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Concept of a BNCT line with in-pool fission converter at MARIA reactor in Swierk

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BNCT facility in the Institute of Atomic Energy in Otwock-Swierk is under construction at the horizontal channel H2 of the research reactor MARIA. Measurements of the neutron energy spectrum performed at the front of the H2 experimental channel, have shown that flux of epithermal neutrons (above 10 keV) at the BNCT irradiation port was below 10^9 n cm^{-2} s^{-1} i.e. it was too low to be directly used for the BNCT treatment. Therefore, a fission converter will be placed between the reactor core and the periphery of the graphite reflector of MARIA reactor. The uranium converter will be powered by the densely packed EK-10 fuel elements with 10% enrichment. Preliminary calculations have shown that the total neutron flux in the converter will be about 10^{13} n cm^{-2} s^{-1} and flux of epithermal neutrons at the entrance to the filter/moderator of the beam will be about $2{\cdot}10^9$ n cm^{-2} s^{-1}.

Key words: BNCT, reactor facility, fission converter.

Introduction

BNCT research program started in Poland in 2001, as collaboration of the Institute of Atomic Energy in Swierk and the Institute Maria Curie Oncology Centre in Warsaw. The MARIA reactor in Swierk is to be used as the neutron source for the planned Polish BNCT facility.

At the front of experimental channels the neutron flux is strongly thermalized – neutrons with energies above 0.625 eV constitute only ~2% of the total flux. Therefore it was necessary to place a fission converter between the reactor core and the BNCT irradiation port. The optimum position for the converter is either close to the front of the channel (near the reactor core) or at the mouth of the channel. In the first design, two aluminium caissons, coupled with a pneumatic system for emptying and refilling, were placed between reactor beryllium matrix and H2 channel front to increase the neutron flux at the channel front. Still, the neutron spectrum of the beam contained mostly thermal neutrons, so that a fission converter was foreseen at the mouth of the channel, before the filter/moderator NCT assembly.

After six years in the reactor pool, one of the caissons was broken beyond repair. It was decided then to remove both caissons and to replace them by a pipe segment coupled with the pneumatic system used previously for the caissons. Besides, a new concept of an underwater, in pool fission converter has been elaborated with the converter replacing one graphite block at the periphery of MARIA graphite reflector.

Technical conditions

The multipurpose, high flux research reactor MARIA is of loop type, water and beryllium moderated and graphite reflected. The fuel elements of MR-6 type are of tubular type with six concentric tubes. The fuel channels are situated in a matrix, made of beryllium blocks and surrounded by lateral reflector made of graphite blocks in aluminium cladding. The nominal power of the reactor is 30 MW(th). Thermal neutron flux is $3.5 \cdot 10^{14}$ cm^{-2} s^{-1} resulting in the output thermal neutron flux of horizontal channels of 3-5 $\cdot$ 10^{9} cm^{-2} s^{-1}.

The reactor reached its first criticality in 1974. It was in operation until 1985 when it was shut down for modernisation with respect to safety and efficiency. Operation was resumed in 1993. Actually the reactor is operating on MR-6 type fuel assemblies with 36% enrichment in U-235.

Flux of the epithermal neutrons from the reactor MARIA is too low to be directly used for the NCT treatment. Therefore two pneumatic caissons were constructed, in order to transfer neutrons directly from beryllium matrix to H2 channel entrance [2].

Both caissons were designed as suitably shaped, welded aluminium boxes [1] emptied and refilled by means of a pneumatic system. The caissons were filled with nitrogen for the time of irradiation and then refilled with water, in order to restore the biological shield of the reactor.

Measurements of the neutron energy spectrum performed at the front of the channel H2 after construction of the caissons, confirmed that the dominating component in the spectrum was due to thermal neutrons. Therefore, a fission converter containing ^{235}U had to be installed.

As mentioned above there were two possibilities for the location of the converter – either at the channel mouth or at the front.

The most important advantages of the design with the converter at the mouth were low thermal power of the fission converter and low burnup rate of the fuel in the converter. There were however also serious disadvantages.

The primary beam should be broad, so that in MARIA conditions the caissons had to be designed as boxes of very complicated shapes. With such design, it was not possible to avoid presence of water gap between the caissons. This resulted in considerable attenuation (scattering) of the primary beam. The beam was also attenuated by connector pipe of the horizontal channel.

The shielding of the external fission converter had to be very heavy, even if the working load was assumed to be moderate.

Taking into account the considerations mentioned above and also the practical problems associated with the reconstruction of the damaged caisson, it was concluded that an alternative solution with in-pool fission converter will be realised.

Design of the NCT beam line with in-pool fission converter

According to the new concept the uranium converter will be placed in the reactor pool, near the front of the H2 channel.

The simple and compact tubular design of the internal channel makes the construction resistant to mechanical load, especially to the load associated with filling the system with nitrogen and refilling with water.

The converter will consist of densely packed EK-10 fuel elements with 10% enrichment and will be placed at the periphery of the graphite reflector of the reactor. The EK-10 fuel rod elemental composition is described in Table 1.

Before the fuel elements can be mounted in the converter, they have to be re-tested. Special attention will be paid to leak tightness.

Table 1. Elemental composition of the EK-10 fuel element. *For the fuel containing part (500 mm).

Element	Mass [g]
^{235}U	8.05
^{238}U	73.33
Mg	13.03
O	12.19
Al	64.4/54.1*

There are several important requirements which should be taken into account at the design stage. Some of them are mutually contradictory.

- Maximum efficiency of the converter can be reached at the maximum number of the installed fuel elements.
- Proper cooling conditions can be ensured by an appropriate water flow, so the resistance to flow has to be reduced and the number of the fuel elements has to be limited.
- The water flow through the converter cannot exceed ~5% of the total water flow in the reactor pool.
- The requirement of the minimum resistance to water flow leads to the openwork design of the fuel element separator, which, on the other hand, has to be strong enough to ensure the needed strength for mechanical load due to the fuel weight and forces associated with the water flow.

It was shown [4] that the conditions described above can be ensured when the fuel elements are placed in the triangular lattice with the spacing of 12 mm.

In order to minimize the neutron activation of the fuel in the converter, the possibility was envisaged to remove the converter and to replace it with an aluminium dummy for the time when the beam at the channel H2 is not used. This means that both, the converter and the dummy have to be easily removable from the converter socket. There has to be also the place in the water pool, near the BNCT facility, where the converter can be safely stored.

Thermal and neutron load of the fuel rods in the converter are highly inhomogeneous. The maximum load is in the rod closest to the reactor core. In order to equalize these loads, the converter was designed in such a way that it is possible to mount it turned 180° around the vertical axis.

The calculations showed that there will be a ~40°C increase in the water temperature near the elements with the highest load. Therefore, the design at the converter socket provides a measuring probe with two thermocouples, which will measure the temperature increase in the converter. The probe is placed near the fuel element with the highest load.

The flux and neutron spectra will be monitored by means of activation foils and wires attached to the converter socket. The most important are the positions near the fuel element with the highest load and the surface adjacent to the internal channel.

Preliminary calculations have shown that the total neutron flux at the entrance to the converter will be $\sim 10^{13}$n cm^{-2} s^{-1} and the flux of epithermal neutrons at the entrance to the filter/moderator of the beam will be $\sim 2 \cdot 10^{9}$ n cm^{-2} s^{-1}.

Conclusions

A new design was proposed for the BNCT line in the MARIA reactor. It was shown that the in-pool uranium converter placed at the periphery of the graphite reflector may serve as an efficient source of epithermal neutrons.

The converter is constructed using low-enrichment reactor fuel of EK-10 type. Cooling of the converter will be ensured by the cooling circuit of the reactor pool.

The beam of epithermal and fast neutrons will be transferred from the converter to the H2 channel through the tubular internal channel filled with nitrogen. Such design helps to diminish scattering and absorption of epithermal and fast neutrons by construction materials of the channel and by intra caisson gaps filled with water of the previous design.

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