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# Development of a sample exchange system for irradiations in the BH-3 channel of the IEA-R1 reactor at IPEN

de Paula[a*], M.L.; Moralles[a], M.; Genezini[a], F.A.; Siqueira[a], P.T.D.; Ribeiro Junior[a], I.S.; da Silva Júnior[a], I.A.

[a] Nuclear and Energy Research Institute (IPEN), 05508-000, São Paulo, SP, Brazil.

*Correspondence: engmarcioprojetos@gmail.com

**Abstract**: This work was developed with the aim of improving the current sample exchange system of the BH-3 irradiation channel of the IEA-R1 reactor at IPEN. The instrument's operating concept will provide a better use of the irradiation space as well as greater safety and confidence to the operator. The development of the system involved 3D modeling, sizing, construction and non-destructive testing of the various parts, and analysis of neutron-induced activation of the materials most exposed to the beam. A programmable logic controller (PLC) was implemented for the system's control inside a dedicated electrical panel that was built with materials compatible with the location. The system was designed to support samples weighing up to 15 kg. Bench tests were carried out and showed that the system performs the necessary functions to accurately position samples in three locations: outside the biological shield, at the irradiation channel and at the decay waiting station. The implementation of this instrument will contribute to the application of the ALARA principle in the operator activities at the BH-3 irradiation channel.

**Keywords:** IPEN Reactor IEA-R1, Neutron Irradiation, ALARA.

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# Desenvolvimento de um sistema de troca de amostras para irradiações no canal BH-3 do reator IEA-R1 no IPEN

**Resumo**: Este trabalho foi desenvolvido com o objetivo de melhorar o atual sistema de troca de amostras do canal de irradiação BH-3 localizado no reator IEA-R1 do IPEN. O conceito de operação planejado para o instrumento permitirá melhor aproveitamento do espaço de irradiação e proporcionará maior segurança e confiança ao operador. O desenvolvimento do sistema envolveu modelagem 3D, dimensionamento, construção e ensaios não destrutivos das diversas peças e análises em relação à ativação induzida por nêutrons dos materiais mais expostos ao feixe de nêutrons. Um controlador lógico programável (CLP) foi implementado para o controle do sistema dentro de um painel elétrico dedicado que foi construído com materiais compatíveis com o local. O sistema foi projetado para suportar amostras de até 15 kg. Testes de bancada foram realizados e mostraram que o sistema desempenha as funções necessárias para posicionar com precisão as amostras em três locais: fora da blindagem biológica, no canal de irradiação e na estação de espera para decaimento. A implementação deste instrumento contribuirá para a aplicação do princípio ALARA nas atividades dos usuários do canal de irradiação BH-3.

**Palavras-chave:** Reator IPEN IEA-R1, Irradiação de Nêutrons, ALARA.

## 1. INTRODUCTION

The irradiation of materials with neutrons has applications in several areas, such as chemistry, physics, medicine, biology and materials science and technology [1]. Research reactors stands as one of the main sources of neutrons to perform experimental neutron irradiations. The IEA-R1 research reactor at the Nuclear and Energy Research Institute, IPEN-CNEN/SP (Instituto de Pesquisas Energéticas e Nucleares) provides several neutron irradiation facilities. One of them is the BNCT (Boron Neutron Capture Therapy) research facility which is built along the beam hole (BH) number 3 [2]. BH is basically a neutron beam extractor duct which drives the neutron from the reactor core to an experimental room. The BNCT research facility was designed to attend four demands: provide high neutron flux (~$10^8$ $n \cdot cm^{-2} \cdot s^{-1}$), allow irradiation of large samples (up to 3 liters), field modulation flexibility and independent irradiation time control [3].

The high flux demand led to the development of a facility in which the irradiation position is in the reactor pool wall, in midway from the reactor core to the experimental room. This solution was solved by dividing the facility lying along the BH-3 (Bean hole 3) into 2 sections:

1- an upstream section, in which filters and moderators may be placed (attaining the field modulation flexibility) and

2 - a downstream section, in which the sample is placed and which may move out from the pool wall and back into irradiation position of the BH, so to allow sample changing.

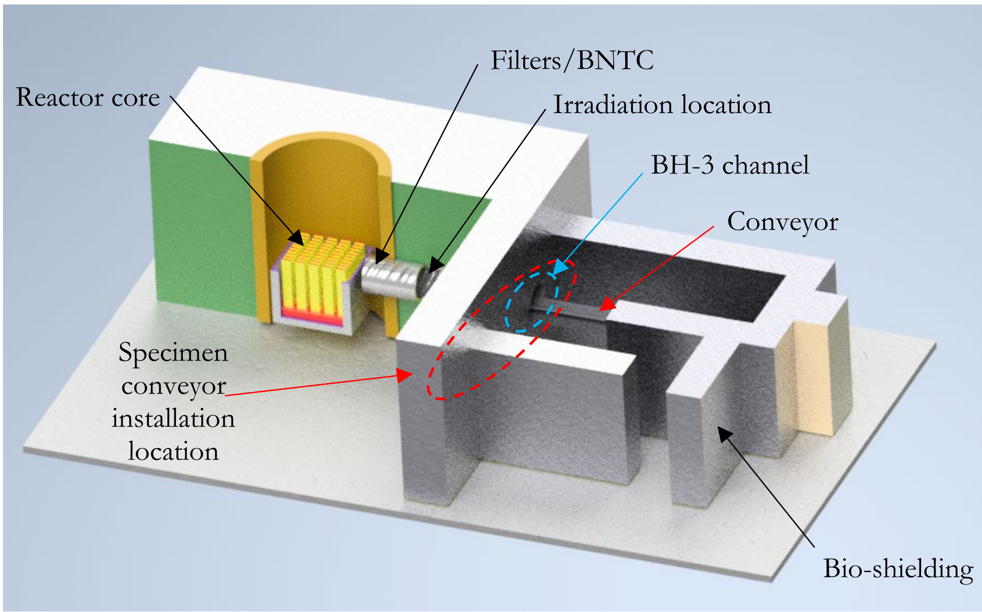
The downstream section also houses the inner shielding facility. During the sample changing procedure, this inner shield is retrieved from the BH-3. To enhance radiation safety, a biological shielding made of lead, concrete bricks and volumes of packaged paraffin structure has been mounted at the exit of BH-3's irradiation beam [4]. This biological shielding ensures safe conditions for sample exchanges even when the reactor is operating at full power (4.5 MW). Safety measures are effective only outside the biological shielding, necessitating the development of a sample exchange system to facilitate movement through it [5]. This system has been used and improved ever since, with beam characterizations determined by calculations and measurements [6,7]. Figure 1 shows a schematic of the BNCT experimental facility built along the BH-3.

The irradiation of samples with neutrons requires the knowledge of some parameters, among which three are of great importance: the neutron flux of the radiation field at the irradiation position, the neutron energy spectrum and the irradiation time. Regarding radiation fluxes, neutron beams produced in reactors are usually accompanied by gamma radiation. The ratio between neutron and gamma ray fluxes, as well as the definition of the energy spectra of these fluxes can be fine-tuned with the choice of materials used as absorbers and filters. Regarding the irradiation time, in a continuous operating reactor, a mechanical system capable of transporting the sample to the irradiation position and removing it after the desired time must be assembled.

Currently, there is a growing demand for studies of damage and failures in electronic components and systems caused by the incidence of radiation. This is due to the increased use of electronic systems in environments subject to radiation and the trend towards miniaturization of electronic components, which makes them more vulnerable to the effects of radiation. Neutrons, in particular, are present in power and research reactors, in particle accelerators, at the altitude of commercial flights, and in radiotherapy treatments. Several applications, such as studies of damage caused by neutron irradiation, involve different samples that require a system for inserting and removing samples with characteristics different from those existing for BNCT studies.

The need to offer an irradiation facility with better controlled conditions for sample exchange, necessary for studies that require good precision in positioning and control of exposure time like the study of damage in an electronic module performed at the BH-3 [8], motivated the development of a new sample exchange system. This system shall provide conditions to irradiate larger samples, by making a better use of the sample irradiation space and to perform more reliable and accurate sample exchange procedures, which shall lead to more precise sample positioning and time exposition setting. This system shall be presented in the following sections.

**Figure 1**: Diagram of the BH-3 installation of IPEN's IEA-R1 reactor



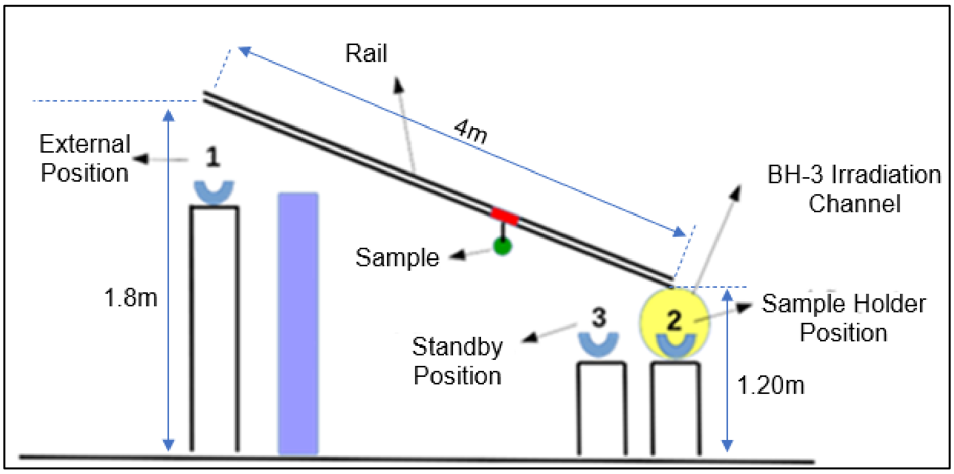
## 2. MATERIALS AND METHODS

Compared to the system previously designed for BNCT studies [5], the present system presents new functionalities implemented to be carried out semi-automatically, replacing manual methods with electromechanical ones. The description of the system, as well as the precautions related to the activation of its materials and radiological protection are described in this section.

## 2.1. System´s functionalities

The sample will have three possible stop positions, according to the diagram shown in Figure 2: external position (1), sample holder (2) and waiting position for radiation decay (3). In the vicinity of positions (1) and (2), sample movement monitoring will be carried out using video cameras. In position (3) a radiation detector will be included to monitor the dose rate near the sample after irradiation.

**Figure 2**: Diagram of the sample positions foreseen for the sample exchange system

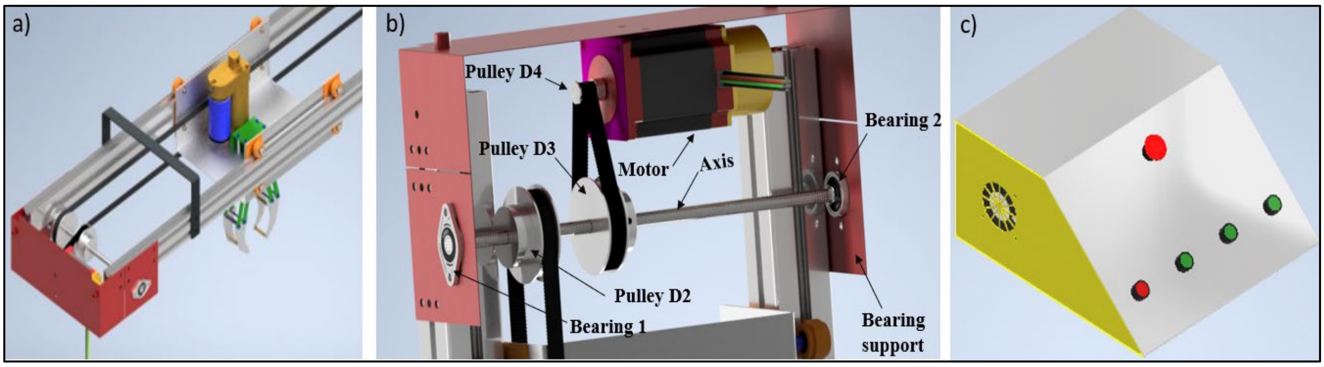


The movements of the sample are semi-automatic, requiring step-by-step interaction from the operator by commands carried out from a safe distance. The operator does not need to be close to the facility as the sample is inserted into or withdrawn from the sample irradiation space, as the sample exchange system may be operated remotely. It brings an important safety operational feature, as the operator may be at places subjected to lower radiation levels than those found in the vicinity of the facility when the rear part of the irradiation line (holding the inner shielding) is withdrawn from the BH-3. The system produces movements with precision and reliability at each stage, that are monitored by video camera systems placed at the external and internal parts of the biological shield.

## 2.2. Instrument description

The system was developed and modeled using the Autodesk Inventor software [9] (Figure 3). All components were assembled within the software, and any potential interference in the integration was thoroughly checked. In the final assembly stage, the sample exchange system was built with a length limited to 1150 mm, in order to allow easy transport and handling for bench tests in a controlled environment. Figure 4 shows the completely assembled system, with the names of some main components identified by text.

**Figure 3**: Sample exchange system 3D modeling: a section of the rail and the trolley with the linear actuator (a), details of the trolley's engine, belts and traction system (b) and control panel (c).

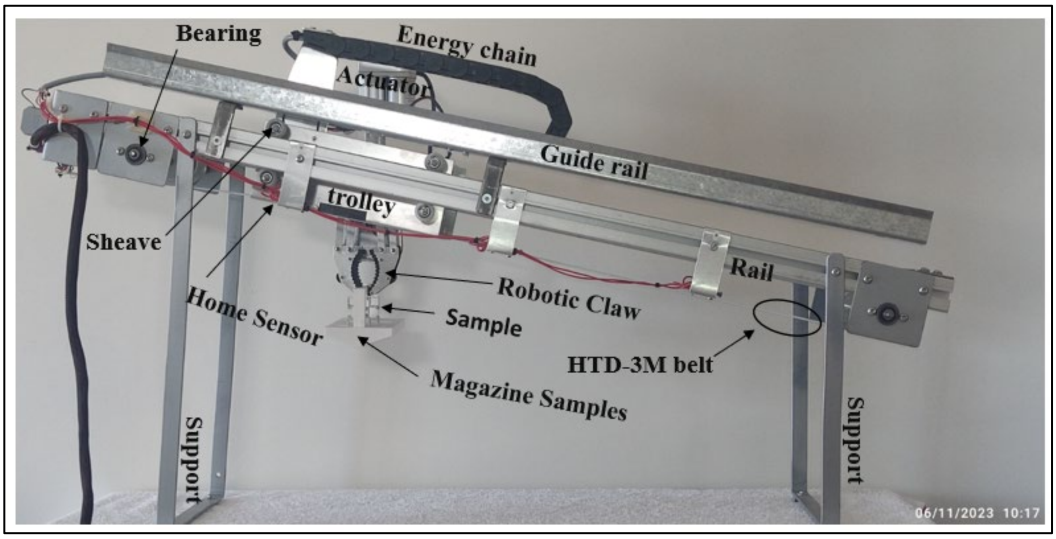


Source: Authors

The electrical control panel (Figure 3c), was modeled using 2 mm thick aluminum, enabling the safe shelter of control devices, providing an external mechanical protection. The panel was also implemented with a fan type cooler ventilation system.

The prototype was validated by performing tests and adjustments in a controlled bench environment, using a 3D printed sample holder. The tests carried out consisted of automatic transport of samples for irradiation, removal of samples to home position and power outage tests.

**Figure 4**: Picture of the final assembly: the rail (1150 mm) with the trolley and some parts of the system are identified.

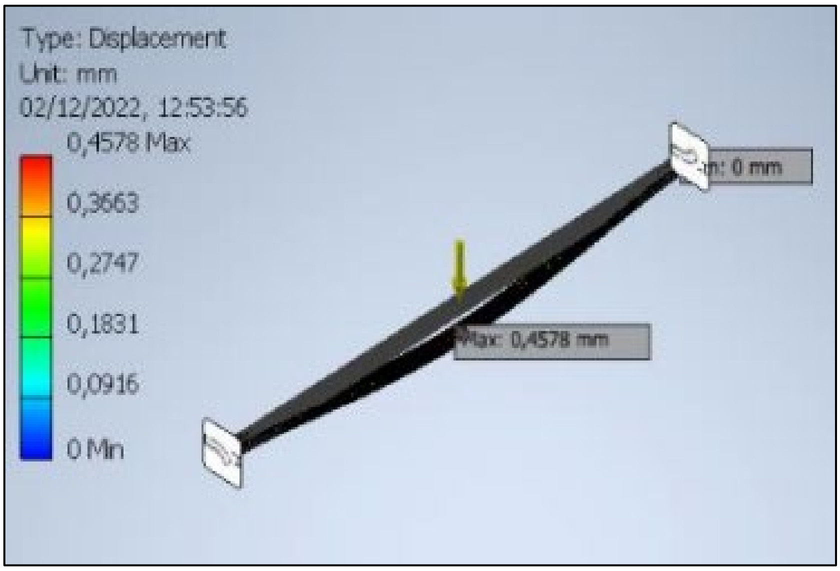


## 2.2.1. Fixing: the aluminum rail

The rail sizing was carried out through simulations using Autodesk Inventor software, evaluating deformations of the rail though the "arrow effect", illustrated in Figure 5. The deformation of the rail is not uniform throughout its length, which means that one part of the straight line can lengthen and another can retract [10]. This study was necessary to ensure that the mass of the complete sample holder and the trolley assembly do not produce deformations that compromise the functionalities of sliding and braking of the trolley as it travels along the rail.

The system was designed to support a complete sample holder with a total load of 15 kg. The deflection test carried out in the software showed that the maximum displacement deformation is 0.45 mm for the 4 m rail, which does not compromise the sliding of the trolley when the 15 kg load is placed in the sample holder.

**Figure 5**: Result of the "arrow effect" study of the rail's deformation.



## 2.2.2. Trolley and motorization for horizontal movement

As shown in Figure 2, the sample will be transported over a distance of 400 cm. Assuming a time of 30 s to cover this distance, it was determined that the speed of the trolley would be 13 cm/s. All sizing calculations for the elements involved in the movement and breaking phases of the trolley were based on this speed and a 15 kg load. The main elements that had their materials and dimensions calculated are the motor, pulleys and belts. The motor chosen was the HT23-401-BRAKE model, which has the technical characteristics presented in Table 1.

**Table 1**: Stepper motor characteristics

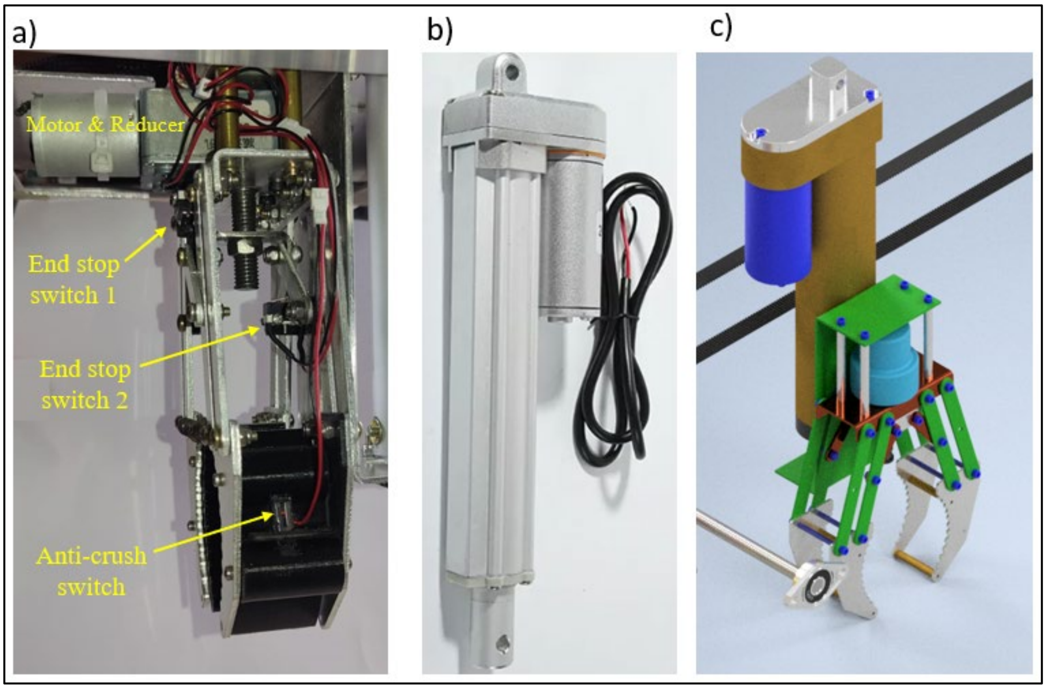
| **Motor connection** | **Minimum static torque (N.m)** | **Step (angle)** | **Amps (Current DC)** | **Rotor inertia ($g.cm^2$)** | **Motor weight** |
|---|---|---|---|---|---|
| Series | 1.90 | 1.8 | 2.1 | 480 | 1.0 |
| Parallel | 1.90 | 1.8 | 4.2 | 480 | 1.0 |
| Unipolar | 1.90 | 1.8 | 3.0 | 480 | 1.0 |

Source: Kalatec [11]

### 2.2.3 Linear actuator for vertical movement

Linear actuators are a type of actuator that converts the rotational movement of electric motors into linear movement, aiming to push or pull a certain mechanism. These devices are ideal for all types of applications where it is necessary to tilt, lift, pull or push using force. The samples move horizontally but it is also necessary to move the sample vertically by a displacement of 100 mm to insert and remove the samples at the positions described in Figure 2. The process of picking up and dropping the sample is carried out by a mechanical gripper (Figure 6a) driven by its own stepper motor. For the vertical movement of the sample holder, a linear actuator from the Santoro Atuadores brand was specified, whose operation is simple using 24 V voltage to extend the rod and reverse voltage to retract it. The equipment model is illustrated in Figure 6b [12] and the assembly of the gripper and actuator is illustrated in Figure 6c.

**Figure 6**: Gripper (a), linear actuator (b) and assembly of the gripper and actuator (c).

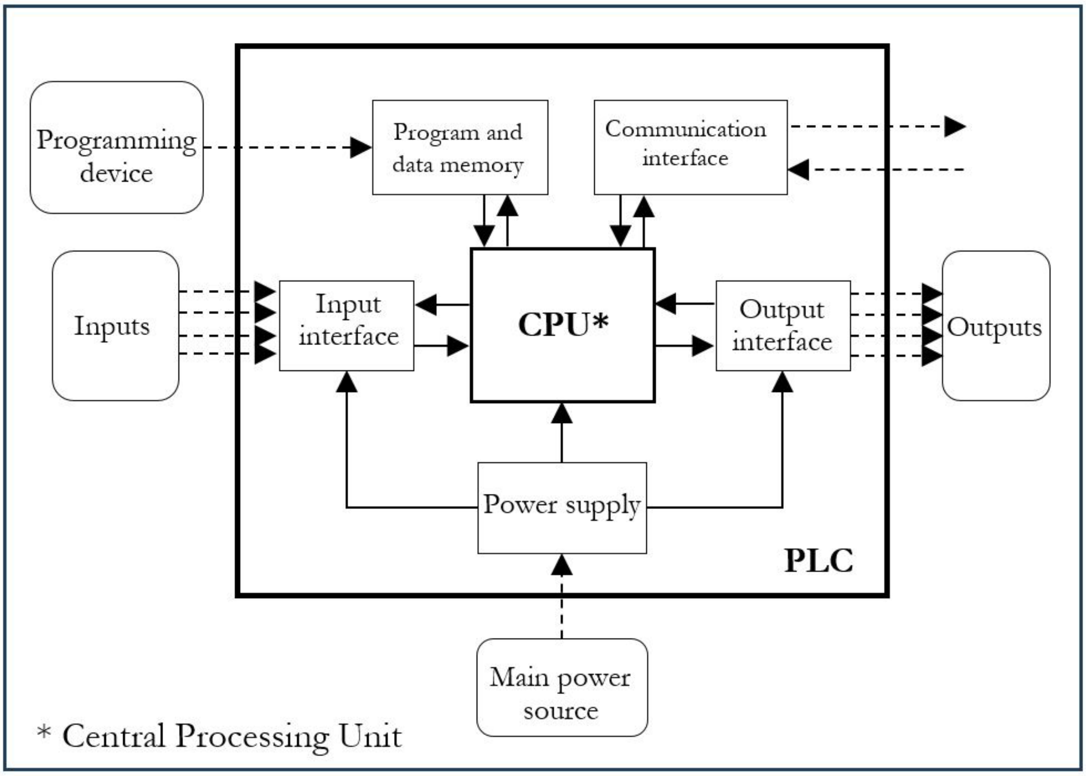


Sources: Authors (a) and (b), Manufacturer's manual [12] (b)

### 2.2.4. Control panel and PLC

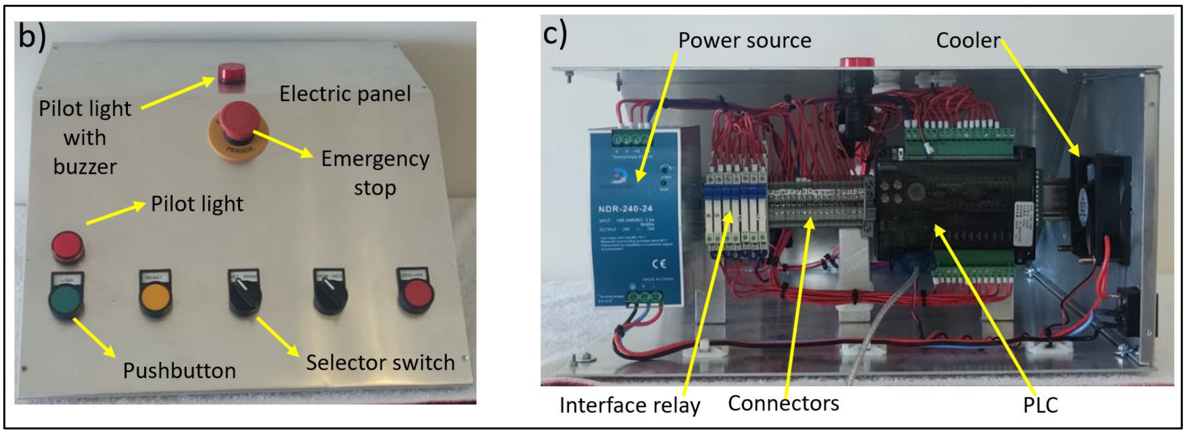
The control of the movements of the sample exchange system is performed using a PLC (Programmable Logic Controller), with its architecture illustrated in Figure 7. It is composed of a central processing unit (CPU) containing the system's microprocessor, a program, a memory unit, and input and output circuits. The PLC contains many relays, counters, timers, registers (memory) and function blocks, all virtualized on the CPU. Some manufacturers already provide artificial intelligence (AI) in their CPUs, separate data storage units, and internet connection [13].

**Figure 7**: PLC basic schematic architecture.



In this work, the sample conveyor system was designed in such a way that the control can be continuously improved and easily updated, provided by the embedded technology of the PLCs. To control the movements of the trolley, a versatile and modern panel was developed, capable of simultaneously housing the control buttons and the entire control and automation system. It was modeled in the format of a bench panel made of 2 mm thick aluminum plate, easy to handle and built with materials compatible with the external conditions of the location to be installed, including the installation of a cooler to dissipate the heat generated inside the panel (Figures 8a and 8b).

**Figure 8**: External (a) and internal view (b) of the control panel.



## 2.3. Considerations for radiological protection

Measurements were carried out to evaluate quantities relating to radiological protection, which correspond to the possible activation of materials exposed to emerging neutrons and the dose rates in the vicinity of BH-3.

### 2.3.1. Material´s activation

The transport system will be exposed to neutrons emerging from the BH-3 due to the fact that the shields and filters are positioned outside the channel during the sample exchange process. Due to this this exposure, the materials that make up the structural profile (rail), gripper and trolley can be activated. The trolley contains bearings that, according to the manufacturer's specifications, are made of treated steel. Other materials, such as the structural profile and claw, are made of aluminum and its alloys. The evaluation of the activation of materials most exposed to neutrons was carried out using the neutron activation technique. It has been estimated that sample exchange procedures require opening the channel for time intervals that can typically reach between 2 and 3 minutes. For the activation tests carried out, a conservative margin of time and neutron flux was considered. The duration of the irradiation was 20 minutes in the highest exposure situation, corresponding to the end of the clamp in the position to hold or release the sample in front of the open irradiation channel. Three parts were irradiated: a trolley bearing (mass of 4.91 g), an aluminum tube (mass of 2.47 g) and a sample of the aluminum alloy sheet that makes up the trolley (mass of 3.95 g).

Gamma spectroscopy of the pieces was performed after irradiation, using a calibrated hyperpure germanium detector (HPGe). An example of the gamma ray spectrum of the aluminum tube is shown in Figure 9. The radioactive isotopes identified in the irradiated samples are listed in table 2.

**Figure 9**: Gamma ray spectrum of the aluminum tube obtained after 20 min. exposure at the BH-3 channel output.

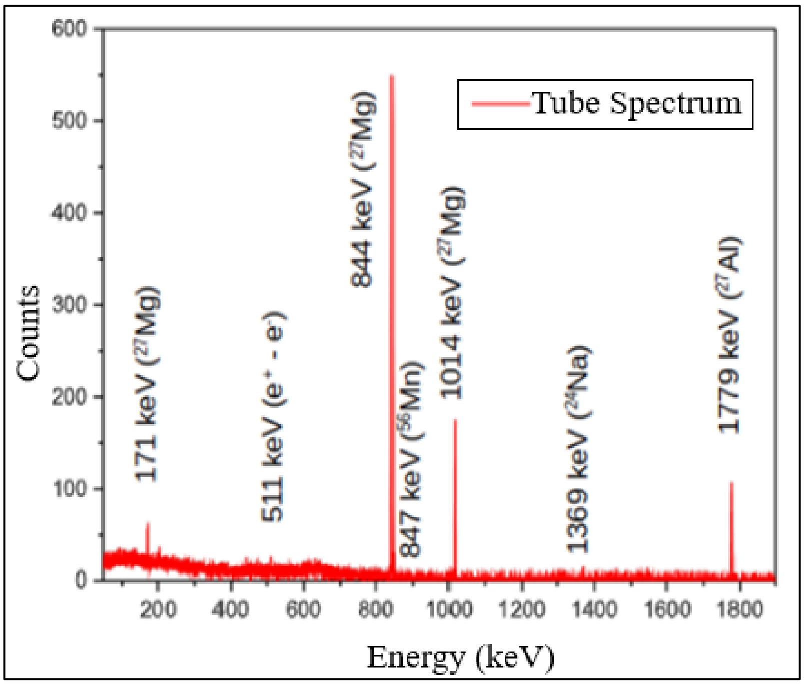


**Table 2**: Gamma rays observed after activation of some irradiated parts at the outlet of the BH-3 channel for 20 minutes.

| Piece (mass) | Energy (keV) | Counts/s | Isotope | Half-life |
|---|---|---|---|---|
| sheet (3.95g) | 843.7 | 0.25 | $^{27}$Mg | 9.46 min |
| | 846.7 | 0.20 | $^{56}$Mn | 2.58 h |
| | 1014.4 | 0.082 | $^{27}$Mg | 9.46 min |
| | 1368.6 | 0.095 | $^{24}$Na | 14.96 h |
| | 1810.7 | 0.012 | $^{56}$Mn | 2.58 h |
| bearing (4.91g) | 846.7 | 2.04 | $^{56}$Mn | 2.58 h |
| | 1810.7 | 0.26 | $^{56}$Mn | 2.58 h |
| Tube (2.47g) | 170.7 | 0.12 | $^{27}$Mg | 9.46 min |
| | 843.7 | 3.10 | $^{27}$Mg | 9.46 min |
| | 846.7 | 0.20 | $^{56}$Mn | 2.58 h |
| | 1014.4 | 1.1 | $^{27}$Mg | 9.46 min |
| | 1368.6 | 0.057 | $^{24}$Na | 14.96 h |
| | 1779 | 0.895 | $^{28}$Al | 2.24 h |

The activities measured for all activated materials were more than an order of magnitude lower than the sources used in detector calibration (typically 37 kBq or less) being negligible in relation to radiological protection limits.

### 2.3.2. Dose in the sample exchange process

Neutron and gamma dose measurements were performed in the external part of the biological shield around the BH-3, in positions where the user needed to be present to manipulate the previous sample exchange system. In a typical sample insertion and removal procedure, the operator needed to stay for several minutes in areas where dose rates are on the order of 80 µGy/h for neutrons and on the order of 60 µGy/h for gamma rays, when the BH-3 channel is open. With the new sample exchange system, the operator only occupies these areas when the BH-3 channel is closed; in this condition the neutron dose rates are on the order of 2 µGy/h and gamma rays on the order of 1.2 µGy/h. Therefore, the implementation of this system contributes significantly to the application of ALARA principles in sample exchange procedures at BH-3 [14].

## 3. RESULTS AND DISCUSSIONS

Transporting samples in the BH-3 between the external and internal parts of the biological shield presents several inconveniences for handling, mainly due to the inaccuracy of the claw displacement movements and sample capture and release movements. Many failures in this process were reported, which caused, among other problems, the sample falling during transport. These failures have different consequences, depending on when they occur. When failures occur during sample insertion, they can result, for example, in the loss of the sample and damage to the sample holder. When they occur during sample removal, they can also cause environmental contamination and expose the user to unnecessary doses. The development of this new sample exchange system shall overcome these types of problems.

In addition to problems in the sample transport process, radiological protection aspects were also considered in this project. The analysis of the neutron activation of the materials used in the construction of the sample changer allowed a qualitative and quantitative investigation of the radioisotopes which may be produced in the sample exchange system. Based on this investigation, it was found that the choice of materials is appropriate so that activation due to neutrons does not put the operator at risk.

Possible problems related to damage or malfunction of the electronic components of the sample changer were mitigated by positioning the control panel and the driver´s stepper motor outside the biological shield. In this location, the doses of neutrons and gamma rays are within limits that should not cause problems in electronic equipment.

Other complementary studies were carried out in the vicinity of BH-3, mapping the operator's positions which resulted in low dose rates, ensuring the safe operation of the sample exchange.

## 4. CONCLUSIONS

The new sample exchange system developed in this work will provide several advantages in research related to sample irradiation in BH-3 of the IEA-R1. The versatility of this system allows an increase in the diversity of the types of samples to be irradiated, as well as the positioning of the sample with precision and safety in operation. Currently, operator exposure to prohibitive doses is not due to deficiencies in the existing biological shield, but is associated with human operational failures in the handling of the current sample exchange system, which is subject to failures that mainly cause radioactive samples to fall. As a conclusion, the sample exchange system developed in this work was evaluated with functional tests in a controlled environment, bench laboratory tests, and proved to be efficient and versatile. In the evaluation of the automated control of the system, it was found that it meets the expected functionality.

The optimization of user protection by the ALARA principle was made possible by the correct choice of materials, using neutron activation analysis criteria, preventing selected materials in the construction of the new system from causing prohibitive doses to the operator.

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## CONFLICT OF INTEREST

We have no conflicts of interest to disclose.

All authors declare that they have no conflicts of interest.

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