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THE JAMAICAN SLOWPOKE UTILIZATION AND CORE CONVERSION PLANS

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ABSTRACT

ICENS is an institution with a formidable range of applications that have impacted on local and regional issues using a combination of science, technology and local expertise. The main thrusts thus far have been geochemical mapping, environmental monitoring and the sustainable development of agricultural and mining sectors. More recently however, our attentions have turned to the impact of the environment and farming practices on food security and health. At the centre of these investigations is the SLOWPOKE-2 Research Reactor which has been successfully utilized for Neutron Activation Analysis for the past 26 years.

As a result of the limitation on the current HEU core lifetime and the desire to comply with the spirit of the global threat reduction initiative and RERTR program, ICENS will convert the core from HEU to LEU. This paper reports on the utilization of the SLOWPOKE-2 reactor and the progress/issues encountered/foreseen for the conversion process.

1. Introduction

Impacts of population growth and improved living standards place extreme demands on the biosphere through agricultural expansion, and industrial development frequently leading to local and even global environmental concerns. These issues are of even greater concern in developing countries where development is often placed before environmental issues. The capacity to determine the fate of elements in the environment provides the opportunity to directly track and quantify the impact of certain anthropogenic practices, these findings can then in turn be used to inform policy makers and influence future legislation. It was the potential of this kind of research aimed at sustainable socio-economic development that garnered initial support of SLOWPOKE locally and today it is the realization of such research that has influenced the decision for the continued operation of SLOWPOKE. Although Instrumental Neutron Activation Analysis (INAA) is now a mature technique it still remains at the centre of our analytical capabilities. INAA has the particular advantages that the method is largely matrix independent, and that little sample preparation is generally necessary compared to other methods of analysis. Our laboratory has taken advantage of the ability of SLOWPOKE to measure a wide range of elements in very different matrices to determine the distribution and fate of both essential and potentially toxic elements in the biosphere. After 26 years of operation the results produced by SLOWOKE are still relevant as the research has begun to focus on the critical areas of food security and health. With the current core configuration the SLOWPOKE in Jamaica has another 16 years of conventional operation at which time a large beryllium annulus can be added extending the core life-time by an additional 15 years. With the expansion of the research into health related matters and the renewed interest in nuclear energy, we foresee SLOWPOKE being fully utilized for at least the remainder of its present scheduled life time. However, in keeping with the spirit the global threat reduction initiative and Reduced Enrichment for Research and Test Reactors (RERTR) program, the core of the SLOWPOKE will be converted from HEU to LEU. This paper reports on the utilization of the SLOWPOKE to programs that helped to bolster support for the continued operation of reactor through their relevance to local developmental issues. A summary of the planned core conversion process and the likely problems to be encountered are also presented.

2. Small reactor utilization

The definition of a “small reactor” is not precise but is generally taken as having thermal powers less than 250 kW [1]. The IAEA Research Reactor Database [2] lists 60 small research reactors operating worldwide. These include TRIGA (~30%), SLOWPOKE/MNSR (~25%), Tank and Pool type (~20%), and ARGONAUT (~8%), these low power reactors produce irradiated samples that are not highly radioactive so that fewer handling restrictions are required, and administrative procedures may be less stringent. The main disadvantage of low power reactors is the reduced activation of long-lived isotopes. The average flux density for the sixty research reactors that fall into the “small reactor” category is 2.7×10^{12} $ncm^{-2}s$-1 with a median of 1×10^{12} $ncm^{-2}s^{-1}$, similar to that of SLOWPOKE. Only TRIGA reactors have significantly higher average neutron flux densities than SLOWPOKE.

2.1 SLOWPOKE

The design and operating conditions of SLOWPOKE eliminate the need for the conventional complex instrumentation and electromechanical emergency shutdown systems. This high degree of intrinsic safety is achieved by a large negative temperature coefficient and by severe limitations on both the excess reactivity (maximum 0.04%) and the operating conditions. The power level is controlled by a single cadmium control rod via a feed back to a neutron detector located within the beryllium annulus. The neutron flux is measured by a Reuter-Stokes self-powered cadmium flux detector with a nominal sensitivity of 1×10^{-20} amps per unit flux.

The reactor core illustrated in Figure 1, consists of an assembly of 296 fuel pins containing a total of 817 g of 93% enriched ^{235}U as co-extruded alloy containing 28% by weight of U in Al in a cylindrical fuel cage of size 23 cm by 25 cm. A 100 mm thick pure beryllium annulus encases the fuel cage, and acts as a side reflector for neutrons and a 50 mm thick beryllium disc forms the bottom reflector. The top reflectors, known as shims, consist of semi circular plates of beryllium each only a few millimeters thick. Since no adjustments to the core are allowed, burn-up is corrected for by the increased neutron reflection provided by adding shims as required.

There are five (5) small inner irradiation sites within the beryllium annulus, and four (4) large sites outside of the beryllium. In addition, an in-pool irradiation system [3] has been installed.

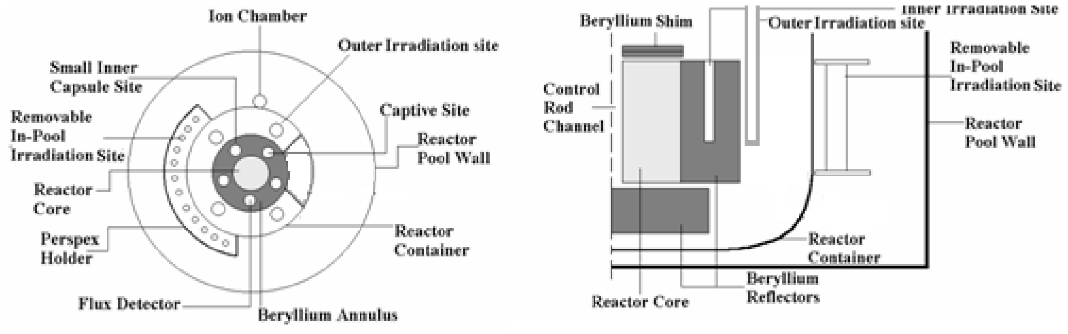


Figure 1 Schematics of the Slowpoke 2 reactor core showing in-core and in-pool irradiation sites.

The SLOWPOKE neutron Flux is uniformly distributed about the axis of the core and extends a short distance outside the reactor container The maximum operational in-core flux is a modest 1 x 10^{12} n cm-^{2} s-^{1}, the site-specific flux variation is less than ± 3%, the flux as measured in the large outer site and in-pool irradiation facility are approximately 51% and 2.6% respectively of the nominal flux. For SLOWPOKE the epithermal and fast components of the reactor neutron spectrum account for approximately 5 % and 23% respectively of the total inner site flux. The fast component of neutron spectrum of SLOWPOKE is composed of both fission neutrons and those generated by (γ,n) reaction from the Be reflector.

2.2 Neutron Activation Analysis

Unlike most reactors quantification by NAA with SLOWPOKE using the in-core irradiation sites does not require co-irradiation of flux monitors or standards. The uniformity, stability and reproducibility of the neutron spectrum within the core, and with time facilitates the use of activation constants (k) according to equation (1) in which m is the mass of a particular element in grams, R is the peak area, ti, td, tc, are the times of irradiation, decay, and counting respectively, and λ is the decay constant, i.e.

$$m = R \Big/ k \cdot e^{-\lambda t_d} \cdot (1 - e^{-\lambda t_i}) \cdot (1 - e^{-\lambda t_c})$$

Equation 1 Improved Relative Activation Equation

Where

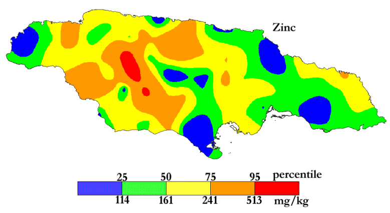
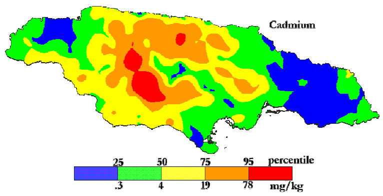
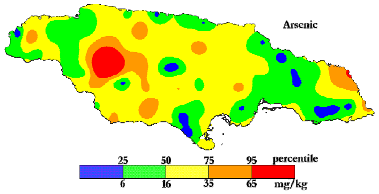
$$k = \varepsilon \cdot \theta \cdot N_A \cdot \sigma \cdot \varphi \Big/ A_w$$

with ε = detector efficiency; θ = abundance of the activated nuclide; NA = Avogadro's number = 6.023x1023; σ = effective isotopic activation cross-section; φ = neutron flux in ncm-2s-1; Aw = atomic weight of the irradiated element. Details on the methodology adopted for the Jamaican SLOWPOKE can be found elsewhere [4, 5].

3. Results

3.1 Geochemical Mapping

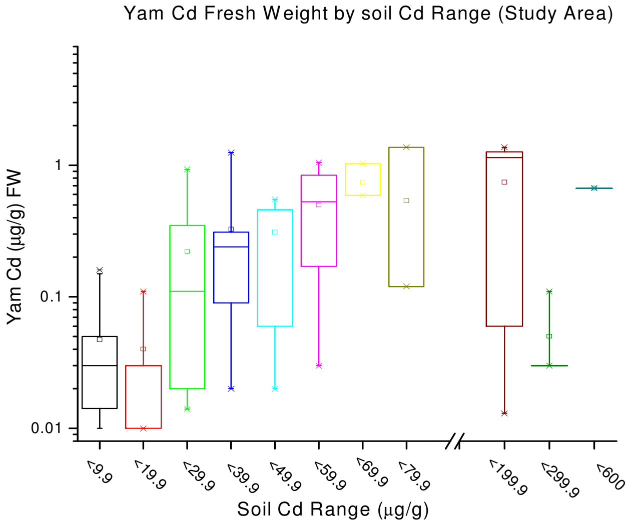
During an island wide soil survey it was found that some Jamaican soils, especially the bauxitic soils that overlie White Limestone geological group, are much enriched in several heavy metals compared with world levels [6].

Figure 2a. Zinc distribution	**Figure 2b. Cadmium distribution**	**Figure 2c. Arsenic distribution**
		

The soil cadmium levels in particular are up to a thousand times higher than the world averages. These high levels in soils have encouraged efforts to establish relationships between plant animal and human health.

3.2 Food Security

The exact locations of over 600 paired soil and food samples were recorded by use of global positioning systems (GPS). This allowed precise plotting of maps showing Cd in soils and foods stratified by soil Cd concentrations. There were significant soil/plant Cd correlations (R^2 >0.5). These data confirm the significant uptake of Cd by some foods and show that low-Cd products can be produced by judicious land use selection; a technically simple solution to meeting food standards. [7]



and soil

3.3 Animal studies

Paired liver and kidney samples from 100 free-range cattle in different parts of Jamaica were analyzed for the essential and non-essential trace elements. The map shows that the Cd levels found in cattle kidney closely followed that of the soil on which they reared. The intake of Cd from bovine liver and kidney was estimated to be 5.2µg/day based on an Island wide survey or 7% of the Provisional tolerable daily intake. [8]

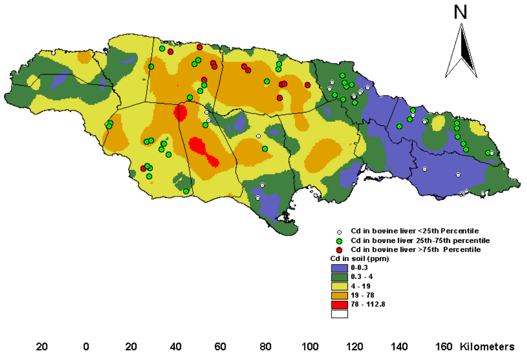


Figure 4. Cadmium in Bovine Kidney

3.4 Human studies

We evaluated the placentae of 52 Jamaican mothers with a mean age (range) 29 years (18 – 42 years) delivering singleton neonates with a mean birth weight of 3.1 kg (1.3 – 5.5 kg) at term were collected. The birth weights observed in this work are slightly less than the average birth weight found in the literature for developed countries. The distribution of birth weight follows a normal distribution with approximately 16% of the population having low birth weight , <2.500 g, with a further 4% with very low birth weight, 1.500g, more than double that of the USA at 7.6% . Birth weight is a strong predictor of an infant's chances of survival and low birth weight has also been associated with profound later life health effects, even after recovering from low weight at birth. The significant correlation (R= 0.38, P=0.007) between calcium and birth weight, correlation was also observed for Zn and birth weight (R=0.26, P=0.07), a low zinc intake has been associated with approximately a twofold increase in the risk of low birth weight [9].

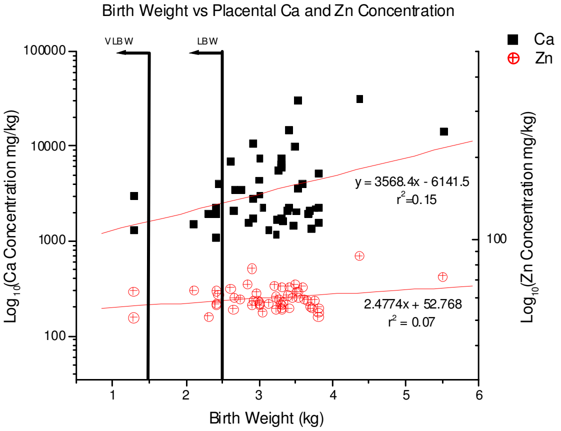


Figure 5. Ca & Zn with birth weight

3.5 Forensic Analysis

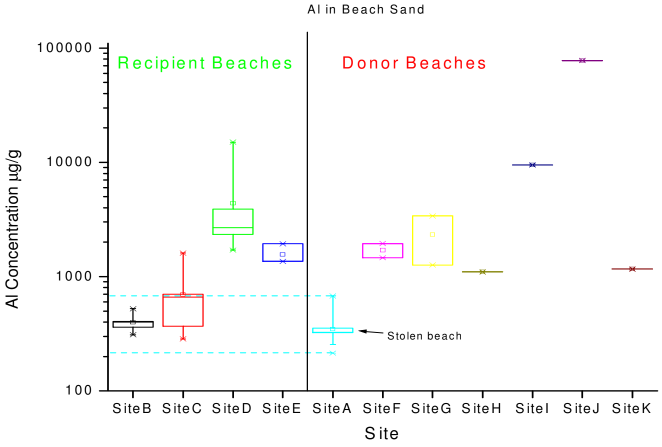


Figure 6. Al variation in beach sand

Investigation of beach sands from an actual court case in Jamaica involving the analysis of 35 elements by Neutron Activation Analysis identified 14 elements that could be possible geochemical markers or “finger prints” for various beach sands. Aluminum, Iron, Manganese and Scandium showed the most promise as “finger print elements” as the concentration of these elements seemed to be site specific. Figure 6 shows the variation of Aluminum in various beach sands; it clearly shows that sites B and C are similar to A (stolen beach) while sites D and E are quite different.

Using this methodology we were able eliminate potential recipient beaches D and E from having received sand from donor (stolen) beach A. We were also able to determine that sites I and K were not possible sources of sand for any of the potential recipient beaches in this investigation.

4. HEU Core assessment

4.1 Fuel Burn-up

As SLOWPOKE reactors are built with a lifetime core there is no need for on-site spent fuel storage.

Figure 7a. History of Shim Adjustments

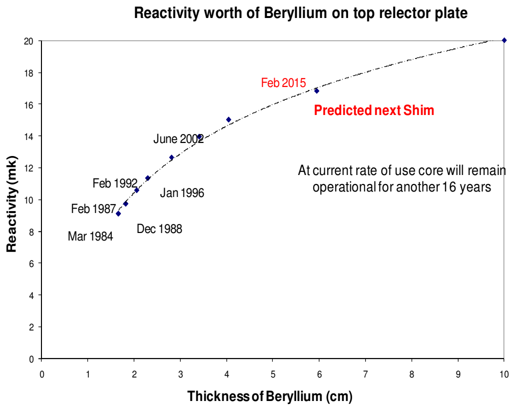
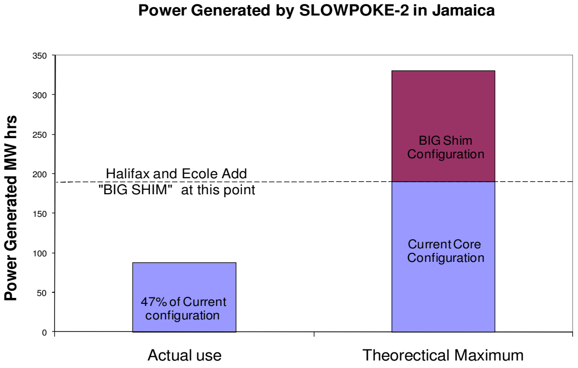


Figure 7b. Power Generated by SLOWPOKE



At current rate of usage the current core configuration will last another 16 years, at which time an additional beryllium annulus can be added giving a further 15 years.

4.2 Fission Product Activity

The fission product activity of the used fuel, which is a function of the reactor flux hours, will be estimated based on an AECL calculation. The calculation is based on a SLOWPOKE reactor which was operated for 5 years at a neutron flux of 1 x 10^{11} n.cm-^{2}s^{-1} (2kW) and then 10 hours at a neutron Flux of 1 x 10^{12} n.cm-^{2}s^{-1} (20 kW) [10]. The calculated activity 30 days after shutdown was 23 TBq. The average flux over the last 5 years (8766 hours per year) for the Jamaican SLOWPOKE is approximately 0.37 x 10^{11} n.cm-^{2}s^{-1} (0.69 kW). Based on our average flux over the last 5 years the expected activity of core 30 days after shutdown will be approximately 8 TBq. Previous experience (Montreal) has shown this calculation to be reasonably accurate (~18 TBq) [11] and that a one month cooling period is sufficient before the conversion process takes place. It is therefore our intention to shutdown 6 weeks before conversion, the reactor water and auxiliary systems will continue to be maintained as per standard operating procedures outlined in AECL document CPR-26.

4.3 LEU Fuel Composition

The previously developed LEU fuel was fabricated from zircaloy-4 clad uranium oxide pellets and contained 1100g of ^{235}U (total mass of U ~5600g) at an enrichment of 19.9%. The core itself was 22cm in diameter and 22.7 cm in height. At criticality there were a total of 198 fuel pins in the fuel cage, each pin was 5.26 mm in diameter and 234 mm in length. At present, AECL are in the process of defining the requirements to re-qualify the fuel production process. A side by side comparison shows that the fuel pins are physically very similar, Table 1.

Table 1 Comparison of the HEU-fuelled and the LEU-fuelled reactor cores

Parameter	**HEU-fuelled**	**LEU-fuelled**
core diameter	220 mm	220 mm
core height	228 mm	234 mm
number of fuel pins	296	198
Fuel pin diameter, with	5.23 mm	5.26 mm
Fuel length	225 mm	234 mm
cladding	Aluminum	Zircaloy-4
Fuel	U-Al 28% alloy	UO2
total mass of uranium	0.9 kg	5.6 kg
enrichment U-235	93%	19.89%
total mass of U-235	0.82 kg	1.12 kg
volume of water in core	7.8 L	8.1 L

This similarity simplifies the core conversion as the beryllium annulus and other auxiliary systems can be reused.

The large negative temperature coefficients of both the HEU and LEU cores ensure that power excursions are self-limiting, however the characteristics of the temperature coefficients differ greatly, Figure 8.

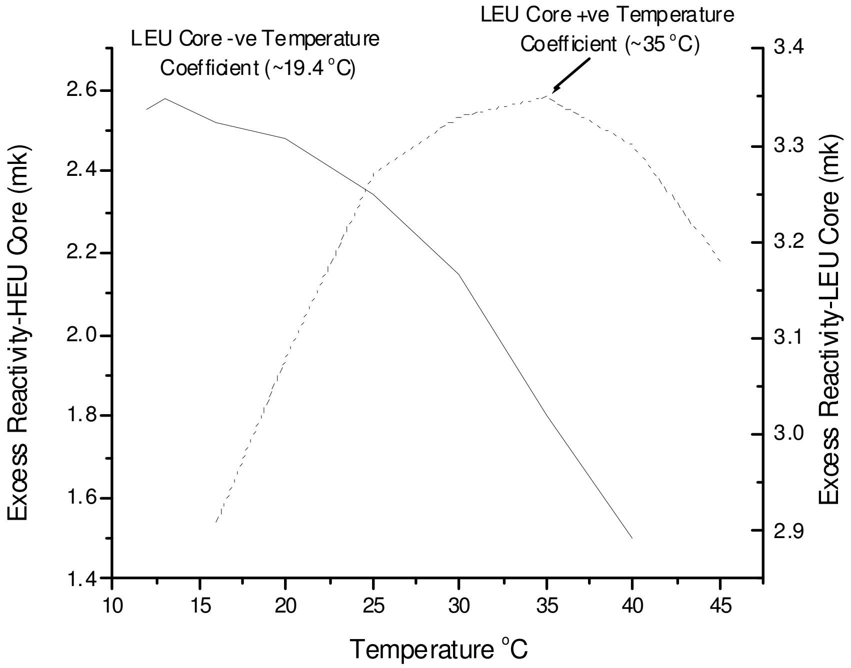


Figure 8. Temperature Coefficients for HEU & LEU Cores

The difference in the temperature coefficient has resulted in improved performance of the LEU SLOWPOKE core, notably in the reactor runtime; this is particularly true for the Jamaican situation where higher ambient temperatures further reduced our operating time of the HEU core, Table 2.

Table 2 Performance Comparison of HEU & LEU **Cores**

Parameters	**HEU**	**LEU**
Maximum operating power	20 kW	20 kW
Maximum operating time at 3 mk	6 hrs	12 hrs
Maximum operating time at 4 mk	16 hrs (13 hrs*)	24 hrs
Operating range between shim additions	2.5 – 4.0 mk	1.5 – 4.0 mk
Core Life-Time	20 Years	40 Years

* Operating time in Jamaica

4.4 Radiation Protection

The International Centre for Environmental and Nuclear Sciences provides radiation monitoring services and is responsible for monitoring all radiation workers in Jamaica, Barbados and the Turks and Caicos Islands, as such; we are well equipped to provide all radiation monitoring services during the conversion process. Additional consultation will be provided from the Government Health Physics Department.

4.5 Core Replacement

In all likelihood the core will be removed in accordance with procedures developed at Montreal. The moving of the F 257 transportation flask will be contracted to a local haulage company with experience in moving heavy equipment. A detailed account can be found elsewhere [12]

4.6 Regulatory Approval

At present licenses for the use of, importation and exportation of radioactive materials are granted through Ministry of Health Pharmaceutical Division; however it has now been proposed that a Radiation Safety Authority be established within the Bureau of Standards Jamaica, which falls under the Ministry of Industry, Investment & Commerce. The radiation safety authority will regulate the importation, storage, usage, transportation and disposal of radiation sources. Legislation will also be enacted to provide the requisite legal and institutional framework, detailing the organization’s remit, oversight and authority structures with regard to radiation issues. It is under this regulatory body that we propose to set up the external nuclear oversight committee independent of ICENS. The committee will have all necessary authority to conduct the review, approval and provide regulatory oversight related to reactor safety.

5. Conclusion

After 26 years of operation the SLOWPOKE-2 reactor in Jamaica is well utilized producing results that are relevant to socio-economic development and academia. With the renewed interest in nuclear energy and the ongoing work of ICENS we envisage that the reactor will continue to be well utilized for some time to come. The core conversion, with funding provided by the DOE, will preferably be contracted to AECL as they have previous experience in the fabrication of the fuel and conversion process for SLOWPOKE, the LEU will likely be provided by the Y12 facility. It is envisaged that the process from shutdown to commissioning can be completed in a six week window. Presently we see no major legal or physical obstacles that could hinder the conversion process. A firm timetable for the conversion cannot be established until the LEU fuel fabrication process has been re-qualified

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