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Design of a Visual System to Monitoring Thermal Power in Pool-Type Nuclear Research Reactor

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***Abstract*— *Nuclear research reactors are often found in open pools, allowing visibility of the core and the bluish luminosity of the Cherenkov radiation. In general, the thermal energy released in these reactors is monitored by chambers that measure neutron flux. There are other methods used to measure the power, including: nitrogen formation, measure of the fuel rod central temperature, and the energy balance in the heat exchanger. The brightness of Cherenkov radiation is caused by the emission of visible electromagnetic radiation (in the blue band) by charged particles that pass through an insulating medium (water in research reactors) at a speed greater than that of light in this medium. The objective of this research is to propose, design, and assemble a prototype of an equipment, which uses an innovative and alternative method to monitor the power of nuclear research reactors by measuring the intensity of luminosity generated by the Cherenkov radiation produced within and around the core. An Arduino Uno board was used, with color and luminosity sensors. The work was performed simulating and monitoring experimentally in laboratory, the intensity of luminosity generated by the Cherenkov radiation. The prototype presents potential as an auxiliary methodology for measuring thermal power of research nuclear reactors. It is intended to use this measurement system in the IPR-R1 Triga reactor of the Nuclear Technology Development Center - CDTN (Brazil).*

Keywords* — Arduino, Cherenkov radiation, Nuclear research reactor, Power, Triga reactor.

I. INTRODUCTION

Two important criteria for power measurement in nuclear reactors are redundancy and diversity. Other criteria such as accuracy, reliability and speed in response are also of major concern. Power monitoring of nuclear reactors is always done by means of nuclear detectors, which are calibrated by thermal methods. The nuclear instrumentation is used to detect neutrons when sub-critical multiplication occurs during the reactor starp-up, after achieving the criticality, and during the neutron flux variation to obtain the automatic control of reactivity maintaining a stable power level.

The IPR-R1 Triga research reactor will be used for the tests proposed in this paper. This reactor is located in the Nuclear Technology Development Center - CDTN (Brazil). In the IPR-R1 four neutron-sensitive chambers are mounted around the reactor core for flux measurement. The type of chamber used and its position with respect to the core determine the range of neutron flux measured [1]. Unfortunately, the ionization chamber neutron detector measures the flux of neutrons thermalized in the vicinity of the detector. This signal is not always proportional to the integral neutron flux in the core and consequently to the core power. Besides the response of a single nuclear detector is sensitive to the changes in the core configuration, particularly to the control rod position. This is important in the Triga reactor, which do not have distributed absorbers for reactivity control and maintaining criticality is by insertion of control rods [2].

The IPR-R1 Triga reactor is an open pool-type reactor and the fuel is cooled by natural convection. The system was updated in the 1970s to reach up 100 kW. Later, it was updated again to its current system, which allows it to reach 250 kW in the steady-state.

Triga reactors are the most popular research reactors in the world. There are more than sixty facilities operating in several countries [3]. Their popularity derives from the fact that they are the only research reactors that can provide true inherent safety, in addition to the usual engineering safety. This is possible due to the properties of the fuel: uranium hydride and zirconium provide unparalleled safety features, allowing flexibility in settings, with minimal environmental effects [4].

In any nuclear installation, the main concern is safety. The IAEA states that the fundamental objective of safety is to protect people and the environment from the harmful effects of ionizing radiation. They suggest ten safety principles that must be followed. The IAEA recommendations focus on the concepts of redundancy, diversity and independence; in other words, there must be

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more than one device, with different operating principles, completely independently performing the same function [5].

Safety begins with controlling the parameters and variables in a nuclear reactor; the primary one is the power, which allows the determination of other relevant factors. In power measurements, safety, reliability, accuracy are critical, and very important. For this reason, nuclear reactors use several devices to measure the power of the core [6].

The objective of the project was to develop an innovative and alternative method to monitor the power of nuclear research reactors. This will be done by analyzing and monitoring the intensity of luminescence generated by the Cherenkov radiation in the reactor core.

II. CHERENKOV RADIATION

Electromagnetic radiation known as Cherenkov light is emitted when a charged particle moves in a dielectric medium at a speed greater than the speed of light for that medium. A conspicuous example of that effect is the characteristic blue glow of a pool-type reactor (Fig. 1).

Cherenkov radiation is produced through a number of ways when: (a) beta particles emitted by fission products travel with speeds greater than the speed of light in water and (b) indirect ionization by gamma radiation produces electrons due to photo electric effect, Compton effect and pair production effect. Among these electrons, Compton electrons are the main contributors to Cherenkov radiation [7]. Compton scattering of gamma rays and its intensity is linearly related to reactor fission power, and can be transmitted from the source at the reactor core to a sensing device by means of a highly reflective metallic tube [8].

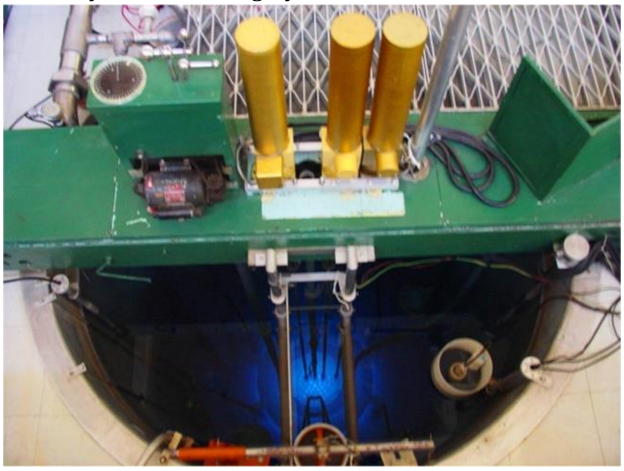

Fig. 1: Cherenkov radiation glowing in the core of the IPR-R1 Triga reactor

According to classical physics, a moving charged particle emits electromagnetic waves. In a quantum mechanical picture, when a charged particle moves inside a polarizable medium with molecules, it excites the molecules to the higher levels and excited states. Upon returning back to their ground state, the molecules re-emit some photons in the form of electromagnetic radiation. According to the Huygens principle, the emitted waves move out spherically at the phase velocity of the medium. If the particle motion is slow, the radiated waves bunch up slightly in the direction of motion, but they do not cross. However if the particle moves faster than the light speed, the emitted waves add up constructively leading to a coherent radiation at angle θ with respect to the particle direction, known as Cherenkov radiation. The signature of the effect is a cone of emission in the direction of particle motion [9].

III. MATERIALS AND METHODS

The proposed device will use an algorithm developed in the C++ programming language to establish a relationship between the intensity of the Cherenkov luminosity and the power of the nuclear reactor. C++ is a high-level programming language, with slight modifications for the Arduino Uno system (Fig 2), that will be used in this project [10].

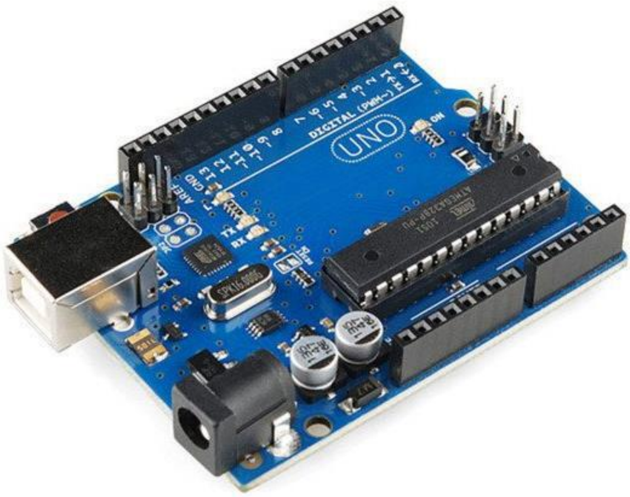

Fig. 2: Arduino Uno System.

In the program the information inputs, the conditions and intervals for the readings, the necessary calculations, and the information output method will be established. The input information will be obtained by the color sensor, and brightness sensor. The output information will be displayed on a Liquid Crystal Display (LCD).

The programming language will be compiled into the Arduino IDE software, and loaded onto the device via USB (Universal Serial Bus) cable.

The main components to be used are described below.

Color sensor:

A color sensor will act to isolate the Cherenkov radiation from other light sources by limiting the luminosity readings for the presence of the blue color characteristic of the Cherenkov radiation.

Luminosity sensor:

A luminosity sensor will be set for the function of determining the intensity of the Cherenkov radiation, giving values in lux.

Output information:

The main device output information is the nuclear reactor power, which will be calculated after processing of input information, and application of the necessary mathematical calculation.

It is intended to perform experiments in the IPR-R1 Triga reactor for the validation of the assembled instrument. Thus, the final adjustments will be made to the luminance to power conversion equations.

The equations will be established after the tests in the Triga reactor, where the luminance values measured by the device will be recorded for each kW varied in the reactor power. The power variation will be observed by the neutron measuring channels of the control console.

IV. RESULTS

The first step in the elaboration of the algorithm was the design of a simplified operating diagram to identify the hierarchical relations, constraints and barriers between the input and output information of the sensors (Fig. 3). The main indicators and conditionals for the algorithm were:

- The system will only operate in the presence of visible electromagnetic radiation in the blue band.
- The sensors will be side by side to ensure homogeneous radiation exposure.

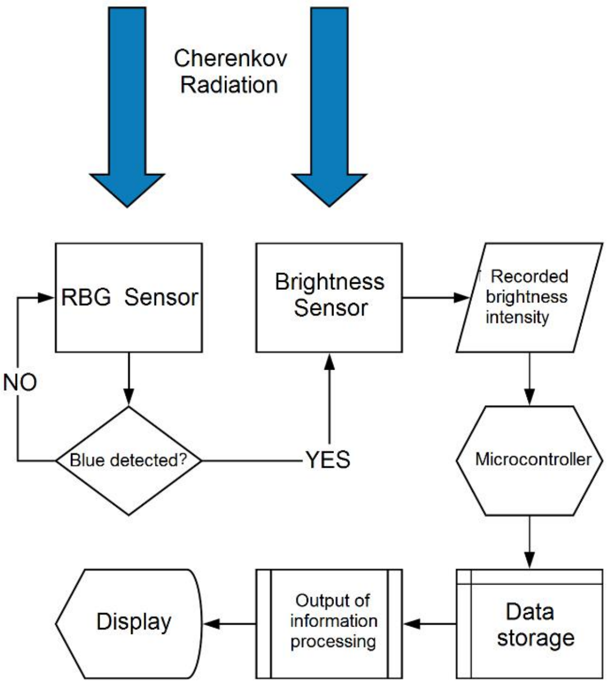

Fig. 3: Block diagram of the system.

The algorithm in high level language was elaborated after the choice of all the components (sensors and display). Due to the need to meet the specificities of each one regarding the libraries (of codes) and routines. It can be divided into four sections, each with an interdependent function for the full operation of the device, ie: initial settings, subroutines, setup and loop.

Simulated tests were initially performed using Fritzing software (Fig. 4) and AutoCAD software (Fig. 5) to determine the best arrangement of the components for the device assembly. Next, it was used sets of LEDs (Light Emitting Diode) to simulate the Cherenkov luminosity to perform the sensors calibration.

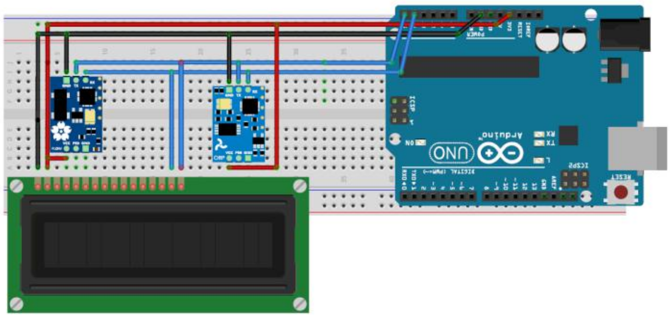

Fig. 4: System modeling in Fritzing software

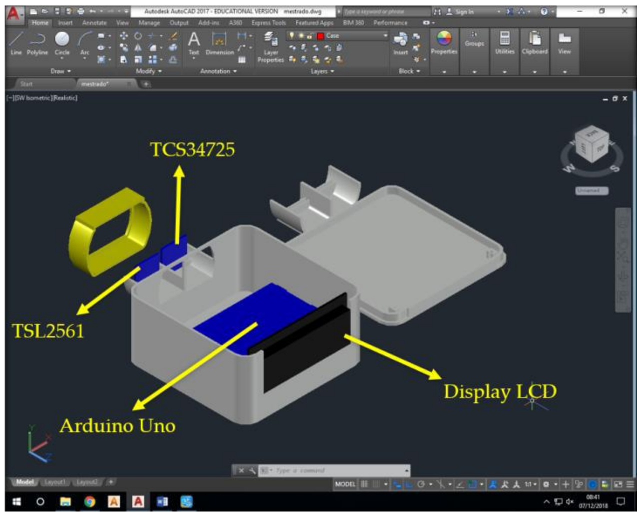

Fig. 5: Three-dimensional model of the device

Tests were performed to verify the device response to the variation of light intensity caused by blue luminosity inserted in the environment. The tests were conducted recording the device response compared to a Thermo-Hybrid-Anemometer Portable Digital Luximeter Model THAL-300 made by Instrutherm. This instrument works in the range of 0 to 20,000 lux, with resolution of 1 lux and accuracy of ± 5% of reading ± 8 digits [11].

In the program, the information entries, the conditions and the intervals for the readings, the necessary calculations, information and exit methods will be established. The input information will be obtained from the color and brightness sensors and the output information will be transmitted via Bluetooth. The programming language will be compiled in the Arduino IDE software and will be loaded to the device via a USB cable.

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4.1 Color sensor

A color sensor will be used to isolate the Cherenkov radiation from other sources of luminosity by limiting the luminosity readings in the presence of blue coloration, characteristic of Cherenkov radiation. The sensor selected for the device was the TAOS TCS34725 with infrared filter [12]. The reason was because of its RGB logic (Red, Green, Blue), and infrared filter, which guarantee greater precision in the readings with smaller noises.

4.2 Luminosity sensor

A luminosity sensor will be responsible for determining the intensity of the Cherenkov radiation, with values in lux. The TAOS TSL2561 sensor was considered the most suitable for this device, because it is a digital device that accurately captures values between 0.1 and 40,000 lux, and has three precise channels for readings [13].

4.3 Output information

The main output information of the device is the power of the nuclear reactor. It was calculated after processing the input and application information of the required algebra.

The light intensity was displayed on a 16 x 2 LCD display with HD44780U driver model, which has been selected due to its programming base interface, and its reliability [14].

Initially, scale tests will be carried out to assemble and calibrate the device, using LED sets to simulate the Cherenkov luminosity. In Figure 6 is shown photograph of the assembled components prior to being placed in the box.

After the results reach satisfactory levels, the validation in the Triga IPR-R1 reactor will be requested, where the final adjustments in the brightness conversion equations for power will be made.

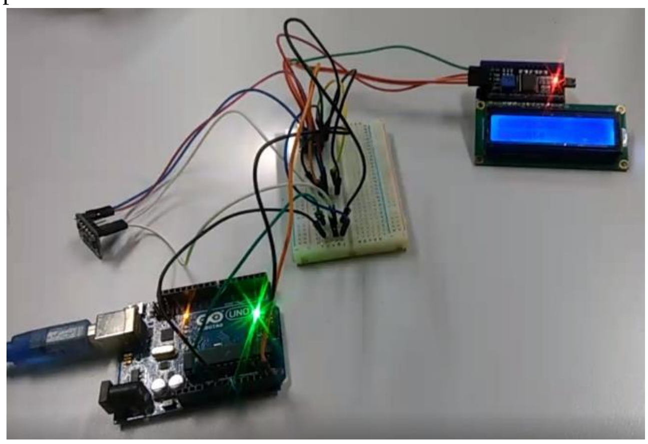

Fig. 6: Assembly of components.

In Figure 7 the system is shown placed inside its housing.

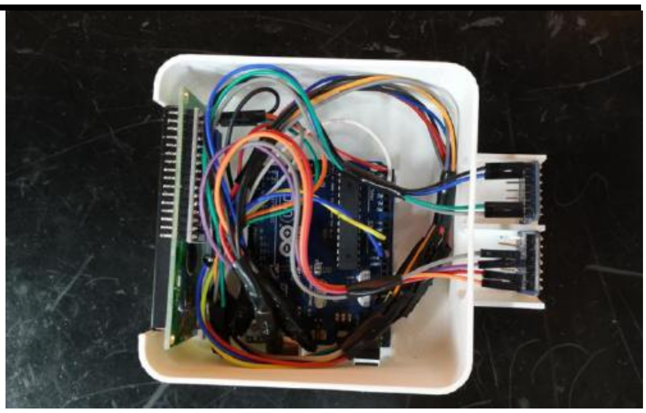

Fig. 7: Internal view of the system

In Figure 8 the system is shown within its housing. In the figure is highlighted the color and light sensors.

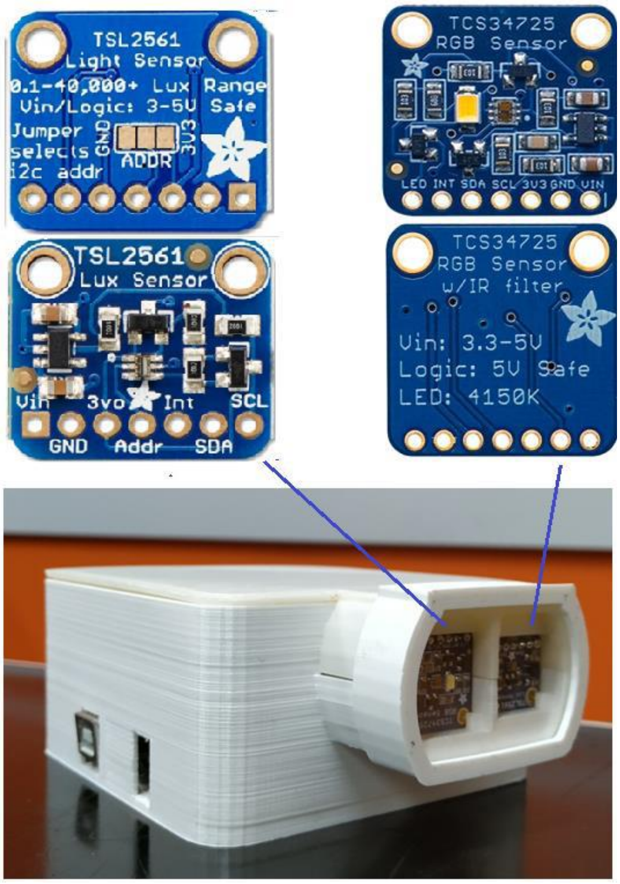

Fig. 8: External view of the device showing highlighted: color and light sensors

The initial tests consisted of attaching an opaque blue acrylic plate near the sensors and focusing light with a flashlight on the other side, varying the beam intensity. The experiments were carried out with natural ambient lighting to simulate the operation of the IPR-R1 Triga reactor, varying the distance between the sensor and the light source, starting one centimeter and increasing one centimeter per step. All tests were performed in triplicate, to validate the values obtained. The mean values of the readings are shown in Table 1. The relationships between

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curves obtained with the data of Table 1 are presented in the graphs of Figure 9.

In the tests carried out up to 15 cm away from the sensors, the readings of the device were compatible with those performed by luximeter Model THAL-300. This was calibrated with ambient light, to record only the variations caused by the insertion of the bluish beam. However, above this distance there was much interference from the ambient light, making it impossible to read.

Table.1: Intensity of Light Obtained Experimentally.

	Prototype			Luximeter		
	Measure (lux)			Measure (lux)		
Distance (cm)	Intensity			Intensity		
	Low	Mean	High	Low	Mean	High
1	44	70	97	43	71	96
2	32	51	71	32	52	72
3	27	47	63	28	46	62
4	18	30	42	18	30	41
5	13	22	32	14	22	32
6	11	12	21	10	13	22
7	7	11	14	7	11	15
8	4	7	13	5	8	12
9	5	7	9	4	6	9
10	2	6	6	3	5	7
11	1	5	5	2	4	5
12	3	5	4	2	4	4
13	2	3	2	2	3	3
14	3	3	4	2	2	3
15	0	0	3	1	1	2
16	0	0	0	0	0	1
17	0	0	0	0	0	0

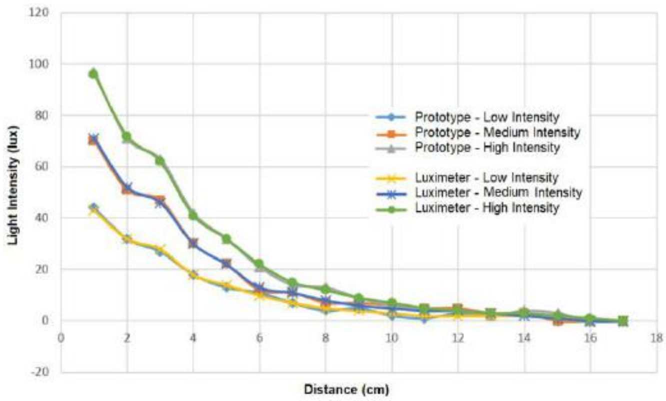

Fig 9: Intensity of light as a function of distance

4.4 Experiment in the IPR-R1 Triga reactor

Due to the large distance (about 6 m) between the sensors and the core of the IPR-R1 Triga reactor, it was not possible to adjust the system to monitor the power released by the core of this reactor. It was identified that the best option to connect the system to the edge of the reactor pool, with the display accessible to the operator and the sensors directed to the core (Fig. 10). Studies are being done on how best to bring the sensors closer to the light source, ie the core. Another possibility is to transmit the luminosity more efficiently to the reactor surface.

Fig. 10: Device fixed in the IPR-R1 Triga reactor

V. CONCLUSION

Cherenkov radiation is a process that could be used as an extra channel for power measurement to enhance redundancy and diversity of a reactor. This is especially easy to establish in a pool type research reactor. Light produced by charged particles when they pass through an optically transparent medium at speeds greater than the speed of light in that medium. In research nuclear reactor the electrons from the core travel through shielding water, they do so at a speed greater than that of light through water and they displace some electrons from the atoms in their path. This causes emission of electromagnetic radiation that appears as a weak bluish-white glow. Cherenkov radiation is used to detect high-energy charged particles. In pool-type nuclear reactors, the intensity of Cherenkov radiation is related to the frequency of the fission events that produce high-energy electrons, and hence is a measure of the intensity of the reaction. Cherenkov radiation is also used to characterize the remaining radioactivity of spent fuel rods.

As noted by the IAEA, a greater number of channels to measure power provides a more reliable and safe operation of the reactor [15]. The advantages of the proposed device are that it will be installed far from the core, making maintenance and adjustment easier than with conventional methods of power measurement. Furthermore, it is a low-cost device, without consumables, easily allowing modifications to improve accuracy and reliability.

The prototype presents potential for monitor thermal power of pool-type nuclear reactor, increasing redundancy and diversity. It will provide stable and reliable readings for power generated in medium-power reactors. It will improve the operation of the reactor by adding one more measurement channel. The system was able to isolate the bluish luminosity, which simulated the blue glow of Cherenkov radiation, from ambient light, and measured its variation. However, it will be necessary to change the way of light capture to enable the operation in the IPR-R1 Triga reactor. This will be the next step in this research.

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