

Burnup Study of SFRs with Monte Carlo Codes (MCNP & SERPENT) and Deep Neural Networks

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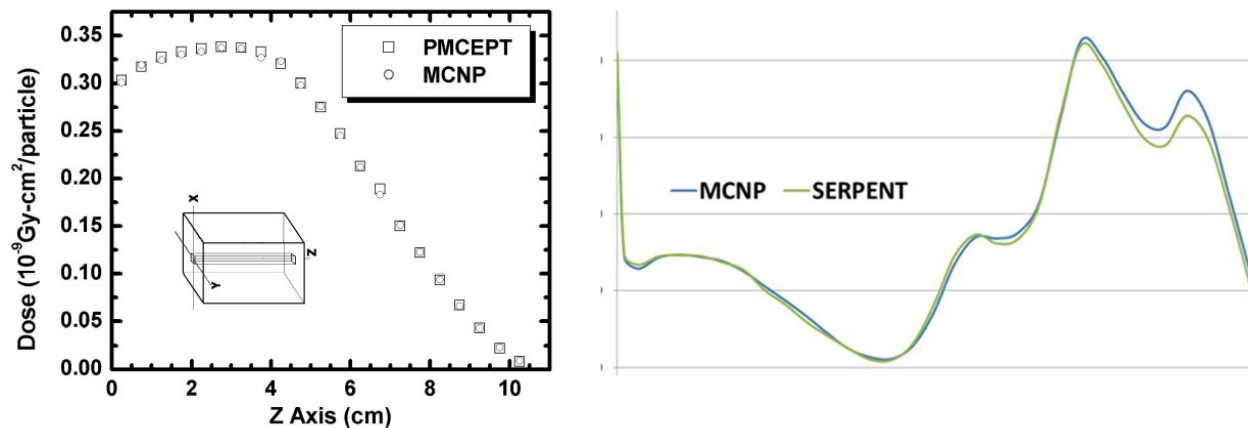
October 24-25, 2024

Warming Up: Characteristics of Monte Carlo codes (quiz 풀이)

- Precise geometry model
- Realistic algorithm
- Accurate physics data

1. MC code 사용자 조사

2. Two MC 코드 비교계산 예: Depth dose & Depletion



3. Quiz: MC code에 대한 참말 거짓말 고르기

제 3의 다른 MC코드를 이용하여 위 그림을 계산하여도 동일한 결과를 얻는다.
만약 결과가 다르다면 제 3의 MC코드에 결함이 있다.

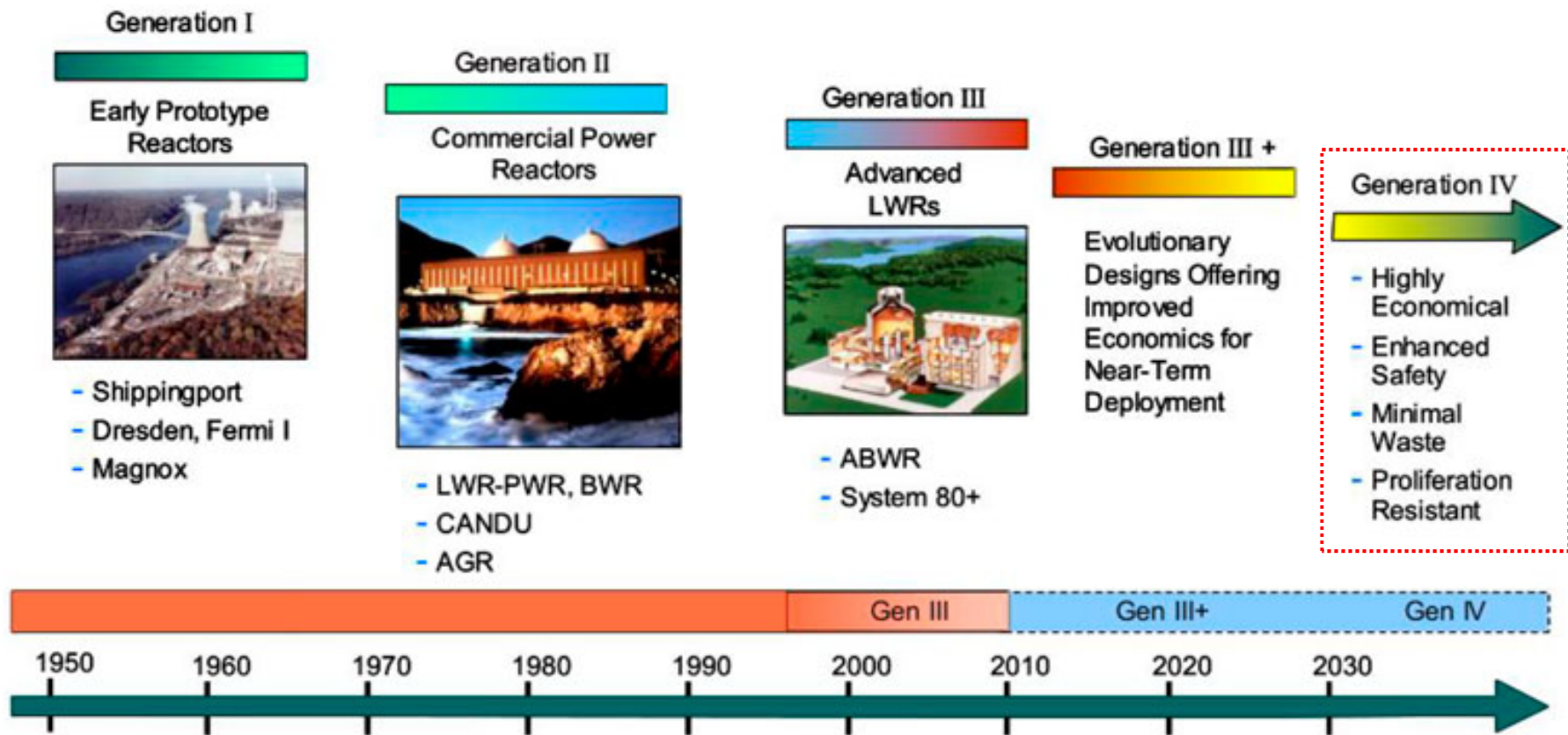
몬테칼로 계산은 핵자료에 있어서나 계산 방식에 있어서 가정이나 근사가 가장 작은 방법으로 노심에
서의 중성자 거동을 모사하는 가장 정확한 방법이므로

저도 MCNP와 같은 몬테칼로코드로 수송계산뿐 아니라 연소계산도 다 해보고 드리는 말씀이며,
몬테칼로계산이든 결정론이든 연소계산시에는 mesh나뉘야 한다는 것은 너무 당연해서

Outline

- **Introduction**
 - History of reactor development
 - Generation IV reactors
 - Sodium-cooled fast reactor system
 - Brief history of ESRF
- **Methods and Models**
 - Comparison of MCNP and SERPENT codes
 - Structure of deep neural networks
- **Results**
 - Rolling windows training and forecasting data set
 - Time series forecasting result
 - Deep neural network regression
- **Discussion**
 - Usefulness of DNNs for computing K_{eff}
 - Issue for scrutiny
 - Example of good agreement between MCNP and SERPENT in PWR
- **Conclusions**

History of Reactor Development

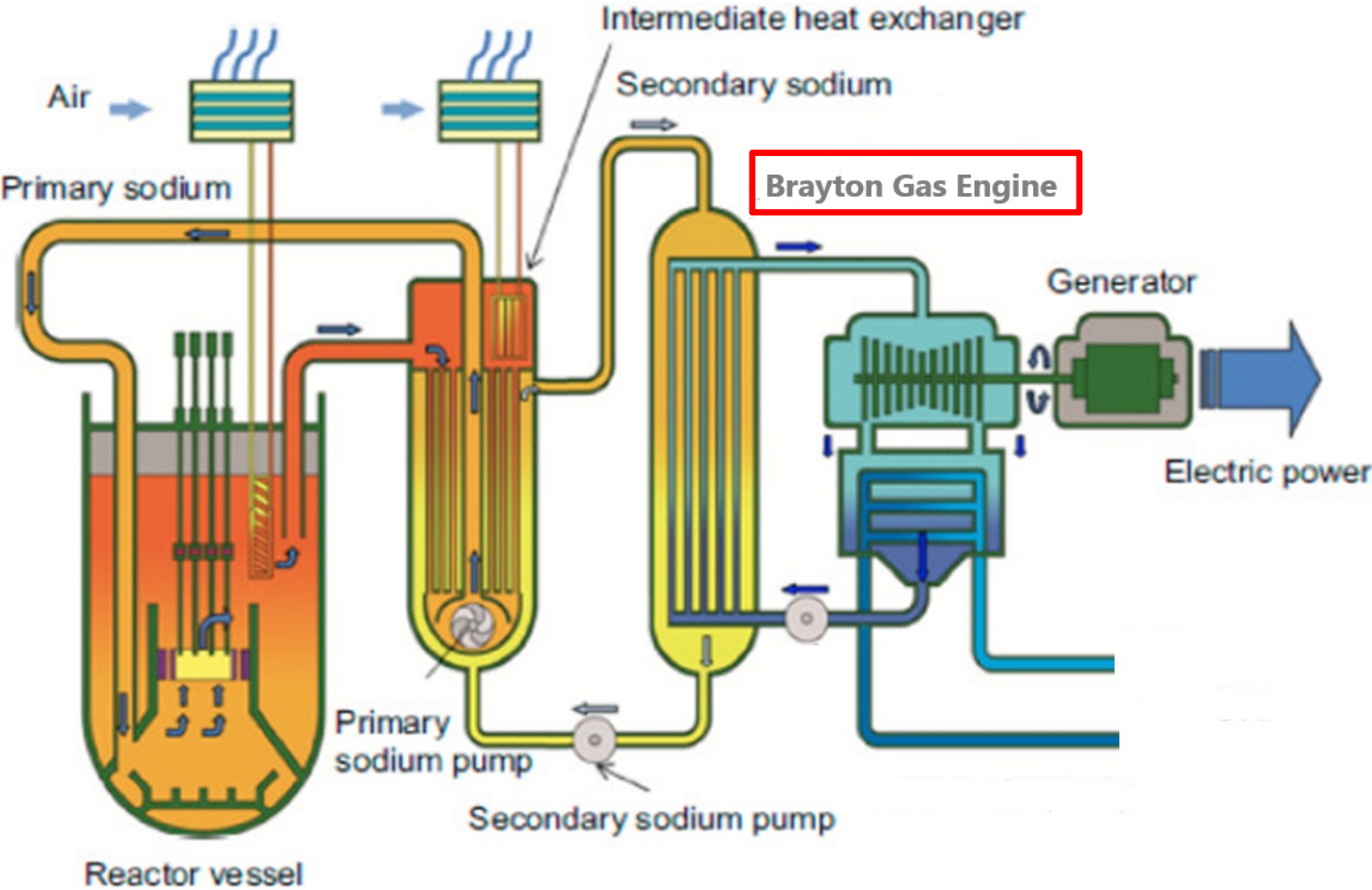


Generation IV Reactors

- The Generation IV International Forum (GIF) – an international organization that coordinates the development of generation IV reactors – specifically selected **six reactor technologies** as candidates for generation IV reactors.
- **The six designs selected were: the gas-cooled fast reactor (GFR), the lead-cooled fast reactor (LFR), the molten salt reactor (MSR), the sodium-cooled fast reactor (SFR), the supercritical-water-cooled reactor (SCWR) and the very high-temperature reactor (VHTR).**
- **The sodium-cooled fast reactor (SFR) has received the greatest share of funding that supports demonstration facilities.**
- **Key usefulness of SFR:** Efficient Fuel Utilization; Waste Reduction; Enhanced Safety Features; Higher Operating Temperatures; Proliferation Resistance; Design Flexibility; Long Operational Lifespan

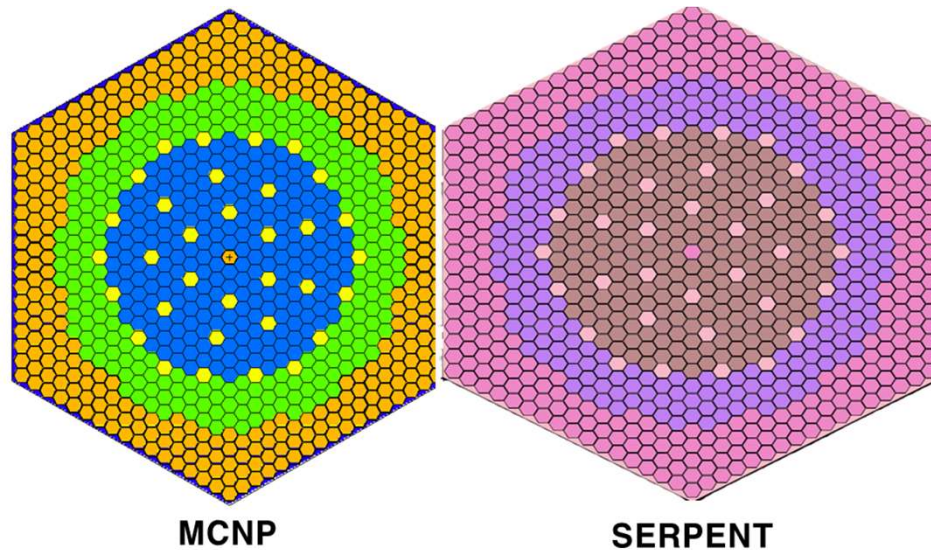
Sodium-cooled Fast Reactor System

Pool Type Reactor



ESFR

- A new European Sodium-cooled Fast Reactor (ESFR) project, with a slightly higher **power of 3600 MW_{th}**, was launched in collaboration between France, Italy, Germany, and the UK.
- **Hexagonal compact core type**

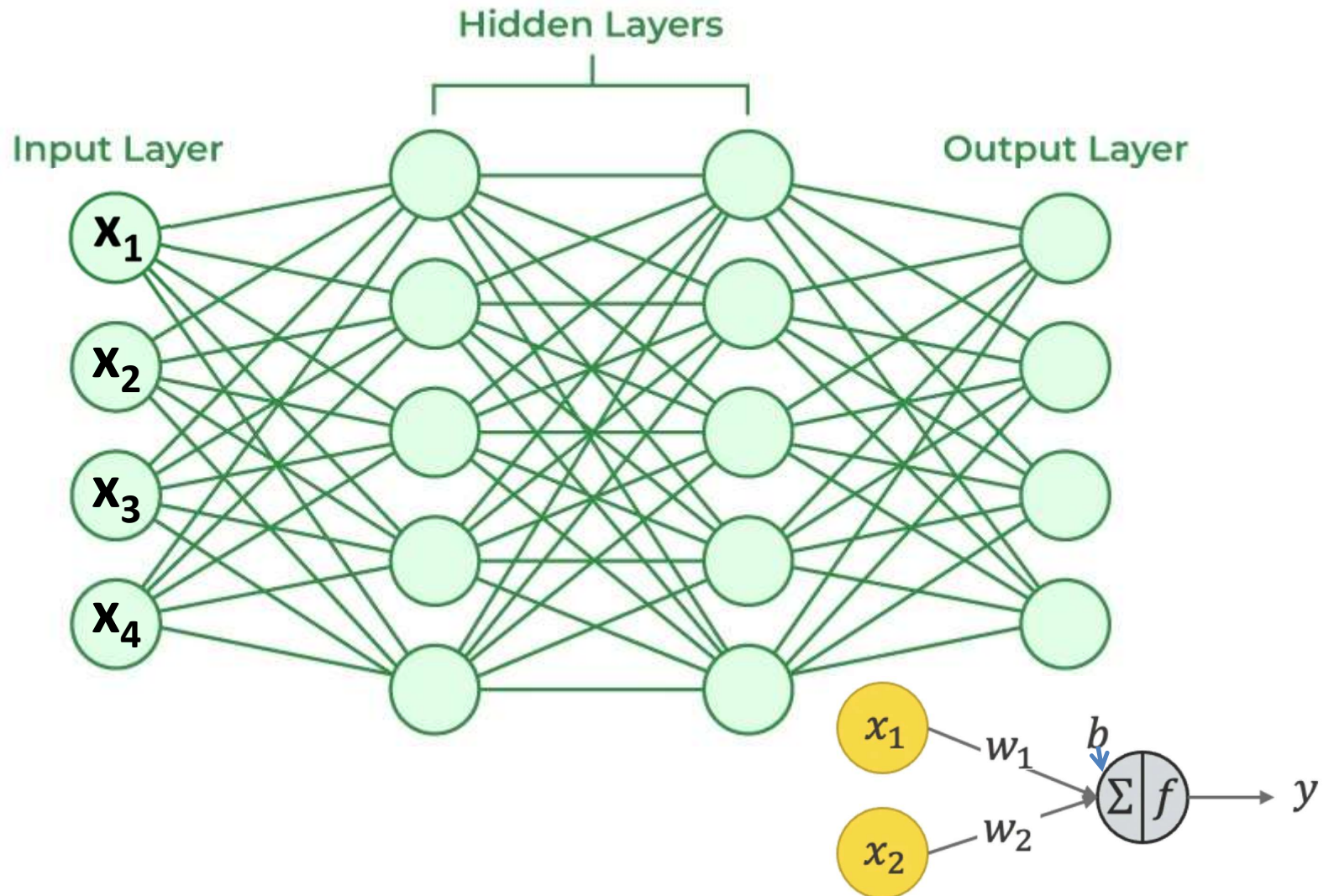


- **The largest Generation IV power reactor ever designed.**

MCNP & SERPENT Codes

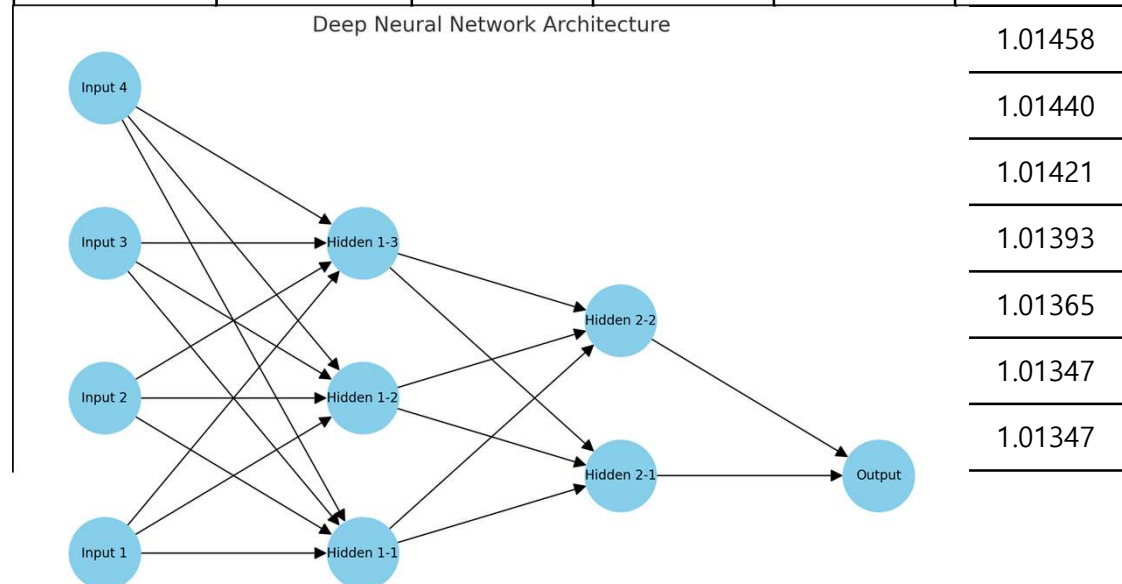
Feature	MCNP6	Serpent 2
Development	Developed by LANL, USA	Developed by VTT, Finland
Application	General-purpose, wide range of applications	Optimized for reactor physics applications
Particle Transport	Neutrons, photons, electrons, and many others(32?)	Primarily focused on neutrons
Photon/Electron Transport	Well-developed	Less developed
Burnup and Depletion	Built-in (CINDER90), detailed capabilities	Advanced (No NJOY & On-The-Fly), efficient calculations(Group constants)
Computational Efficiency	High resource demand	High efficiency for reactor simulations
Learning Curve	Steeper due to complex input syntax	User-friendly input tailored for reactor modeling
Versatility	Suitable for a variety of applications	Less versatile outside reactor physics
Advanced Techniques	Standard Monte Carlo techniques	Utilizes advanced acceleration techniques

Deep Neural Network

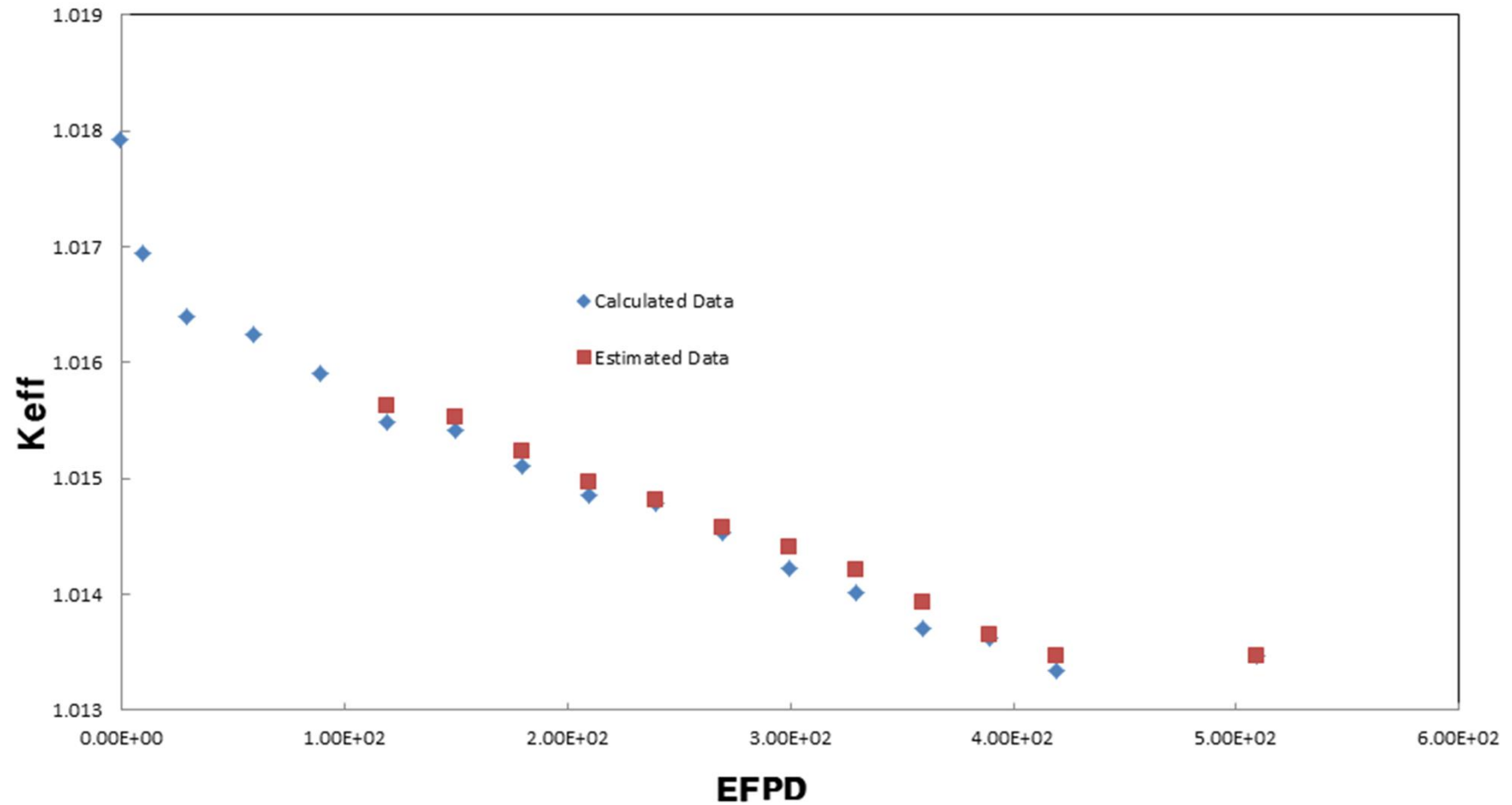


Rolling Windows Training and Forecasting Dataset

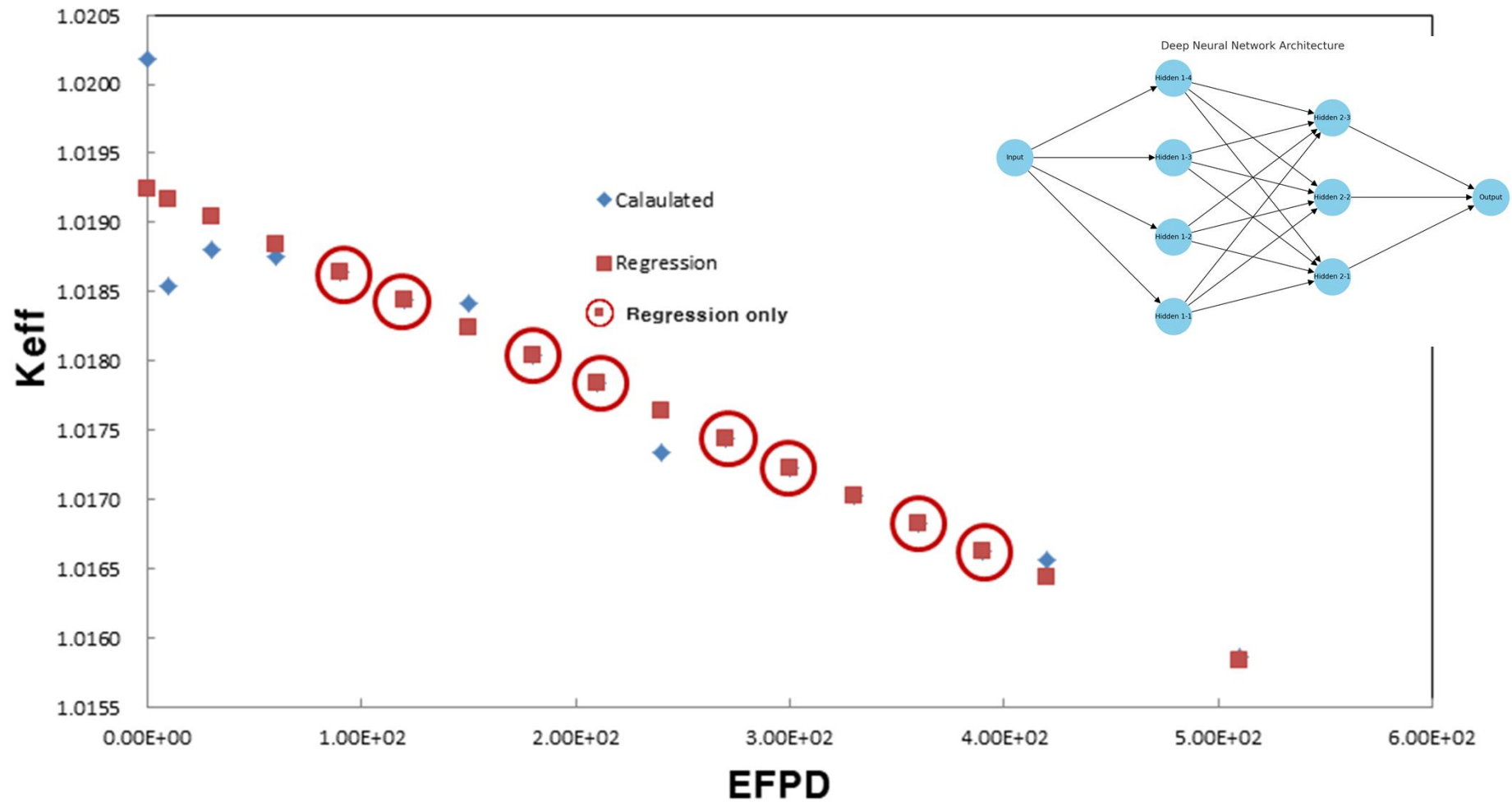
Training Data					Forecasted
Input				Output	
1.01792	1.01640	1.01624	1.01591	1.01548	1.01562
1.01640	1.01624	1.01591	1.01548	1.01541	1.01553
1.01624	1.01591	1.01548	1.01541	1.01511	1.01524
1.01591	1.01548	1.01541	1.01511	1.01485	1.01497
1.01548	1.01541	1.01511	1.01485	1.01478	1.01482



Time Series Forecasting Results




Deep Neural Network Regression



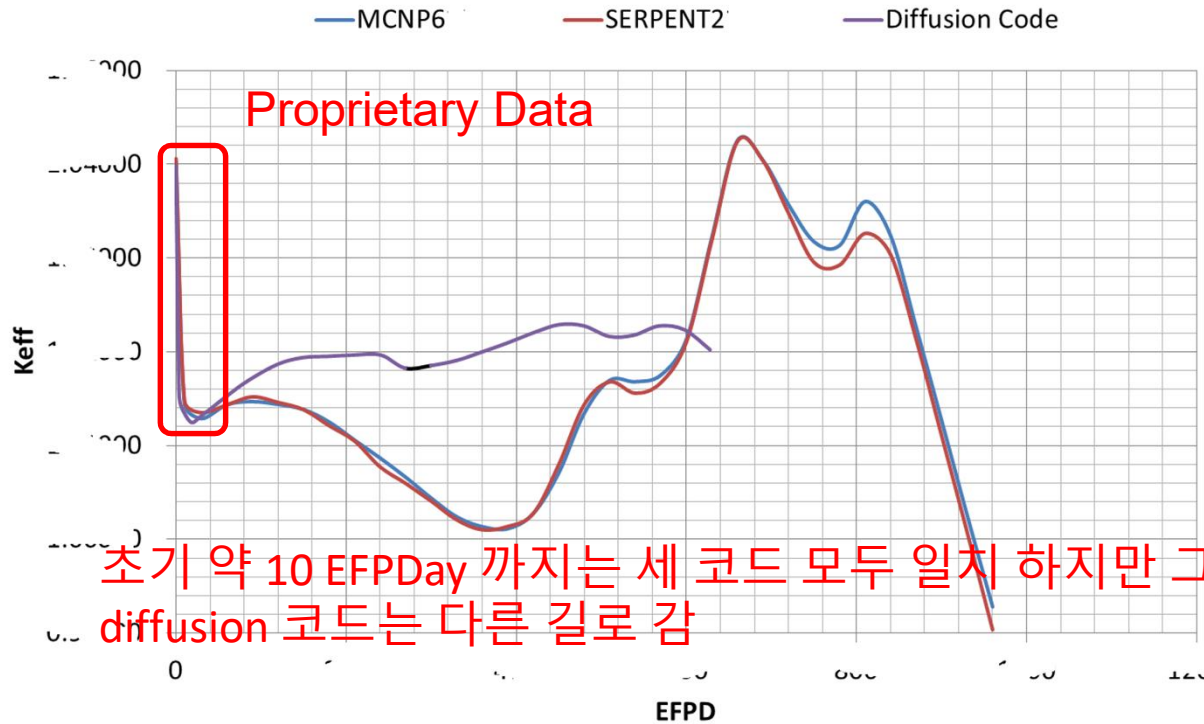
Usefulness of DNN for Computing K_{eff}

- **Understanding and controlling K_{eff} is essential** for the safe design and operation of nuclear reactors, as it directly affects the reactor's stability and power output.
- **Monte Carlo methods are highly regarded for accurately simulating the behavior of neutrons** within a nuclear reactor core due to their probabilistic nature (**Stochastic Nature of Neutron Behavior**) and ability to model complex geometries (**Detailed Geometry Modeling**) and physical processes (**Accurate Microscopic Cross-Section Representation**).
- **Monte Carlo simulations in nuclear physics rely heavily on the principles of Markov processes (local)**. The results have inherent statistical noise, and achieving low uncertainty requires many neutron histories, increasing computational time.
- **DNNs are powerful computational models that have shown exceptional capability in pattern recognition, approximation, and regression tasks (global)**.
- In the context of extracting true values from statistical fluctuations, **they serve as supplementary tools (narrowing the gap)** that can effectively learn underlying patterns and provide accurate estimates even when data is noisy or exhibits random variations.

Issue for Scrutiny

- **Discrepancy in Burnup Step Analysis:** There was a noticeable difference in results between the MCNP and SERPENT codes, especially **in the second and third burnup steps.**
- **Discrepancy Between Monte Carlo Codes:** The study found a difference of up to 300 pcm (**narrowing the gap**) between the effective multiplication factors calculated by the MCNP and SERPENT codes.  **Comparing to Pressurized Water Reactor (PWR) study (Good agreement)**

PWR에서 MCNP와 SERPENT 코드가 매우 잘 일치하는 예



ChatGPT-4o에 질의: 노심 연소 계산에서 MCNP6와 SERPENT2같은 세계적으로 잘 알려진 몬테카를로 코드를 사용한 Keff vs. EFPD 곡선이 EFPD 전 범위에서 서로 잘 일치하지만 diffusion 코드 결과는 초기 약 10 EFPD까지만 일치하고 그 이후 점차 일치하지 않는다면 어느 쪽을 더 신뢰해야 하는가? 그 이유는 무엇인가?

ChatGPT-4o의 대답

- Monte Carlo 코드인 MCNP6와 SERPENT2가 연소 계산에서 Keff vs. EFPD 곡선이 EFPD 전 범위에서 서로 잘 일치한다면, 이 두 코드를 더 신뢰하는 것이 합리적입니다. 그 이유는 Monte Carlo 방식이 중성자 수송을 매우 정밀하게 확률론적으로 시뮬레이션하며, 연소가 진행됨에 따라 발생하는 복잡한 물리 현상과 연료 성분 변화까지 정확하게 모델링할 수 있기 때문입니다.
- 특히, 두 개의 서로 다른 Monte Carlo 코드가 결과적으로 일치한다는 것은 매우 중요한데, 이는 각 코드가 독립적으로 구현되었음에도 불구하고 동일한 물리적 현상을 일관되게 반영하고 있음을 의미합니다. 이는 물리 모델과 크로스 섹션 데이터가 두 코드 모두에서 정확하게 구현되었고, 무작위성에 따른 통계적 변동성을 잘 관리하여 신뢰할 수 있는 결과를 제공하고 있다는 것을 보여줍니다.
- 반면, diffusion 코드는 중성자 수송 방정식을 단순화한 접근법으로, 연소가 진행됨에 따라 복잡한 연료 변화와 상호작용을 세밀하게 반영하기 어려운 경우가 많습니다. 초기 약 10 EFPD에서는 연료 성분의 변화가 크지 않기 때문에 diffusion 코드와 Monte Carlo 코드의 결과가 유사할 수 있지만, 연소가 진행되면서 이러한 단순화된 모델이 점차 실제 현상을 제대로 반영하지 못해 두 코드 간의 차이가 커질 수 있습니다.
- 따라서, Monte Carlo 코드들인 MCNP6와 SERPENT2가 서로 잘 일치하는 경우, 이들 코드를 더 신뢰하는 것이 타당하며, 특히 EFPD가 진행될수록 이들의 결과가 더 정확할 가능성이 높습니다. Monte Carlo 방식은 물리적 상호작용을 더 세밀하게 처리할 수 있기 때문에, 복잡한 연소 과정에서는 diffusion 코드보다 Monte Carlo 코드를 더 신뢰해야 합니다.

Conclusions

- **Monte Carlo methods offer the highest accuracy for simulating reactor burnup: by precisely modeling complex geometries and physical processes, as well as accurately simulating neutron behavior.**
- **Discrepancies in Baseline Calculations:** For the PWR, excellent agreement in the baseline Keff calculation. For the SFR, slight discrepancies of up to 300 pcm, need for further investigation and validation.
- **Integration of Monte Carlo Simulations and Neural Networks:** Supplementary tools (local [MC]+ global [DNN]) for less fluctuation and narrower gaps . Regression is the best interpolation algorithm with step wise data for control (rod) design.
- **Challenges and Limitations:** The study's challenges, stemming from a small dataset and discrepancies between different codes, underscore the need for additional data collection, model refinement, and cross-validation to ensure the reliability and practical applicability of methods in nuclear reactor burnup studies.

END

Any Questions?

ChatGPT-4o와 다른 의견이 있는 분은 아래 주소로
연락주심 감사하겠습니다.

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