The use of Serpent code for investigations at the University of Tartu

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Outline

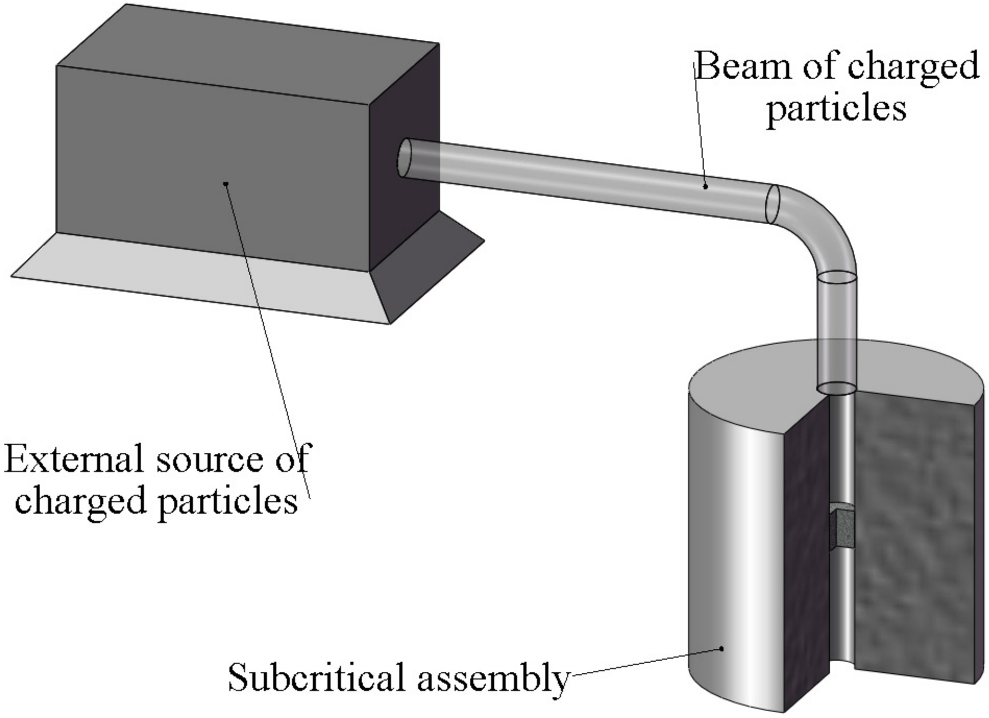
Main directions:

- **The optimization modelling of two-zone subcritical reactor**
- **The modelling of Traveling Wave Reactor (TWR)**
- **The radiation shielding modelling of basalt-concrete materials**

The optimization modelling of two-zone subcritical reactor

The most appropriate option for the transmutation of nuclear waste is a subcritical system driven by an external neutron source (Accelerator Driven System - ADS).

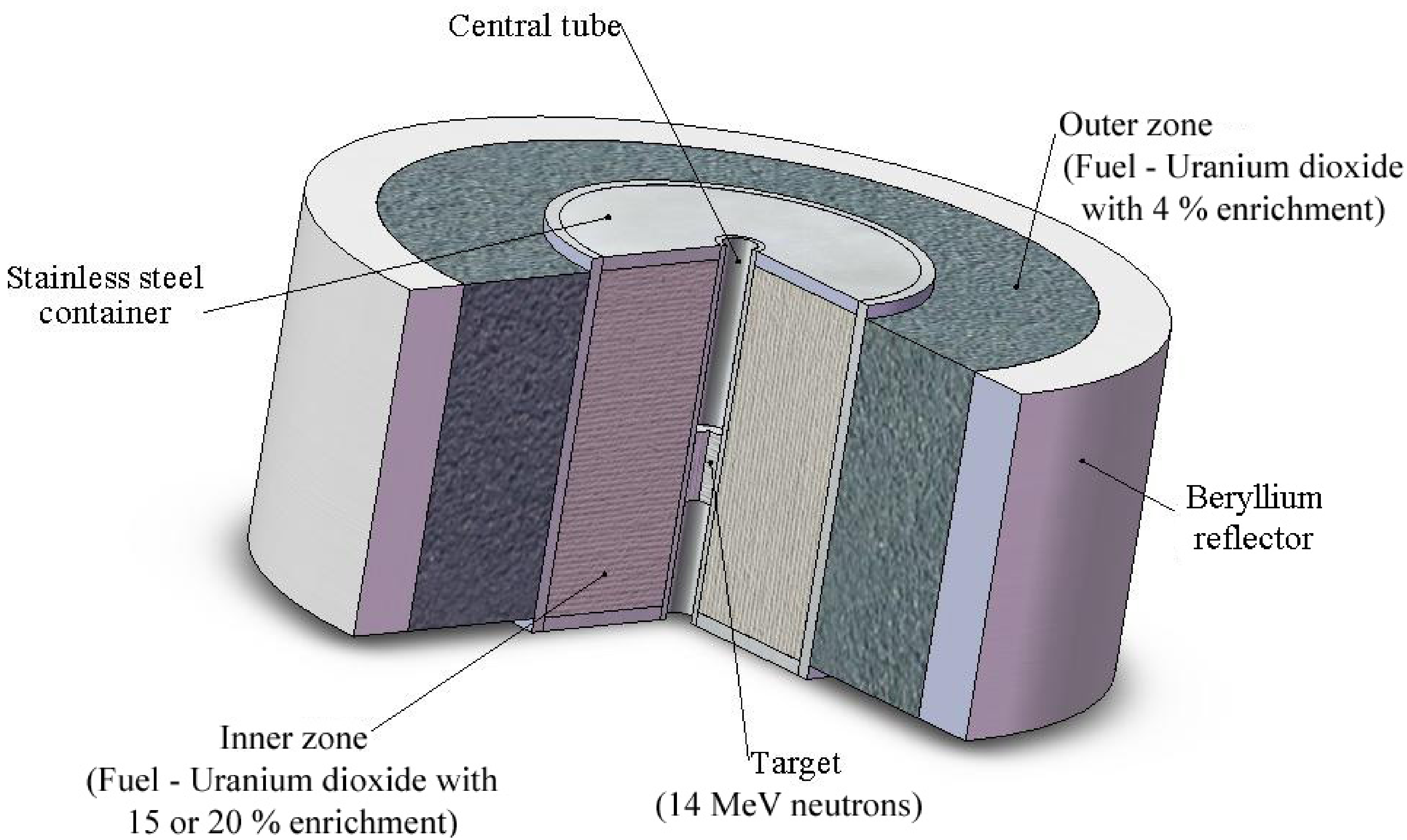
A simple scheme of an ADS is shown in figure.



There are two main advantages for proposed research subcritical reactor:

- External neutron source is high-intensity (D, T) neutron generator
- Two-zone subcritical core

The simple scheme of two-zone subcritical reactor



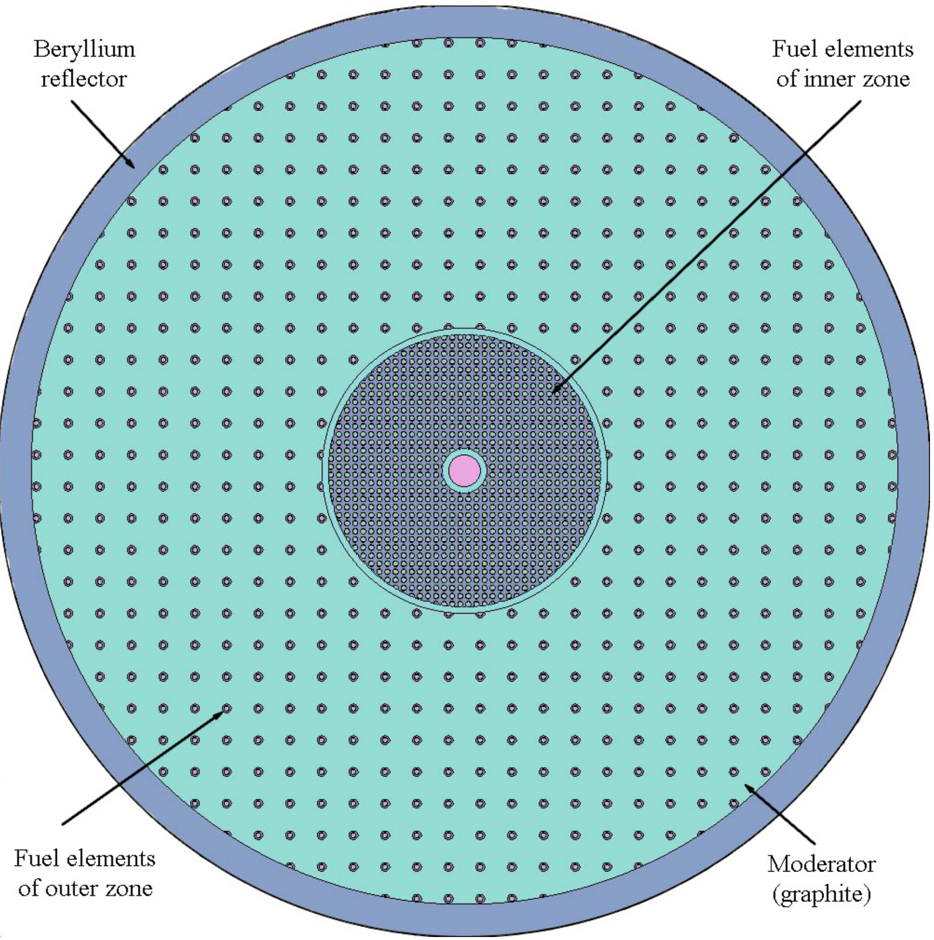
Main goal

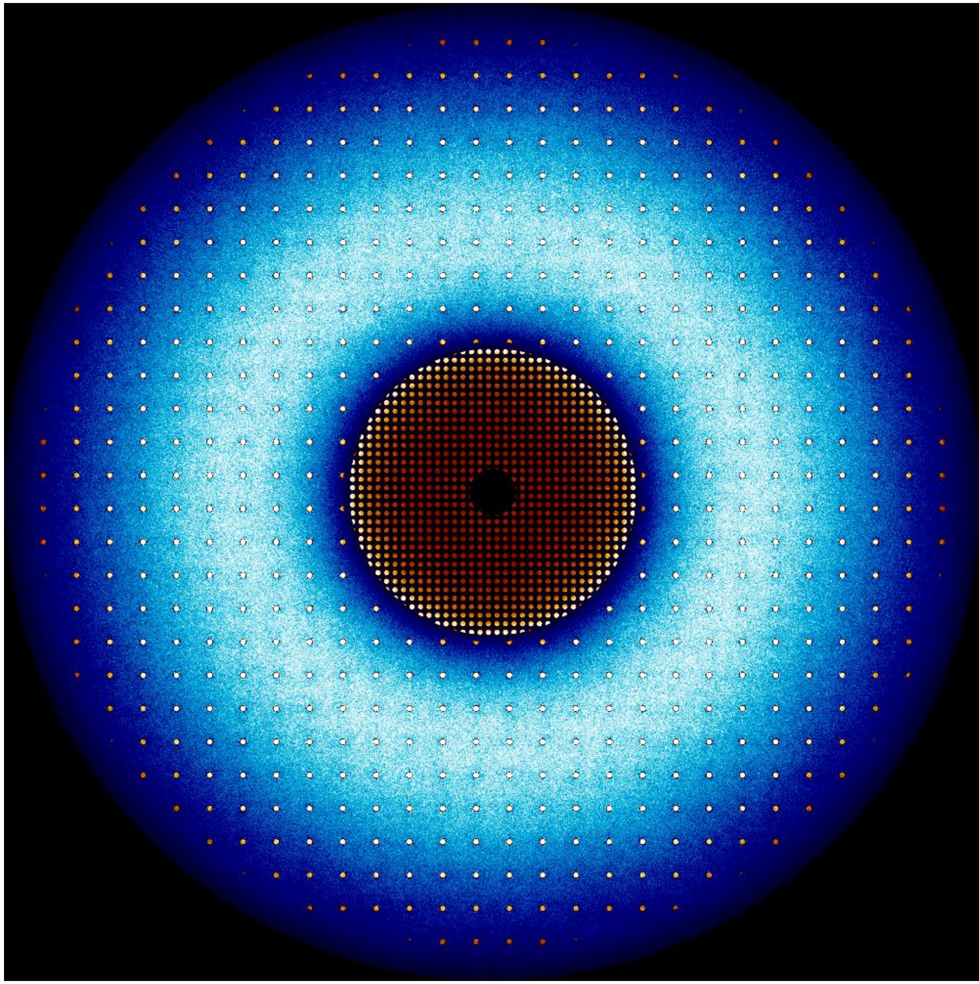
The determination of optimal volume/volume ratio (outer zone volume to inner zone volume) with zones differing in fuel content from viewpoint of neutron-physical and cost characteristics

Modeling conditions

- The diameter-to-height ratio of subcritical core is 1, because this case will minimize the leakage of neutrons
- Isotropic point neutron sources with 14 MeV monoenergetic neutrons were used. The neutron sources were situated inside the target, in the center of the subcritical zone
- The effective neutron multiplication factor (keff) is 0.97 for all calculations. A range of inner zone radii is selected to be analyzed, and corresponding outer zone radii are calculated to achieve overall keff = 0.97±0.0005 for the system
- The total number of source neutrons used is 50000 and the number of batches is 500, these were used in all the calculations
- Serpent 1.1.18 was used for all calculations

Serpent visualization





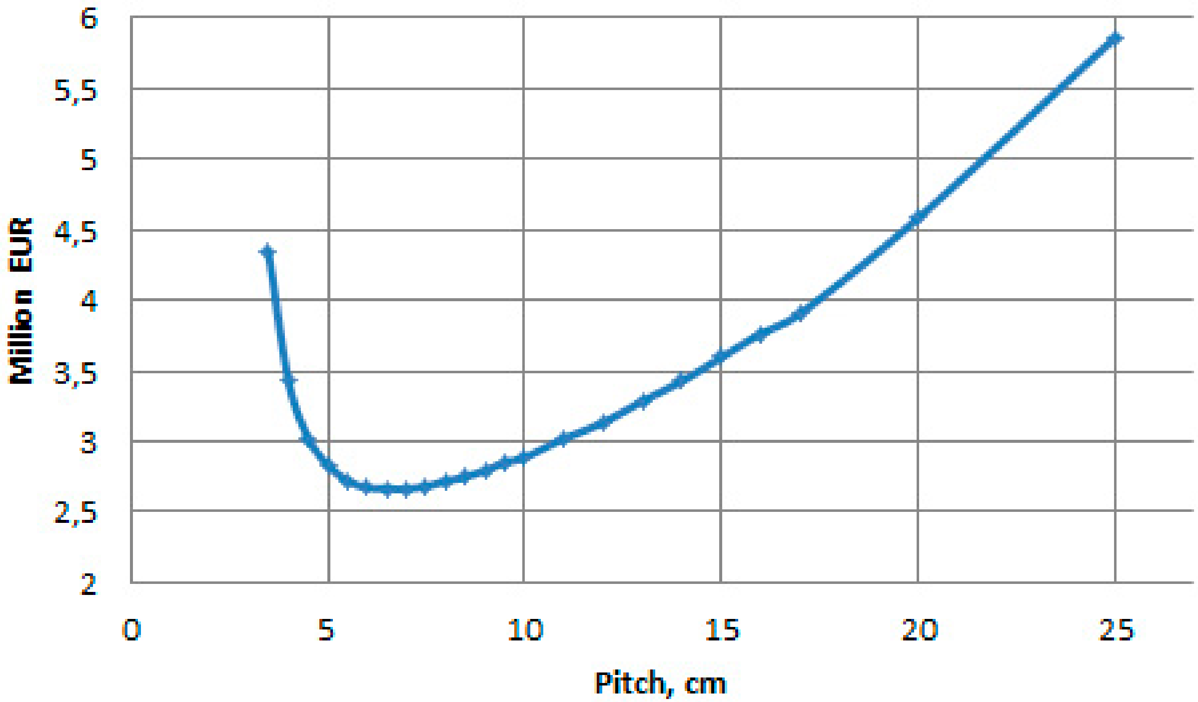
Results

R_{in}, cm	R_{out}, cm	$Flux_{in}$	$Flux_{out}$	Total flux	$Cost_{in}$, mln. EUR	$Cost_{out}$, mln. EUR	Total cost, mln. EUR
10.5	71.4	1.87E-04	1.03E-04	1.08E-04	1.17	0.67	1.84
11.5	70.45	1.93E-04	1.05E-04	1.11E-04	1.41	0.64	2.05
12.5	70.4	1.91E-04	1.04E-04	1.11E-04	1.69	0.64	2.33
13.5	70.2	1.87E-04	1.03E-04	1.10E-04	1.99	0.63	2.62
14.5	70.08	1.85E-04	1.02E-04	1.10E-04	2.31	0.62	2.93
15.5	69.2	1.88E-04	1.04E-04	1.12E-04	2.63	0.59	3.22
16.5	69.18	1.84E-04	1.02E-04	1.11E-04	3.00	0.59	3.59
17.5	68.89	1.83E-04	1.02E-04	1.12E-04	3.37	0.58	3.95
18.5	68.89	1.80E-04	1.00E-04	1.11E-04	3.79	0.57	4.36
19.5	68.59	1.79E-04	9.97E-05	1.11E-04	4.21	0.56	4.76
20.5	68.4	1.77E-04	9.88E-05	1.11E-04	4.65	0.55	5.20
21.5	68.4	1.73E-04	9.73E-05	1.10E-04	5.13	0.54	5.67
22.5	68.18	1.71E-04	9.65E-05	1.10E-04	5.61	0.53	6.14
23.5	68.2	1.68E-04	9.48E-05	1.09E-04	6.14	0.52	6.66
24.5	68.02	1.66E-04	9.39E-05	1.08E-04	6.66	0.51	7.18
25.5	67.6	1.65E-04	9.37E-05	1.09E-04	7.19	0.50	7.68
26.5	67.52	1.62E-04	9.23E-05	1.08E-04	7.76	0.49	8.25
27.5	67.52	1.59E-04	9.09E-05	1.08E-04	8.37	0.48	8.85
28.5	67.28	1.58E-04	9.01E-05	1.08E-04	8.97	0.47	9.44
29.5	67.28	1.55E-04	8.85E-05	1.07E-04	9.62	0.46	10.08
30.5	67.28	1.51E-04	8.69E-05	1.06E-04	10.29	0.45	10.74
31.5	67.28	1.48E-04	8.54E-05	1.05E-04	10.99	0.44	11.43
32.5	67.28	1.45E-04	8.40E-05	1.04E-04	11.70	0.43	12.14
33.5	67.28	1.42E-04	8.25E-05	1.03E-04	12.44	0.43	12.87
34.5	66.8	1.41E-04	8.20E-05	1.04E-04	13.11	0.41	13.52
35.5	66.8	1.39E-04	8.03E-05	1.03E-04	13.89	0.40	14.29
36.5	66.8	1.36E-04	7.91E-05	1.02E-04	14.69	0.39	15.08
37.5	66.9	1.33E-04	7.74E-05	1.01E-04	15.54	0.38	15.92
38.5	66.9	1.31E-04	7.59E-05	9.98E-05	16.39	0.37	16.76

The change of fuel element pitch in the outer (thermal) zone

Pitch, cm	$Flux_{in}$	$Flux_{out}$	Total flux	$Cost_{in}$, mln. EUR	$Cost_{out}$, mln. EUR	Total cost, mln. EUR
3.5	1.41E-04	6.33E-05	6.82E-05	2.57	1.77	4.34
4	1.66E-04	8.38E-05	9.05E-05	2.38	1.06	3.43
4.5	1.86E-04	9.88E-05	1.07E-04	2.29	0.74	3.03
5	1.98E-04	1.08E-04	1.17E-04	2.26	0.58	2.83
5.5	2.11E-04	1.15E-04	1.24E-04	2.25	0.47	2.72
6	2.16E-04	1.20E-04	1.29E-04	2.27	0.41	2.67
6.5	2.17E-04	1.21E-04	1.30E-04	2.30	0.36	2.67
7	2.22E-04	1.23E-04	1.32E-04	2.34	0.33	2.66
7.5	2.25E-04	1.23E-04	1.32E-04	2.38	0.30	2.68
8	2.24E-04	1.22E-04	1.30E-04	2.43	0.28	2.72
8.5	2.26E-04	1.21E-04	1.29E-04	2.48	0.27	2.75
9	2.27E-04	1.19E-04	1.27E-04	2.54	0.26	2.79
9.5	2.27E-04	1.17E-04	1.24E-04	2.60	0.25	2.85
10	2.27E-04	1.15E-04	1.22E-04	2.65	0.24	2.89
11	2.24E-04	1.09E-04	1.15E-04	2.79	0.23	3.02
12	2.24E-04	1.05E-04	1.11E-04	2.91	0.22	3.13
13	2.17E-04	9.80E-05	1.03E-04	3.07	0.22	3.29
14	2.15E-04	9.26E-05	9.72E-05	3.21	0.22	3.43
15	2.09E-04	8.61E-05	9.01E-05	3.38	0.22	3.60
16	2.04E-04	8.02E-05	8.38E-05	3.54	0.22	3.76
17	2.04E-04	7.59E-05	7.93E-05	3.68	0.22	3.91
20	1.82E-04	5.80E-05	6.02E-05	4.32	0.26	4.58
25	1.55E-04	3.62E-05	3.74E-05	5.51	0.35	5.86

The change of fuel element pitch in the outer (thermal) zone



- Also, the transmutation characteristics (reaction rates, fission and capture microscopic cross sections) for Np-237, Am-243, and I-129, Tc-99 were considered
- The neutron spectra for inner (fast) and outer (thermal) zone were obtained

The journal and conference papers

- *V.O. Babenko, V.I. Gulik, V.M. Pavlovych*. Modeling of Two-zone Accelerator-Driven Systems. Nuclear Physics and Atomic Energy, 13(3), 266 – 275, 2012

- *V. Gulik, A. H. Tkaczyk*. Optimization of geometry, material and economic parameters of a two-zone subcritical reactor for transmutation of nuclear waste with SERPENT Monte Carlo code, Proceedings of Joint International conference on Supercomputing in Nuclear Applications & Monte Carlo (SNA&MC2013), Paris, France: 27-31 October, 2013

- *V. Gulik, A.H. Tkaczyk*. Cost optimization of ADS design: Comparative study of externally driven heterogeneous and homogeneous two-zone subcritical reactor systems. Nuclear Engineering and Design, 270, 133 – 142, 2014

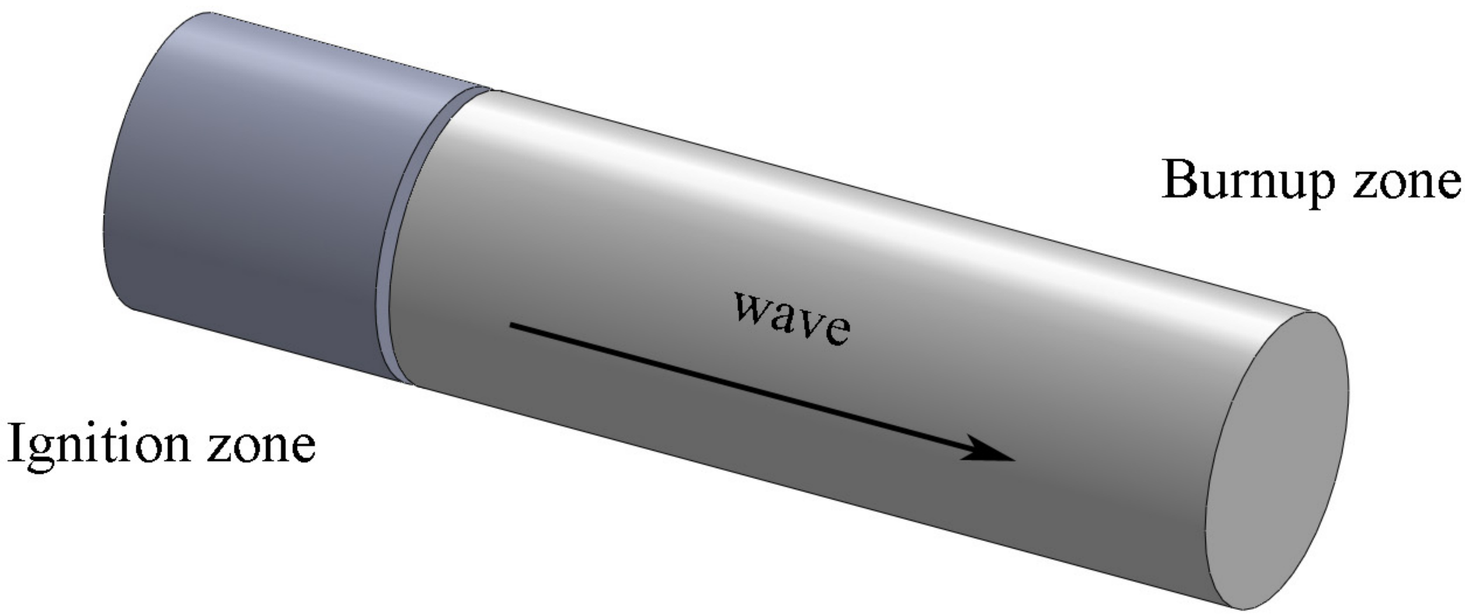
- *V. Gulik, V. Pavlovych, A.H. Tkaczyk*. The development of neutron-physical model of two-zone research subcritical reactor for transmutation of nuclear waste. Nuclear Physics and Atomic Energy, 2014 [forthcoming]

The modelling of Traveling Wave Reactor (TWR)

TWR description

The main idea of the reactor in question is quite simple and elegant. Let us imagine a long cylinder or a box of feed material which is irradiated by neutrons from an end. For example, an ADS or a small reactor, constructively attached to the end of the main reactor (the so-called "ignition zone") could act as an external neutron source for the proposed reactor.

In the simplest case, the wave reactor is a cylinder, which is divided into two main regions: the ignition zone and the burnup zone.



Method description

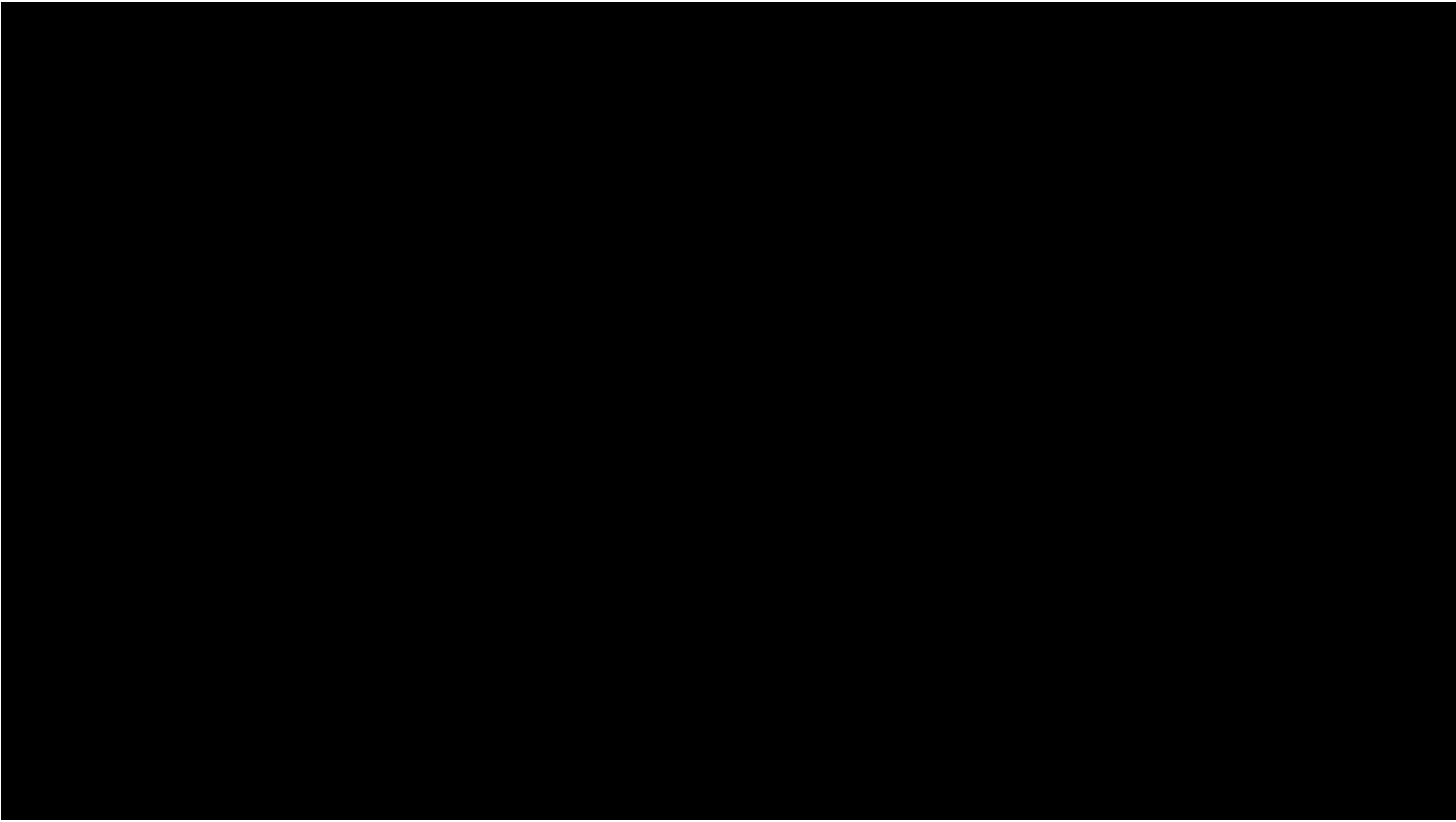
The Monte Carlo code SERPENT is used for neutron-physical simulations. SERPENT-1.1.18 and SERPENT- 2.1.11 codes were used

In the present simulations, the workgroup's personal computer (PC) workstations and high performance computing (HPC) clusters of the University of Tartu have been used.

Model description

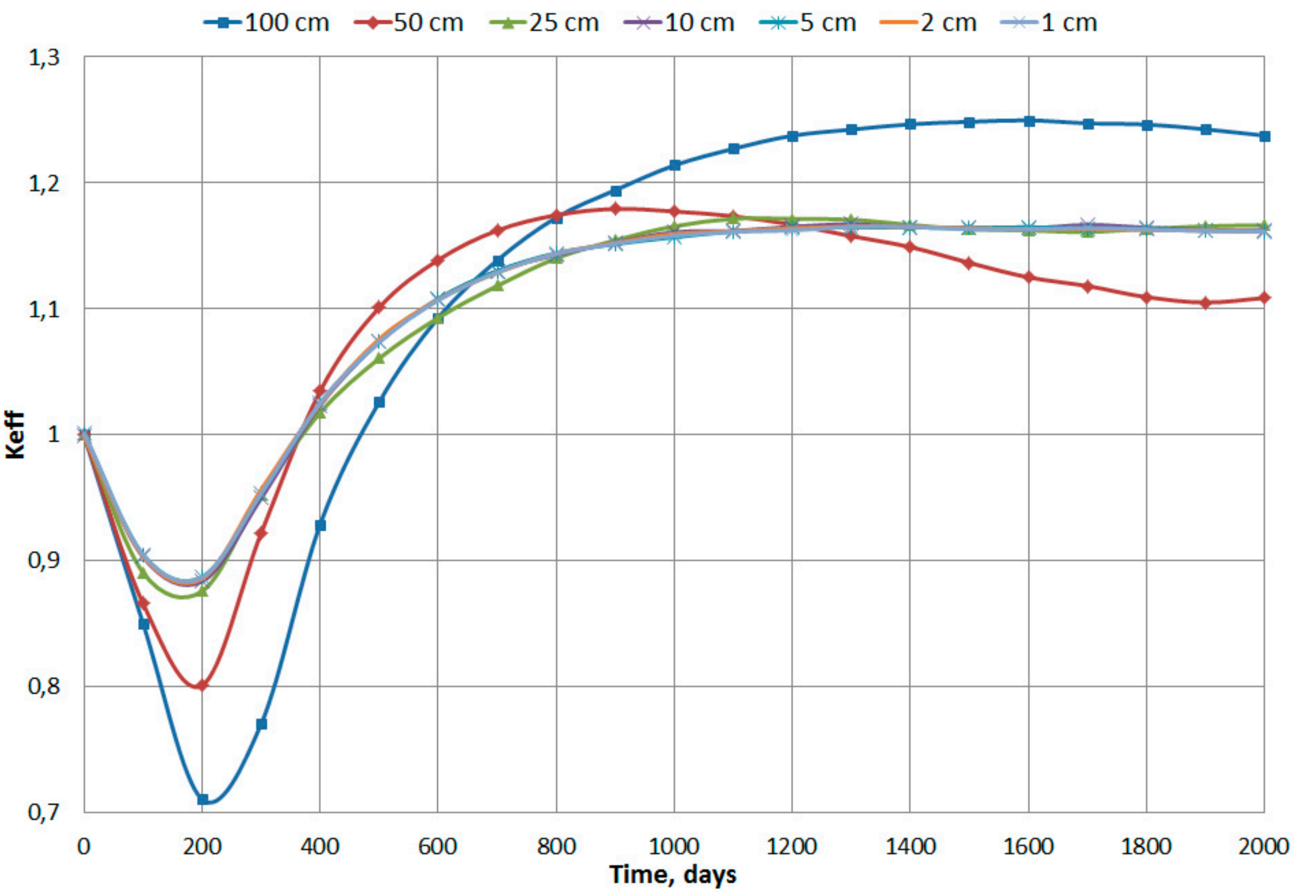
Enriched metallic uranium, enriched uranium dioxide, plutonium-239, and uranium-plutonium mixed oxide (MOX) fuel with different isotopic compositions are used as the fissile material in the ignition zone. Enriched metallic uranium, enriched uranium dioxide, depleted uranium and pure uranium-238 are used as the feed material in the burnup zone.

Visualization of obtained results



Results

The simulation with various fragmentations of burnup zone



Ignition zone: pure metallic uranium-235;
Burnup zone: pure metallic uranium-238;
The number of source neutrons per cycle is 2000;
The number of active cycles is 2000;
Length of burnup zone – one meter;

The change with time of effective neutron multiplication factor for various fragmentations of the burnup zone (SERPENT 1.1.18 code)

The journal and conference papers

- *V. Gulik, V. Pavlovych, A. H. Tkaczyk.* Using SERPENT Monte Carlo and Burnup code to model Traveling Wave Reactors (TWR), Proceedings of Joint International conference on Supercomputing in Nuclear Applications & Monte Carlo (SNA&MC2013), Paris, France: 27-31 October, 2013

- *V.M. Khotyayintsev, A.V. Aksonov, O.M. Khotyayintseva, V.M. Pavlovych, V. Gulik, A.H. Tkaczyk.* Velocity characteristic and stability of wave solutions for a CANDLE reactor with thermal feedback. Annals of Nuclear Energy, 2014 [forthcoming]

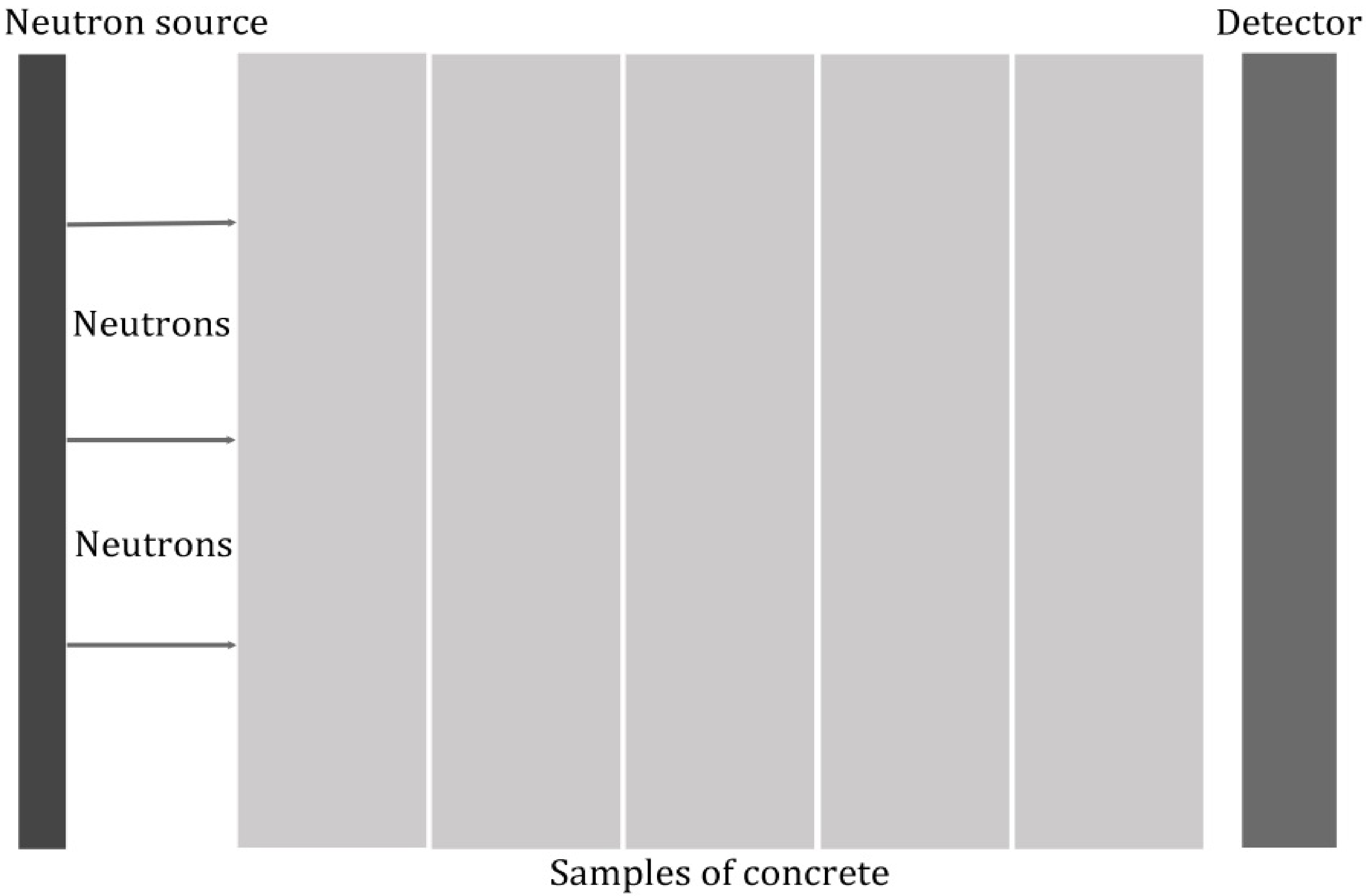
The radiation shielding modelling of basalt-concrete materials

We study the basalt fibre reinforced concrete as new material for nuclear energy application with radiation shielding properties

Basalt fibre in concrete

Basalt fibre

The model for neutron radiation shielding calculations

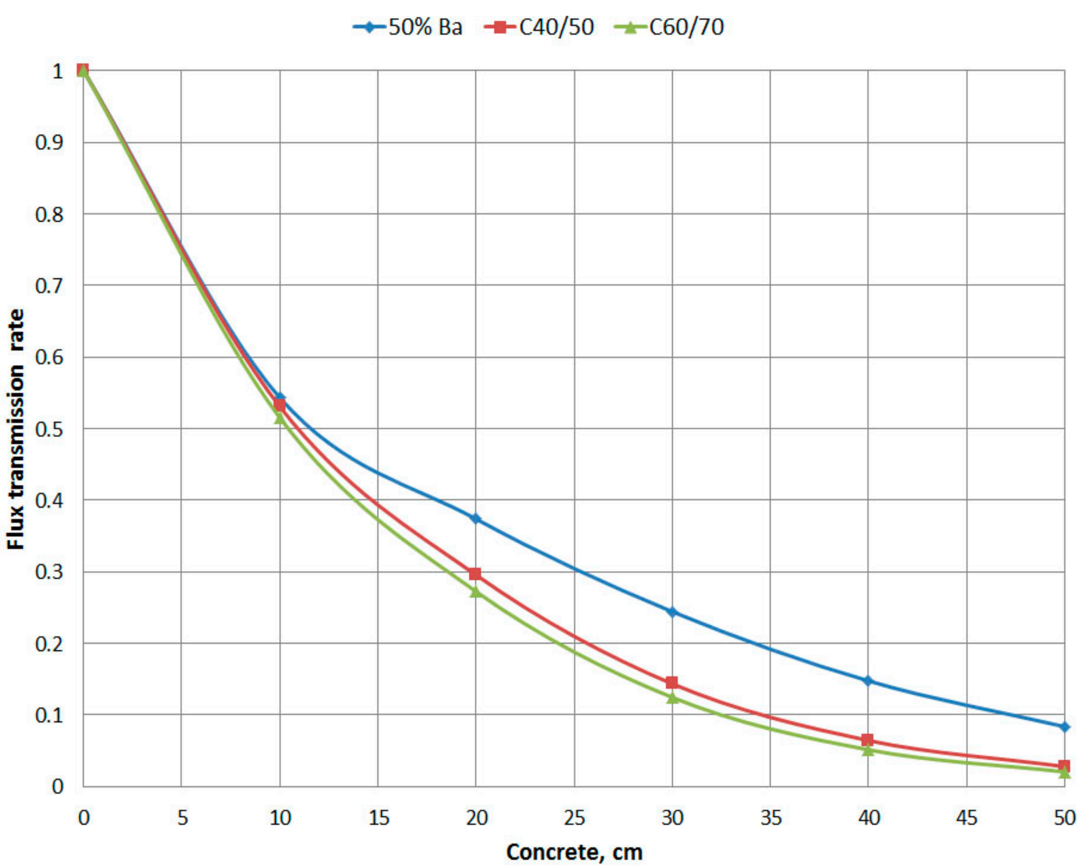


The presented model allows the calculation of the passage of neutrons through concrete layers with different thicknesses. The plane source of 14 MeV fast neutrons is used in our model

Results

The reducing of neutron radiation is estimated by two methods:

1) Calculation of the neutron current that crossed the boundary layer of the detector (left side of the detector).
2) Calculation of the neutron flux in the detector volume.



The flux transmission rates for different types of concrete

The journal and conference papers

- *V.I. Gulik, A.B. Biland*. The Use of Basalt, Basalt Fibers and Modified Graphite for Nuclear Waste Repository, Proceedings of International Waste Management Conference (WM2012), Phoenix, Arizona, US: 26 February - 1 March, 2012

- *H. Nulk, C. Ipbüker, V. Gulik, A. Biland, A. H. Tkaczyk*. The investigation of gamma and neutron shielding properties of concrete including basalt fiber for nuclear energy applications. Proceedings of 2nd International Symposium on Cement-based Materials for Nuclear Wastes (NUWCEM2014), Avignon, France: 3-6 June, 2014

- *C. Ipbüker, H. Nulk, V. Gulik, A. Biland, A.H. Tkaczyk*. Radiation shielding properties of a novel cement-basalt mixture for nuclear energy applications. Nuclear Engineering and Design, 2014 [forthcoming]

Thank you for your attention

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