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Optimization of spent nuclear fuel canister loading using a neural network and genetic algorithm

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Work done at PSI (Master thesis)

Under the supervision of Dimitri Rochman (PSI)

Current situation in Switzerland

In Switzerland, 12'000 spent nuclear fuel are expected for the final repository

The spent nuclear fuels will be placed in canisters, for the geological repository, located several hundreds meters below the surface

Image Ref: Model of a storage tunnel for used fuel elements. © LMS/EPFL, Mont Terri underground lab

Current situation in Switzerland

- Around 12 000 nuclear spent fuel assemblies expected for final repository
- 4 (*9*) assemblies per canister for PWR (*BWR*)

- **Choice of the assemblies inside the canisters, but also the location and orientation within the canister**
- Safety and design requirements: $k_{eff} < 0.95$ and DH < 1.5 kW for each canister
- Homogenization of canisters

Problem description and goals

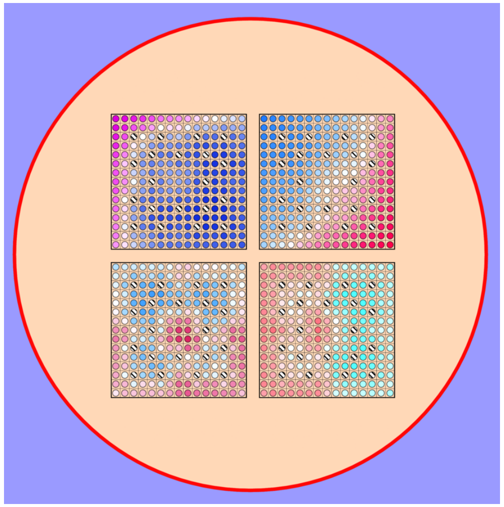
- **Optimize the canister loading using a genetic algorithm**
- High number of arrangements possible
  - Over 10^4 arrangements for 4 assemblies in one canister, over 10^9 for 2 canisters

- A k_{eff} Monte Carlo calculation takes several hours per canister
- Need for faster methods to calculate k_{eff} $\Rightarrow$ Neural Network
- No need for surrogate model to compute the canister decay heat

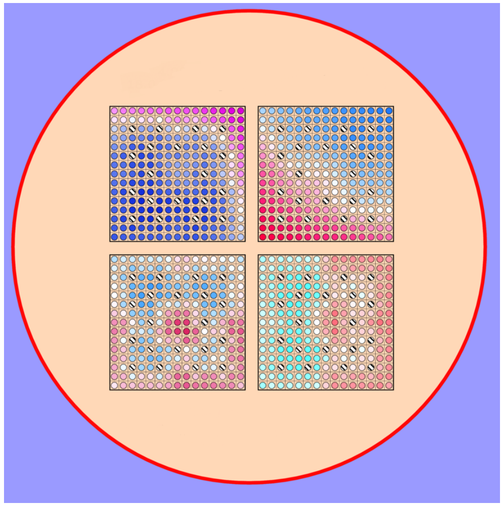
Input data for the neural network

- k_{eff} computed with the Serpent Monte Carlo code (20 pcm, pcm=10^{-5})
- 212 different assemblies (different IE,BU)
- 46 746 canister loadings (randomly loaded)

- Serpent model is 2D (central node)

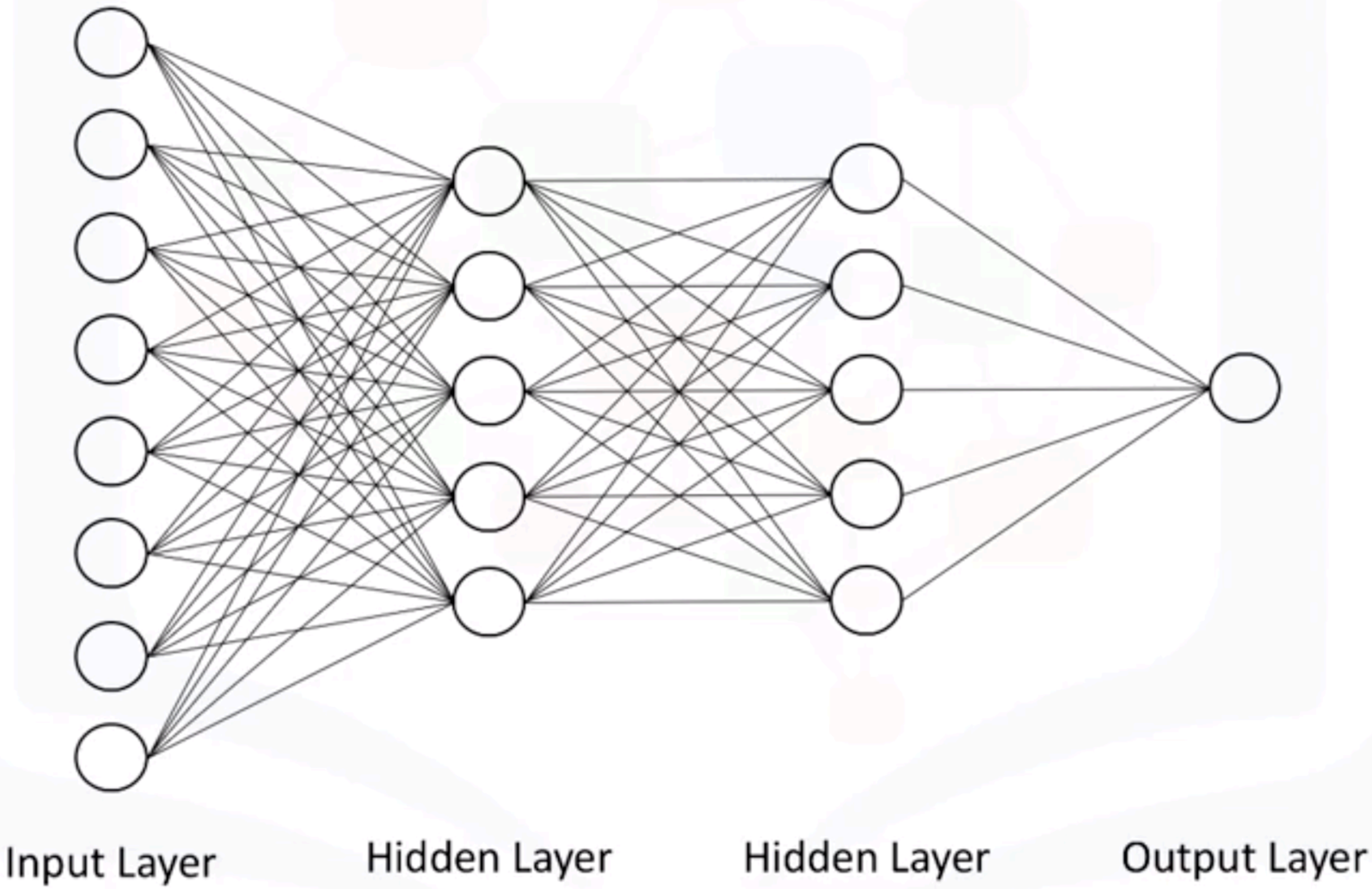


k_{eff} = 0.95533



k_{eff} = 0.94803

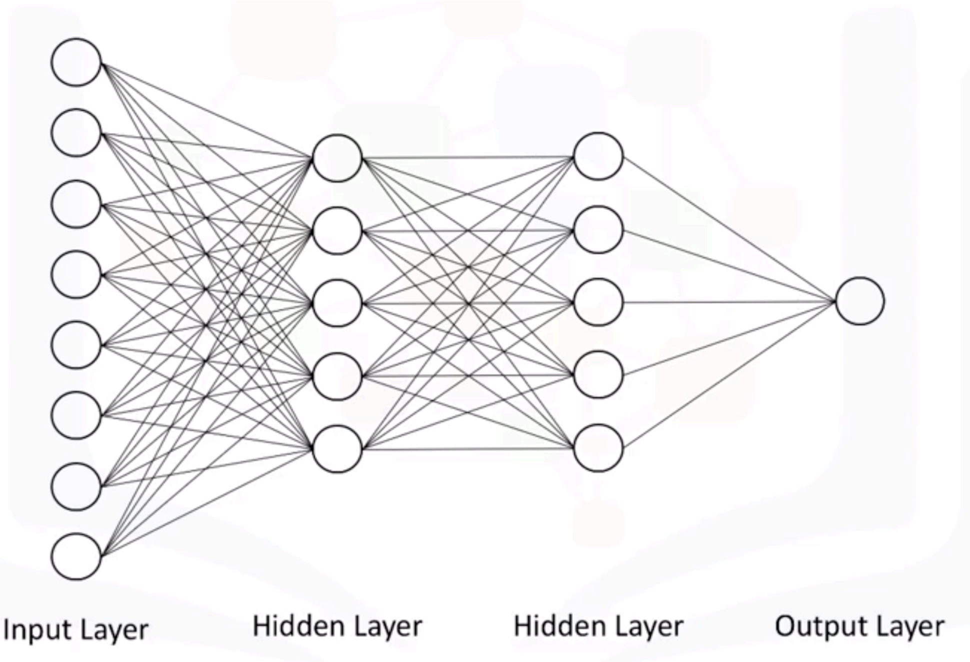
Artificial neural network



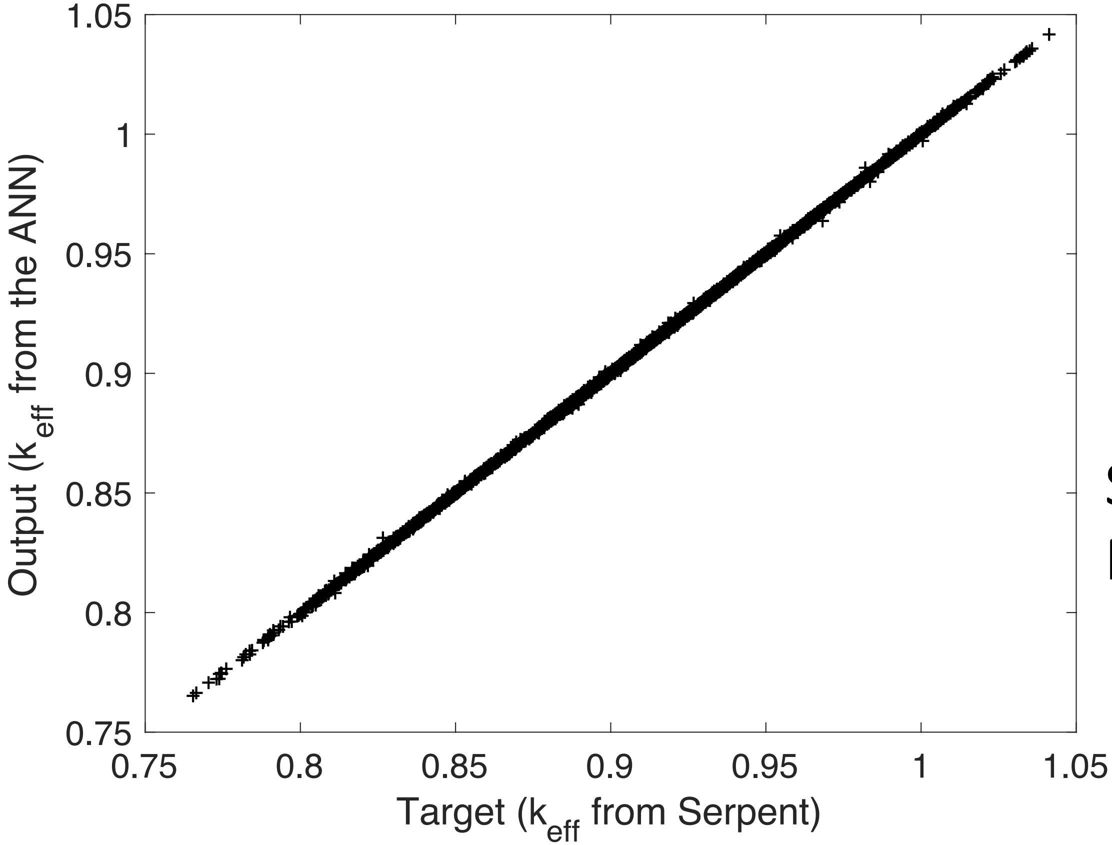
Neural Network

- Residual = (k_{eff} from Serpent) – (k_{eff} from Neural Network)

- **Minimize standard deviation of the residual on the testing set**
- Mean residual should be “close to” 0 (no bias)



Prediction of the k_{eff} values



The test set is 10% of the samples

Std= 45 ± 3 pcm,
Mean= 0 ± 1 pcm

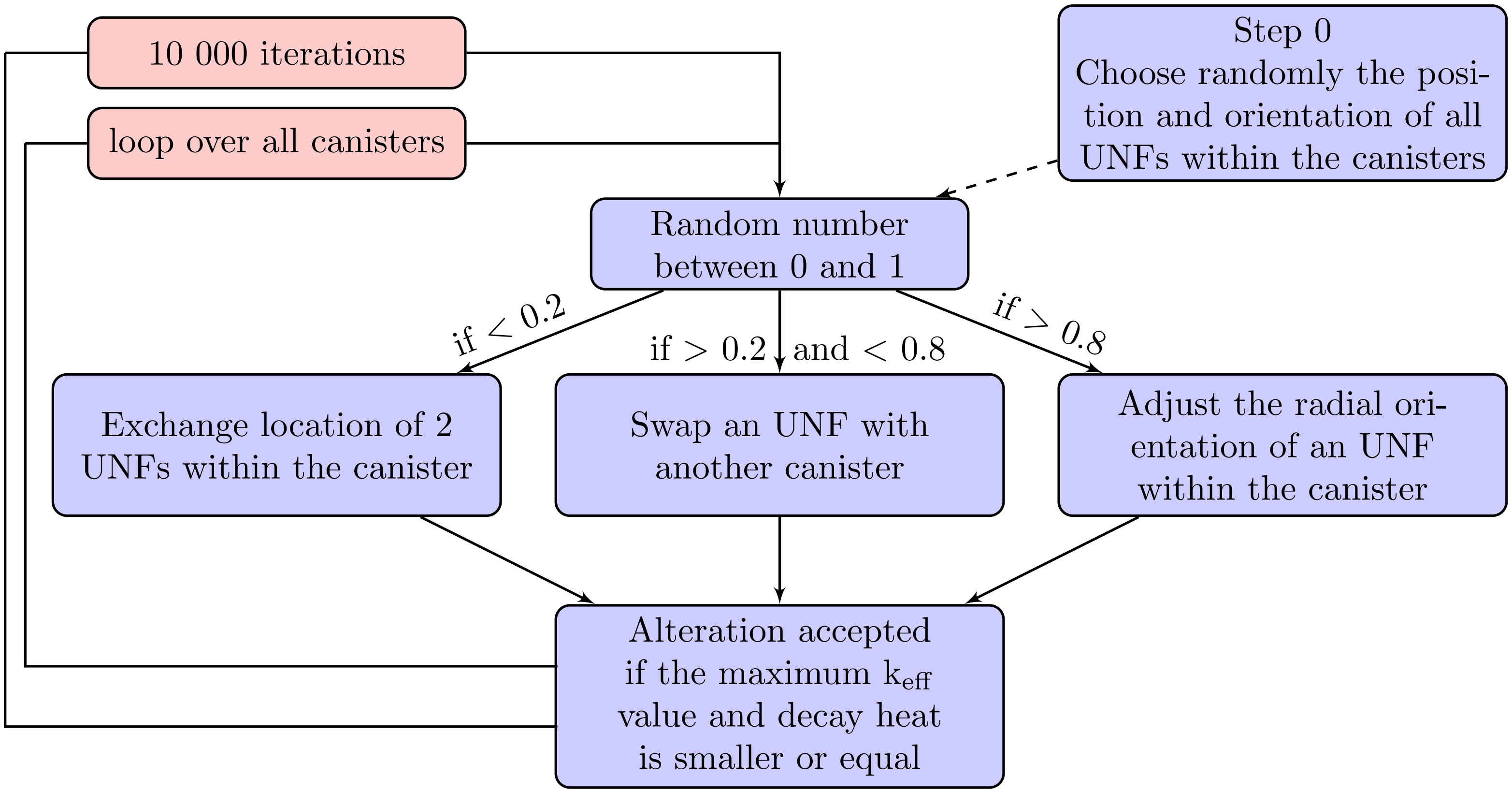
Statistical uncertainty from Serpent is about 20 pcm

Genetic Algorithm

- Find an optimized loading for 212 assemblies into the 53 canisters
  - k_{eff} computed with the neural network

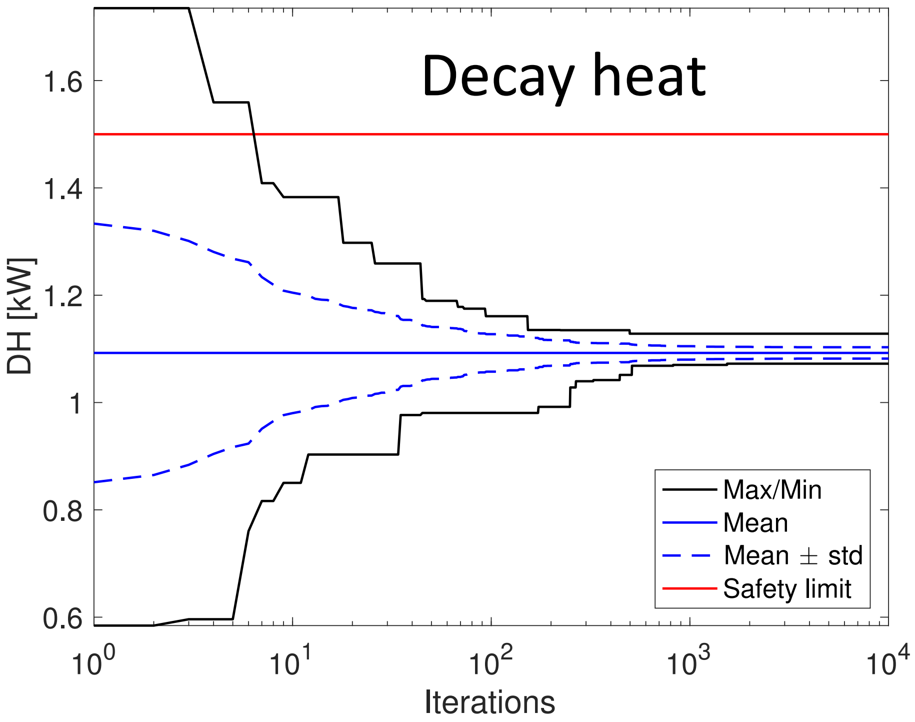
- Goals:
  - Minimize the maximum k_{eff} and DH
  - Homogeneous distributions for k_{eff} and DH

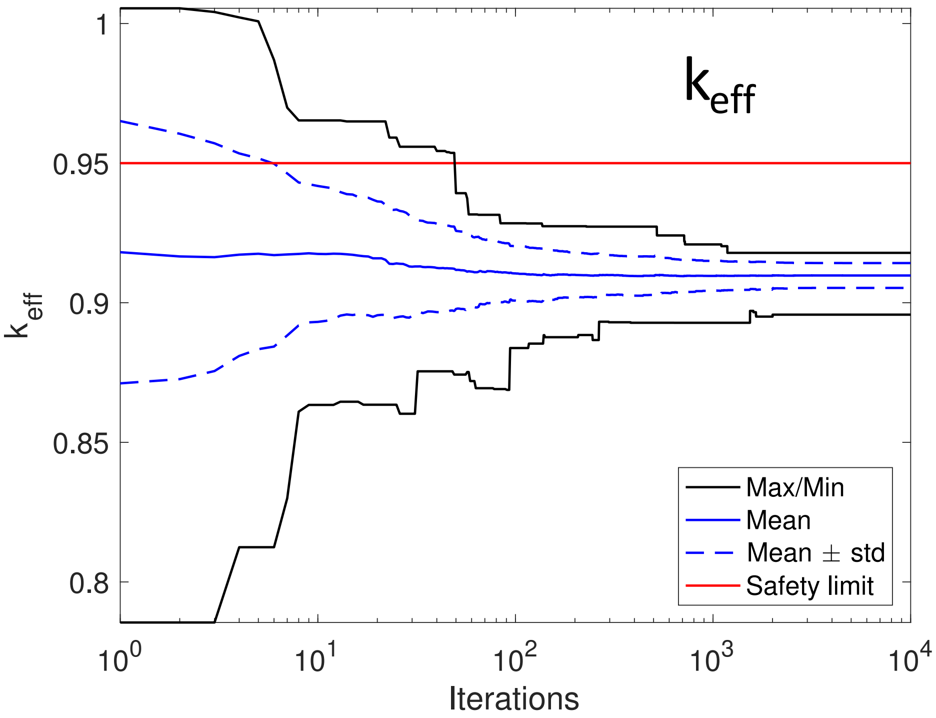
Genetic Algorithm



UNF= used nuclear fuel

Simultaneous optimization of k_{eff} and DH





Validation with Serpent: Mean difference is 30 pcm

Minimum number of canisters reached (53 canisters)

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Limitations and future improvements

- Generalization to all expected assemblies
  - Need large number of samples
  - Different assemblies with different isotopic concentrations

- Main limitations from physical specifications
  - Consider the case in 3D
  - Consider more safety parameters (dose rate)
  - Realistic loading conditions (docking stations)

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Conclusion

This study aims at providing preliminary results on the optimization of canister loading

Aim: Optimization on a reduced set of assemblies for the k_{eff} value and decay heat

a) Development of a surrogate model (artificial neural network) to substitute Serpent to compute k_{eff}
b) Development of a genetic algorithm to find an optimized loading (the neural network is used to compute the k_{eff} values in the GA)

Results: All assemblies have been loaded with a minimum number of canisters using genetic algorithm

Reference

V. Solans, D. Rochman, C. Brazell, A. Vasiliev, H. Ferroukhi and A.Pautz, “Optimisation of used nuclear fuel canister loading using a neural network and genetic algorithm”, submitted to Neural Computing and Applications, June 2020.