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DESCRIPTION OF THE DELPHI SUBCRITICAL ASSEMBLY AT DELFT UNIVERSITY OF TECHNOLOGY

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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} ($\approx$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 lowered 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 pneumatically be inserted to its experimental position in the steel vessel. This document gives a description of the various parts of Delphi and of the safety aspects during the operation of the assembly.

FUEL

The Delphi assembly contains 168 fuel pins, each of which contains 43 to 45 pellets made of 3.8% enriched UO_2 fuel. The pellets are stacked in an aluminum tube with outer diameter of 12 mm and wall thickness of 0.95 mm. Despite the fact that the number of fuel pellets in a pin varies from 43 to 45, the UO_2 weight per fuel pin is fairly the same ($\approx$356.5 gram). Each pellet has an outer diameter of 5.05 mm and a height of 10 mm. 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 a part of 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 then done by grabbing the fuel pin with the special handling tool, lifting it a few mm and rotating it by about 90 degrees, and lowering it to its experimental position in the assembly.

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

Figure 1B: The stainless-steel head grabbed by the special handling.

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. Figure 3 shows the k_{eff} of the assembly as a function of the water temperature. In the range of interest, k_{eff} is virtually independent of temperature. To avoid that a fuel pin can stick to the grid, eight acrylic plates with diameter of 425 mm and thickness of 10 mm (see Figure 4) guide and hold the fuel pins while (un) loading the assembly. Because the grid plates are transparent, the fuel pins remain visible when loaded in the steel vessel. The upper grid plate has a thickness of 15 mm and contains slots to accommodate the small bar attached to the head of each fuel pin. During storage the fuel pins hang with the small bar resting in the slot of the upper grid plate. The lower grid plate, upon which the fuel pins rest in the steel vessel contains no holes and has a thickness of 15 mm too.

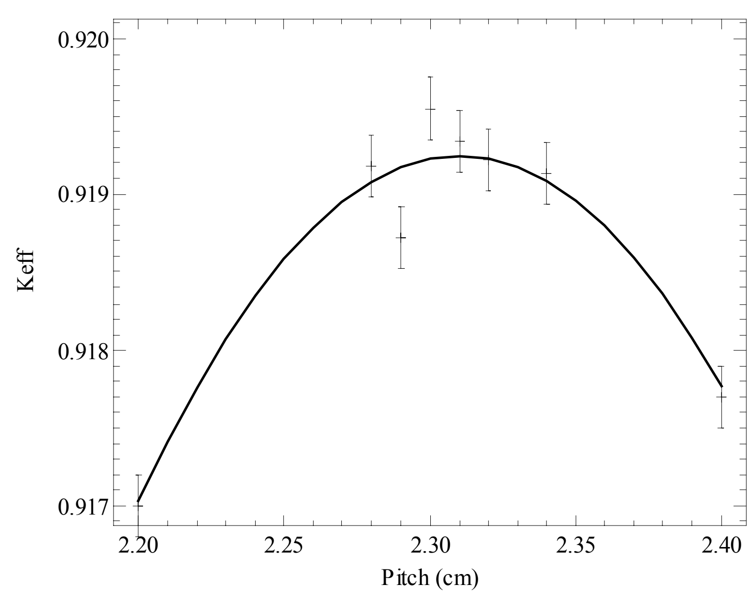

Figure 2: The k_{eff} as a function of the pitch for a water temperature of 20 ^{0}C. The solid line is a second-order least-squares fit.

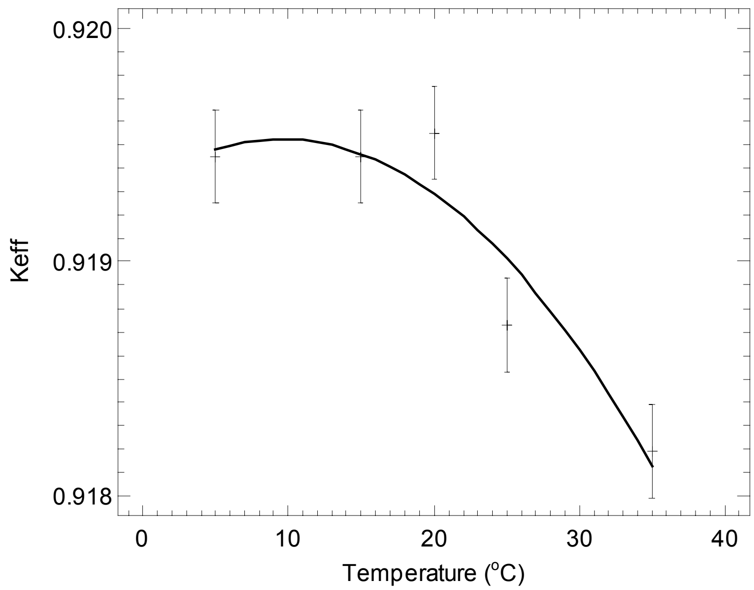

Figure 3: The k_{eff} as a function of the water temperature for a pitch of 23 mm. The solid line is a second-order least-squares fit.

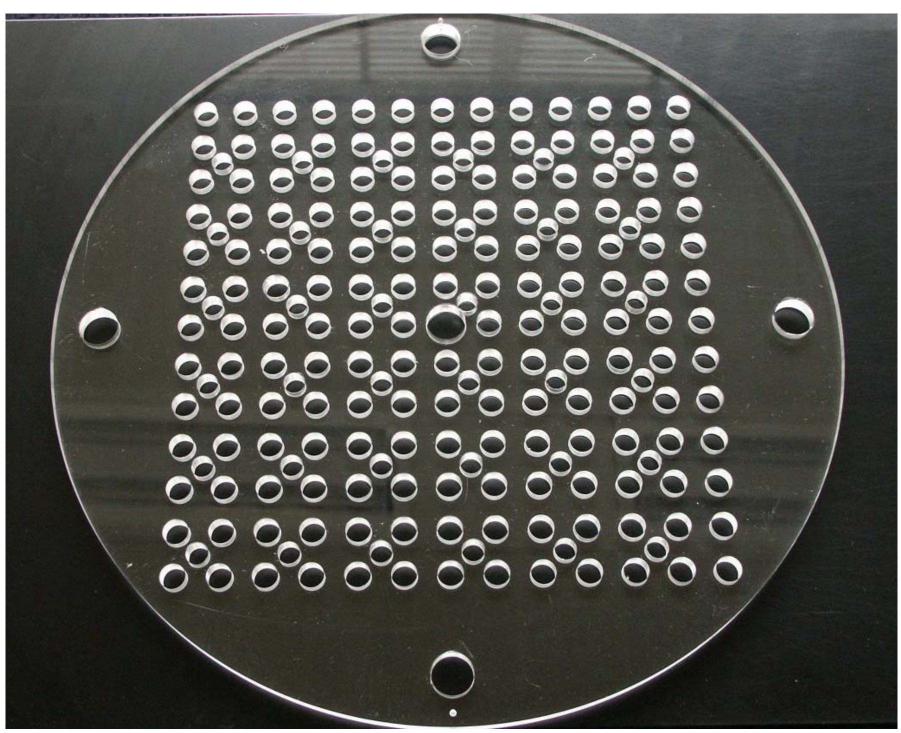

Figure 4: One of the acrylic grid plates with diameter of 425 mm. Between the holes for the fuel pins (13x13-1=168 positions), smaller holes for the detector tube can be seen. The center hole contains the source tube (up to 2 cm below the fuel zone of the pins) and water (for the remainder). The upper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

VESSELS

The cylindrical stainless steel vessel has both an inner diameter and height of 100 cm and a wall thickness of 3 mm (see Figure 5). 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, height of 80 cm and wall-thickness of 8 mm is mounted containing the fuel pins when they are 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.

Figure 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. The small flange at the right of the vessel can be used in future for special purposes. The acrylic vessel that contains the fuel pins in storage will be mounted on top of this vessel.

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 will be 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 halfway the fuel zone, 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 are not yet foreseen and require an extension to the operating license.

Figure 6: The bottom of the steel vessel. The four large holes will be used to insert spotlights, the central hole to connect a stainless steel tube for the source and the two remaining holes to fill and drain the vessel.

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 8 kg of B_4C grains (radius < 45 μm). 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 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. 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. Furthermore, the location of Delphi in the reactor hall of the Hoger Onderwijs Reactor gives that the shielding box fixed to the massive steel construction of the assembly meets the requirements of a storage location.

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 then 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.

Figure 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.

LOADING PLATFORM

From bottom to top, Delphi contains the shielding box, the steel vessel and the acrylic vessel. In total, the height reaches about 250 cm, which makes it necessary to manipulate the fuel while standing on a loading platform (see Figure 8). 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.

Figure 8: The loading platform used to perform experiments with Delphi.

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.

The logic programmed in the PLDs can be described as follows:

- All actions below need the safety and control system switched on.
- Filling the steel vessel with water:
    - The steel vessel can only be filled when both the source and the shielding plug are positioned in the shielding box, and when the two floats on top of the steel vessel do not detect any water.
    - The electrical valve closes when both the lower and upper floats detect water. The water level then reaches up to 5 cm below the top of the steel vessel.
    - When the vessel is filled a manual valve between the electrical valve and the vessel can be closed to isolate the vessel from the power grid and water supply.
- Draining the water:
    - The vessel can only be emptied when both the source and the shielding plug are positioned in the shielding box.
    - The vessel can only be emptied when the manual valve between the water outlet of the vessel and the electrical pump is opened.
    - The water is pumped from the vessel to the sewer. The pump shuts-down automatically when the vessel is empty, and the one-way valve between the pump and the sewer prevents any backward water flow. All water released to the environment is controlled for radioactivity.
    - When the vessel is empty the manual valve between the pump and the vessel can be closed to isolate the vessel from the power grid and water supply.
- Loading/unloading the source:
    - The source tube can only connect to the steel vessel when:
        - The source capsule is in the shielding box,
        - The shielding plug is removed,
        - The lower float in the steel vessel detects water (to secure shielding),
        - The 'connect switch' is pushed to make contact.
    - The source capsule can only be loaded in its experimental position when:
        - The source tube is connected to the steel vessel,
        - The source capsule is in the shielding box,
        - The lower float in the steel vessel detects water (again to secure shielding),
        - The 'load switch' is pushed to make contact. Alternatively, a software program to automate the measurements can control this contact.
    - The source capsule can only be unloaded from its experimental position when:
        - The source tube is connected to the steel vessel,

- The 'unload switch' is pushed to make contact. Alternatively, a software program to automate the measurements can control this contact.

- A green light mounted on the loading platform indicates that the source capsule is at its storage position. Otherwise a red light is turned on.
- The source tube can only disconnect from the vessel when:
  - The source capsule is in the shielding box,
  - The shielding plug is not present in the box,
  - The 'disconnect switch' is pushed to make contact.

INSTRUMENTATION

Delphi is equipped with a 10-bar ^{3}He proportional counter tube 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. Figure 9 shows the detector and the amplifier.

Figure 9: The gas-filled detector tube and amplifier/pulse shaper in use at DELPHI. The diameter of the detector is 6 mm only.

CONCLUSIONS

The new DELPHI subcritical assembly is a new facility for education and research at the Interfaculty Reactor Institute. In Figure 10, the whole assembly is shown, although at the time this picture was made, not all parts were already finished. For example, the pneumatics to move the source have to be installed and checked, after which the shielding box can be filled with paraffin and B_4C. The source has to be ordered and stored in the shielding box. The special handling heads have to be fixed to the fuel pins and the fuel has to be loaded into the acrylic vessel. Also the pumps and valves have to be mounted to the steel vessel after which the water-level control device can be installed and checked. According to the planning, the first loading of the DELPHI assembly is expected to occur in December 2003 or January 2004.

Figure 10: 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.

REFERENCES

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