Research Article

Design and Construction of Pneumatic Transfer System Controller Unit for Ghana MNSR

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Pneumatic Transfer System (PTS) is an auxiliary system of Ghana Research Reactor-1 (GHARR-1) used to transfer sample capsule in and out of the reactor irradiation sites. The PTS' controller unit design and construction were carried out because the original transfer system was not designed to operate in cyclic NAA. To address these situations, a Programmable Logic Controller (PLC) has been used to design and construct a control unit to facilitate a cyclic neutron activation analysis (CNAA) application for GHARR-1. The design has been simulated successfully using a LOGO Soft Comfort software, version 8. The constructed control unit has been tested experimentally using 220 AC volts electric bulbs to represent solenoid valves. The results show that the sample-IN and sample-OUT bulbs come ON and go OFF to represent the solenoid valves opening and closing for sample transfer. The study has shown that the computer based PLC controller unit for PTS is capable of facilitating both cyclic and conventional NAA application for the GHARR-1.

1. Introduction

Ghana's Miniature Neutron Source Reactor (MNSR) also known as Ghana Research Reactor-1 (GHARR-1) is used mainly for Neutron Activation Analysis (NAA) [1]. The pneumatic transfer system (PTS) for Miniature Neutron Source Reactor (MNSR) is an experimental facility of GHARR-1. The basic function of the facility is to transfer samples to the irradiation position of the reactor and to retrieve activated samples to the lead chamber where the sample is picked up manually onto a gamma detector for counting. The designed and constructed PTS control unit is to facilitate cyclic neutron activation analysis. The PTS depends on compressed-air to achieve either a sending of sample or a retrieval of sample, [2]. Similar systems are installed in MNSR member states, such as Nigeria [3], Syria [4], Iran [5], and Pakistan for one-shot conventional NAA. The existing PTS is required to facilitate the determination of short-lived nuclides by instrumental neutron activation analysis (INAA) technique [6]. Instead, it is not suitable for the determination of very short-lived nuclides (half-lives <1 min) such as ^{110}Ag, ^{80m}Br,

^{38m}Cl, ^{116m}In, ^{20}F, ^{179m}Hf, ^{24m}Na, ^{46m}Sc, ^{77m}Se, and ^{207m}Pb. This limitation is due to the fact that the current one-shot irradiation-counting sequence does not achieve optimum activity levels (approaching saturation activity). There is therefore the need to repeat the irradiation cycle while summing the counting from each spectra to help it approach saturation activity level. This technique has been widely applied in biological, environmental, geological, industrial, and forensic studies, and the most often measured elements include Se, F, Pb, Hf, Sc, O, Ag, and Rh. The advantages of CNAA, as compared to conventional activation analysis (a one-shot irradiation-counting sequence), include significant improvements of the detection limits, analytical precision, and accuracy of elements detection, short experimental time, and increased number of samples per unit time [7]. A computer based Programmable Logic Controller (PLC) with a LOGO Comfort software version (V8) was used to design and construct a control unit to facilitate a cyclic neutron activation analysis for the GHARR-1 PTS to replace the old controller meant for conventional NAA mode of operation [8].
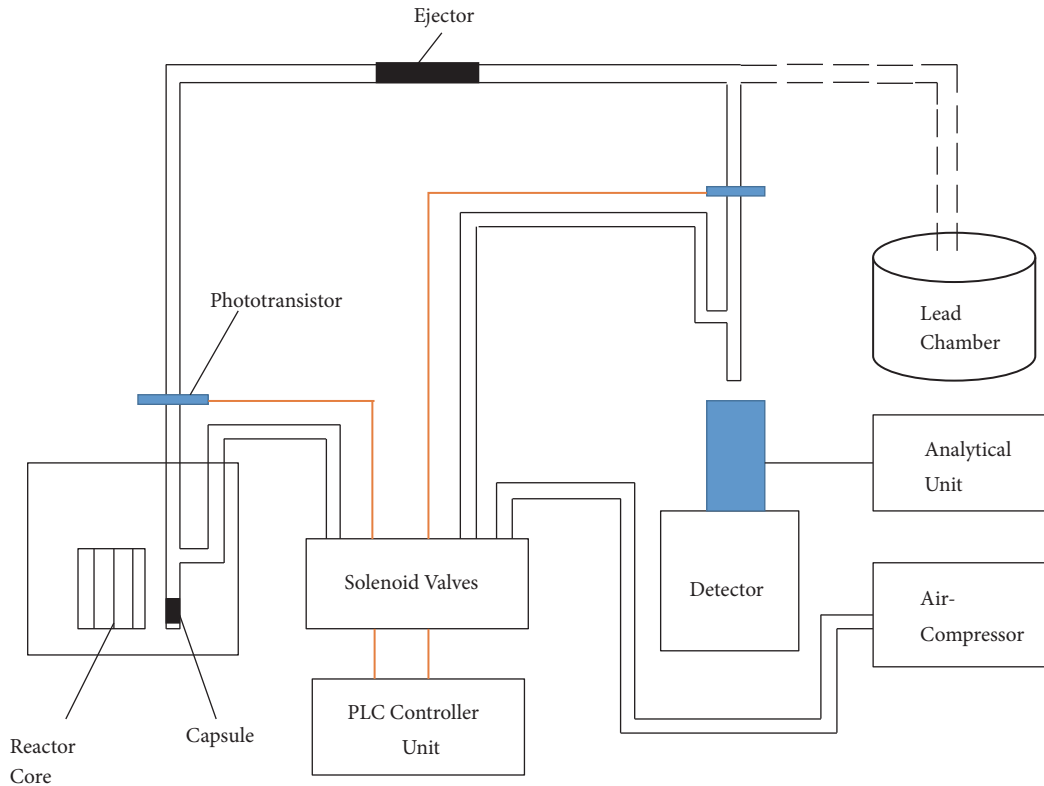
FIGURE 1: Schematic diagram of cyclic neutron activation analysis (CNAA).

Figure 1 shows the schematic diagram of PTS with little modification for cyclic neutron activation analysis (CNAA) application with regard to this current study. Similar facilities have been set up for CNAA in institutions such as the Dalhousie University, Canada [9], MNSR, China Institute of Atomic Energy [10], and University of Missouri, USA. [11]. Atomic Institute, Vienna University of Technology-TRIGA Mark II, has recently developed a fully automated fast pneumatic transport system for short-time activation analysis [12]. The control unit is equipped with a Programmable Logic Controller, software package, and other devices to facilitate optimal analytical procedures. 950 ms were only necessary to transfer the irradiated sample capsule (diameter: 17 mm, length: 56 mm, weight: 500 mg) to the HPGe detector at a distance of 18 meters using a compressed-air (0.2 MPa) as a transport gas. Figure 1 consists of an ejector in which sample capsules are put and air-compressor releasing a compressed-air at an operating pressure of 0.2 Mega Pascal (MPa) to transfer the capsule sample into the reactor for irradiation. The pressure in the storage tank or receiver is held higher (between a max. of 0.6 MPa and a minimum of 0.4 MPa) than the system operating pressure (0.2 MPa) to compensate pressure loss in the pipes. A phototransistor is fixed at an appropriate location on top of the reactor and the detector respectively for two purposes; the first is to guarantee that the sample capsule has passed a certain point in the system; if that is not the case, the total process will be interrupted. The second is to start specific processes, such as irradiation timer, decay of sample, and measurements or

counting of activity. With the existing PTS, the phototransistor was located on the receiving lead chamber, where the operator picks the sample manually and places it on the detector. As part of this current study, the phototransistor has been relocated onto the detector to facilitate the CNAA application. The designed and constructed control unit of this current study consists of a PLC, a high current dual voltage regulated power supply, and a relay bank to control the solenoid valves (open and close) for the compressed-air to transfer the sample capsules into the reactor for irradiation.

The detector is a High Purity Germanium (HPGe) for detection of photons. The analytical unit is a spectrometry system consisting of a high voltage to bias the detector, preamplifier to provide an output pulse with an amplitude proportional to the integrated charge output from the detector, main amplifier for amplification, and pulse shaping, and multichannel pulse height analyzer sorts successive signal pulses into parallel amplitude channels [13].

2. Materials and Methods

The illustration of the controller unit to be designed and constructed is shown in Figure 2. The controller unit consists of three main components: the high current dual voltage regulated power supply, PLC device, and an 8-way relay bank. The designed and constructed power supply has a dual voltage of +24 VDC and +12 VDC and can be regulated from its internal reference voltage minimum of 1.25 to a safe

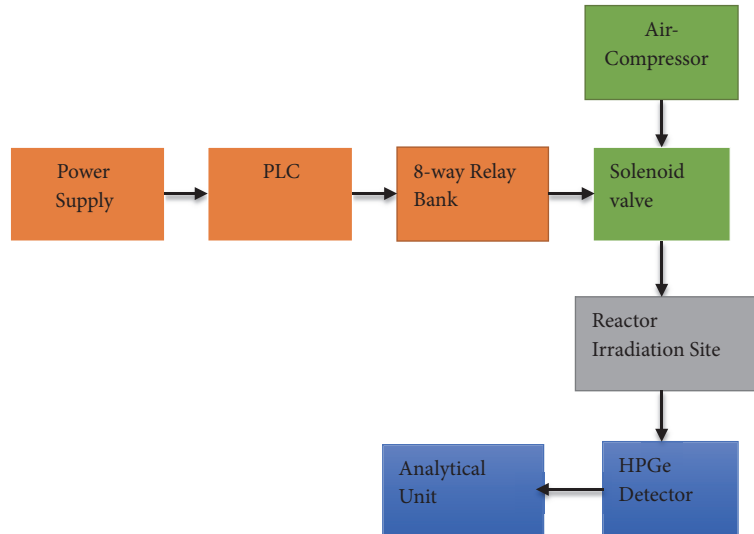FIGURE 2: Block diagram of the controller unit.

FIGURE 3: A complete block diagram of pneumatic transfer system (PTS) of the GHARR-1.

maximum voltage of 30 VDC at a safe operating current of 5 Amps. Two high current power transistors, 2N3055 and MJ 2955, are used alongside LM 317 voltage regulator which is capable of supplying 1.5 A [14]. The +24 VDC operates the PLC and the +12 VDC controls the output switching system of the PLC to operate the relay bank. The 8-way relay bank has eight +12 VDC relays that are controlled by the PLC output to supply a 220 VAC to operate the solenoid valves. Figure 3 shows a block diagram of a complete system flow of the PTS.

Figure 4 shows the control flow chart for cyclic mode activation analysis with conventional mode analysis as an option. The context analysis diagram shown in Figure 5 depicts the PLC software controlling six inputs and four outputs. Figure 6 is the flow chart showing the Data Flow Diagram (DFD) depicting the flow of information through the irradiation of sample processes.

2.1. Design Requirements for Safety Systems and Components (SSCs)

2.1.1. Engineering Safety Features. According to International Atomic Energy Agency (IAEA) documents (NS-R-4 and SSG-39) the design of Safety Systems and Components (SSCs) of Research Reactors (RRs) following a certain criteria so not to compromise the safety operations of RRs [15, 16].

The PTS control unit designed satisfies the design requirements as follows.

2.1.2. Predesign Appraisal. (i) The PTS control unit designed satisfies the surveillance requirements, and decommission and disposal aspects will not interfere with the Reactor under normal operation.

(ii) Provisions have been made for the inspection, periodic testing, and maintenance (including simulation of the program) to verify that the engineering safety features continue to function or in a state of readiness to perform the functions and will be reliable and effective upon demand.

(iii) Surveillance test points have been provided as means to measure the AC and DC voltages using externally connected testing devices. Potentiometers (POTs) have been provided for recalibration of the +12 and +24 DCV power supply.

(iv) Under the design for testability, provision has been made for the PTS control unit to be put under real conditions by exposing the sensors (the phototransistors) of the system to actual process variable rather than simulation.

2.1.3. Safety Considerations for the Design of an Experiment or Modification [17]. The design of the controller unit for modification on the existing PTS demonstrates that

(i) the designed PTS control unit can fulfill the task for which it is intended;

(ii) it can be installed and operated without compromising the safety of the Research Reactor;

(iii) the unit can be removed or decommissioned without compromising the safety of the RR.
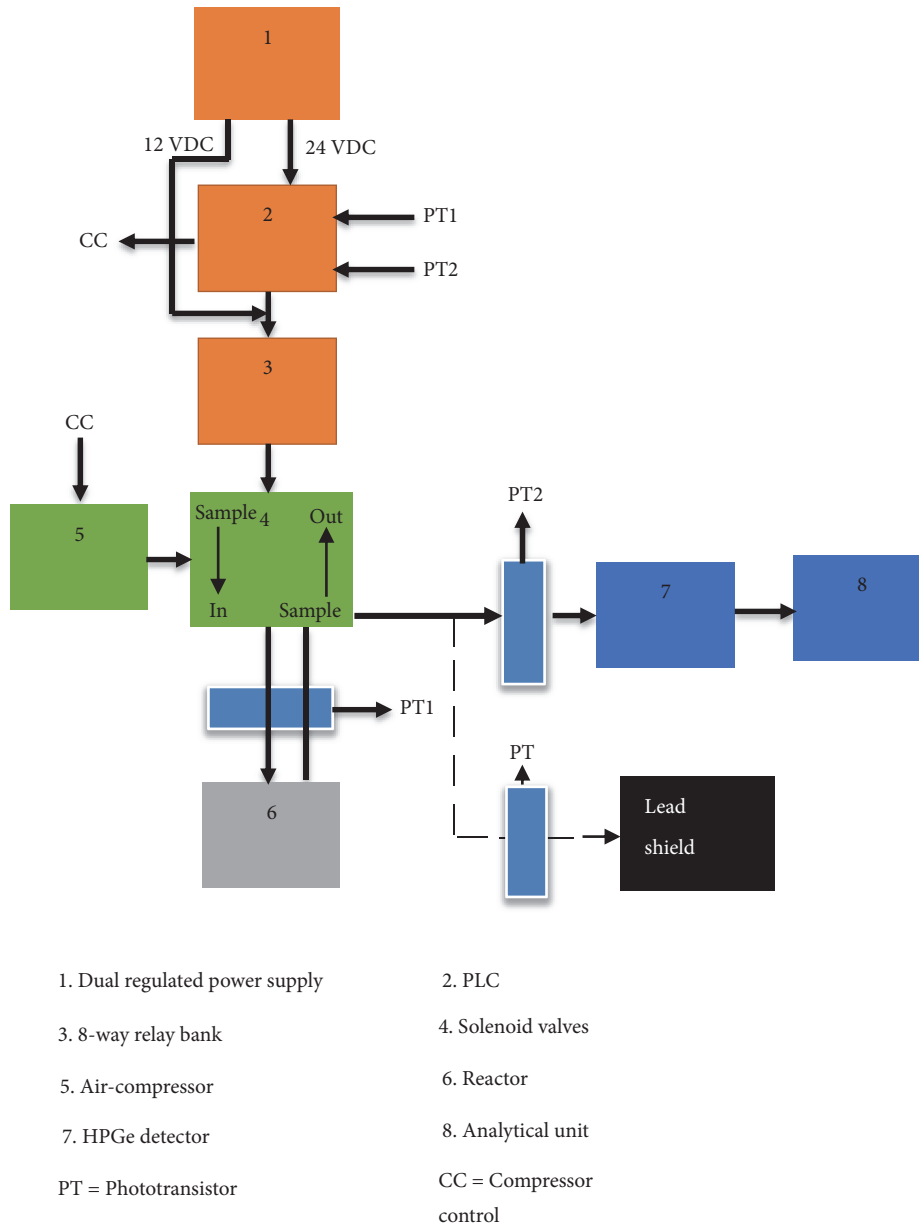
FIGURE 4: Flow chart for cyclic mode analysis with conventional mode option.

1. Dual regulated power supply

2. PLC

3. 8-way relay bank

4. Solenoid valves

5. Air-compressor

6. Reactor

7. HPGe detector

8. Analytical unit

PT = Phototransistor

CC = Compressor control

2.2. Theory for CNAA. The detected radiations at each counting period are summed and finally a total cumulative detector response is obtained. The cycle period T is given:

$$T = t_i + t_d + t_c + t_w \qquad (1)$$

where t_i is the time of irradiation, t_d is the delay time, t_c is the counting time, and t_w is the waiting time.

The detector response (or the number of counts) for the first cycle is given by

$$D_1 = \frac{N\sigma\Phi I\varepsilon}{\lambda}\left(1 - e^{-\lambda t_i}\right)e^{-\lambda t_d}\left(1 - e^{-\lambda t_c}\right) \qquad (2)$$

where N is number of target nuclei, σ is activation cross-section, Φ is neutron flux, I is the intensity of the radiation of interest, and ε is the efficiency of the detector.

In the second counting period, the detector response is the same number of counts due to the second irradiation plus what was left from the first irradiation and is expressed as

$$D_2 = D_1 = +D_1 e^{-\lambda T} = D_1\left(1 + e^{-\lambda T}\right) \qquad (3)$$

Similarly, for the nth cycle, it is expressed as

$$D_n = D_1\left(1 + e^{-\lambda T} + e^{-2\lambda T} + e^{-3\lambda T} + \cdots + e^{-(n-1)\lambda T}\right) \qquad (4)$$

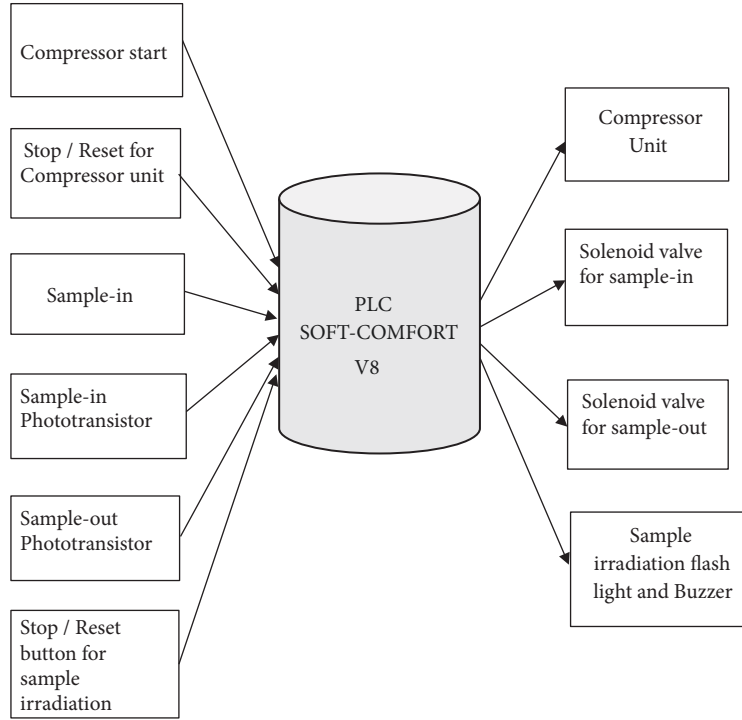The total cumulative detector response in all n cycles is given by

Figure 5: Context analysis diagram of PTS controller unit designed.

$$D_c = \sum_{i=1}^{n} D_i \qquad (5)$$

$$= D_1 \left[\frac{n}{\left(1 - e^{-\lambda T}\right)} - \frac{e^{-\lambda T}\left(1 - e^{-n\lambda T}\right)}{\left(1 - e^{-\lambda T}\right)^2} \right] \qquad (6)$$

$$= \frac{N\Phi\sigma I\varepsilon}{\lambda} \left[\frac{n}{1 - e^{-\lambda T}} - \frac{e^{-\lambda T}\left(1 - e^{-n\lambda T}\right)}{\left(1 - e^{-\lambda T}\right)^2} \right] x \left(1 - e^{\lambda t_i}\right)$$
$$\cdot e^{-\lambda t_d} \left(1 - e^{-\lambda t_c}\right) \qquad (7)$$

Equation (7) is the basic relationship for CNAA.

Figure 7 shows the schematic diagram of the designed pneumatic transfer system controller unit. The wiring starts from the dual voltage regulated high current power supply through the PLC, terminal block (T_1) to relay bank. The relay bank connects through the terminal block (T_2) and (T_3) to the solenoid valves. I_1 to I_6 are the input switches used and Q_1 to Q_3 are the outputs of the PLC used to control five (5) relays on the relay bank. Q_4 connects directly to an irradiation flash light and buzzer.

The working principle of the cyclic mode activation program shown in Figure 8 operates as follows: The PLC software program is designed to control the air compressor during sample irradiation through a timer B018. When a momentary switch I_1 start-button is pressed, timers B018 and B008 will start working per the preset time allotted to the timers. The timer B008 has a special function of ensuring that the maximum pressure of the air compressor is built-up to 0.6 MPa, after which the sample-in start-button could be

operated. The air-compressor contactor coil Q_1 is energized by a 220 VAC, enabling a 3-phase 415 VAC to be connected across the compressor motor; see Figure 9. The timer B018 starts to count down as per the preset value and stop when irradiation period is over. The momentary button I_2 could be pressed to interrupt the operation when a problem is detected and reset later to resume operation.

The direct-on-line starter connection for the air compressor consisting of a Three-Phase and Neutral (TPN) isolator connected to a compressor motor through a magnetic contactors and an Overload Relays (OLR). The contactor coil is connected to a 220 VAC and in series to a pressure regulator and an overload relay contact; see Figure 9.

A high current dual voltage regulated power supply (+12/+24 VDC) was designed and constructed to operate the PLC and the relays in the relay bank. A center tapped (15-0-15 CT) transformer U_1 converts the 240 VAC to 30 VAC and 15 VAC, respectively, and rectified by a separate full-wave rectifiers (bridge type) D_1 and D_2. The outputs of the rectifiers are filtered by capacitors C_1 and C_4, shown in Figure 10.

Figure 11 shows an 8-way solid state relay (SSR) bank designed to operate the solenoid valves. The SSRs are rated at 20 A / 12 VDC and 10 A / 220 VAC for the solenoids. A 220 VAC is connected across the solenoid valve (S) through the SSR contacts to operate it using the Soft Comfort V8 of LOGO! Siemens software.

3. Results and Discussion

3.1. Construction of PTS Controller Unit. Figure 12 shows the internal features of the designed and constructed PTS

```
                          ┌─────────────────┐
                          │   User Login    │
                          └────────┬────────┘
                                   │
                          ╱─────────────────╱
                          ╱  Initialization ╱
                          ╱─────────────────╱
                                   │
                              ◇ Cyclic ◇        No      ┌─────────────────┐
                              ◇ Mode   ◇ ─────────────▶ │     Normal      │
                              ◇        ◇                │   Irradiation   │
                                   │                    └─────────────────┘
                                 Yes
```

```
  ╱──────────────────────────╱              ┌─────────────────┐
  ╱  Compressor start button ╱ ───────────▶ │  Timer starts   │
  ╱──────────────────────────╱              └─────────────────┘
```

```
  ╱──────────────────────────╱       ┌─────────────────────────┐
  ╱      Sample-in button    ╱ ─────▶ │   Solenoid valves open  │ ◀──────── A
  ╱──────────────────────────╱        └─────────────────────────┘
```

```
  ┌──────────────────────────┐    ┌─────────────┐    ┌──────────────────┐
  │ Sample-in phototransistor │    │  Sample-in  │    │ Irradiation Starts, │
  │     detects sample        │──▶ │ LED lights-up│──▶│ Red light flashes,  │
  └──────────────────────────┘    └─────────────┘    │ Buzzer beeps        │
                                                       └──────────────────┘
```

```
  ┌──────────────────────┐    ┌──────────────────┐    ┌──────────────┐
  │ Irradiation time      │    │ Sample-out solenoid│  │   Sample     │
  │     elapsed           │──▶ │    valves open     │─▶│ Transferred  │
  └──────────────────────┘    └──────────────────┘    │ to detector  │
                                                        └──────────────┘
```

```
  ╱──────────────────────────╱    ┌─────────────┐
  ╱ Sample-out phototransistor╱    │ Sample-out  │
  ╱     detects sample        ╱─▶  │ LED lights-up│
  ╱──────────────────────────╱     └─────────────┘
```

```
  ┌──────────────────────────┐
  │  Counting process begins  │
  └──────────────────────────┘
```

```
  ┌──────────────────┐    ┌──────────────────┐
  │ Sample decay Timer│    │  Counting Timer  │
  │     starts        │──▶ │                  │
  └──────────────────┘    └──────────────────┘
```

```
                          ┌──────────────────┐
                          │  Waiting Timer    │
                          └──────────────────┘
```

Repeat Process

```
              ◇ Any more ◇    Normal Irradiation (Conventional NAA)
  A ◀── Yes ──◇ irradiation◇
              ◇          ◇
                   │
                  No
                   │
                 (Stop)
```
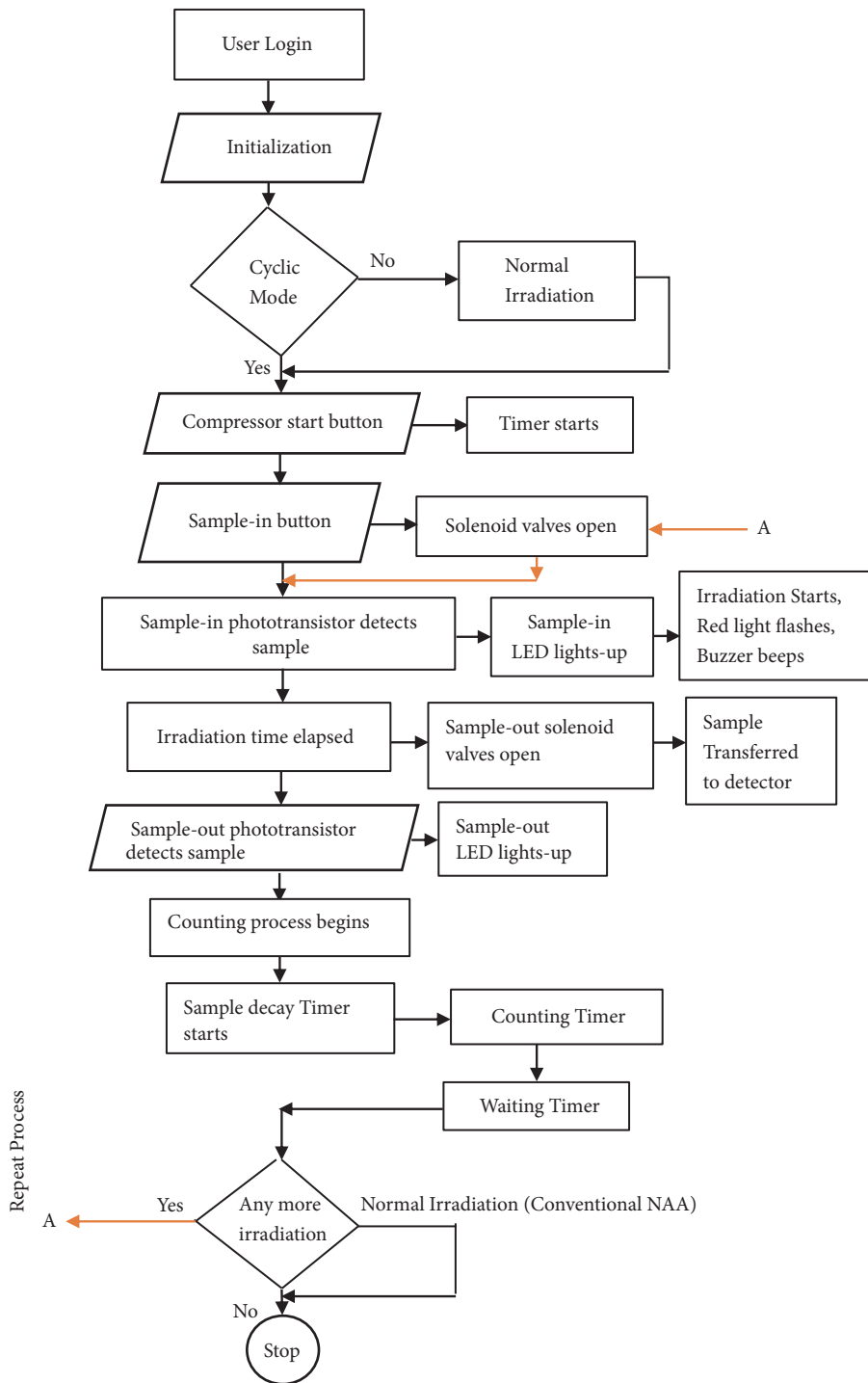
Figure 6: Flow chart for cyclic and conventional mode analysis.

controller unit. Figure 13 is the photograph of the front view and the location of the Programmable Logic Controller (PLC).

3.2. Experimental Results. The system was plugged into a 220 VAC socket to test how the controller unit performs in relation to the objective of the study. The red Light Emitting

Diode (LED) on the controller unit, Figure 14, indicates that the relay bank is powered. The compressor start-button is depressed and the contactor coil bulb lights up to indicate that 220 VAC is connected across contactor coil of the compressor unit. The contactors are closed and the compressor motor received 415 VAC, 3PH supply to start the compressor unit. The compressor-start indication light on the controller comes
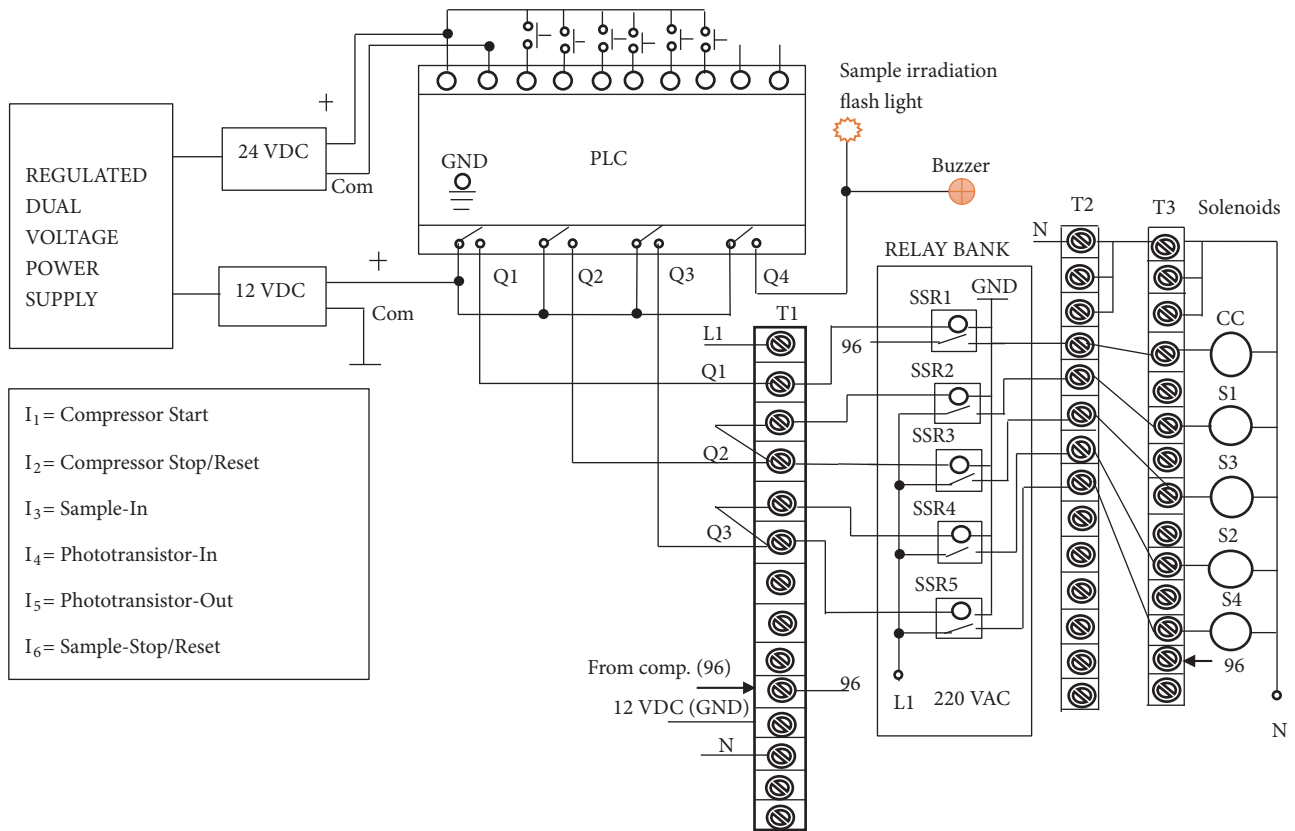
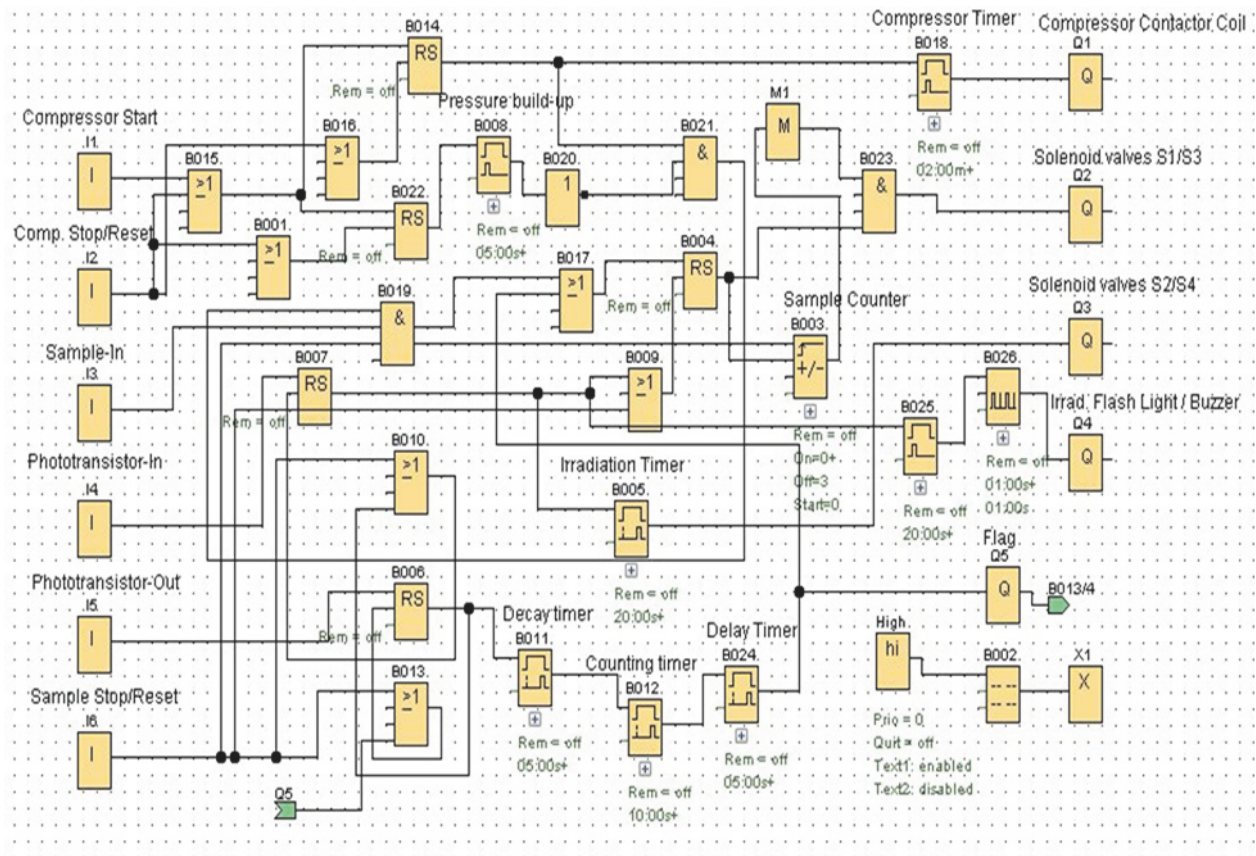FIGURE 7: Schematic diagram of the designed PTS controller unit.

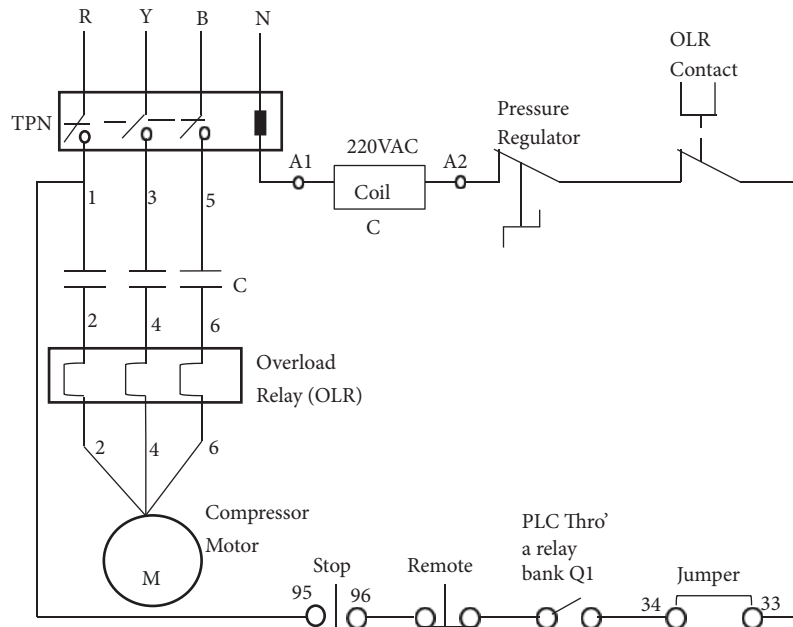FIGURE 8: Designed cyclic mode activation program.

FIGURE 9: Schematic diagram for a remote control of air-compressor system by PLC.
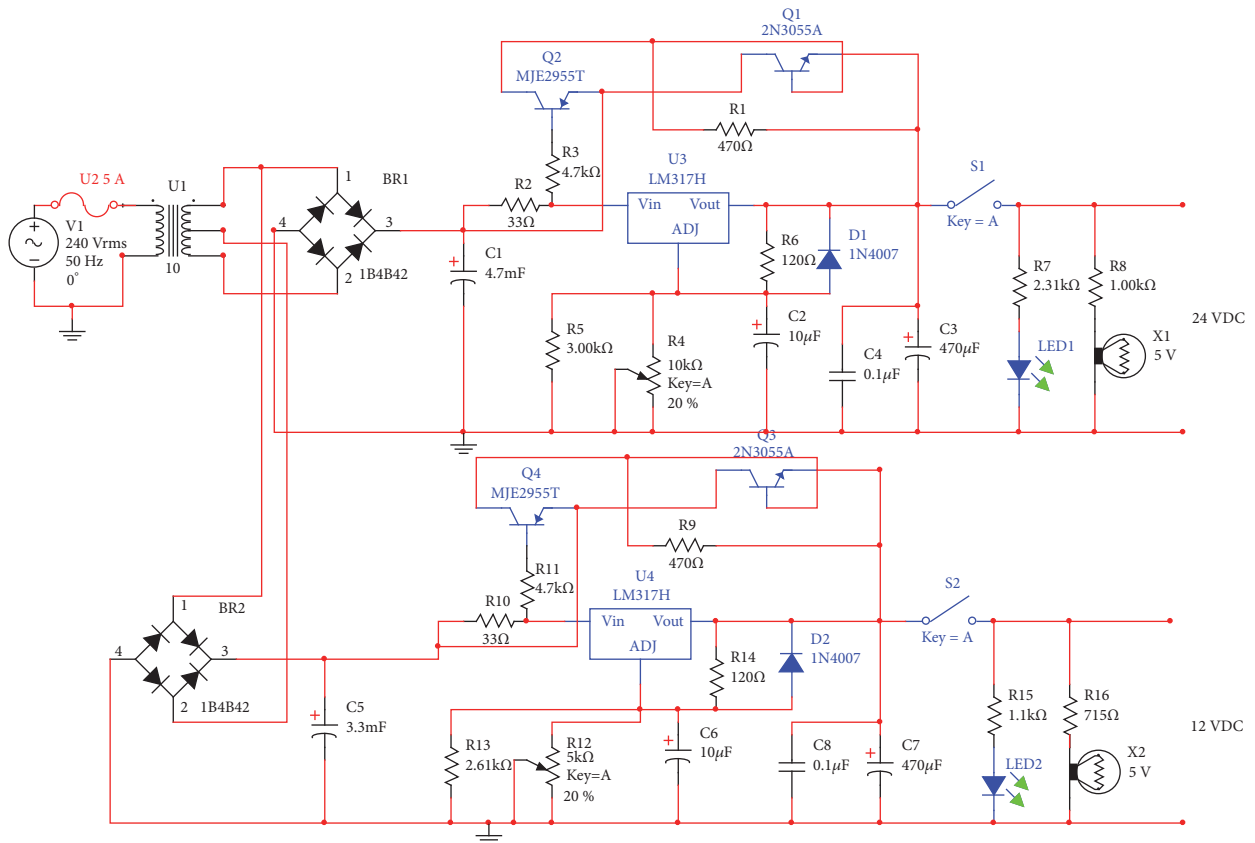
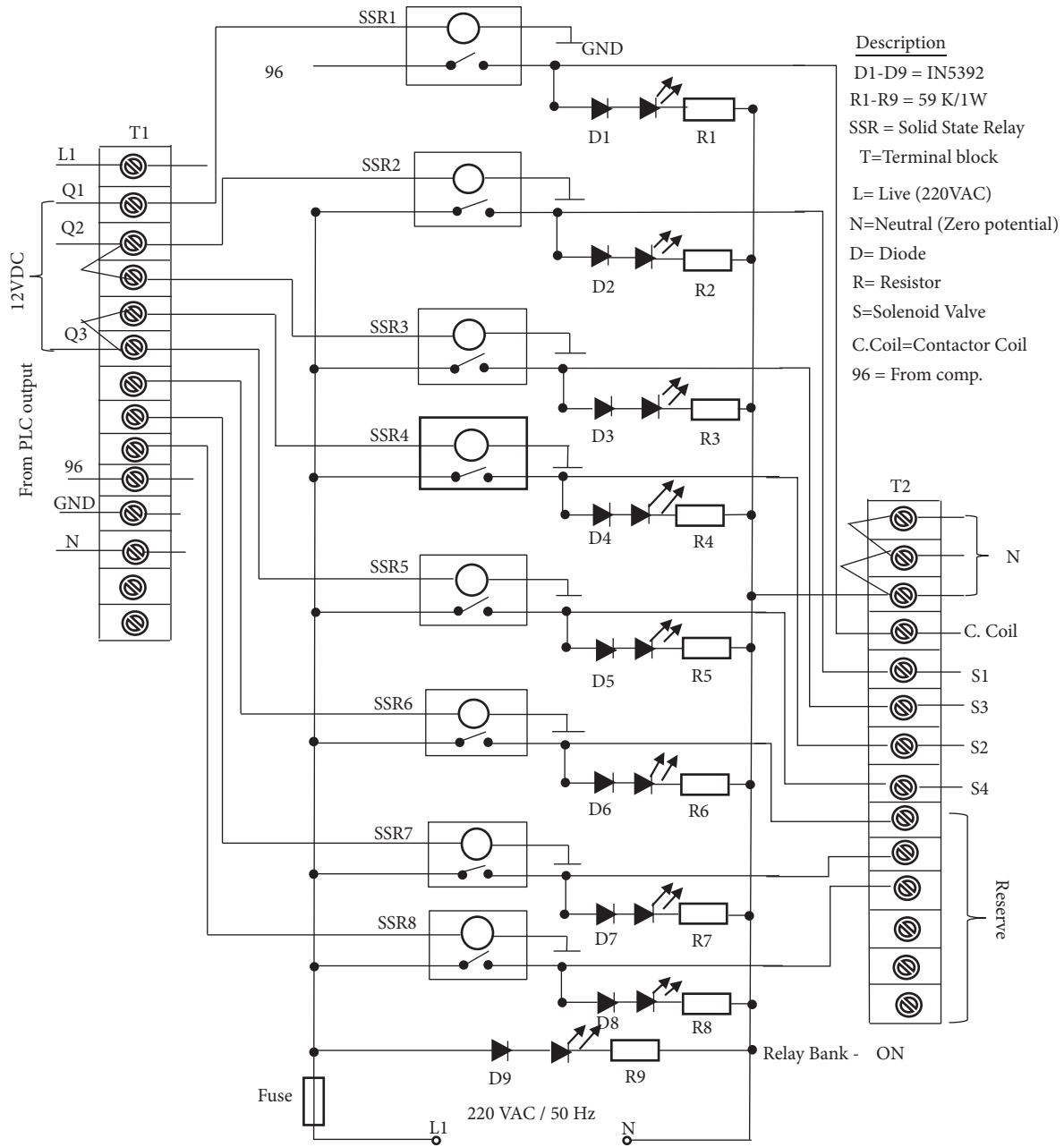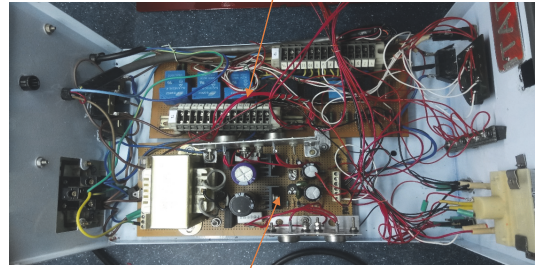FIGURE 10: Dual voltage regulated power supply (+12 / +24 VDC.

FIGURE 11: Designed eight (8)-way relay bank to operate the solenoid valves.

ON to alert the operator that the compressor is in operation. Bulbs for S_1 and S_3 of Figure 15 light-up to indicate that the solenoid valves are opened for the compressed-air to transfer sample into the irradiation site of the reactor. The yellow LED on the controller alerts the operator that the sample is pumped into the irradiation site of the reactor. When the phototransistor detects the sample capsule either on top of the reactor or on top of the detector, it switches out +24 VDC as shown in Figure 16. In case of the reactor top, the +24 VDC signal pulse deactivates (close) the sample-IN solenoid valves S1 and S3 per the PLC program software

and irradiation begins. In this case, the phototransistor on top of the detector, the +24 VDC, starts the counting timers. The two bulbs are switched-OFF to indicate that the solenoid valves are closed and the sample irradiation is in progress. The irradiation red LED flashes up together with a beep from a buzzer to alert the operator that irradiation is in progress; see Figure 17. The setup in Figure 18 illustrates the sample capsule out of the reach of the phototransistor detection. The phototransistor outputs 0.00 VDC, because the LED is direct on the phototransistor base and no sample is transferred through the sample capsule slot. In this case,

8-WAY RELAY BANK

HIGH CURRENT VOLTAGE RREGULATED POWER SUPPLY

FIGURE 12: Internal features of PTS controller unit designed and constructed.

(a) Front view of the pts controller unit

(b) PTS controller unit showing the PLC

FIGURE 13

the phototransistor does not switch, and the output indicates 000 volts; see Figure 19. Bulbs for S_2 and S_4 of Figure 20 are "ON" to indicate that sample-out solenoid valves are opened to transfer the irradiation sample onto the High Purity Germanium (HPGe) detector for counting. The green LED on the controller alerts the operator that the irradiated sample is transferred from the reactor onto the detector. Bulbs for S_1 and S_3 of Figure 21 are "ON" to show the repetition of the irradiation cycle. The compressor bulb will go "OFF" only when the irradiation is over as per the program of the PLC.

FIGURE 14: Contactor coil energized, compressor starts.

FIGURE 15: Sample-in button depressed, solenoid valves (S1 and S3) open.

4. Conclusion

Pneumatic Transfer System (PTS) control interface to facilitate cyclic neutron activation analysis (CNAA) application at GHARR-1 and for MNSR's has been successfully designed and constructed. The designed and constructed controller was simulated using electric bulbs to represent the solenoid valves and momentary switches for the phototransistors. The phototransistors detect the samples and send positive signal to timers for irradiation and counting respectively. Cyclic mode of operation is achieved by the LOGO! Comfort software V8 which provided timers, counters, momentary switches, and other logic parameters to control the sample movement. The study has shown that the computer based
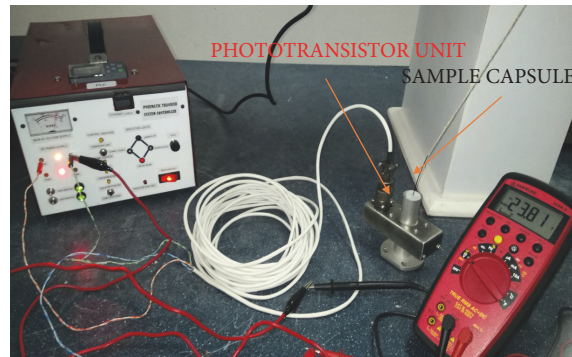
FIGURE 16: Phototransistor detects sample capsule, output +24 VDC.

FIGURE 17: Solenoid valves S1 and S3 close, sample irradiation starts with flash light/beeps of buzzer.

FIGURE 18: Sample capsule moved out of detection and phototransistor outputs 0.00 volts.

FIGURE 19: Illumination of led in sample slot phototransistor outputs 0.00 volts.

FIGURE 20: Irradiated sample transferred onto detection for counting. Solenoid valves S2 and S4 open.

FIGURE 21: Irradiation cycle repeats and solenoid valves S1 and S3 open (second cycle).

Table 1

24 VDC		12 VDC	
Component ID	Part Number	Component ID	Part Number
IC U3	LM 317 TO-220	IC U4	LM 317 TO-220
Transistor Q1	2N3055 Metallic	Transistor Q3	2N3055 Metallic
Transistor Q2	MJE 2955	Transistor Q4	MJE 2955
Resistor R1	470 Ohms 0.5Watts	Resistor R9	470Ohms 0.5 Watts
Resistor R2	33 Ohms 5 Watts	Resistor R10	33 Ohms 5 Watts
Resistor R3	4.7 K 0.5 Watts	Resistor R11	4.7 Ohms 0.5 Watts
Resistor R4	10 K Potentiometer	Resistor R12	5 K Potentiometer
Resistor R5	3 K 0.5 Watts	Resistor R13	2.61 K 0.5 Watts
Resistor R6	120 Ohms 0.5 Watts	Resistor R14	120Ohms 0.5 Watts
Resistor R7	2.31 K 0.5 Watts	Resistor R15	1.1 K 0.5 Watts
Resistor R8	1 K 0.5Watts	Resistor R16	715 Ohms 0.5 Watts
Capacitor C1	4700 μF / 50 V Electrolytic	Capacitor C5	3300 μF / 63 V Electrolytic
Capacitor C2	10 μF / 50 V Electrolytic	Capacitor C6	10 μF / 50 V Electrolytic
Capacitor C3	470 μF / 50 V Electrolytic	Capacitor C7	470 μF / 50 V Electrolytic
Capacitor C4	104 Ceramic	Capacitor C8	104 Ceramic
Diode D1	IN4007	Diode D2	IN4007
Rectifier BR1		Rectifier BR2	
Transformer U1	15-0-15 Center Tapped 2 Amps Step Down Transformer		

PLC control unit for PTS is capable of facilitating both cyclic and conventional NAA application for GHARR-1 per the simulation results.

Data Availability

The electronic circuit data used to support the findings of this study are included within the article.

Additional Points

Logo 8 Siemens Programmable Controller Logic (PLC). The PLC used for this study is LOGO! Base Module 12/24 RCE Controller, 8 digital inputs and 4 relays (10Amps) outputs (6ED1 052-1MD00-0BA8) from Siemens Industrial Automation Products Ltd. LOGO!Soft Comfort V8.0 is LOGO! programming software used for the study. It runs under Windows (including Windows XP, Windows 7, and Windows 8), Linux, and Mac OS X. Additional support is available on the Siemens LOGO! website (http://www.siemens.com/logo). *Power Supply Design.* The power supply was designed using Multisim version 12.0 from National Instruments. The program could be retrieved from (www.ni.com/Multisim). 2N3055 (NPN), MJ2955 (PNP) (2015). Complementary Silicon Power Transistors (6th revision)". Retrieved from http://www.onsemi .com/pub_link/.Collateral/2N3055-D.PDF) Semiconductor Components Industries, LLC. *Mendeley Desktop.* Mendeley desktop version 1.19.4 was used for the citation and generation of the bibliography. *List of Used Circuits Components.* See Table 1.

Disclosure

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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