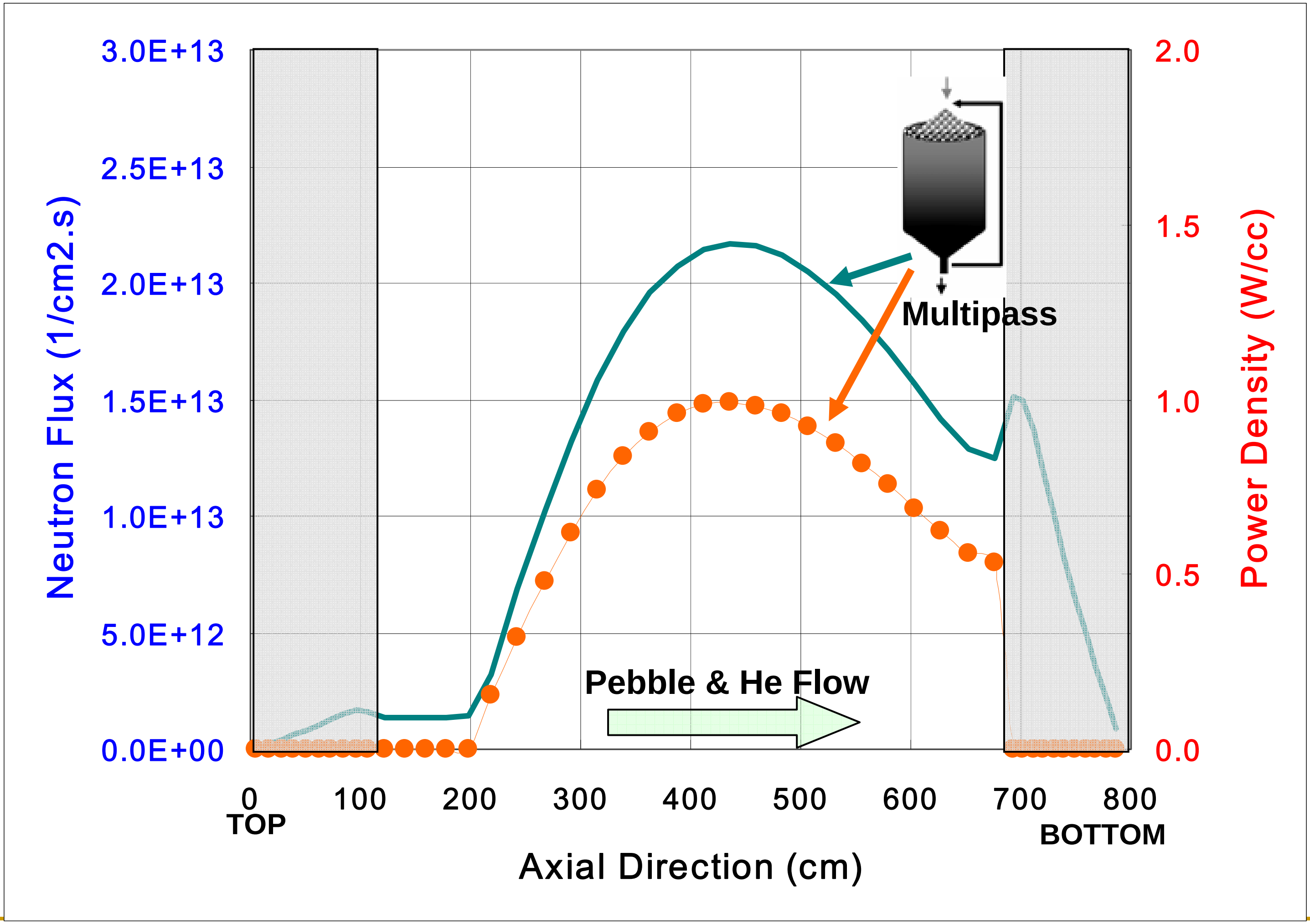
CANDLE, Uranium Fuel, 25 MWth (Equilibrium)



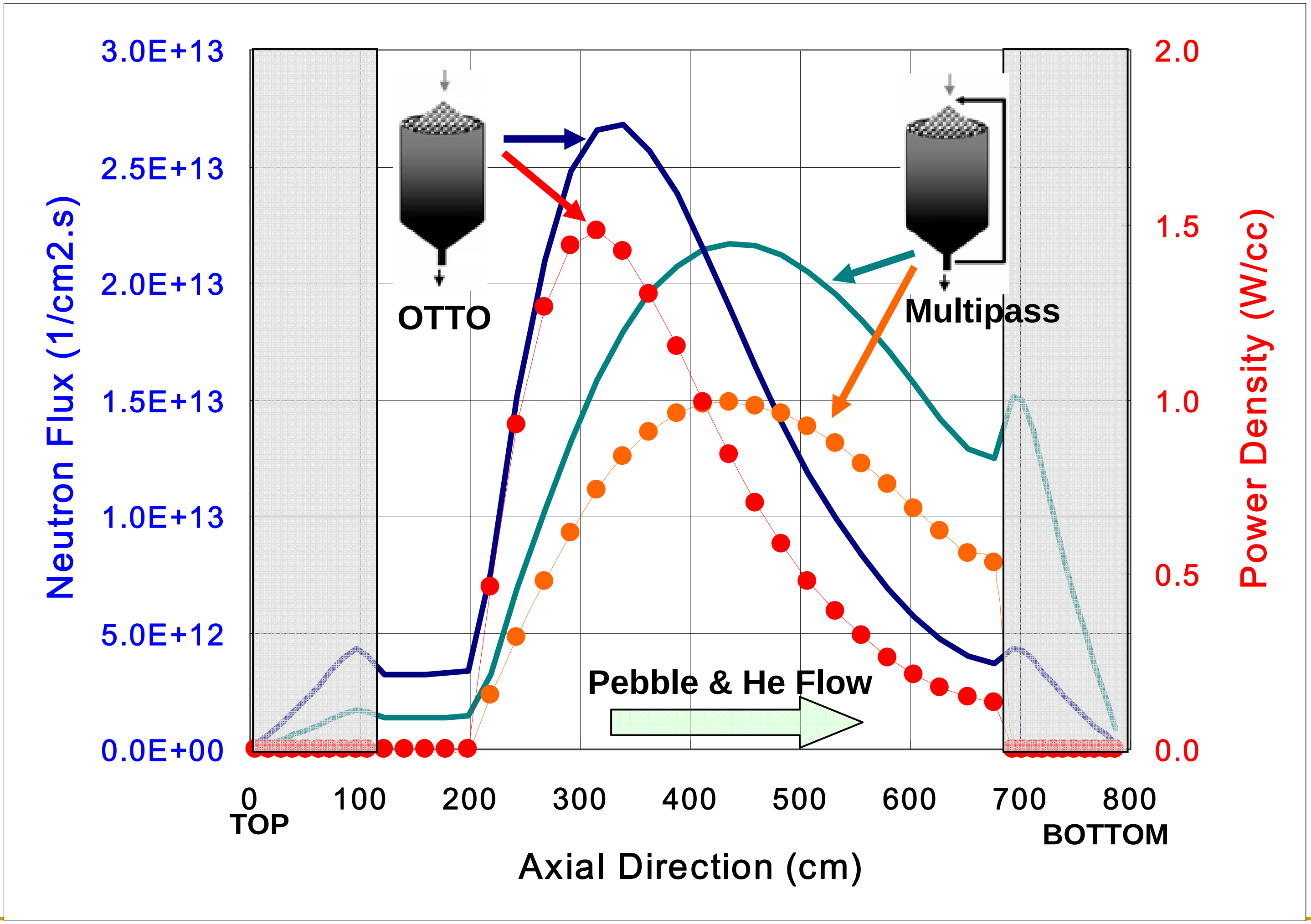
CANDLE, Thorium Fuel, 25 MWth (Equilibrium)



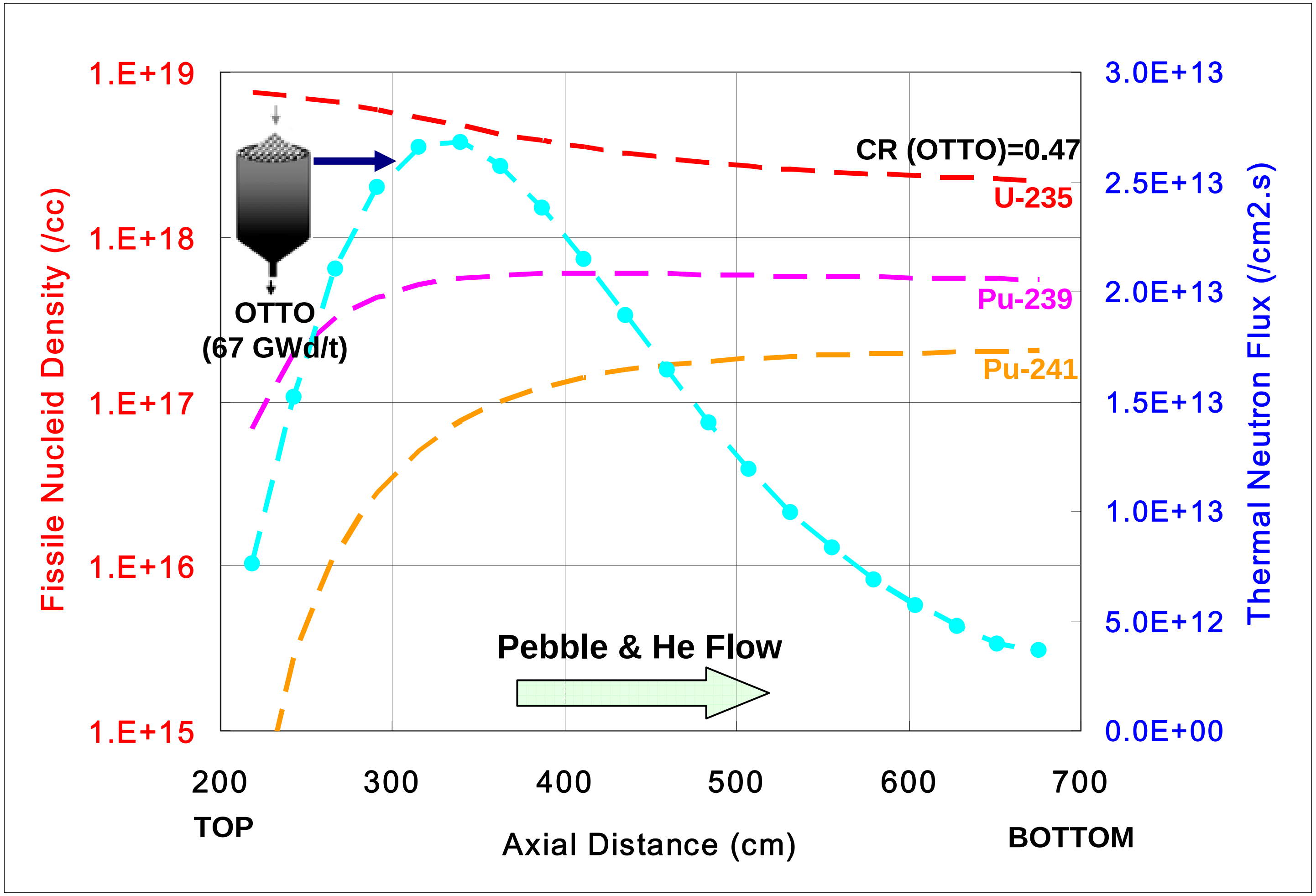
Multipass & OTTO, Uranium Fuel, 25 MWth (Equilibrium)



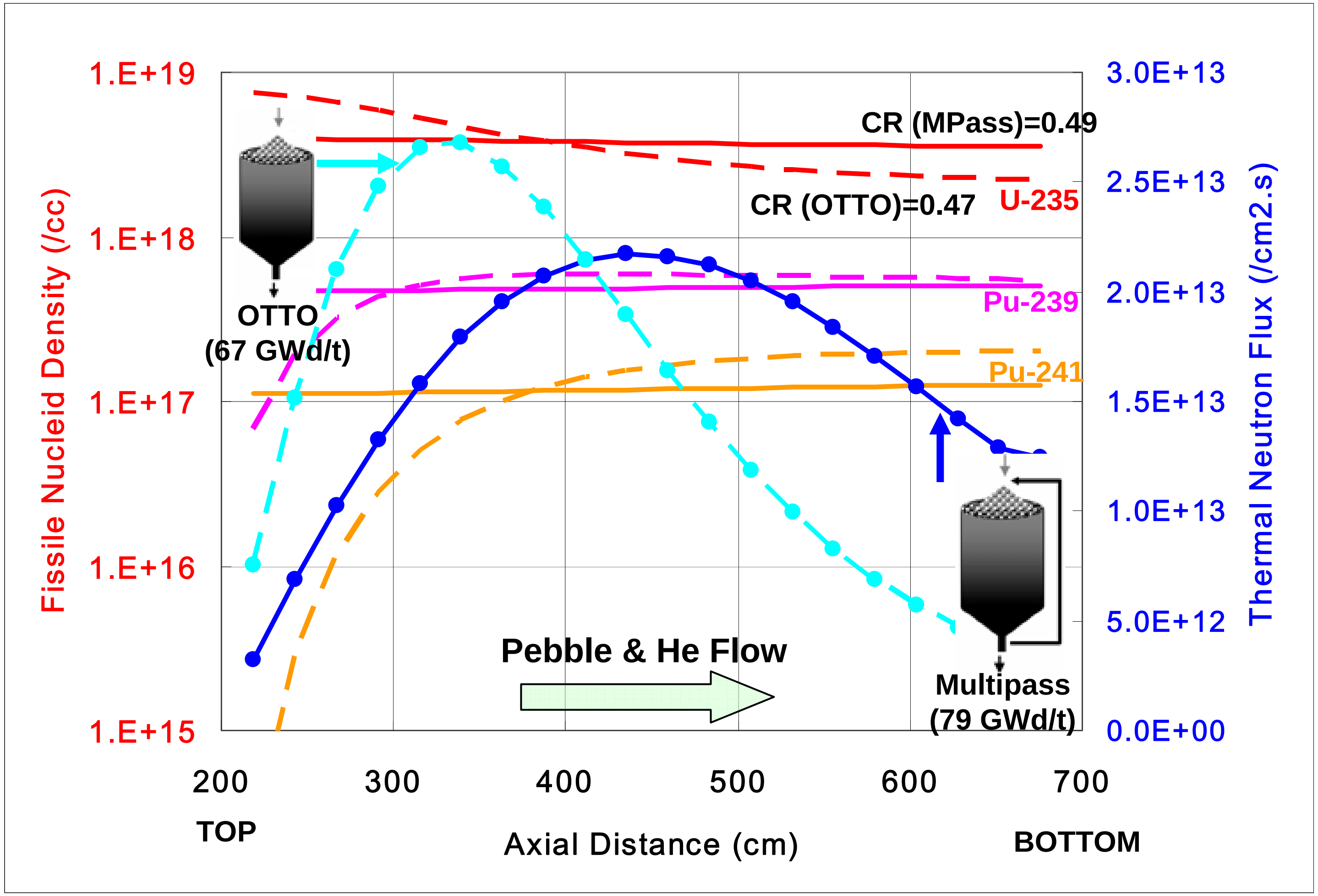
Multipass & OTTO, Uranium Fuel, 25 MWth (Equilibrium)



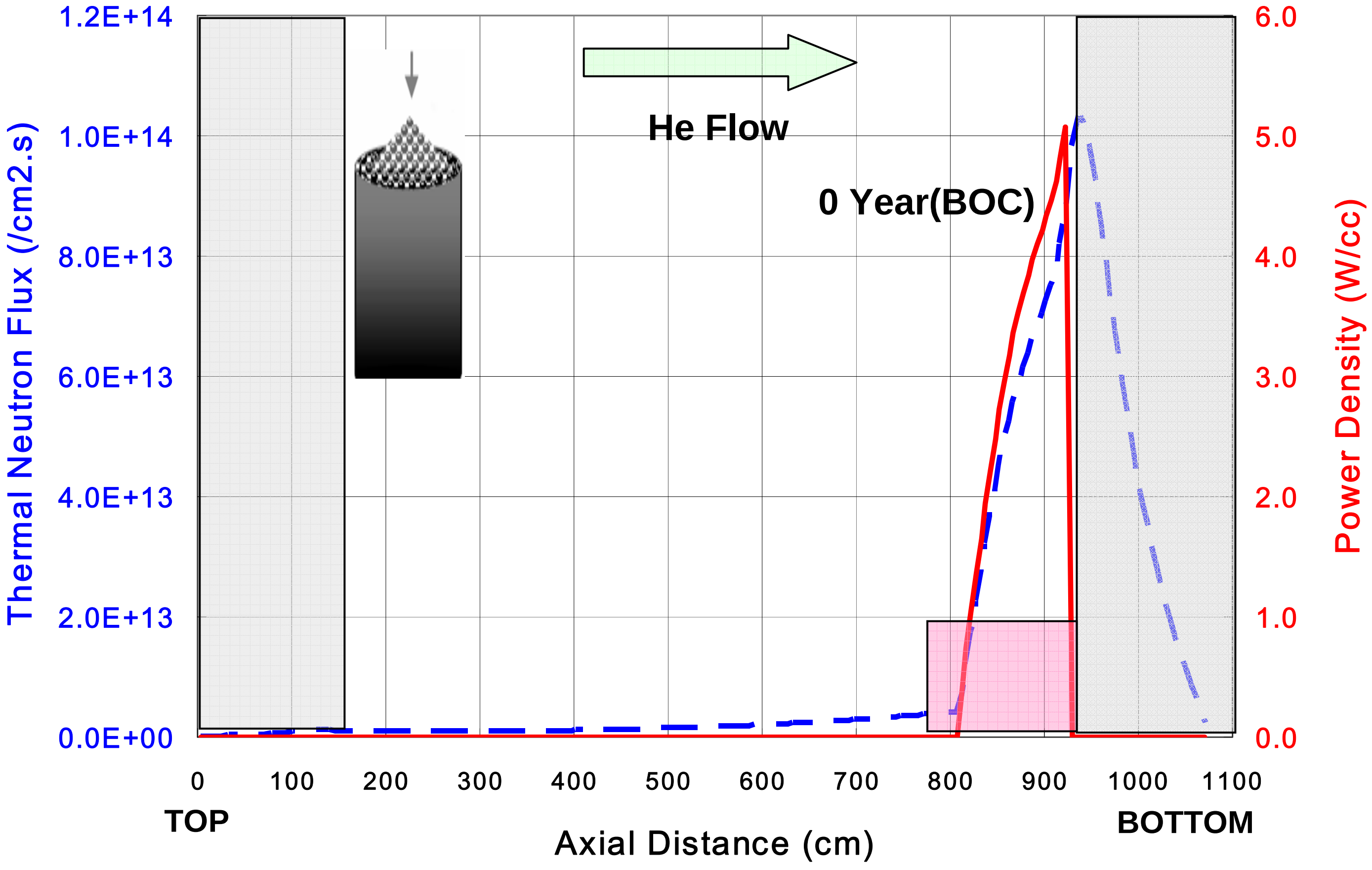
Multipass & OTTO, Uranium Fuel, 25 MWth (Equilibrium)



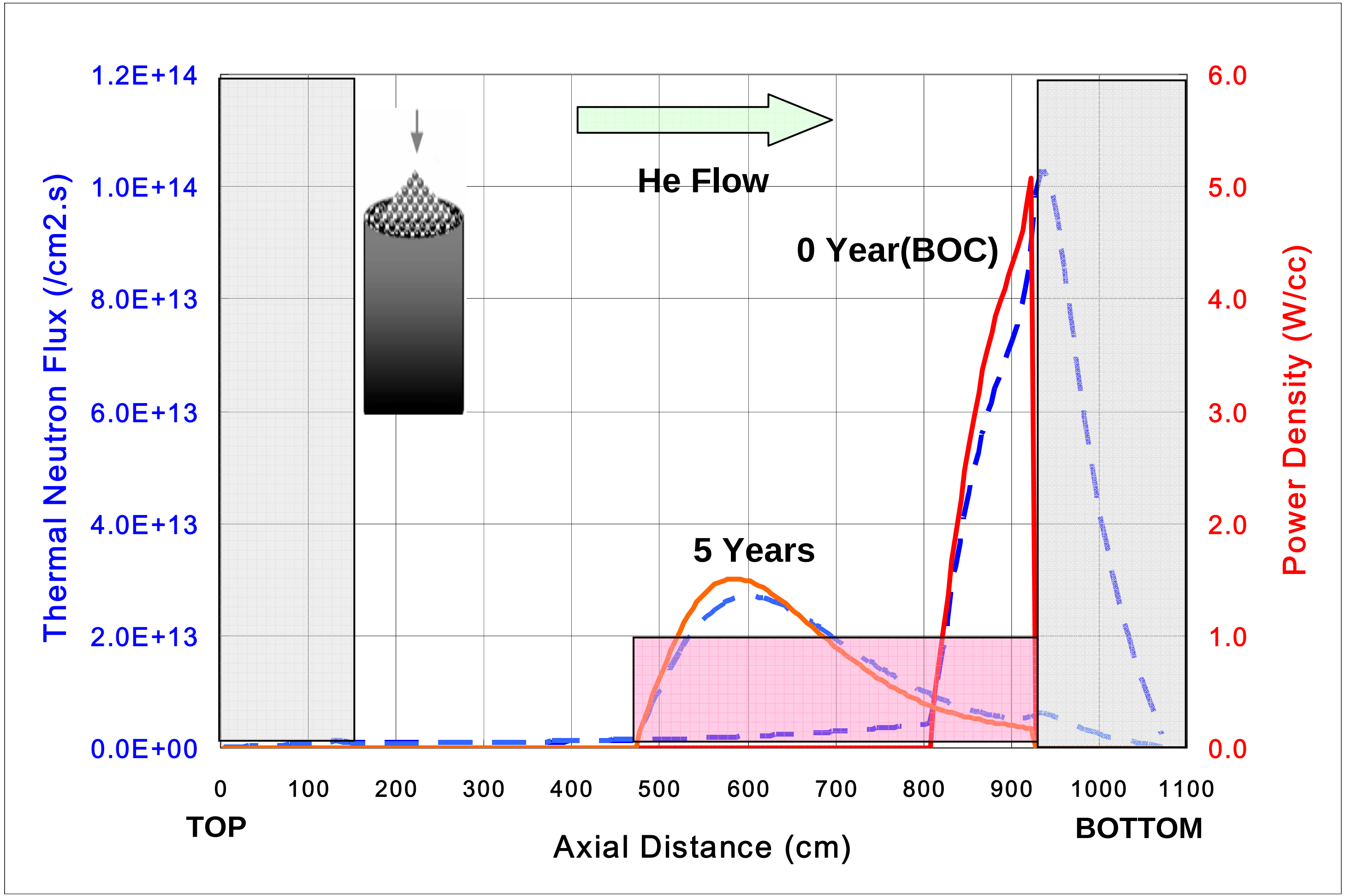
Multipass & OTTO, Uranium Fuel, 25 MWth (Equilibrium)



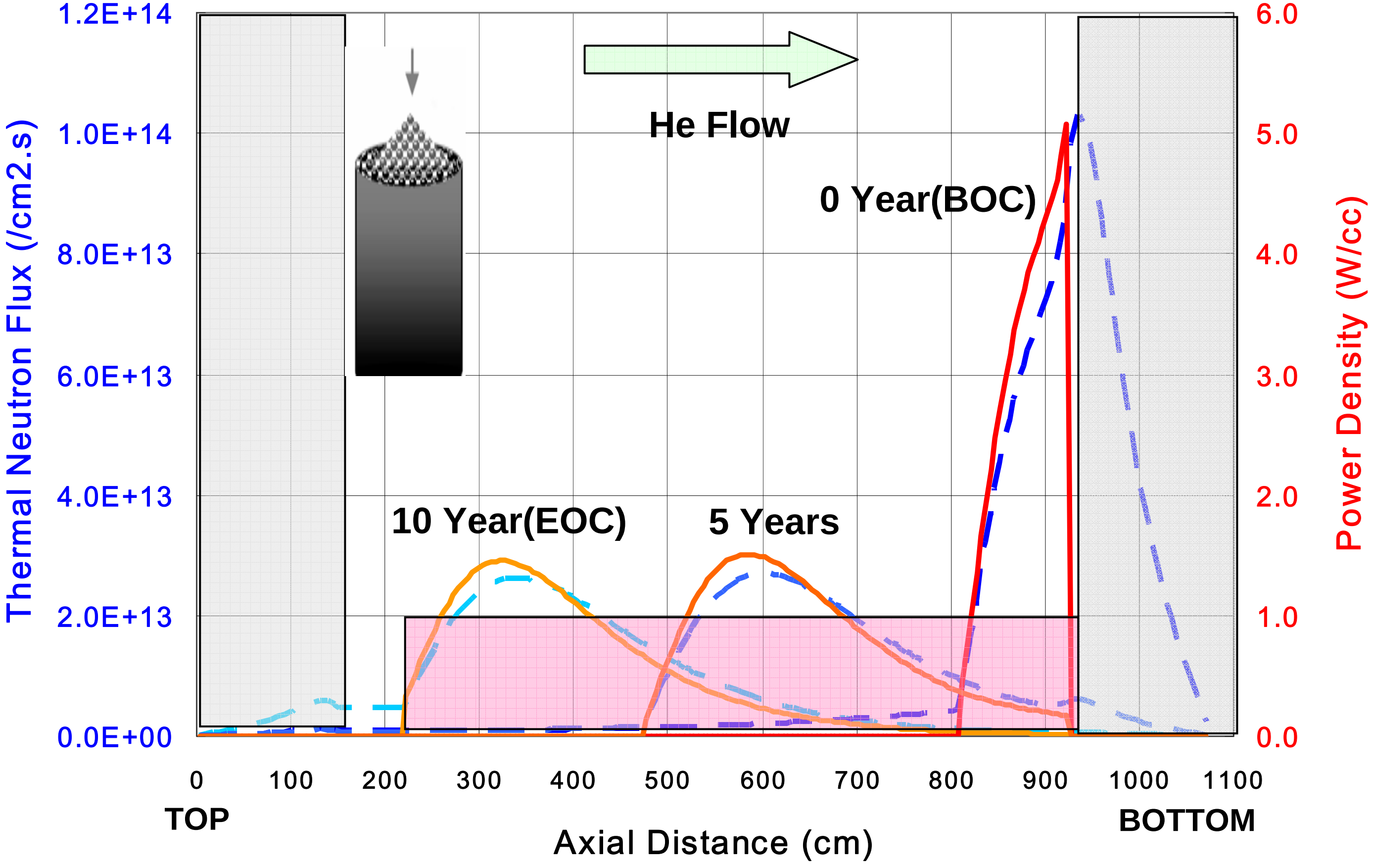
Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



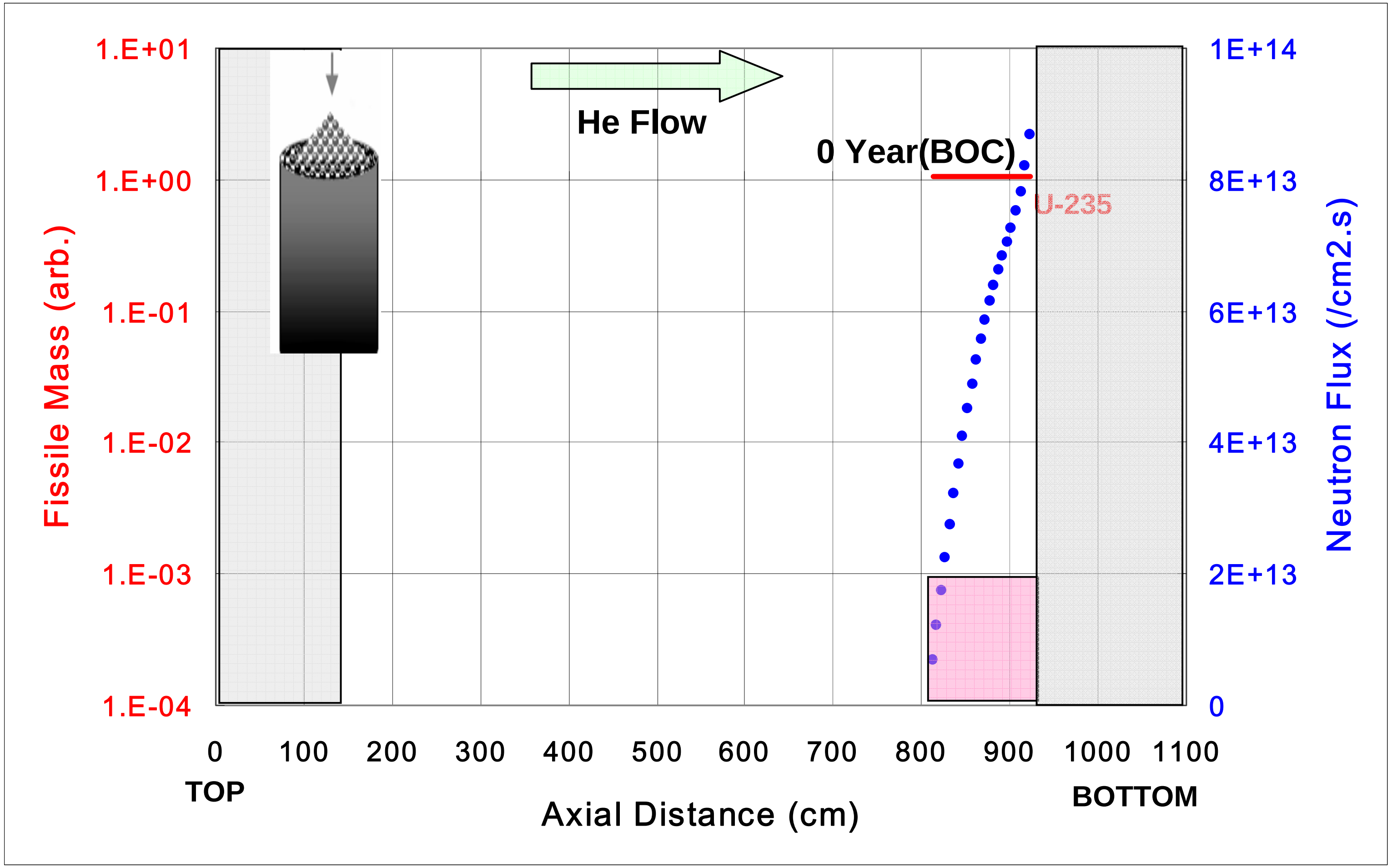
Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



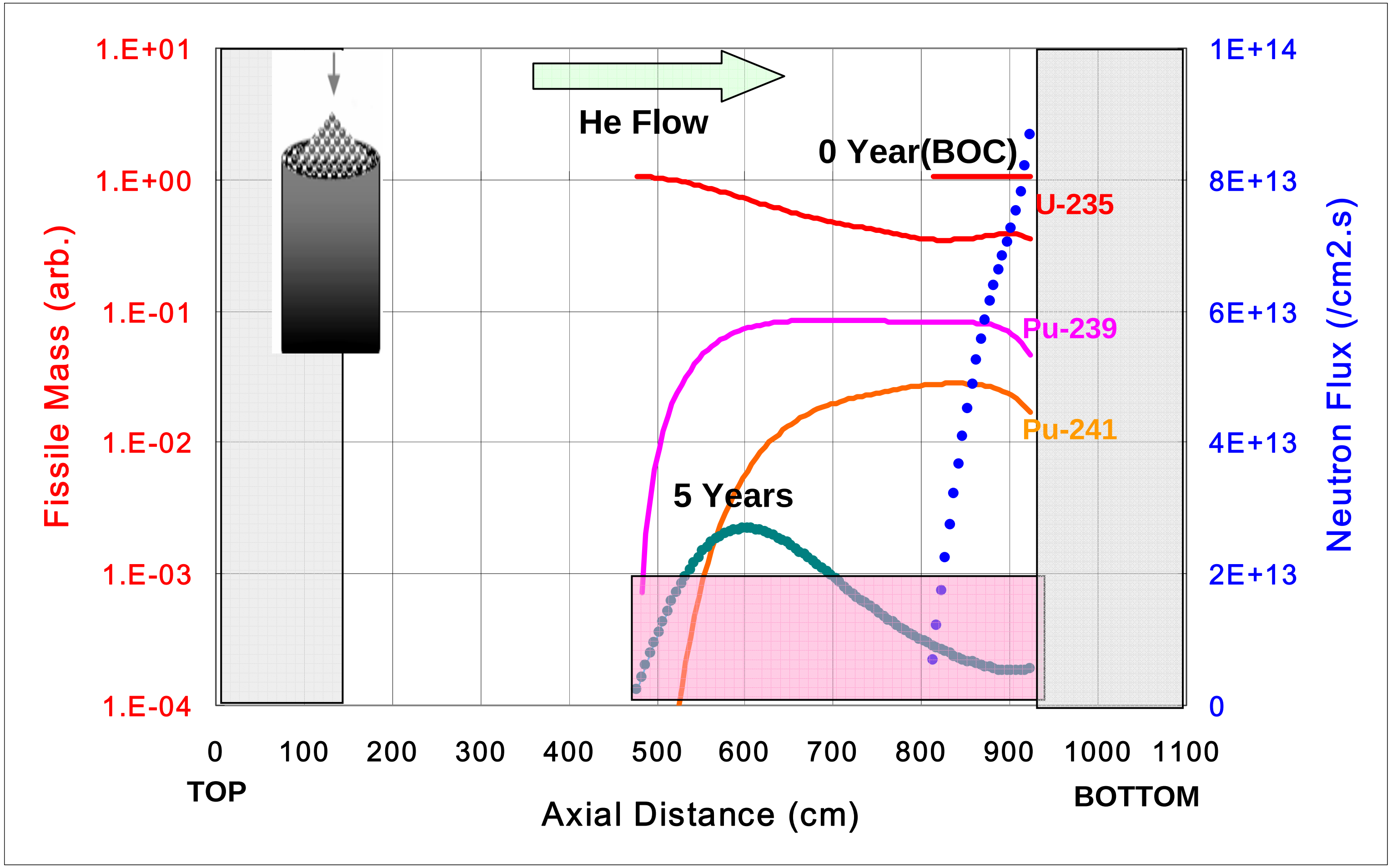
Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



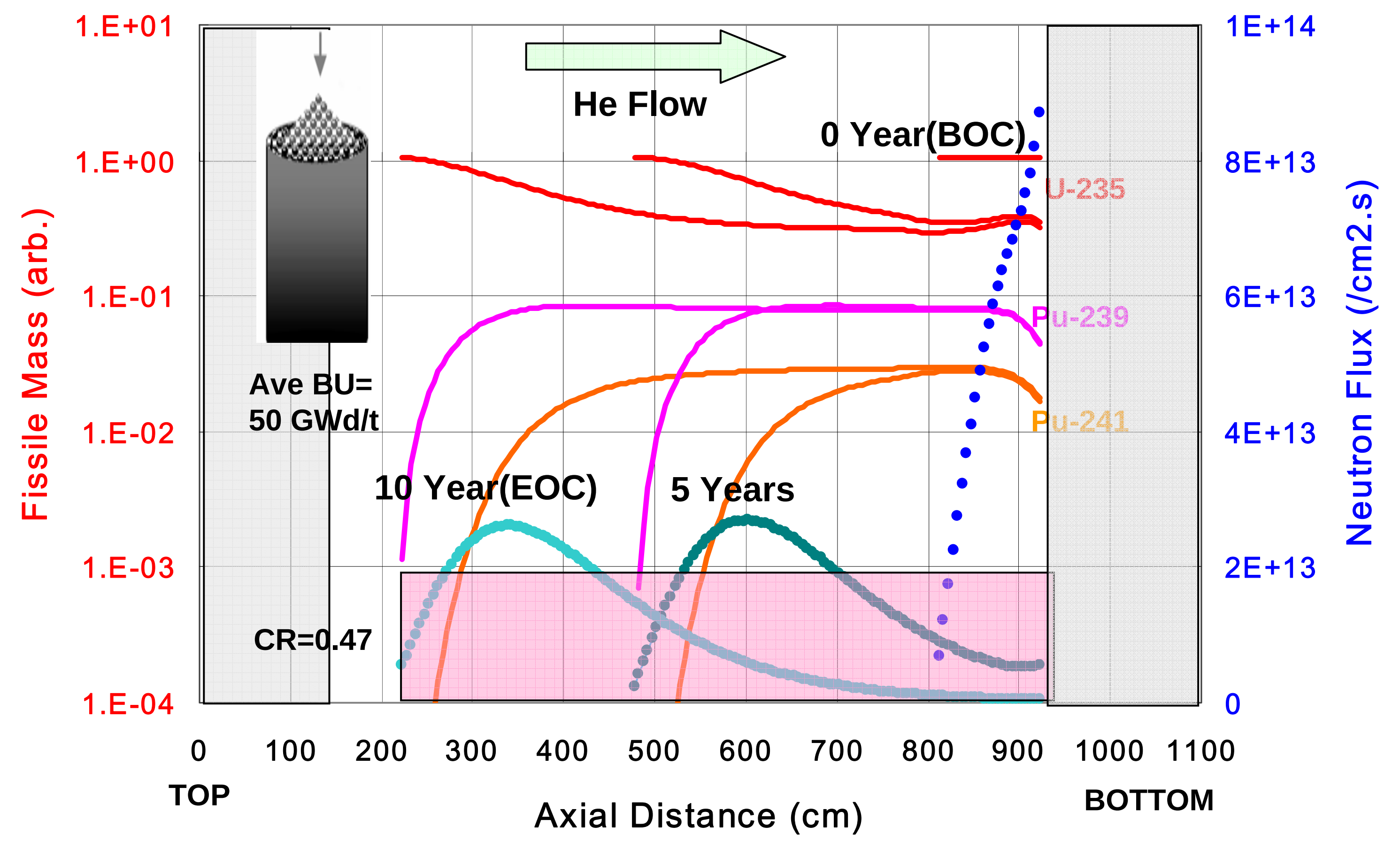
Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



Peu A Peu, Uranium Fuel, 25 MWth (BOC-EOC)



BURNING SCHEME	Multipass	OTTO	Peu-a-Peu	CANDLE
Fuel Element Type	Pebble-type			Block-type
Fresh Fuel Loading Method	On-line, Continuous			Off-line, Batch
Thermal Power (MWth)	25.0			
Core Diameter (m)	3.0			
CFP and Fissile Enrichment	TRISO, 8.0 % 2)			
Core Height (m) and Volume (m³)	4.5 / 31.8	4.5 / 31.8	6.9 / 48.8	4.1 / 29.0
	4.5 / 31.8	4.5 / 31.8	4.0 / 28.3	2.9 / 20.5
Core Life Time (year) or	11.0	9.4	10.0	10.0
Residence Time (year)	16.5	14.0	10.0	10.0
Velocity (cm/day) or	1.8	0.14	1774.0	0.113
Fueling Rate (ball/month)	1.2	0.09	703.0	0.080
Fissile Loading (kg/GWD)	1.03	1.20	1.61	1.53
	0.68	0.81	1.13	1.05
Ave. Burn-up (GWD/t)	78.5	67.2	49.8	52.3
	117.0	99.4	71.1	76.3
Conversion Ratio (CR) or	0.486	0.468	0.471	0.492
Fissile Inventory Ratio (FIR)3)	0.549	0.490	0.488	0.271
Max. Power Density (W/cm³)	0.99	1.53	4.78	3.55
	1.02	2.10	7.33	4.96

Concluding Remarks

- CANDLE and other innovative burning schemes with the current fuel and HTGR technologies are potential to be adopted for small sized, long life HTGRs which are expected to be deployed in remote areas or less developed regions where only minimum infrastructures and resources are available
- Needs of CANDLE burning demonstration
- More works are still required for improving CANDLE burn-up performance (burnable poison design etc.), further study for start-up, “end effect” for short core, thermal design, accident analyses etc.

Thank You !