RERTR 2014 – 35TH INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

OCTOBER 12-16, 2014
IAEA VIENNA INTERNATIONAL CENTER
VIENNA, AUSTRIA

# Status Report of Activities for the Core Conversion of Nigeria MNSR to LEU

S.A. Jonah
Centre for Energy Research and Training,
Ahmadu Bello University, P.M.B. 1014 Zaria, Nigeria
Jonahsa2001@yahoo.com

**ABSTRACT**

This report contains a summary of results of design and safety analyses performed under the aegis of the IAEA CRP entitled "Conversion of MNSR to LEU" 2006 – 2012 for the conversion of NIRR-1. The objective of the CRP was to identify an LEU core with similar operational capabilities as the original HEU core and with acceptable safety margins under both normal and accident conditions. In order to provide comparisons between the proposed LEU core and the initial HEU core, thorough analyses were performed for both cores. Results obtained indicate that the conversion of the NIRR-1 to LEU fuel does not present any new potential accidents nor does the conversion increase the consequences of any of the postulated design basis accidents identified in the current approved SAR. At present, activities leading to the eventual conversion have slowed down. The challenges responsible for the lull in activities currently being encountered and the way forward are presented

## 1. INTRODUCTION

The Nigeria Miniature Neutron Source Reactors (MNSR) code named the Nigeria Research reactor-1 (NIRR-1) is a low power, tank-in-pool research reactor currently fueled with about 1 kg of HEU. NIRR-1 is currently in its first fuel cycle and was designed mainly for neutron activation analysis and production of some short-lived radioisotopes [1]. Over the years, studies under the aegis of the IAEA CRP and RERTR programme have been performed to convert MNSRs in general and NIRR-1 in particular to LEU [2]. As the name suggests, the MNSR is a compact low-power research reactor designed mainly for training and research. The prototype MNSR was built by the China Institute of Atomic Energy (CIAE), Beijing, China and was critical in 1984. Subsequently, the commercial versions of the reactor have been installed in China, Ghana, Iran, Nigeria, Pakistan and Syria. The nominal power of MNSR is approximately 30 kW and they have common operational, utilization and spent fuel management issues. The cores are fueled with HEU (>90% enrichment) consisting of a total $^{235}U$ loading of approximately 1 kilogram. In 2005, the IAEA in collaboration with RERTR program organized a Technical Meeting of owner organizations of MNSR and SLOWPOKE reactors to discuss issues related to conversion to low enriched uranium (LEU) as part of the global efforts at minimizing the civil use of HEU. Thereafter, the Coordinated Research Project (CRP) entitled “Conversion of MNSRs to LEU” was initiated in 2006. A major objective of the CRP was to perform feasibility studies to identify a single fuel for the conversion to LEU. Results of the feasibility studies carried out by the CRP participants have been presented in the past RERTR meetings [3]. In this paper, the status of activities for the conversion of Nigeria MNSR and the perspective for conversion will be discussed. Specifically, the accomplishments of CERT under the aegis of the RERTR program and the IAEA CRP with regards to HEU minimization are highlighted. At present, activities leading to the eventual conversion have slowed down. The challenges responsible for the lull in activities currently being encountered and the way forward are presented

## 2. STATUS OF ACTIVITIES PERFORMED UNDER NIRR-1 CONVERSION PROGRAMME

In order to perform enrichment search, the Monte Carlo N-Particle transport code (MCNP) was used for neutronics analysis of the current HEU core. On this basis an accurate model of the HEU core was established. The established model was used to search for LEU fuels for the conversion of NIRR-1 from HEU to LEU. Furthermore, a computational method was developed to assess the impact of conversion to LEU on utilization. In order to address the single point failure posed by the use of a single control rod in both commercial and prototype MNSR, the inclusion of two additional control rods in the design of MNSR facilities was performed using the established MNCP HEU model of NIRR-1. A summary of results are presented below. However, a detailed version of the results has been published in [4, 5, 6, & 7].

Some of the results are presented as follows

(i) Comparisons of the main characteristics of the HEU and LEU cores are given in Table 1.

(ii) Results of neutronics data obtained for the HEU core and the proposed LEU core are provided in Table 2 for the flux performance. Furthermore, the reactivity worth of top Be shims for the HEU core (measured and calculated) are compared with calculated data for the LEU core in Fig. 1. Data indicate that the power of commercial MNSR would have to be increased to 34 $kW_{th}$ so as to maintain the same neutron flux of $1 \times 10^{12}$ $n/cm^2.s$ in the inner irradiation channel.

(iii) In order to further assess the performance of the proposed LEU fuel with respect to NAA, a computational method has been developed for the calculation of neutron spectrum parameters in the irradiation channels. The MCNP code was used to calculate the neutron spectral distributions in a 640-group energy structure from $10^{-10}$ to 20 MeV. The calculated data in combination with the neutron capture cross section data of some dosimetry reactions extracted from the ENDF-VII data library were used to determine the Cd-ratios, which were then used to deduce the $f$ and $\alpha$ parameters in the inner and outer channels of the current HEU core as well as the proposed LEU core. The simulated energy-dependent neutron flux distributions obtained by MNCP in an inner and outer irradiation channel of NIRR-1 HEU core are displayed in Fig. 2. A summary of results obtained depicted in Table 3 indicate slightly "hardened" neutron spectra distributions in the inner and outer irradiation channels of the proposed LEU core with no significant impact on utilization.

(iv) With regards to the one point failure criteria of MNSR, two additional safety control rods (ASCRs) were included in the design using MNCP. Results displayed in Table 4 indicate that it would be possible to introduce additional safety control rods to enhance the safety of the MNSR with little or no modification to the existing core configuration.

Table 1. A comparison of the main specifications of the HEU core and proposed LEU core of NIRR-1

| | HEU | LEU |
|---|---|---|
| Type | Tank-in-pool | Tank-in-pool |
| Nominal core power ($kW_{th}$) | 31 | 34 |
| Coolant/Moderator | De-ionised light water | De-ionised light water |
| Loading of U-235 in core (g) | 1006.65 | 1357.86 |
| Reflector | Metallic beryllium | Metallic beryllium |
| Excess reactivity - cold, clean (mk) | 3.77 | 3.89 |
| Neutron flux at inner irradiation sites | 1 x $10^{12}$ $cm^{-2}s^{-1}$, stability ± 1%, horizontal and vertical variation < 3% | 1 .04 x $10^{12}$ $cm^{-2}s^{-1}$, stability ± 1%, horizontal and vertical variation < 3% |
| Daily operation fluence in inner irradiation sites | < 9 x $10^{15}$ $cm^{-2}$ | < 9 x $10^{15}$ $cm^{-2}$ |
| Fuel life in core (fluence) | > 3.24 x $10^{19}$ $cm^{-2}$ | > 3.24 x $10^{19}$ $cm^{-2}$ |
| Number of irradiation sites | 10 sites (5 inner and 5 outer) | 10 sites (5 inner and 5 outer) |
| Control rod | 1, stainless steel clad, cadmium absorber | 1, stainless steel clad, cadmium absorber |
| Reactor operation modes | Manual and automatic | Manual and automatic |
| Temperature in irradiation sites | Inner site < 54 $^oC$; outer sites < 40 $^oC$ (at pool temperature of 20 $^oC$). | Inner site < 54 $^oC$; outer sites < 40 $^oC$ (at pool temperature of 25 $^oC$). |
| Core reactivity temperature coefficient | -0.1 mk/$^oC$; for core temperature 15-40 $^oC$ | -0.1 mk/$^oC$; for core temperature 15-40 $^oC$ |
| Average radiation dose in reactor hall (μSv/h) | < 1 | < 1 |

Table 2 Comparison of Neutron Flux Data at Inner Irradiation Channels, Outer Irradiation Channels, Fission Chambers, and Slant Tube in NIRR-1

| Neutron Energy / Flux | Thermal (0 – 0.625) eV (n/cm$^2$-s) x $10^{12}$ | | Epithermal (0.625 eV – 0.825 MeV) (n/cm$^2$-s) x $10^{12}$ | | Fast (0.825 – 20) MeV (n/cm$^2$-s) x $10^{12}$ | |
|---|---|---|---|---|---|---|
| Location | Inner IC | Outer IC | Inner IC | Outer IC | Inner IC | Outer IC |
| HEU-90.2% | 1.16 ± 0.01 | 0.66 ± 0.01 | 1.29 ± 0.01 | 0.19 ± 0.01 | 0.27 ± 0.01 | 0.04 ± 0.03 |
| LEU-12.5% | 1.04 ± 0.01 | 0.62 ± 0.01 | 1.26 ± 0.01 | 0.18 ± 0.01 | 0.26 ± 0.01 | 0.04 ± 0.03 |
| | | | | | | |
| Location | Fission Chamber | Slant Tube | Fission Chamber | Slant Tube | Fission Chamber | Slant Tube |
| HEU-90.2% | 1.19 ± 0.01 | 0.026 ± 0.02 | 1.33 ± 0.01 | 0.004 ± 0.05 | 0.26 ± 0.01 | 0.002 ± 0.04 |
| LEU-12.5% | 1.06 ± 0.01 | 0.024 ± 0.02 | 1.28 ± 0.01 | 0.003 ± 0.05 | 0.25 ± 0.01 | 0.002 ± 0.04 |

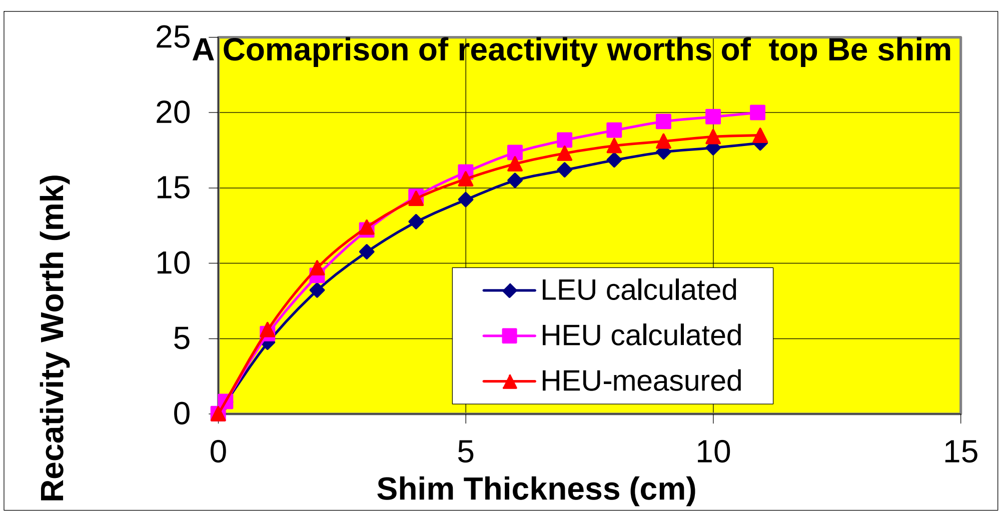


Fig. 1 Reactivity worths of top Be shims for HEU and LEU cores

Table 3 Comparison of neutron spectrum parameters of NIRR-1 HEU and LEU cores

| | α | | *f* | |
|---|---|---|---|---|
| Core | Inner | Outer | Inner | Outer |
| HEU (Experiment) | -0.052±0.002 | 0.029±0.005 | 19.2±0.5 | 48.3±3.3 |
| HEU (calculated) | -0.056±0.004 | 0.021±0.005 | 17.2±1.1 | 46.7±2.9 |
| LEU (calculated) | -0.047±0.006 | 0.028±0.006 | 14.7±0.7 | 43.7±2.8 |

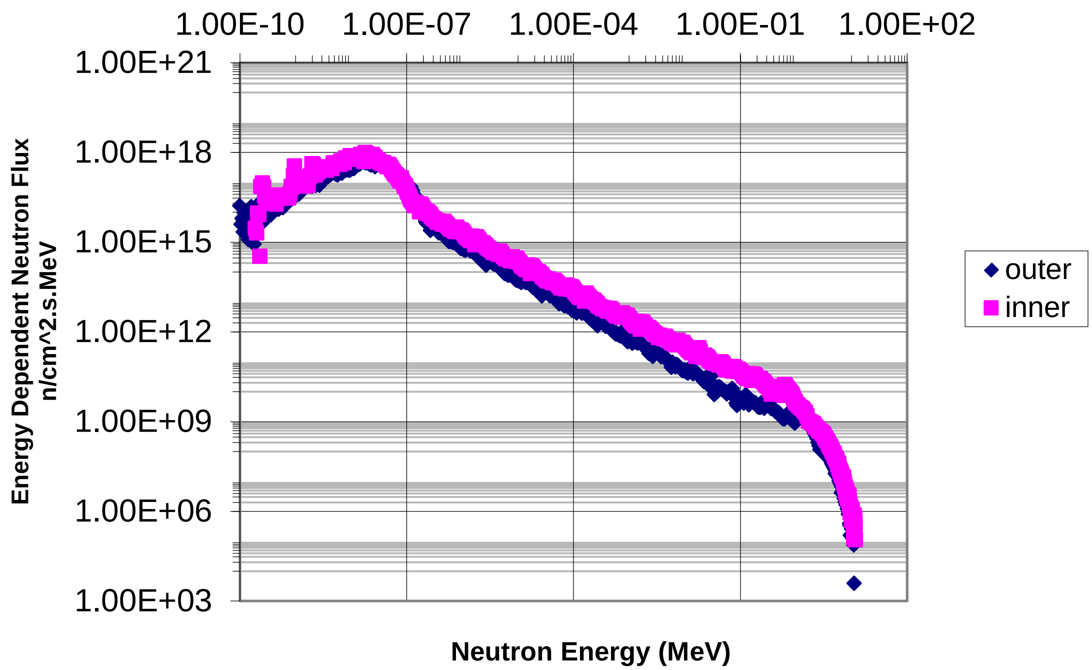


Fig 2. Comparison of MCNP simulated energy dependent neutron flux distributions in the 640 energy groups in inner and outer irradiation channels of NIRR-1

Table 4 Modified and Un-Modified neutronics data for NIRR-1HEU core

<table>
<tr><th>Parameter</th><th colspan="3">Modified core</th><th>Un-Modified core</th></tr>
<tr><td>Rods-out ($k_{eff}$)</td><td colspan="3">1.00474±0.00021</td><td>1.00476 ±0.00021</td></tr>
<tr><td>Main Rod-In ($k_{eff}$)</td><td colspan="3">0.99712±0.00021</td><td>0.99712±0.00021</td></tr>
<tr><td>A-In $k_{eff}$</td><td colspan="3">1.00164±0.00021</td><td>No data</td></tr>
<tr><td>B-In $k_{eff}$</td><td colspan="3">1.00170±0.00021</td><td>No data</td></tr>
<tr><td>A and B-In ($k_{eff}$)</td><td colspan="3">0.99856±0.00021</td><td>No data</td></tr>
<tr><td>Core excess reactivity $\rho_{ex}$ (mk)</td><td colspan="3">4.72±0.05</td><td>4.74±0.05</td></tr>
<tr><td rowspan="2">Worth of each rod (mk)</td><td>Main</td><td>A</td><td>B</td><td rowspan="2">7.61</td></tr>
<tr><td>7.62</td><td>3.12</td><td>3.04</td></tr>
<tr><td>Worth for ASCRs (mk)</td><td></td><td colspan="2">6.16</td><td>No data</td></tr>
<tr><td>Shutdown margin (mk)</td><td colspan="3" rowspan="2">2.90<br>1.44</td><td rowspan="2">2.87</td></tr>
<tr><td>Main CR<br>A and B</td></tr>
<tr><td>$B_{eff}$ x $10^{-3}$</td><td colspan="3">8.37±0.09</td><td>8.37±0.09</td></tr>
<tr><td>$\Phi_{th}$(n/cm$^2$s) x $10^{12}$inner</td><td colspan="3">1.16±0.01</td><td>1.16±0.01</td></tr>
<tr><td>$\Phi_{th}$(n/cm$^2$s) x $10^{12}$ outer</td><td colspan="3">0.66±0.01</td><td>0.66±0.01</td></tr>
</table>

Under the thermal hydraulics investigations, the PLTEMP/ANL 4.1 code was modified and was used to calculate some steady state parameters of HEU and LEU cores of NIRR-1. Data obtained for the HEU core compare well with measured data and those from the manufacturer. For the transient analyses of the two cores, the PARET/ANL code version 7.3 was used to simulate reactivity insertion transients including the insertion of 3.77 mk reactivity being the maximum credible as demonstrated during the on-site commissioning of NIRR-1. Detailed results have been presented in Refs. [8], [9] and [10]

## 3. CERT PARTICIPATION AND CHALLENGES

The Nigeria MNSR codenamed Nigeria Research Reactor-1 (NIRR-1) is the 8$^{th}$ commercial MNSR and one out of the five outside China. It went critical in 2004 and like all MNSRs has HEU fuel (>90%). The operating organization is the Centre for Energy Research and Training (CERT), which is a government funded, university based research institute. CERT and by extension, Nigeria has demonstrated its support for the global effort at elimination of the civil use of HEU by actively participating in all CRP related meetings and the annual RERTR meetings since 2005. The Centre has established collaboration with the RERTR Program, MNSR laboratories in China and Ghana through the IAEA Technical Cooperation Program. Furthermore, the Government has also demonstrated support for the conversion through pronouncements made by the President of Nigeria at the NSS Meetings in South Korea in 2012 and more recently at the Hague, Netherlands in 2014.

At present, activities leading to the eventual conversion have slowed down. The challenges responsible for the lull in activities currently are internal to CERT and are being addressed. The way forward is that our partners should exercise patience because the solutions adopted will yield positive dividends in a short while.

## 4. SUMMARY AND CONCLUSION

Nigeria is signatory to the Non-Proliferation Treaty (NPT) and as part of the non-proliferation program, there is a global effort to convert MNSR to LEU. This report contains results of activities performed for the conversion of NIRR-1 from the use of HEU fuel to LEU fuel. The changes required for the conversion are to replace the current HEU fuel pins with LEU fuel enriched to 12.5% in U-235, increase the diameter of the cadmium absorber central control rod and increase the operating power level from 31 $kW_{th}$ (kW thermal) to 34 $kW_{th}$ . The reactor control systems, auxiliary systems and facility support systems currently in operation will not be modified and are described in the current approved Final Safety Analysis Report (FSAR) for the NIRR-1. Therefore, the conversion of the NIRR-1 to LEU fuel does not present any new potential accidents nor does the conversion increase the consequences of any of the postulated design basis accidents identified in the current approved SAR. It is expected that activities leading to the conversion, which include the request for a PSA and approval by the Regulatory Agency in Nigeria (NNRA) will be invigorated as soon as possible

## 5. ACKNOWLEGEMENTS

This work has been supported through financial assistance form the IAEA Coordinated research Project, CRPNo:NIR/13934. The US Department of Energy, DOE through the ANL/RERTR Program has continued to provide financial and technical support since 2005 through training opportunities to staff of CERT and the Regulatory Agency in Nigeria.

## 6. REFERENCES


[1] NIRR-1 Final Safety Analysis Report (SAR) 2005.

[2] IAEA TECDOC 2014, NIRR-1 Final Report on CRP for the Conversion of MNSR, in press

[3] www.rertr.anl.gov/meetings RERTR Meetings 2006 to 2010;

[4] Jonah S. A., Liaw J. R., Matos J. E., Monte Carlo Simulation of Core Physics Parameters of Nigerian Research Reactor-1. Annals of Nuclear Energy 34 (2007) 953-957.

[5] Jonah S. A., Ibikunle K, Li Y. A Feasibility Study of LEU Enrichment Uranium fuels for MNSR conversion using MCNP, Annals of Nuclear Energy, 36 (2009) 1285-1286.

[6] Jonah S.A., Ibrahim Y.V., Ajuji A.S., Onimisi M.Y. The impact of HEU to LEU conversion of commercial MNSR: Determination of neutron spectrum parameters in irradiation channels of NIRR-1 using MCNP code. Annals of Nuclear Energy, 39 (2012) 15-17.

[7] Ibrahim Y.V., Odoi H.C., Njinga R.L., Adeleye M.O., Jonah S.A. Monte Carlo Simulation of additional safety control rod for commercial MNSR to enhance safety. Annals of Nuclear Energy 44, (2012), 71 – 75

[8] Jonah S.A. Ibrahim Y.V. Kalimulah M., Matos J.E., 2012: ENC Transactions 2012; Steady state thermal hydraulic operational parameters and safety margins of NIRR-1 with LEU fuel using PLTEMP-ANL CODE: http://www.euronuclear.org/events/enc/enc2012/transactions/ENC2012-transactions-research-reactors.pdf

[9] A. Olson, S. A. Jonah, "MNSR Transient Analysis and Thermal-Hydraulic Safety Margins for HEU and LEU Cores Using PARET, "Proceedings of the XXIX International Meeting on Reduced Enrichment for Research and Test Reactors, Prague, Czech Republic, September, 23-27,2007.

[10] Jonah S.A. Measured and simulated reactivity insertion transients charcteristics of NIRR-1. Annals of Nuclear Energy, 38 (2011), 295-297.