Fast neutron transmission spectroscopy for the non-destructive analysis of concrete

Naledi Segale

Tanya Hutton, Andy Buffler & Sizwe Mhlongo

DEPARTMENT OF PHYSICS
UNIVERSITY OF CAPE TOWN

MeASURe
Metrological and Applied Sciences University Research Unit

n lab

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Concrete in nuclear power plants

… is used for:

- structural support
- containment
- radiation shielding

… and is exposed to:

- cyclic loadings
- radiation
- extremely varying temperatures

… induces concrete degradation over time, particularly with respect to water (hydrogen) content

Ordinary concrete composition

Constituent	Percentage by mass (%)
Large aggregate (stone)	61
Small aggregate (sand)	11
Portland cement	13
Water	15

Additives, voids, variations in the mixing and curing increase the complexity of the composition of concrete

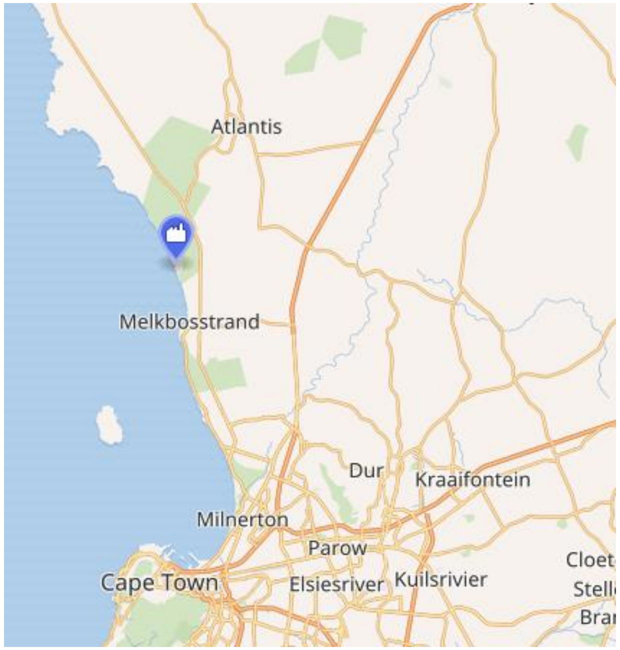
Koeberg NPP

2 x 970 MW PWR units

Commissioned in 1980s and its license expires in July 2024

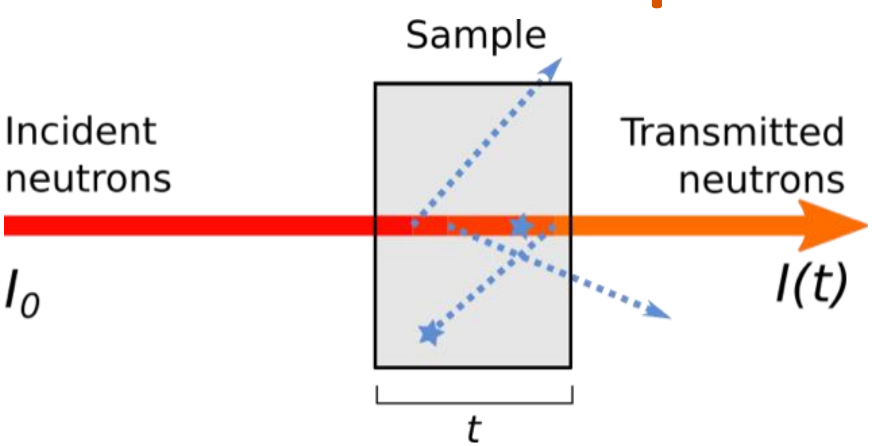
The plan is to extend its life by 20 more years, overseen by National Nuclear Regulator

The non-destructive testing of existing concrete structures is crucial to the plant life extension



Koeberg, Eskom

Fast Neutron Transmission Spectroscopy

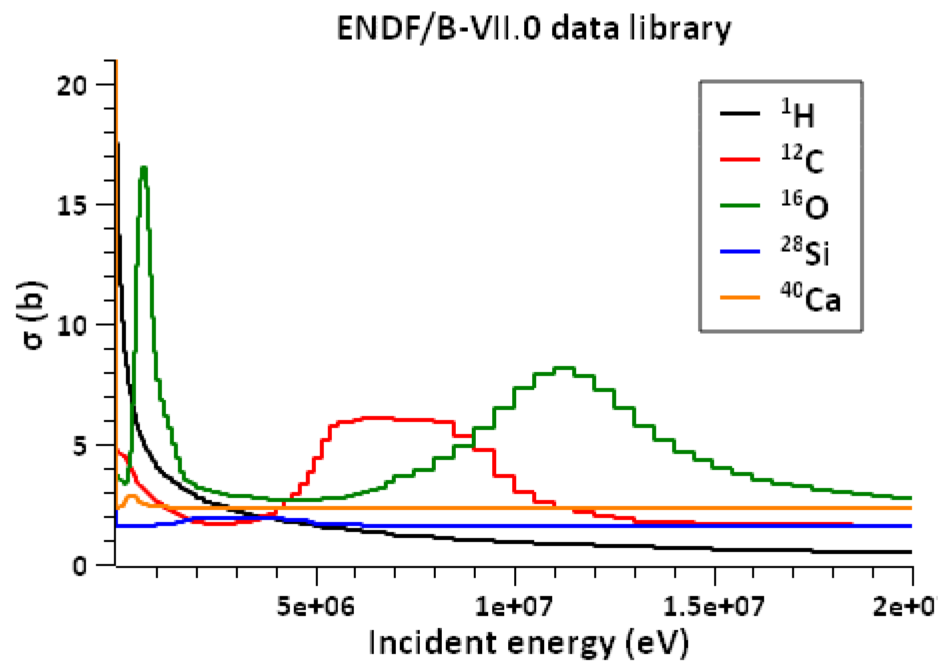


$$\frac{I(t)}{I_0} = e^{-\Sigma_R t}$$

Effective removal cross section

Mass ratio of component *k*

$$\frac{\Sigma_R}{\rho} = \sum_{k=1}^{n} m_k \frac{\Sigma_{R,k}}{\rho_k}$$



Energy dependent cross section is unique to each element

Aim

To build a repository of elemental response functions, thus determine the elemental composition of aging concrete used in nuclear facilities. Starting off with sand, an integral part of any concrete as an example case

Objectives

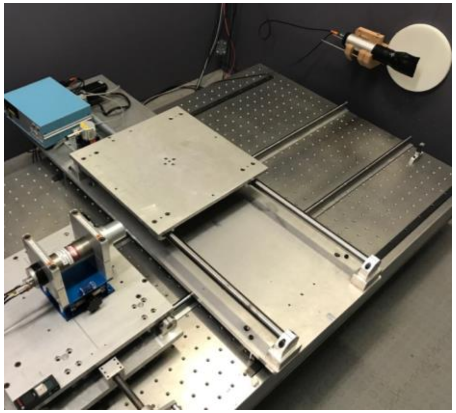
Measure Σ_R for $\mathrm{SiO_2}$ and $\mathrm{CaCO_3}$

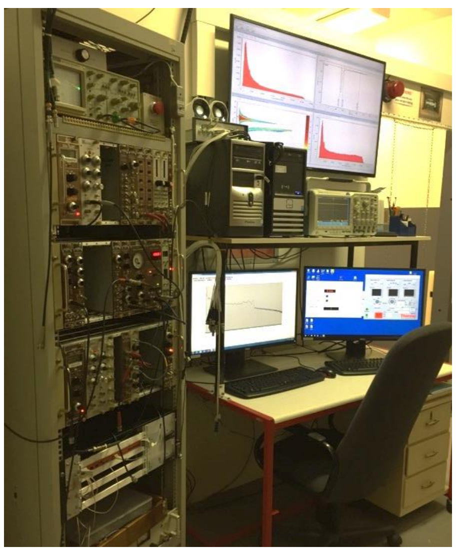
Simulate Σ_R for $\mathrm{SiO_2}$ and $\mathrm{CaCO_3}$ in FLUKA

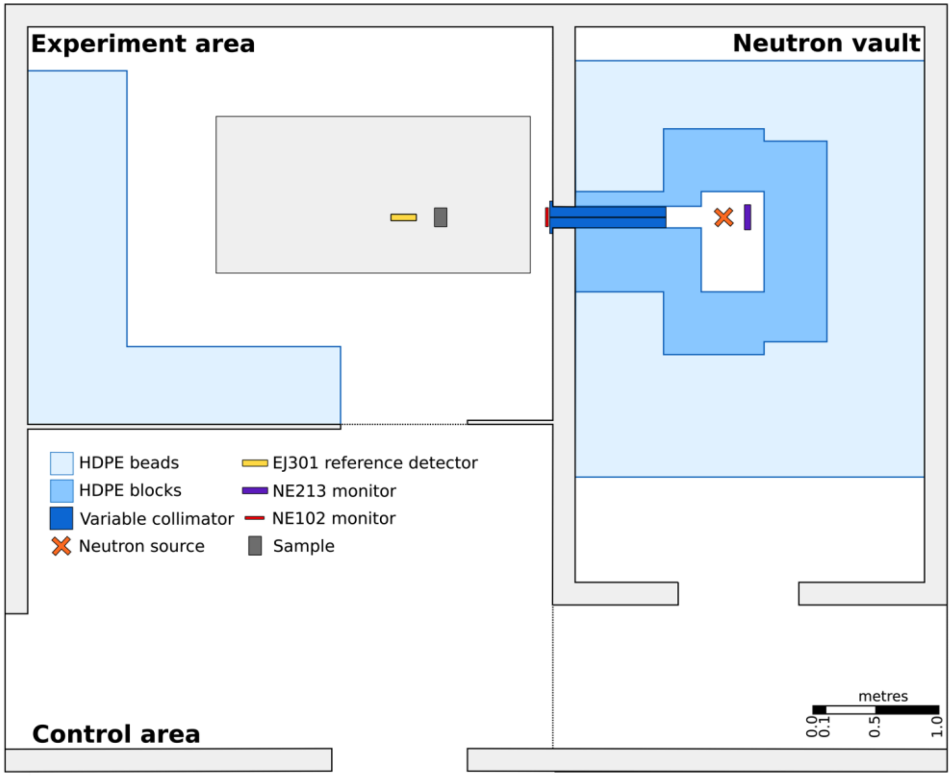
Validate FLUKA simulations in the context of neutron transmission

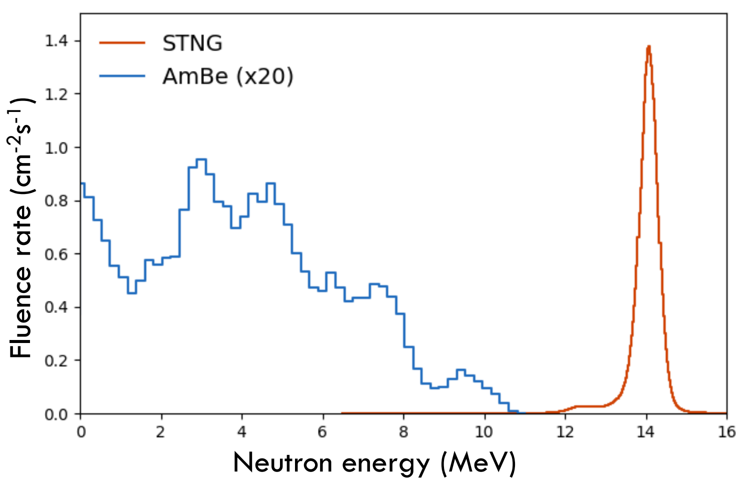
Use XRF data to reconstruct Σ_R for sand and compare to measured and simulated data

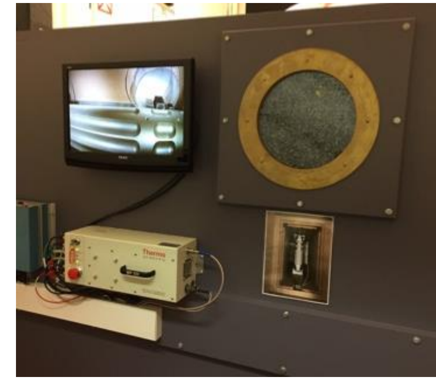
Fast neutron facility at UCT







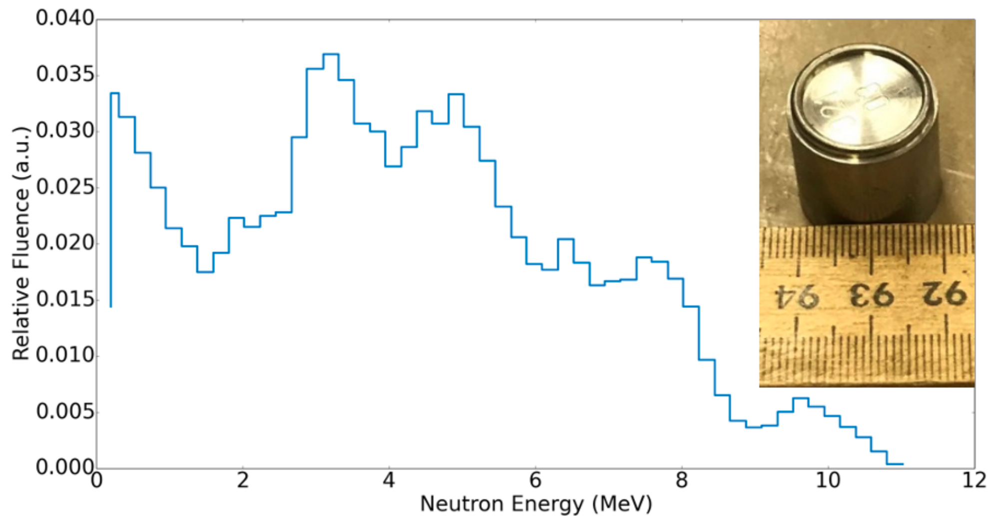




	STNG	AmBe
Type	Accelerator	Radioisotopic
Reaction	t(d, n)a	^{9}Be(a, n)^{12}C*
Energy	14.1 MeV	< 11 MeV
Yield	10^{8} s^{-1}	10^{7} s^{-1}

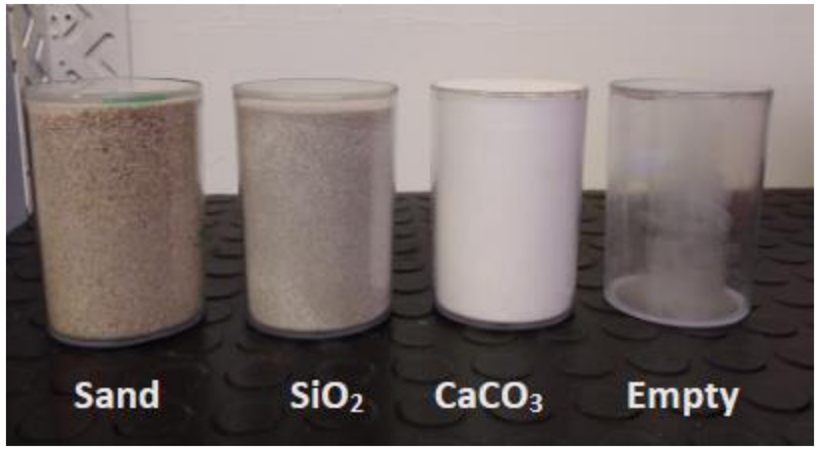
neutron source → **sample** → **detector** → **analysis**

220 GBq ^{241}Am-^{9}Be radioisotopic source



Neutron beams produced with HDPE collimator (Ø 0.8 cm)

Neutron fluence rates of 40 $cm^{-2}\,s^{-1}$ at 1.50 m neutron source → **sample** → detector → analysis

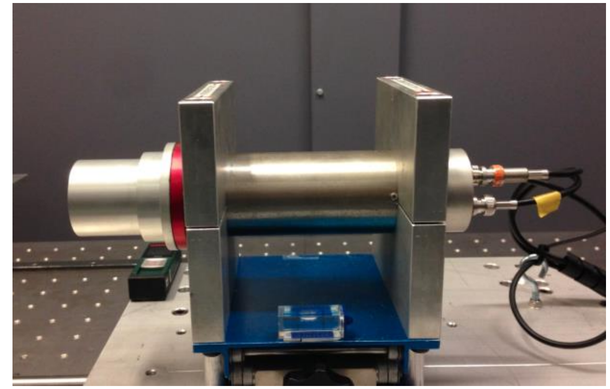


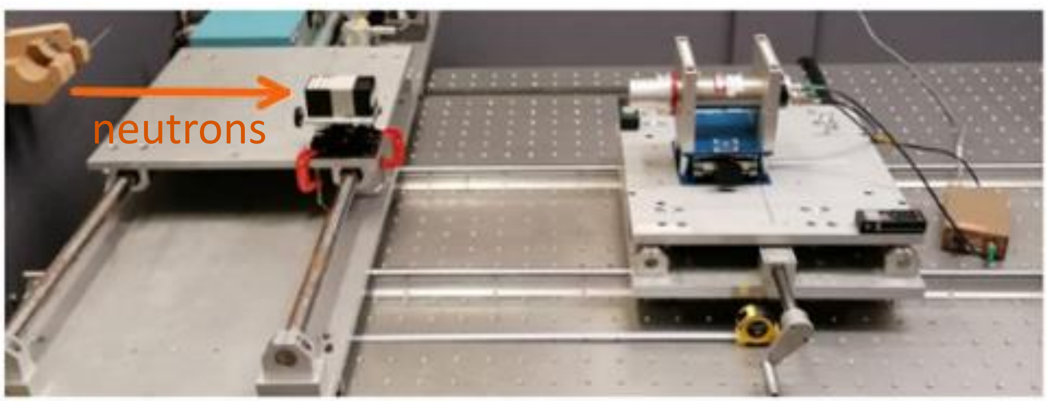
Sample	ρ [g cm^{-3}]
Sand	1.53 ± 0.03
SiO_2	1.26 ± 0.03
$CaCO_3$	0.693 ± 0.029

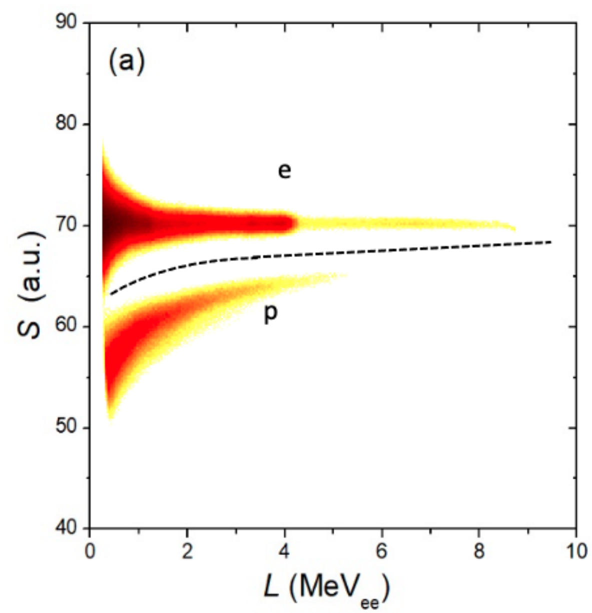
Sample container has dimensions of 6.2 (b) × 6.6 (t) ϕ × 10.0 cm neutron source → sample → detector → analysis

EJ-301 reference detector

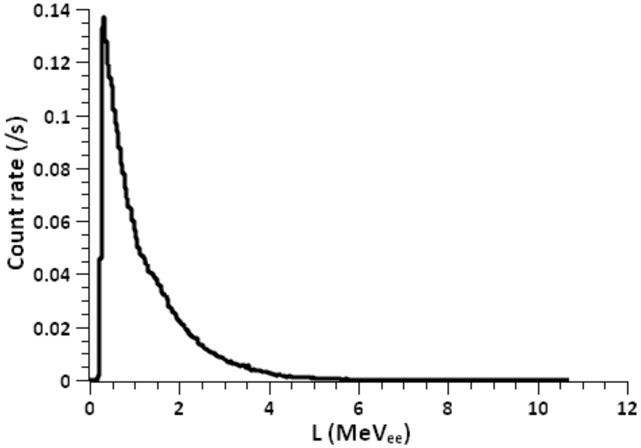
- 2”x 2” organic liquid scintillator
- Well characterised
- Pulse shape discrimination to exclude gamma rays
- Digital data acquisition and pulse processing (QtDAQ)

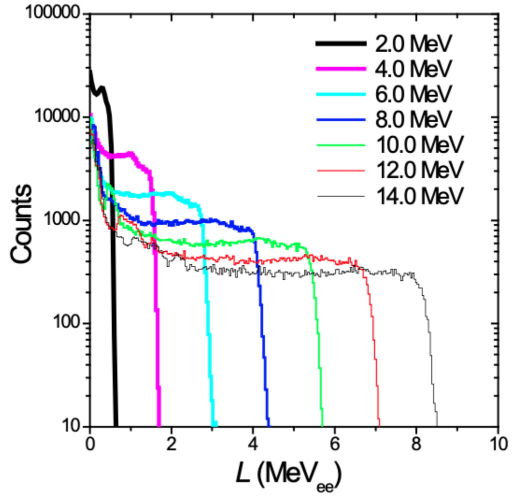


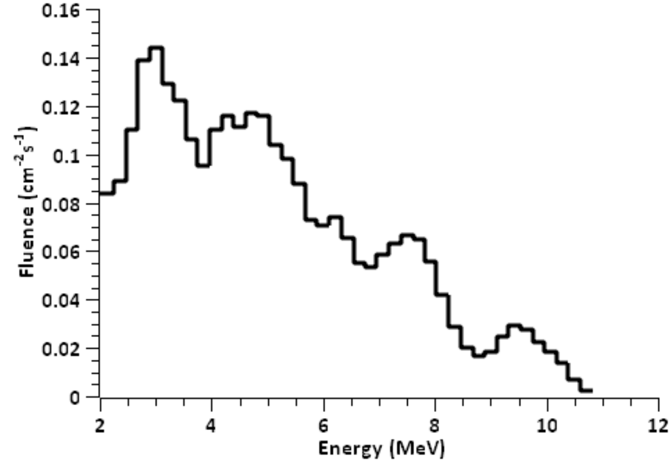




Spectrum unfolding







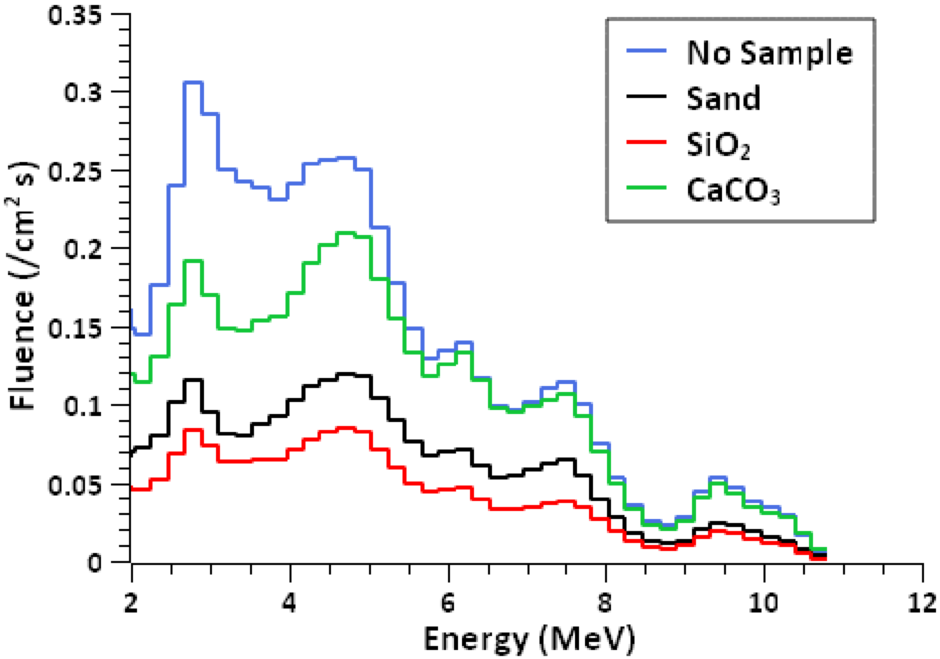
Measured pulse neutron height spectrum…

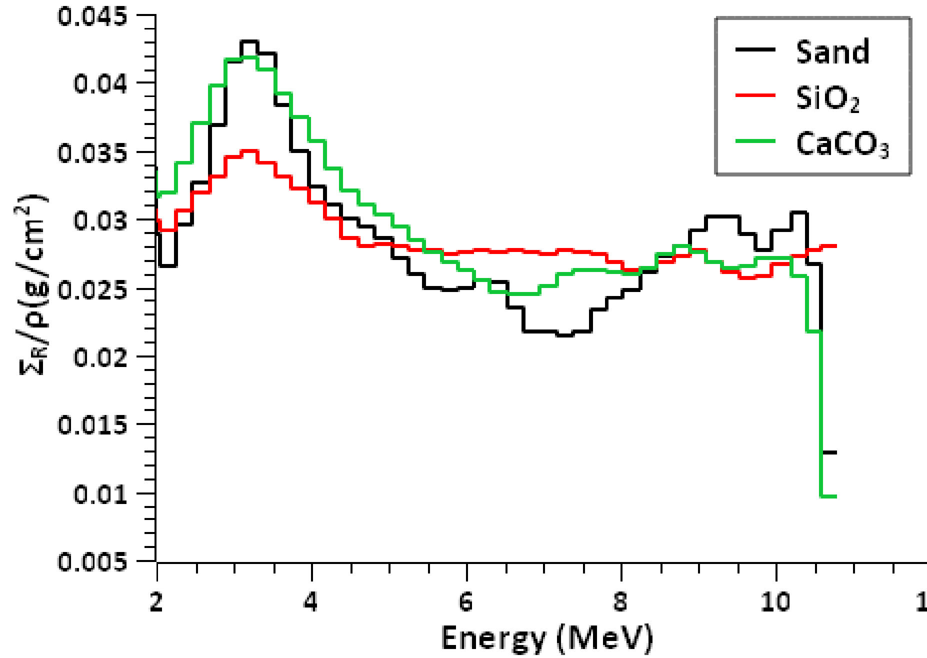
… is unfolded (GRAVEL) using detector response functions…

… to produce neutron energy spectrum

$$z_i = \sum_{j=1}^{m} R_{ij}\phi_j$$

Measurements with sand



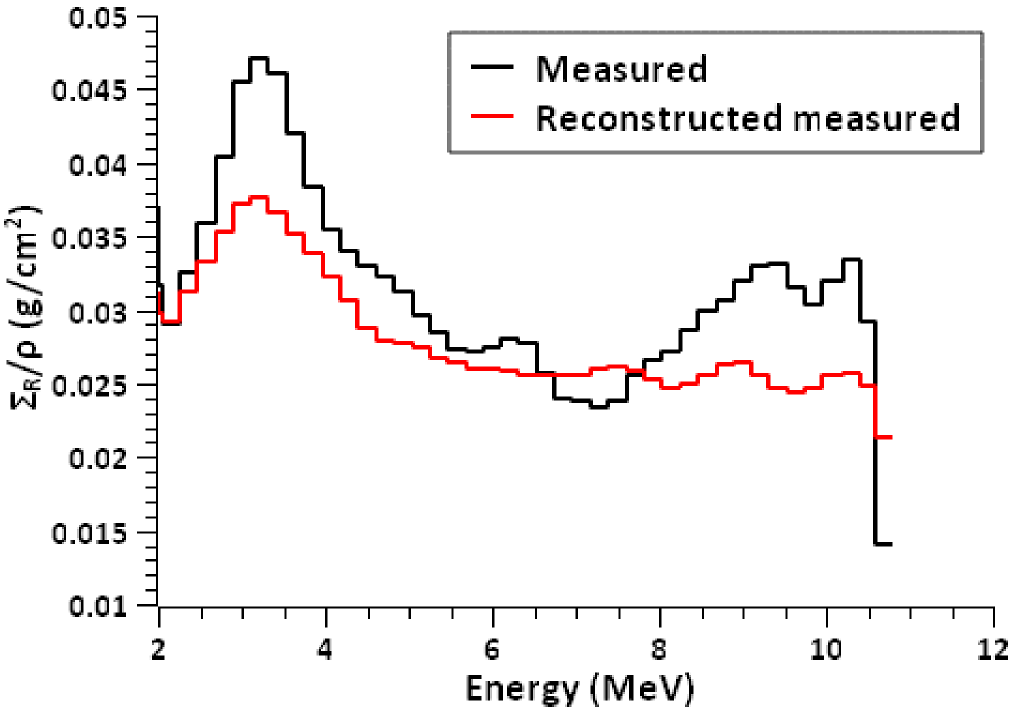


Neutron energy unfolded with GRAVEL

Energy dependent removal cross sections

$$\frac{\phi(t)}{\phi_0} = e^{-\Sigma_R t}$$

Measured sand



Sand is made up of 78.5 % SiO_2 and 18.6 % $CaCO_3$ with the remaining 2.9 % consisting of other oxides

$$\Sigma_R/\rho = \sum_{k=1}^{n} m_k \, \Sigma_{R,k}/\rho_k$$

FLUKA simulations

Simulate the energy dependent neutron fluence transmitted through sand, SiO_2 and $CaCO_3$

Source:
^{241}Am-^{9}Be neutron source

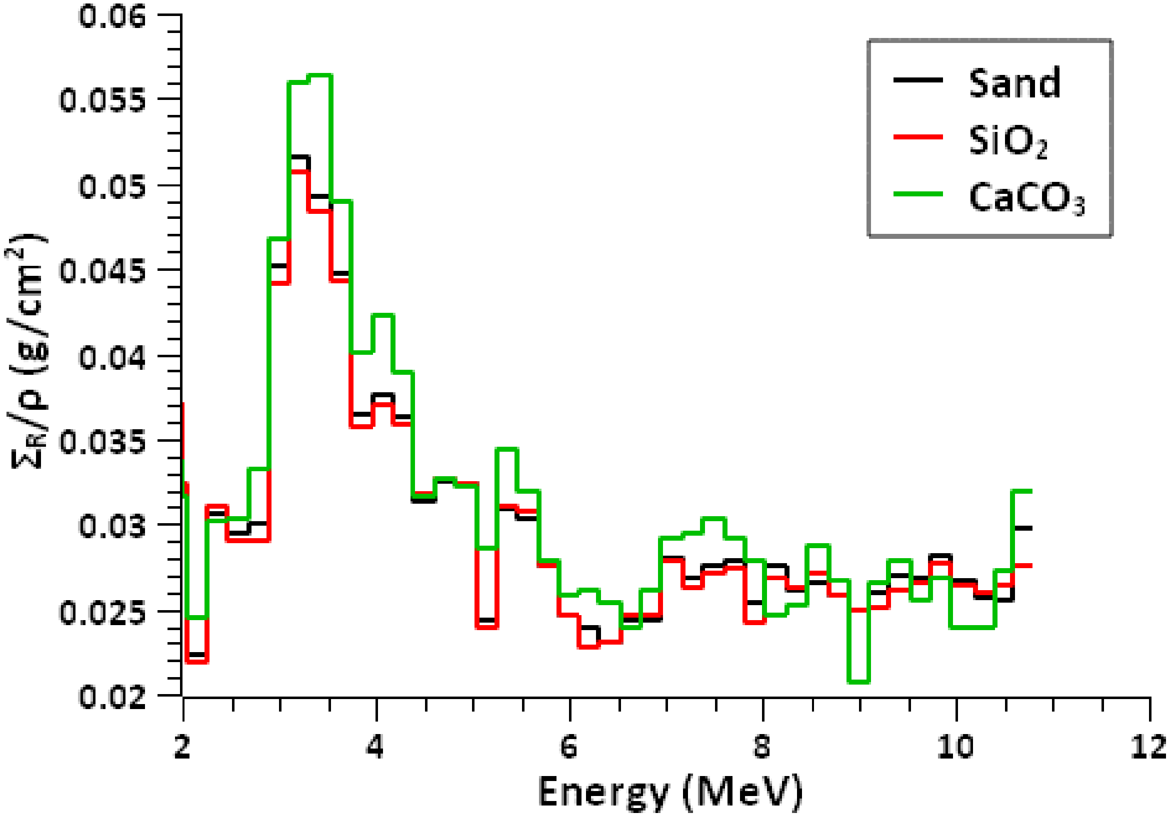
Sample:
t= 10.0 cm, r= 5.0 cm

Detector:
$r = 5.0$ cm
Energy dependent neutron fluence

Sample	ρ(g cm^{-3})
SiO_2	1.42
$CaCO_3$	0.372

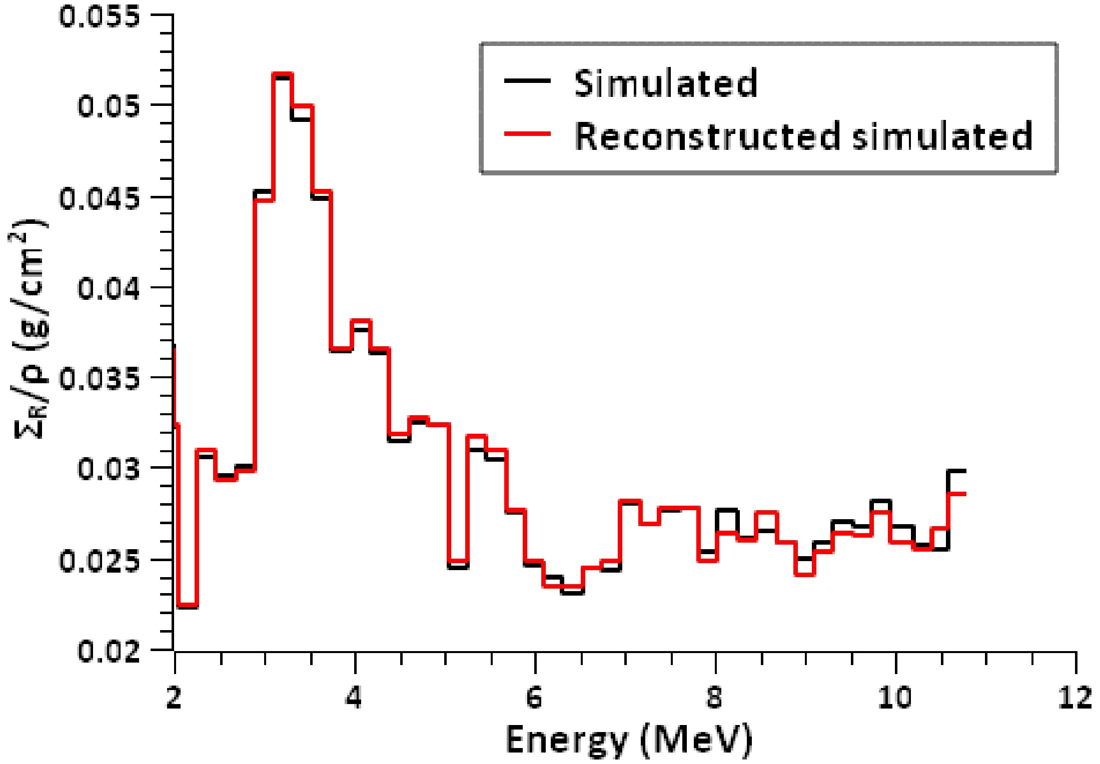
FLUKA

Simulated Σ_R / ρ



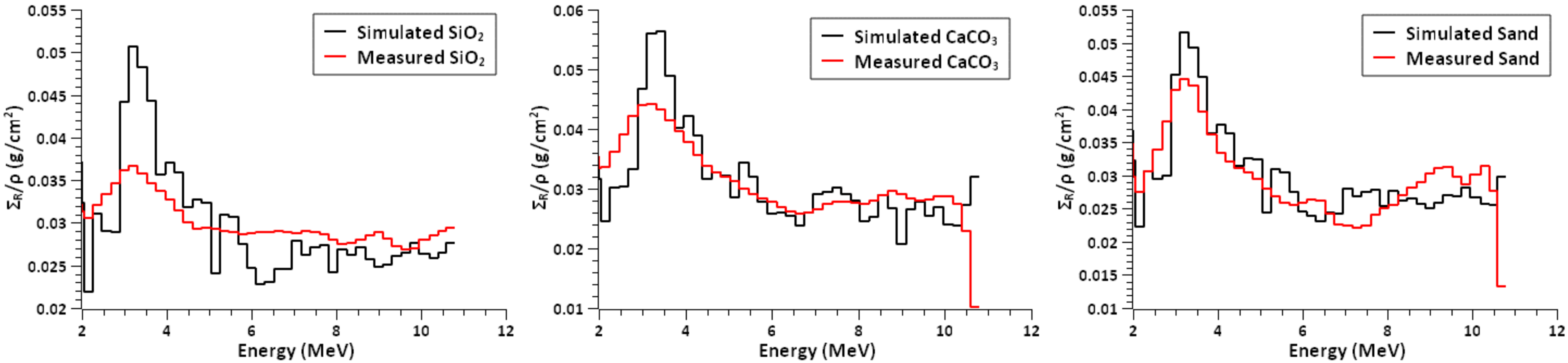
Preliminary simulation results for all three samples.

Simulated sand



Known ratios were applied to simulated SiO_2 and $CaCO_3$.

Results



Overall shape is well matched between simulation and measurement.

Around the 3 MeV region, the enhancement due to O is consistent in simulated and measured data.

Broadened features in measured data due to measurement process.

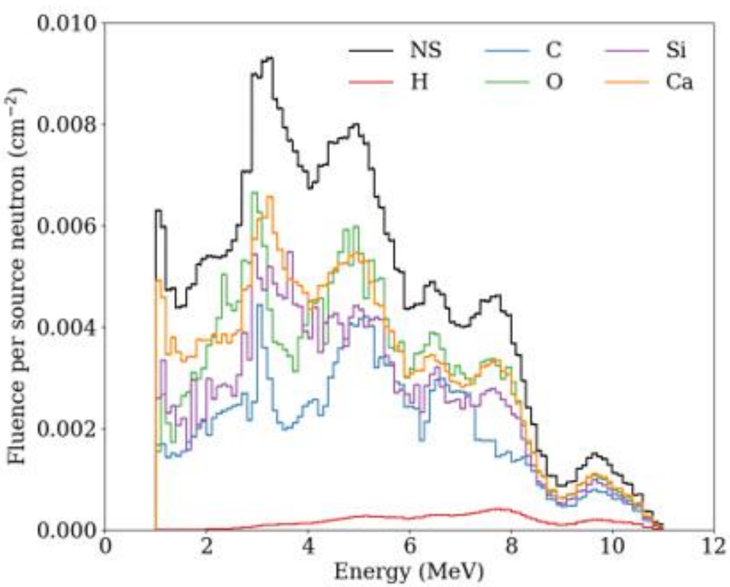
WORK IN PROGRESS

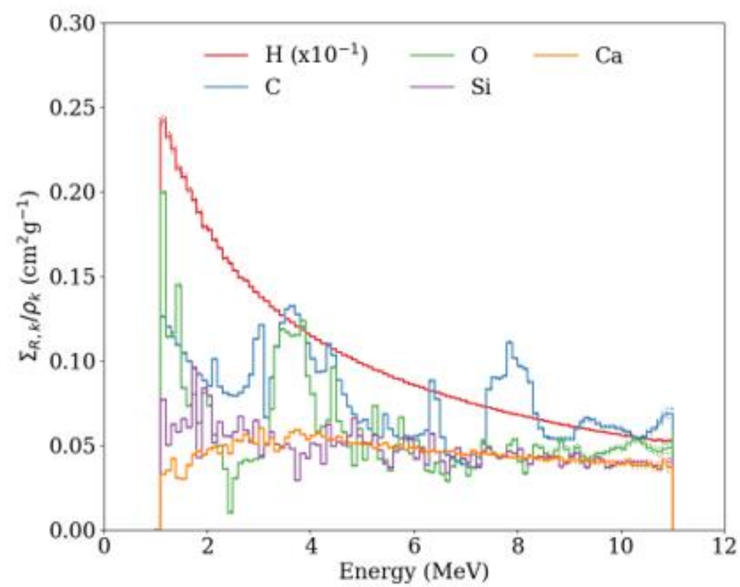
Summary

- Non-destructive testing of concrete is crucial to nuclear industry.
- Fast neutron transmission measurements for sand and its constituents were made.
- Effective removal cross sections determined via measurement and simulation.
- Preliminary investigations show good agreement between measured and simulated removal cross sections.

Next steps

- More experimental validation is required to investigate the energy broadening in measured vs. simulated data.
- Build a repository of elemental response functions.
- Investigate elemental unfolding to determine mass ratios for known and unknown samples.





Thank you

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