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DELPHI: a New Subcritical Assembly at Delft University of Technology

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This paper describes the new subcritical assembly called DELPHI at Delft University of Technology. It consists of two vessels one upon the other, and contains 168 fuel pins made of 3.8 % enriched UO_2 fuel. The upper acrylic vessel is used to store the fuel pins when the assembly is not in use. With a special handling tool the fuel pins can be loaded into the water-filled steel vessel. The source is stored in a shielding box below the steel vessel and can be inserted pneumatically up to a height of 2 cm below the fuel zone of the pins.
DELPHI became operational at the beginning of 2004 and will be used for training of students and reactor operators from the Netherlands and abroad and for basic research on reactivity determination methods.

KEYWORDS: Subcritical assembly, LEU fuel, Cf-252 source driven

1. Introduction

For educational purposes, the Reactor Physics Department of IRI used to operate a subcritical assembly containing 253 fuel pins made of natural uranium (metal) in a hexagonal lattice. As a moderator, light water was used. However, for some practical reasons, like the heavy weight of each fuel pin (almost 7 kg), the rather low k_{eff} (≈0.85) and the fact that some fuel pins stuck to the grid plates, this assembly is not used anymore. Therefore, it was decided to build a new assembly, called DELPHI, for both the purposes of training and research. The following training exercises are foreseen:

- Static determination of the multiplication factor by the so-called critical assembly approach [1] [2].
- Axial and radial neutron flux measurements.
- Source jerk experiments.
- Neutron noise experiments like Feynman-α, and correlation measurements.

In principle, DELPHI consists of two vessels one upon the other. The lower vessel is made of stainless steel and is filled with de-mineralized water before the start of an experiment. The upper acrylic air-filled vessel is used to store 168 fuel pins that can be loaded into the steel vessel one after the other using a special handling tool. Below the steel vessel, a shielding box is positioned containing a ^{252}Cf-neutron source that can be inserted pneumatically to its experimental position in the steel vessel. This document gives a description of DELPHI and of the various safety aspects.

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2. Description of the facility

2.1 Fuel

The DELPHI assembly contains 168 fuel pins, each of which contains 44 pellets made of 3.8% enriched UO_2 fuel that are stacked in an aluminum tube. Each pin contains about ≈356.5 gram of UO_2. From bottom to top a fuel pin contains 5 cm of aluminum, 6 cm of corundum, 44 cm of fuel, 3 cm of corundum, 3.15 cm of void (spring), and 5 cm of aluminum. The total length of an original fuel pin is 66.5 cm. Attached to the top of each fuel pin, a special stainless steel head facilitates manipulation with a tailor-made handling tool that can hold of a fuel pin very much like a refillable lead pencil. Including this head, the length of a fuel pin reaches about 69.5 cm. Figure 1 shows the stainless steel head without and with the handling tool. The small bar slots the fuel pin in the upper grid plate (see later on). Loading a fuel pin into the assembly is done by grabbing the fuel pin with the handling tool, lifting it a few mm and rotating it by about 90 degrees, and lowering it to its experimental position in the water-filled steel vessel.

Fig.1A The stainless-steel head for a fuel pin.

Fig.1B The stainless-steel head grabbed by the special handling tool.

2.2 Lattice

The fuel pins are positioned in a square lattice of 13x13 positions, with the central position being occupied by a water-filled tube. This leaves 168 positions for the fuel pins. Note that under no circumstance more than 168 fuel pins can be loaded into the assembly, which is considered to be an important safety aspect. The pitch between the fuel pins is 23 mm, being the value at which the k_{eff} of the assembly is maximal. Consequently, every influence disturbing the pitch will reduce the k_{eff}. Figure 2 shows the k_{eff} of the DELPHI assembly as a function of the pitch for a water temperature of 20 ^{0}C, as calculated by the Monte Carlo code MCNP-4C [3]. It is clear that the maximum k_{eff} value reaches 0.92, which in fact is a slight overestimation because of two conservative approximations in the calculations: an enrichment of 3.9% and the omission of some structural materials. Without this conservatism, calculations show that the resulting k_{eff} is expected to be close to 0.916 (ENDFB/VI data). Figure 3 shows the k_{eff} of the assembly as a function of the water temperature. In the range of interest (T<20 ^{0}C), k_{eff} is virtually independent of temperature. Monte Carlo calculations by NRG [4] applying a modified version of MCNP give a k_{eff} of 0.920 (JENDL-3.3 data), a β_{eff} of 0.766% and an average fission lifetime of 61.7 μs.

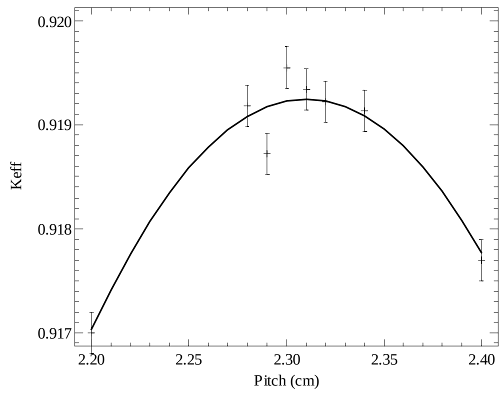

Fig.2 The k_{eff} as a function of the pitch for a water temperature of 20 ^{0}C. The solid line is a second-order least-squares fit.

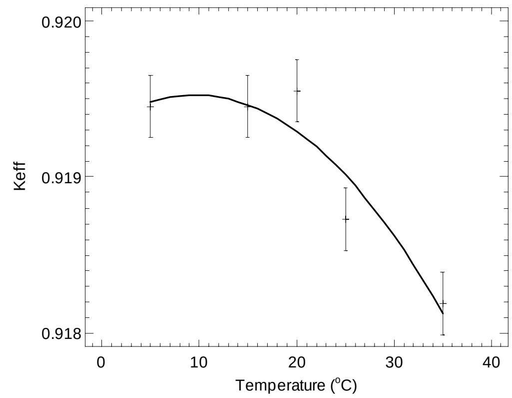

Fig.3 The k_{eff} as a function of the water temperature for a pitch of 23 mm. The solid line is a second-order least-squares fit.

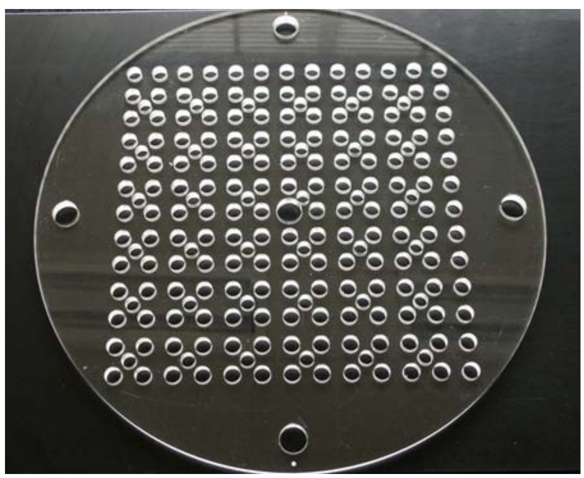

Fig.4 One of the acrylic grid plates with diameter of 425 mm. Between the holes for the fuel pins (13x13-1=168 positions), smaller holes for the detector tubes can be seen. The center hole contains the source tube (up to 2 cm below the fuel zone of the pins) and water (for the remainder). The upper plate contains slots to hold the fuel pins, while the lower plate contains no holes at all.

2.3 Vessels

The cylindrical stainless steel vessel (see Figure 5) has both an inner diameter and height of 100 cm. Before starting an experiment, the vessel is filled with de-mineralized water until a preset level (about 5 cm below the top of the vessel) controlled by two floats and some electronics. Both the water inlet and outlet flanges are located at the bottom of the vessel (see Figure 6). When the vessel is filled, a manual valve between the vessel and the electrical valve can be closed. To drain the water, the manual valve in the outlet should be opened and the pump started. When the vessel is empty, the pump shuts down automatically. The one-way valve between the pump and the drainage prevents any backward water flow.

On top of the steel vessel, a cylindrical transparent acrylic vessel with outer diameter of 50 cm and height of 80 cm is mounted containing the fuel pins in storage. The assembly is loaded by a controlled movement of each fuel pin from its upper position in the air-filled acrylic vessel to its lower position in the water-filled steel vessel. As mentioned before, a special handling tool is made to grab a fuel pin, to lift and rotate it, and to lower it to its experimental position.

At the bottom of the steel vessel, a leak-tight stainless-steel tube will be positioned straight right up through which the ^{252}Cf-neutron source can be loaded in its experimental position 20 mm below the fuel zone of the pins. Furthermore, four spotlights are mounted to the bottom of the vessel to illuminate the assembly from the inside (see Figure 6).

In the cylindrical wall of the vessel, at a height of core midplane, a flange is made (see Figure 5), through which an aluminum tube can be inserted. This option is of interest for experiments that require a (pulsed) neutron generator close to the fuel pins. However, these experiments require an extension to the operating license.

Fig.5 The stainless-steel vessel of DELPHI. The small flange on top of it will be used to mount two floats to control the water level inside.

Fig.6 The bottom of the steel vessel. The four large holes will be used to insert spotlights, the central hole to insert the source tube and the two others to fill and drain the vessel.

2.4 Source

The ^{252}Cf-neutron source contained in a plastic capsule has an initial strength of 18.5 MBq corresponding to a neutron source emission rate of 2.4E6 s^{-1} and a gamma-ray emission rate of 1.3E7 s^{-1}. It is stored in a stainless steel rectangular box (see Figure 7) with horizontal cross section of 50x50 cm and a height of 40 cm filled with paraffin and B_4C grains. In the box, the source tube (an aluminum tube through which the source capsule moves to its experimental position) is surrounded by a stainless steel tube and wrapped with a 1-cm thick lead cylinder to shield the gamma rays (see Figure 7). Calculations with the Monte Carlo code MCNP-4C [3] show that the expected dose rate at the outer side of the box is limited to 6.5 μSv/hr, while at a distance of 130 cm from the source the dose rate is less than 1 μSv/hr. This distance is the nearest a trespasser can get. Although measurement have indicated a larger dose rate at the outer side of the box (around 20 μSv/hr), the dose rate at a distance of 130 cm is much less than 1 μSv/hr. Because of the good shielding properties of the box, its structural integrity, and its fire-resistance, the source can be permanently stored in the box.

When DELPHI is not in use, the source is stored in the box and the source tube is shielded with a plug. Before the start of an experiment, the box is pulled from its position under the steel vessel to remove the shielding plug, and pushed back under the vessel. Only if the reactor vessel is filled with water, the source tube can be lifted pneumatically and be connected to the steel vessel. Subsequently, the source capsule can be inserted and withdrawn from the vessel by means of air pressure. Both the source capsule and the shielding plug contain a magnet, each of which activates three reed relays when positioned in the shielding box.

Fig.7 Interior of the stainless steel shielding box. The aluminum source tube with inner diameter of 16 mm is surrounded by a stainless steel tube and lead (1 cm) and can be lifted pneumatically to connect the shielding box to the steel vessel. After being filled with paraffin and B_4C, this box will be covered by a stainless-steel plate.

2.5 Loading Platform

From bottom to top, DELPHI contains the shielding box, the steel vessel and the acrylic vessel (see Figure 8). In total, the height reaches about 250 cm, which makes it necessary to manipulate the fuel while standing on a loading platform. This platform is made of stainless steel and sufficiently large to accommodate 8 to 10 persons. Because of its diameter (275 cm) trespassers cannot get any closer to the shielding box than about 130-cm. The height of the loading platform is 145 cm, while the height of the total construction shown in Figure 8 is 245 cm.

Fig.8 The main parts of DELPHI assembled together. Inside the loading platform, the steel vessel is mounted below which the drawer mechanism and the shielding box are seen. On top of the steel vessel, the acrylic vessel is mounted. Because of its transparency, this vessel is less visible.

2.6 Safety

Operation of DELPHI is subject to general safety considerations, like a radiation dose rate less than 1 μSv/hr for trespassers (with the source in the shielding box). The dose rate for the experimentalists with the source at its experimental position is expected to be less than 6.5 μSv/hr at the outer surface of the steel vessel.

Furthermore, active electronics control the safe operation of the assembly. In total 12 switches provide a signal of either 0 or 5 V (open/closed) to Programmable Logic Devices (PLD), which in turn control the solid-state relays that activate the electrical and pneumatic valves needed to operate DELPHI. As mentioned before, both the source and the shielding plug are detected by three reed relays each. This redundancy is needed because the switches in the shielding box cannot easily be replaced in case of malfunctioning.

2.7 Instrumentation

DELPHI is equipped with one (in the near future two) 10-bar ^{3}He proportional counter tubes with diameter of 6 mm and active length of 76 mm (General Electric type RS-P4-0203-212). For each (n,p) reaction in the detector, an energy of 765 keV is released plus the kinetic energy of the incident neutron. Charge multiplication in the detector is controlled by the value of the high voltage and ranges practically up to a factor of 1000. The pulses from the detector are amplified and converted to TTL format (standardized 'square box' pulses with a height of 5 V) by a PDT amplifier (PDT20A-SHV), which also supplies the high voltage. The pulses are subsequently recorded in a PC equipped with a pulse-counter card and LABVIEW software to control the measurements. Besides the detector pulses, this software also records the trigger pulses from the reed relays in the shielding box and/or the signals that control the pneumatic valves for the movement of the source, thus recording each passage of the source synchronized with the neutron pulses.

3. Approach to Critical Experiment

The first experiment carried out was the approach to critical [1,2]. For this experiment, the fuel is loaded in the water-filled steel vessel in batches of 8 pins, and after each loading the detector count rates are measured with and without the source. The difference of these two rates gives the background corrected count rate proportional to $Q/\left(1-k_{eff}\right)$ with Q the strength of the external ^{252}Cf source. Dividing this count rate by the background corrected count rate when only the source is present gives the multiplication factor $M=1/\left(1-k_{eff}\right)$. Although only one detector was available, the experiment was repeated several times to get results at various measurement positions labeled det1, det2 and det3 (see Figure 9).

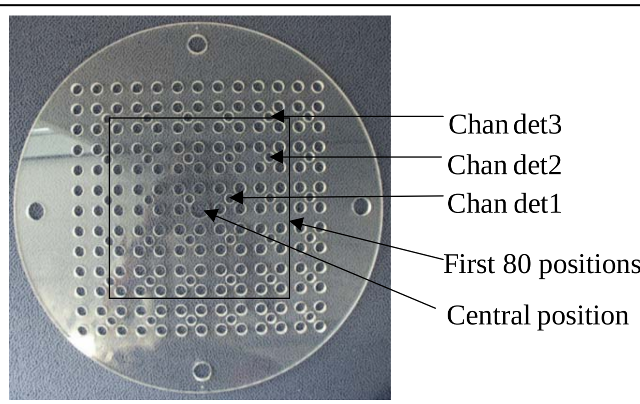

Fig.9 The position of the three channels (det1, det2, and det3) used for the approach to critical experiment. In all cases, the loading was halted after 80 pins (indicated in the figure).

Figure 10 shows the results of the experiment for the loading of 80 fuel pins, after which the experiment was halted to investigate the spatial dependence of the multiplication factor as a function of fuel loading. During loading, the curves in Figure 10 are linearly extrapolated to estimate the number of fuel pins at which the assembly could become critical. The numerical simulation of the experiment is shown in Figure 11.

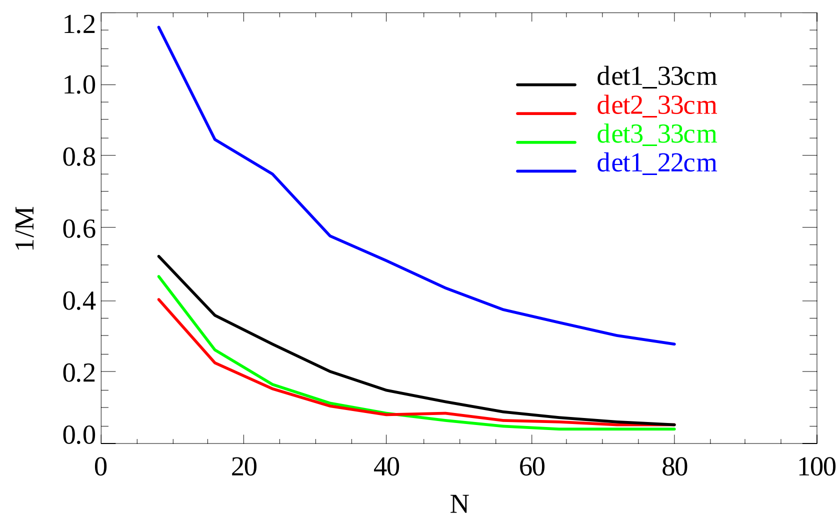

Fig.10 The inverse of the multiplication factor (1/M) as a function of the number of fuel pins (N). Results are shown at three channels at various heights measured from the bottom. At 33 cm the detector is located just above core midplane.

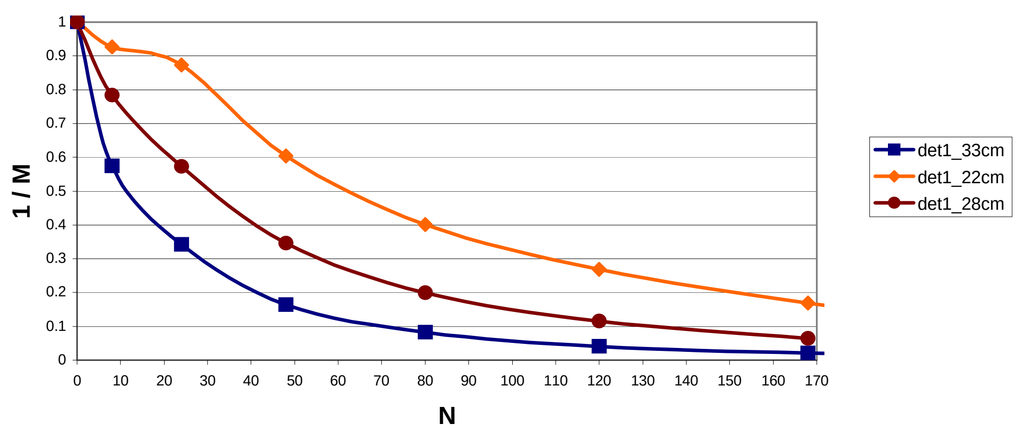

Fig.11 Results for the approach to critical experiment calculated using MCNP [3].

Clearly, for the position close to the source (det1_22cm), the multiplication factor is dominated by the source, which leads to a lower k_{eff} than for the other positions. This effect is very strong in DELPHI because the source is located below the fuel zone, which gives a strong shift in the spatial flux distribution during the loading of the assembly. Calculations indicate that the k_{eff} from the multiplication curve at position indicated det1_28cm correspond best with the integral k_{eff} obtained by Monte-Carlo eigenvalue calculations. The loading will be continued as soon as two detectors are available.

4. Conclusions

A new subcritical assembly called DELPHI has been designed and constructed at the Interfaculty Reactor Institute of Delft University of Technology. It consists of two vessels one upon the other, and contains 168 fuel pins made of 3.8 % enriched UO_2 fuel. The upper acrylic vessel is used to store the fuel pins when the assembly is not in use. With a special handling tool the fuel pins can be lowered into the steel vessel that is filled with water. The source is stored in a shielding box below the steel vessel and can be inserted pneumatically up to a height of 2 cm below the fuel zone of the pins. DELPHI became operational at the beginning of 2004 and will be used for training of students and reactor operators from the Netherlands and abroad, as well as for basic research on reactivity determination methods.

Until now (January 2004), the initial loading of 80 fuel pins has been completed and the dependency of the multiplication factor for the detector position has been investigated. Because the source is located below the fuel zone, the spatial flux distribution changes strongly during fuel loading. As a consequence, the multiplication factor depends strongly on the detector position as well. At short notice, the fuel loading will be continued using two detectors.

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