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Ageing Management Activities at the Ghana Research Reactor-1 Facility

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ABSTRACT

The Ghana Research Reactor-1 (GHARR-1) is a Miniature Neutron Source Reactor (MNSR) designed as a tank in a pool reactor. Its main utilization involves neutron activation analysis and human resource development in nuclear sciences and engineering. The reactor in the erstwhile (1994-2017) used HEU core, 90.2% enriched fuel for the core assembly with a nominal power of 30 kW, corresponding to neutron flux of 1.0 x 10^{12} ncm^{-2}s^{-1}. After a successful feasibility study had been carried out under the auspices of US DoE and IAEA as well as other stakeholders like CIAE of China, SOSNY of Russia, UJV and SKODA of Czech Republic and all MNSR operating Countries, the GHARR-1 was converted to a Low Enriched Uranium (LEU) core (13.0 % U-235) in July 2017. The nominal power of the LEU is 34 kW, corresponding to a neutron flux of 1.0 x 10^{12} ncm^{-2}s-^{1}. The GHARR-1 received a new core but still operates in the old existing structures and auxiliary systems. The control systems circuit boards for the instrumentation and sample transfer system pipes were refurbished. For over two decades of continuous operation, the facility is undoubtedly ageing. This work presents ageing management activities carried out to keep the GHARR-1 HEU core operational until the core was changed to the LEU core. The instrumentation and control problems encountered since the LEU core became operational and how these problems were resolved to keep the LEU core operational including proactive and reactive maintenance programmes put in place to address instrumentation and control problems, obsolescence of components and the reactor structures are also presented.

1.0 INTRODUCTION

Ageing management by the IAEA definition is "engineering, operation, and maintenance strategy and actions to control within acceptable limits the ageing degradation of Structures, Systems, and Components (SSCs)"[1]. These include activities such as "repair, refurbishment and replacement of SSCs, which are similar to other activities carried out at a research reactor in maintenance and testing or when a modification on a project takes place"[2]. Ageing management procedures are carried out on installed facility's SSCs to guarantee uninterrupted safety consistently in the day-to-day operation of the reactor which should ultimately be in conformance with the operational limits and conditions (OLCs). In this regard, managing the safety of a research reactor as its SSCs go through operation many years require, among others, effective maintenance guide for the checking and detecting ageing degradation of SSCs so as to mitigate the degradation through comprehensive Programmes and activities to guarantee the integrity of the reactor SSCs throughout its operational lifetime.

To gain an insight into the SSCs of the Ghana Research Reactor-1 (GHARR-1) a general description of its systems are as presented as follow: The GHARR-1 is a Miniature Neutron Source Reactor (MNSR) designed as a tank in pool reactor. It is similar in design to the Canadian SLOWPOKE [3]. It was originally operating

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with a Uranium 235 isotope core and had a Uranium enrichment of 90.2%. The facility's main utilization involves neutron activation analysis and human resource development in nuclear sciences and engineering. Ghana, in support of the nuclear non-proliferation policy, accepted and converted its Highly Enriched Uranium (HEU) core research reactor to a Low Enriched Uranium (LEU) core (13.0 % U-235) in July 2017[4] after a successful feasibility study had been carried out with support from the US DoE and the IAEA. Other stakeholders like the CIAE of China, SOSNY of Russia, UJV and SKODA of the Czech Republic and all MNSR operating countries cooperated effectively; yielding the desired results.

Comparatively, in terms of thermal power, the GHARR-1 HEU which was in operation from1994 to 2017 had a nominal power of 30 kW corresponding to a neutron flux of 1.0 x 10^{12} ncm-^{2}s-^{1}. The Low Enriched Uranium (LEU) core of which the GHARR-1 has been converted to, has a nominal power of 34 kW producing a peak neutron flux of 1.0 x 10^{12} $ncm^{-2}s^{-1}$. Notably, the HEU was replaced with LEU in the existing structures with increased thermal power, 34kW. "The reactor structure consisted of the reactor vessel. The vessel is a cylindrical aluminium (Al) alloy container with a diameter, of 0.6 m and 5.6 m high. The core was placed 4.7m from the top at the bottom. The vessel is filled with deionized water of volume, 1. $5m^3$. Around the reactor core, is a fission chamber for sensing neutron flux.

Other associated component with the core in the vessel is one central control rod made of cadmium (Cd) and tied to a control rod drive mechanism and temperature sensors (thermocouples) for measuring inlet and outlet temperatures of the reactor water. The reactor vessel structure is suspended in a stainless steel-lined pool, filled with deionised water, $30m^3$ and surrounded by a mass-reinforced concrete of 0.4 m thick. The pool's internal diameter is 2.7m and 6.5m deep below the ground"[5].The reactor core by a design is caged into metallic beryllium. On the top of the core, is a beryllium tray. Spherically around the core, is the side beryllium annulus and at its base is the bottom beryllium support. This arrangement of the beryllium around the core is in the essence of maintaining peak neutron flux in the reactor core and this is achieved through a reflection of the neutron into the core. The top beryllium tray is used for the compensation of the reactivity loss that results from fuel burn-up and samarium poison. Different thickness of beryllium shim discs are available, which are selected through a calculation for placement into the tray to compensate for the reactivity loss. "The reactor is designed to have self-limiting power excursion characteristics. The single control rod made of cadmium located at the centre of the reactor core is used for regulating the power level, compensating for fuel consumption, and startup and shutdown of the reactor. A fail-safe principle is adopted in the design of the reactor control system.

The following are the main auxiliary systems to the reactor. The water purification systems: they are used for regular purification of the reactor vessel and pool water to meet the standard quality (0.5 – 2.0 µS) of the water to prevent corrosion of the system structure and components of the reactor complex. The reactor gas purge system, this is used to purge out harmful gases, such as hydrogen, Ar-1, Kr, Xe and I, which are likely to accumulate at the top space of the reactor vessel"[5].The control and instrumentation systems of GHARR-1 consist of the control console (CC) and Micro-Computer Closed Loop System (MCCLS). Each is used to operate the reactor independently. The control systems circuit boards for the instrumentation and sample transfer system tubes were refurbished. For over two decades of continuous operation, ageing and obsolesces tendency of the facility is inevitable of its SSCs. This work presents ageing management activities which had been carried out to keep the GHARR-1 HEU core operational until the core was changed [6] to the LEU core. The instrumentation and control problems encountered since the LEU core became operational and how these problems were resolved to keep the LEU core operational including routine and corrective maintenance programmes put in place to address instrumentation and control problems. Obsolesce of components and containment structures are also presented. Detailed features of GHARR-1 HEU and LEU are found in references[6].

2.0 GHARR-1 Ageing Management Activities in The Era of HEU core

Management of GHARR-1 has put in place adequate ageing management programs and activities to take care of ageing issues from the reactor SSCs to the human resource succession plan[7]. The scope of this work is limited to the Instrumentation and control systems, the reactor complex and the pneumatic transfer systems' ageing management activities relevant to safety. The methodology in place in managing the ageing of SSCs of GHARR-1 is by routine maintenance and corrective approach [8]. Maintenance activities such as inspections, monitoring, performance tests, periodic tests and visual examination were employed in maintaining the reactor and its auxiliaries to optimum safety. The first day of every week (Monday) is dedicated to routine maintenance where these activities are conducted. Weekly checklists were provided for marking and for reporting SSCs' state of affairs for action. This programme, over the years granted optimum availability of the reactor for safe operation and utilization. Routine maintenance activities for the reactor and its auxiliary systems are scheduled and carried out on a weekly, quarterly and annual basis, depending upon how important safety and complexity needs inherent in the troubled component situation. The following, as shown in Table 2.0 were some principal problem encountered and the various work of maintenance carried out during the HEU core operational era of the GHARR-1.

Table 2.0 Some principal problem encountered and maintenance responses with GHARR-1 HEU Core

S/No.	Principal Problem and Maintenance	Ref. Dates
1.	Snapped-off of control rod wire (the first major problem encountered)	March 29, 1996
2.	Breakdown of high voltage supply to the Gamma monitor located on the control console. Designed and replaced	May 10, 1997
3.	Repair of control rod drive mechanism	Feb.11,2001
4.	Addition of first Beryllium(Be) shim plates (3mm thickness added)	Feb. 26,2002
5.	Reactivity adjustment (Removal of one reactivity regulator)	Jul. 27, 2005
6.	Maintenance and repair of control rod drive mechanism.	Nov.15,2007
7.	Second-time addition of Be shim plates (3mm thickness added)	April 28, 2009
8.	Installation of a new control rod drive mechanism	Aug.4, 2009
9.	Addition of Be shim plate (3 mm thickness added)	Jan. 26, 2011

2.1 GHARR-1 Instrumentation and Control Systems Ageing Management Activities

As mentioned, the GHARR-1 has two independent control systems. The reactor Control Console (CC) and Micro-Computer Closed Loop System (MCCLS). The CC was originally installed with the reactor. The MCCLS was later installed in addition to provide a backup for the CC system. Due to obsolescence, the operating system of MCCLS was changed from Disk Operating System (DOS) to Windows "eXPerience (Win XP) in 2008. The interface board sockets were changed from Industrial Standard Architecture (ISA) to Peripheral Component Interconnect (PCI) making the system user-friendly. Some circuits have been adjusted and some monitoring parameters such as pool water temperature and reactor water outlet temperature included to make the new system better. The new version of the software was programmed in Visual C++ which provides a real-time digital display of the neutron flux, inlet and outlet temperatures, control rod position, reactor water and pool water conductivity. It also has a feature for the reactor flux preset and storage of operational data after the shutdown of operation.

Regular maintenance work which are carried out on the instrumentation and control systems are by calibration and replacement of semiconductor components. Calibrations are done using testing equipment such as Keithley current source, oscilloscope, multimeter and sources. The baseline data given by the manufacturer, operational data and procedures given are strictly followed. Electronic components on the circuit board that often malfunction were listed, purchased and made available for replacement. The MCCLS is robust and did not give much problems during HEU core operational era. Periodic maintenance activities carried out to assess the instrumentation and the control system components' qualification for safety and efficient operation in the past years were as follows: measurement of input and output voltage on active electronic components such as ICs relating to the circuitry board power supply, fission chamber high voltage supply, voltage amplification, temperature, neutron flux, control rod displacement, circuit protection and scram mechanism amongst others. Automatic-over power detection performance and scram test were carried out periodically where currents pulse (IμA) corresponding to full power (30 kW) and above were ejected to assess the effectiveness of the safety system settings for the automatic protective action to prevent the safety limit from not being exceeded per the Operation Limit and Condition (OLCs) requirements, which prescribed that, the reactor shall not exceed 120% of the nominal thermal power. Equations (2.1) and (2.2), P is the thermal power, ϕ is the neutron flux and k is the sensitivity coefficient of the fission ionization chamber. The k values are (5.0 $x10^4$) and (6.0 x 10^4). They were used respectively for control console system and Microcomputer Closed Loop System for the system flux setting and their related electronic components efficiency assessment. The factor 10^{-12} is the change in the ionization current.

$$P = 3.4\ x\ 10^{-8}\ x\ \phi \qquad (2.1)$$

$$I_{\mu A} = \frac{\phi\ x\ 10^{-12}}{k} \qquad (2.2)$$

2.3 GHARR-1 Reactor Systems Ageing Management Activities - ERA of HEU

The reactor complex consisted of the reactor vessel, the core, the irradiation sites, the coolant, the instrumentation and control links, the beryllium(Be) reflector, fission chamber, the control drive mechanism and one central cadmium control rod.

As ageing brings about gradual physical degradation of SSCs, regular verification of core clad failure was put in place. By this the reactor and the pool water samples were analysed for traces of fission elements or products such as $^{131\text{-}135}$I, ^{90}Sr, ^{95}Zr, ^{95}Nb, ^{137}Cs, ^{140}Ba, ^{140}La, ^{85}Kr, ^{133}Xe and ^{135}Xe. It is believed that should there be a clad failure of the reactor core, there would be fission products which will eventually "be transferred through the failed clad to the reactor water. The obtained reactor and pool water assessed for the presence of ^{137}Cs in the 8 years (1994-2011) of its utilization are presented in Table 3.1 of reference[5]. The obtained values for ^{137}Cs were lower than the value set for Operational Limit and Condition prescribed in the Facility's Safety Analysis Report(SAR). According to the SAR, 3.4 x 10^5Bq/L of ^{137}Cs in the reactor and pool water respectively present minimum hazard.

To prevent the presence of water in the vessel and pool not to cause pit corrosion, the water is regularly analysed for its conductivity. The monthly average resistivity values measured are converted to conductivity using the expression (2.3) and the results are compared that of the OLCs. 0.5 – 1.0 µS and 1.0 -2.0 µS are the acceptable range for the reactor and pool water respectively. C in equation (2.3) is the conductance of the water in cm/Ω or (µS) while ρ is the coolant water resistivity in Ω or (MΩ)"[5].

$$C = \frac{1}{\rho}(\mu S) \qquad (2.3)$$

2.4 Ageing Management Activities for the GHARR-1 Control Rod Drive Mechanism-ERA of HEU

Programmes for periodic assessment based on broad operational data collection, preventive maintenance, and continuous monitoring of the control rod drive mechanism revealed that it was deviating from the normal operating condition. The procedure for its removal and replacement was prepared and approval was given by the regulatory authority. The original control rod drive mechanism was removed and a new one supplied from CIAE was replaced successfully. Figures 2.4a, and 2.4b shows respectively staff engaged in the removal of the old control rod drive mechanism and installation of the new one. Reference [5]provides detail of the procedures involved.

Fig. 2.4a: Staff engaged in the control rod drive mechanism replacement

Fig. 2.4b: Old and New Control Rod Drive Mechanism

3.0 Instrumentation and Control Problems Encountered as The LEU Core Became Operational

In the preparation for the first criticality test for GHARR-1LEU core, refurbishment work was done where a lot of active electronic components were replaced. The MCCLS was the main control system used. The first criticality test was performed successfully (August 10, 2017). Ever since the instrumentations and control systems remained effective and have supported operation. However, there were a series of problems encountered with the instrumentations and control systems. The first problem encountered was the software corruption of MCCLS system which halted reactor operation and utilization. The updated software and a detailed approach to the installation to restore the system its normal functionality were received from CAIE. The procedures were followed by the staff and the system was restored. Subsequent problems encountered were due to dry solder joints of active and passive components of the circuits. Other issues encountered with the electronic board were the connecting plugs which were not gripping firmly due to wear and tear that came as a result of periodic opening and servicing. These problems were solved by re-soldering components terminals and tracing the circuit lines and linking those suspected of not working well with a suitable cable. Figure 3.0 shows these conditions. Frantic efforts are still underway in calibrating to install new control circuit boards supplied by CIAE to replace the old ones for the two control console systems.

3.1 Refurbishment work on GHARR-1 Pneumatic Transfer System

Tubes installed in the Pneumatic Transfer System (PTS) for sample transfer into and out of the reactor irradiation site became weak and brittle. The old tubes which existed in operation for over 23 years were removed and new ones installed. The new tubes installed in place have the same dimensions ranging from tubes of internal diameter (mm) of 19.0, 32.0 and16.0 and thickness of 10.0, 8.0 and 4.0 mm respectively. This was done to avoid tubes busting or breaking during reactor operation. Figure 3.1 shows pictures of staff engaged in the replacement work. Safety procedures and work orders were approved before the commencement of the work. Apart from the PTS tube replacement, the Triode for Alternating Current (TRIAC) control unit for the sample transfer system was redesigned. This came as a result of not getting the exact original component (TRAC KS3-8 87.7) in the Ghanaian local market for replacement when it malfunctioned. This issue of the non-availability of the component to buy locally made it difficult to operate the PTS. So the existing circuit was studied and a new control unit has been designed, constructed and installed using an equivalent component (BTA-16) to help do away with the obsolescence of the original TRIAC. Fig. 3.2a and 3.2b show respectively original components, TRAC KS3-8 87.7 on the circuit board and the new board with BTA 16 TRIAC.

Fig. 3.0 Dry Joint, Wear & Tear conditions of Control and Instrumentation Circuit Board

Fig. 3.1 Installation of new irradiation tubes connecting the PTS to the reactor Core.

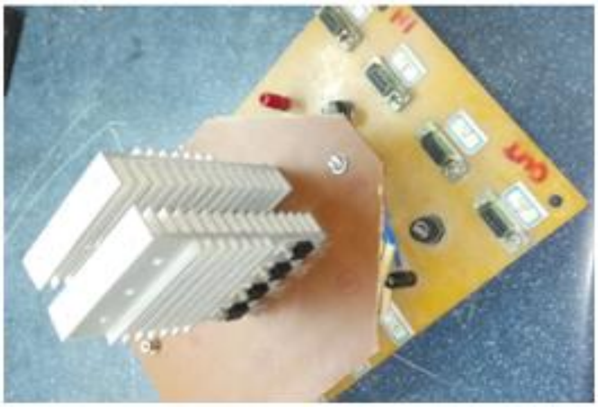

Fig 3.2a The Original TRIAC control unit

Fig. 3.2b the new board with BTA 16 TRIAC

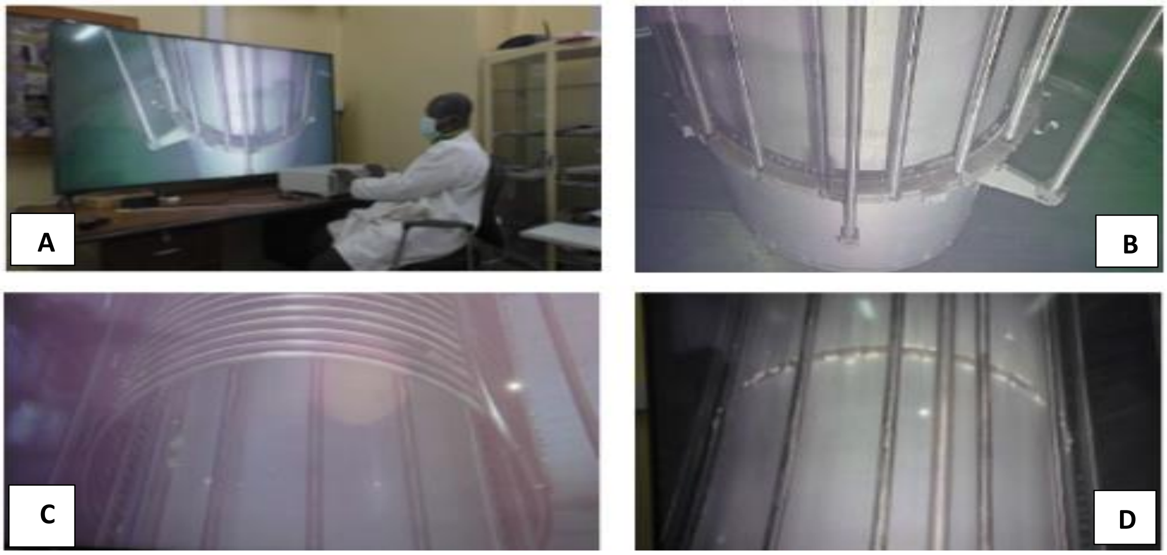

Fig. 3.2 Inspection of SSCs of the GHARR-1 reactor vessel, pool lining and associated structure

3.2 Monitoring of GHARR-1Vessel, Structural Support and Reactor Pool Liner

In order to detect any commencement of deterioration or deformation on the reactor vessel structure, pool liner and associated structures inside the reactor pool, a physical inspection of the above-mentioned elements has been given a new approach in assessing their physical status in the ageing management activities. In this new approach, underwater cameras connected to large-screen LED TV is now being used to view the structures for any hidden developing deformation. Previous work of such inspection after the GHARR-1 core convention is shown in Figure 3.2. The inspection process displayed various sectional views of the reactor structure and the associated components. In Fig. 3.2A is Staff in front of the camera control unit and the television monitor set-up projecting the views of the structures of reactor vessel, pool lining and the related components. Fig. 3,2B is the Reactor vessel and it supporting structures (tie rods) and bottom of reactor pool bottom liner, Fig 3.2C is the reactor vessel and cooling coil arrangement and Fig. 3.2D is the mid-way section of the reactor vessel, showing conspicuously a whitish substance at one of the horizontal welding joints. The monitoring of the outer reactor vessel, pool liner and the associated supporting structures generally show and give a clear state of the structural integrity. As shown in Fig 3.2, the reactor outer vessel, the supporting structures and liner are maintained. However, the formation of the whitish substance will have to be understudied.

4.0 CONCLUSION

The GHARR-1 Facility has been in operation for over 28 years. Throughout this period and now, the following aspect of ageing management activities have been applied, periodic testing of the scram operability and maximum temperature limit detection, control rod rise time and coolant water quality. Integrated Circuit (IC) and power supply components are tested to ensure that they work within the recommended ranges. These activities are in line with appropriate application of maintenance and testing activities based on operational limits and conditions, design requirements provided by manufacturers' recommendations, and following approved operating procedures as provided for in (IAEA SSG-10). Over the years, the operation and maintenance group has developed the competence in dealing with complex ageing management issues.

The refurbishment work carried out on the pneumatic transfer system such as the replacement of the tubes and traic control unit has given strength to the system for efficient operation. Additionally, a new added activity in the GHARR-1ageing management is the use of underwater camera to regularly monitor the reactor vessel and pool liner and the supporting structures for early detection of structural defect. This has come to complement activity of periodic reactor vessel and pool water analysis for clad failure detection.

5.0 ACKNOWLEDGEMENT

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