A Novel Approach to Partial Defect Testing of Spent Nuclear Fuel for Safeguards Applications

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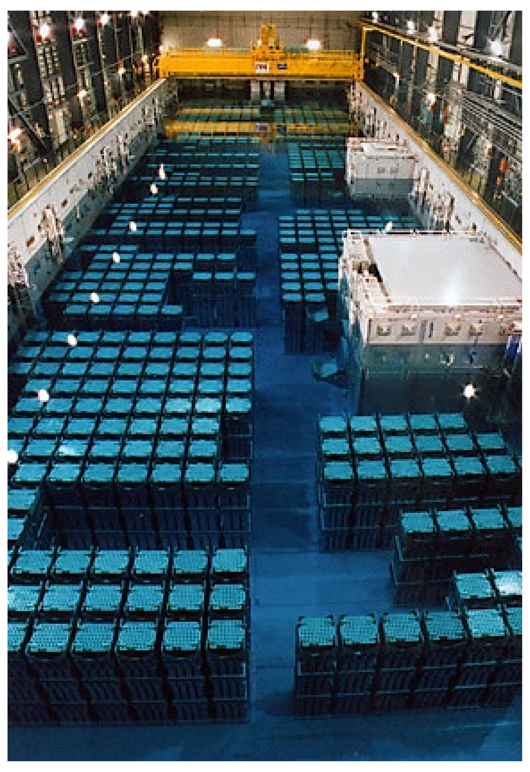
Introduction

Spent, highly radioactive nuclear fuel (SNF) that is discharged from a nuclear power plant, is stored in a water pool before it is sent to the final repository. In this period of time it is important to carry out regular inspections and assure that no radioactive material is missing from the water pool. SNF is particularly important from a safeguard perspective due to its high content of residual fissile-material content.



AREVA spent nuclear fuel storage facility in La Hague.[1]

Objectives

The current PhD research concerns the development of a method to detect missing pins in a spent nuclear fuel assembly in the fuel pool, which is both accurate and non-intrusive, as well as it does not require the movement of fuel.

Significance

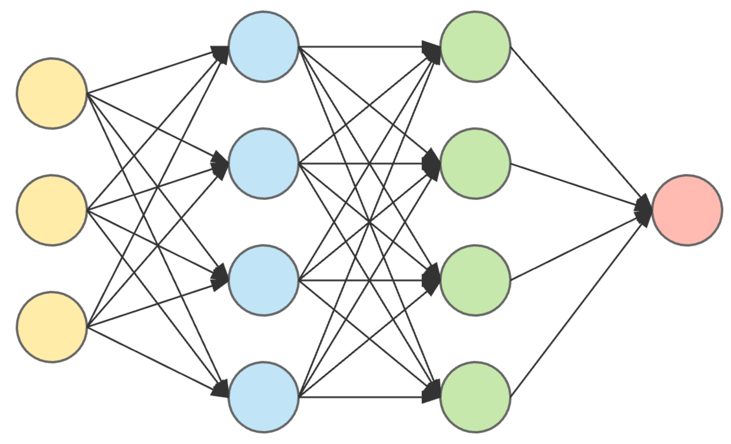
- Safeguard implementation
- SNF represent the majority of nuclear materials under safeguards
- Current methods are limited

Methods

The proposed method is based on performing neutron flux and neutron current measurements with a cluster of movable **neutron detectors**.
These novel detectors consist of a scintillator fixed to the end of an optical fiber. This allows to design detectors of small size that can be used in different fuel assembly geometries, such as the ones in PWR, BWR or VVER.
If the neutron flux is measured in several positions within the assembly and compared with the expected neutron flux distribution, then differences from the expected neutron flux can reveal possible **missing pins and their positions**.

One novelty of the method is to use angularly – sensitive detectors, such that they can be used for the measurement of either the neutron current, or rather its approximation by the flux gradient. The angularly resolved neutron field is much more effective for **identifying the position of localized perturbations**, such as a missing pin.

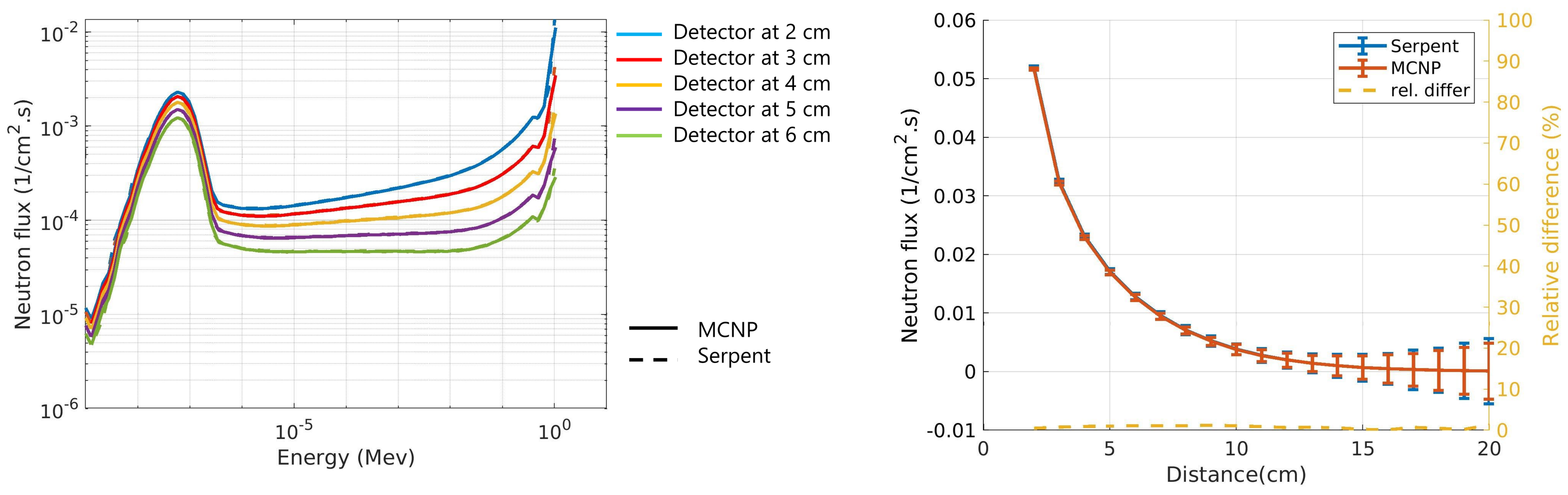
Identifying a missing fuel pin or fuel pins is a so-called "**inverse task**", i.e. going from the distribution of both the scalar neutron flux and the flux gradient to the actual pin distribution that originated those observables. Since even the direct task can only be solved numerically (either with deterministic or Monte Carlo methods), no self-obvious way of solving the inverse problem exists.
To develop an identification algorithm, we propose the use of non-parametric, **machine-learning** based inversion methods, such as artificial neural networks (ANNs).



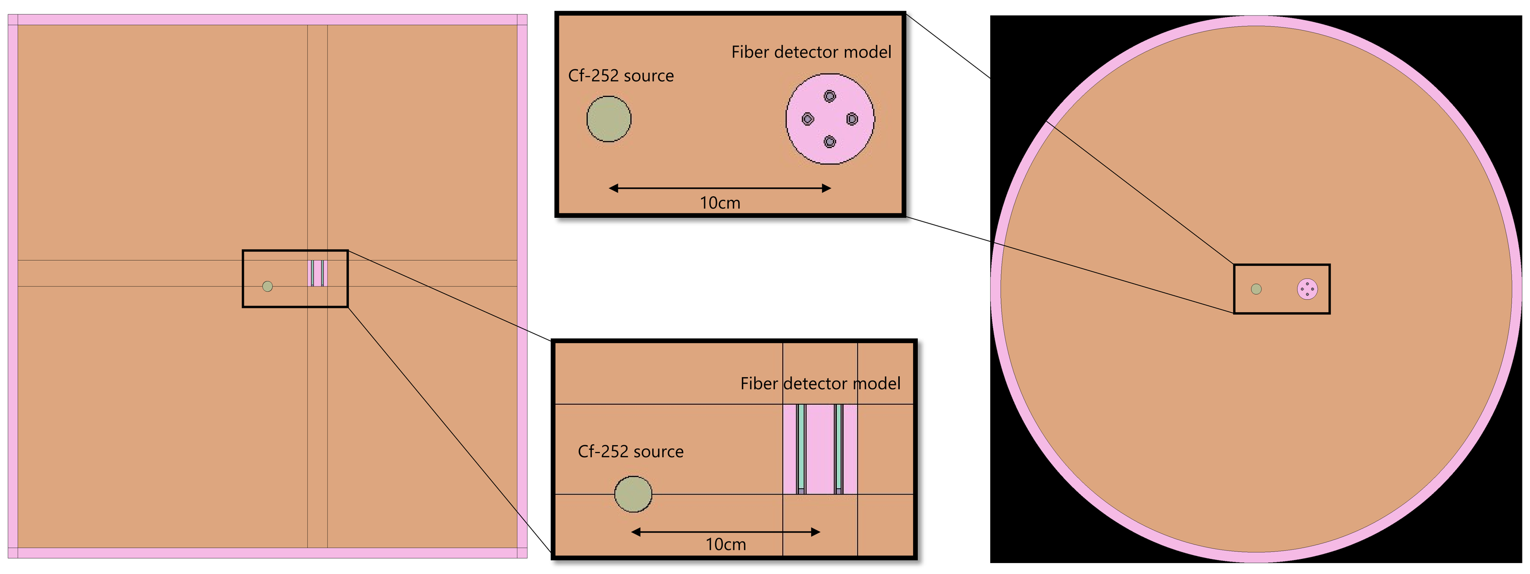
ANN concept scheme.

Results

During the first period of the project the work focused on using the **SERPENT** Monte Carlo code to create a simple model that is similar to the suggested experimental set-up. The model consists of an Aluminum tank (1m in diameter and 1m in height) filled with water with a Californium-252 spherical source (1cm in diameter) at the center of the tank. The work also focused on verifying and benchmarking the results obtained from SERPENT by replicating the model and comparing the same results using the **MCNP** Monte Carlo code. The radial distribution of the neutron flux along with the flux-energy spectrum were compared between the two codes and the results were satisfactory.



(Left) The flux-energy spectrum in water from the first 5 detectors, (Right) The radial distribution of the neutron flux in water.



The Serpent model showing a water tank with a Cf-252 source and the suggested neutron detector model.

Later on the work focused on studying and modelling (via **SERPENT**) various potential designs for the neutron detectors. The main concept is to use four optical fiber-scintillation detectors in order to measure the two components of the neutron flux gradient in the 2-dimensional plane defined by the neutron source and the scintillator tips. From here a feasibility, uncertainty and sensitivity studies will be performed in order to decide the optimal detector design, dimensions and material composition.

Discussion

In order to gain trust and benchmark our SERPENT model, the radial distribution of both the total and thermal neutron flux in addition to the flux-energy spectrum were compared between the SERPENT and MCNP codes for different cases: 1Mev, 1eV and 0,025eV point sources and a Cf252 spherical source. The results were satisfactory.

The super computer cluster at the Chalmers Center for Computational Science and Engineering (C3SE) was used to perform the Monte Carlo calculations with a high number of neutron histories (10^9). This was needed to obtain results with relatively good statistics.

Two different models of the neutron detectors were defined. Using SERPENT simulations, the capability of the detectors to measure the spatial distribution of the neutron flux was investigated. Different dimensions and material compositions will be tested as well in order to optimize the response of the detectors.

Long-term timeline of the PhD project.

Milestones	Time (months)							
	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48
Literature review	x							
Detector development	x	x	x					
Intact assembly simulations			x	x				
Defect assembly simulations				x	x			
Experimental Validation					x	x		
Developing ANN						x	x	
Training ANN						x	x	x
Writing thesis								x
		Chalmers			SCK.CEN		Chalmers	

Conclusion

The research project started in March 2020 and is proceeding according to plan. The following tasks has been performed: a literature review on optical fiber-based neutron detectors, getting familiar with the SERPENT Monte Carlo code, benchmarking the SERPENT model by comparing the results with MCNP, developing the fiber neutron detector model and studying its ability for measuring both the neutron flux and flux gradient.
The next step of the project is to prepare and test the fiber-based detector and characterize its efficiency. For this purpose, experiments are planned in the hot cell laboratory at the department of Physics at Chalmers. In these experiments a neutron source will be used in a neutron moderating environment since the detector is sensitive to thermal neutrons. A SERPENT model of the experimental set-up will be developed and validated so that it can be used to optimize the experiments.

A literature review on machine learning algorithms and artificial neural networks will be done in order to prepare for the second year of the project, which will be carried out at SCK.CEN in Belgium. In the second year the focus will be on the modeling of the fuel assembly and the possible diversion scenarios.

[1]https://www.nti.org/analysis/articles/2016-nuclear-security-summit-progress-report