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EXPERIMENTAL AND COMPUTATIONAL DETERMINATION OF RADIATION DOSE RATES IN THE SLOWPOKE-2 RESEARCH REACTOR AT THE ROYAL MILITARY COLLEGE OF CANADA

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Introduction

The first SLOWPOKE-2 research reactor designed to use Low Enriched Uranium (LEU) dioxide fuel was commissioned at the Royal Military College of Canada/Collège militaire royal du Canada in September 1985. The enrichment is 19.89% in ^{235}U. The reactor is a pool-type design, moderated and cooled by light water with the core located at the bottom of a 5.87 m pool, ensuring a 4.42 m layer of water above the core to provide the necessary radiation shielding. Cooling is by means of natural convection, the reactor power being limited to 20 kW_{th}. The design allows free access to the reactor pool: in addition to the pneumatic irradiation system permitting the positioning of small samples within the beryllium reflector and close to the core, larger samples can be positioned in the pool against the reactor vessel using an "elevator"-type positioning device. Several research projects have taken and are taking advantage of this equipment, most notably investigations of intense radiation effects on advanced polymers such as epoxies and poly-ether-ether-ketones (PEEKs), (Ref. 1).

These research activities however require sound knowledge of the dose rates at the various irradiation sites within the reactor vessel, as well as at incremental positions within the pool. Accurate measurements of the particle fluxes were attempted before (Refs. 2,3), but unfortunately yielded limited information due to the complexity of the composite radiation field and the capabilities of the instrumentation at that time. The present work aims at yet another attempt to gather sound dose rate data, using improved radiation detectors on one hand, and better computational resources (both hardware and software) on the other hand. All research on particle dose rates was performed with the reactor at steady-state half power (10 kW_{th}) and at the reactor core mid-height.

Method and Results

The research focussed on three main classes of particles: neutrons, gammas, and charged particles. For the neutrons, the work concentrated on the computer simulation of the reactor core, including the pool, using the latest WIMS-AECL cell code (Ref. 4) coupled with the ENDF/B-V data library (Ref. 5). WIMS-AECL assumes isotropic scattering, therefore the following steady-state neutron transport code equation is assumed valid, giving $\phi(r,E)$, the neutron flux at position r and at energy E:

$$\phi(r,E) =$$
$$\iiint \frac{e^{-T(r'\to r,E)}}{4\pi|r-r'|^2}\, dV'\left[\int \sum\nolimits_s (r',E'\to E)\Phi(r',E')dE' + \frac{1}{k}\int \chi(r',E'\to E)\nu \sum\nolimits_f (r',E')\Phi(r',E')dE'\right]$$

where

$T(r'\to r,E)$	is the neutron path length between r′ and r in units of optical thickness for neutrons of energy E,
$\Sigma_s(r',E'\to E)$	is the neutron yield cross section for incident energy E′ and outgoing neutron energy E for all events besides fission (includes scattering and accounts for (n,2n) neutron emission),
$\Phi(r',E')$	is the neutron flux at location r′ and energy E′,
k	is the fission multiplication eigenvalue,
$\chi(r',E'\to E)$	is the fission yield spectrum for incident neutron energy E′ and outgoing neutron energy E, and
$\nu\Sigma_f(r',E')$	is the neutron fission-yield cross section.

The neutron flux distributions obtained were compared with the measurements taken by Andrews (Ref. 2), since little improvement would have been obtained by repeating the neutron activation analysis (NAA)-based experimental measurements already done in the neutron flux mapping. The WIMS-AECL-generated thermal flux values compared very well with the measured sub-cadmium NAA values (within 5%, see Figure 1). For the epi-cadmium flux values, the computer simulation proved to be a much more powerful tool than the experimental method, since it allowed a 26-neutron energy group representation of the flux distribution (a significant improvement over the experimental work in which all neutrons are lumped into only two energy groups). This more detailed calculated neutron energy spectrum permitted subsequently a much improved neutron dose prediction for the various irradiation sites around the core and in the pool. The radial distribution of neutron dose rates in the pool at the reactor mid-plane at half power operation can be seen at Figure 2.

The research then concentrated on obtaining data for the gamma radiation, both experimentally and analytically. For the experimental work, CaF_2:Mn thermoluminescent dosimeters (TLDs) were chosen to measure the gamma doses at the various irradiation sites, including at 5-cm increments within the pool at the reactor mid-height. The CaF_2:Mn TLDs were chosen for this experimental procedure as a result of their high sensitivity (in comparison to LiF), high dose saturation levels, and ease of handling and analysis. The CaF_2:Mn TLDs were shielded with tin to suppress the low-energy photon over-response characteristics of this dosimeter. In addition, the TLDs were encapsulated in LiBr to limit any neutron effects on the TLD response. Due to the supra-linearity of the TLD relative response with accumulated dose, the TLDs were re-calibrated with a ^{137}Cs source of known activity following each irradiation cycle. The experimental gamma dose rate distribution across the reactor vessel and into the pool is presented at Figure 3.

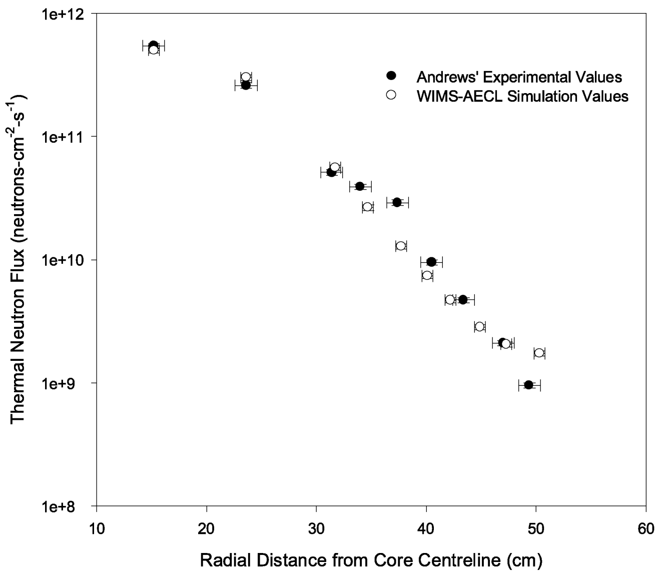

Figure 1
SLOWPOKE-2 Radial Thermal Flux Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

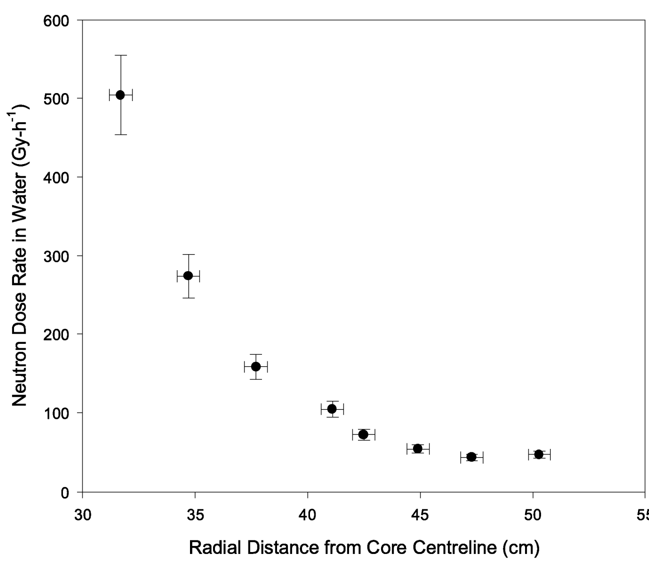

Figure 2
SLOWPOKE-2 Neutron Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

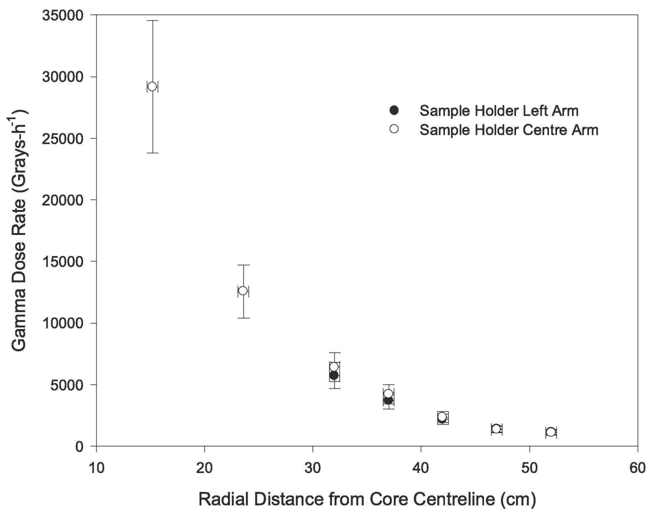

Figure 3
SLOWPOKE-2 TLD Gamma Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} $n\text{-}cm^{-2}\text{-}s^{-1}$) at Core Mid-Height

The analytical work was based on the code MICROSHIELD Version 5 (MS 5), (Ref. 6). MS 5 treated the core as a homogeneous right cylindrical volume with the beryllium reflector, light water annulus, reactor vessel container, and various thicknesses of pool water as annular shields. MS 5 could not account for such internal structures as the central control rod, irradiation sites, and bottom beryllium slab. Gamma source term contributions had to be considered due not only to prompt and delayed fission gammas but, importantly, (n,γ) capture reactions, activation gamma sources, and inelastic scattering gamma sources in the core and shielding materials. Sample calculations revealed that gamma contributions due to inelastic scattering and activation in the shielding materials were negligible and therefore were not included in the MS 5 model. All secondary gamma sources (capture, inelastic scattering, and activation) in the core and shielding materials accounted for 15% - 20% of the total gamma production rate. As expected, the prompt fission and short-lived delayed fission product gamma contributions were the most important for the purposes of this model. In this part of the research, several limitations of this code had to be compensated for by the authors who wrote their own computer codes to account for effects such as the backscattering of gamma photons within the materials located beyond the dose point. The following backscattered gamma current density J_s equation was solved numerically using a FORTRAN program:

$$J_s = \frac{\mu_{sc}}{2\pi} \int_{r=0}^{7HVL} \int_{\phi=0}^{\pi} \int_{\theta=0}^{\pi} \phi \sin\theta \cos\theta d\theta d\phi e^{-\mu_{attn} r} dr$$

where μ_{sc} is the linear Compton scattering coefficient for a given material,
μ_{attn} is the linear attenuation coefficient for the backscattered photons for a given

material, and

ϕ is the incident photon flux at a position relative to the dose point.

It was found that relative photon backscatter contributions varied from 6.4% of the incident photon flux, at the inner irradiation sites, to 15.8% of the incident flux, at a position in the pool 52 cm from the core centre-line. A comparative plot of experimental TLD versus analytical MS 5 gamma dose rate distributions across the SLOWPOKE-2 reactor vessel and into the pool can be seen at Figure 4. The MS 5 gamma dose rates include the dose contribution due to photon backscatter. As can be seen, a significant discrepancy exists between experimental and analytical gamma dose rate distributions.

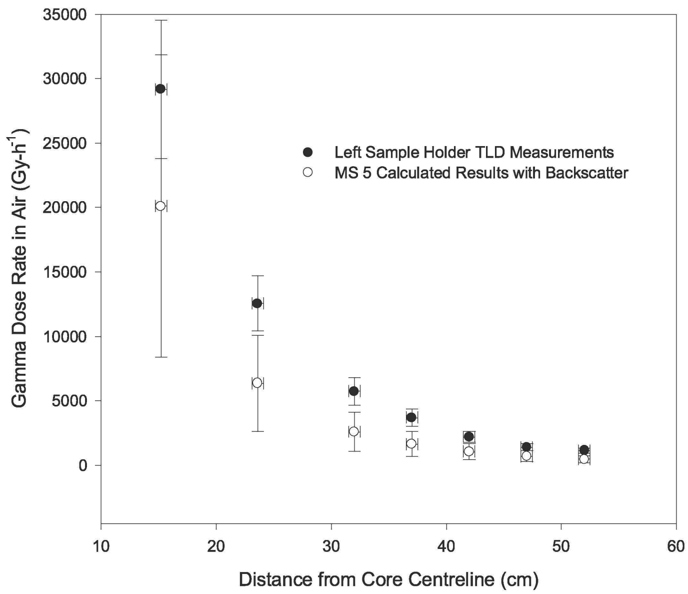

Figure 4
SLOWPOKE-2 TLD vs MS 5 Gamma Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

The research then focussed on charged particle dose rate contributions. In particular, recoil proton effects and proton-stripped electron contributions were examined. Electrons ejected due to photoelectric, Compton, and pair production effects were not considered as MS 5 dose rates already accounted for these dose contributions. Computational models were written based on fundamental physical principles, and calculated dose rate mappings around the core of the SLOWPOKE-2 were obtained for the contributions of these charged particles. Volume integral calculations were solved numerically using a FORTRAN code for protons ejected due to neutron interactions within a sphere of radius R_p (equal to the maximum range of the proton in the target material). Similarly, electron dose contributions were determined using a FORTRAN code which accounted for electrons stripped within a sphere of radius R_e (equal to the maximum range of the electron within the target material).

Unlike the recoil protons, the attenuation of electrons within the sphere had to be accounted for. The equation describing the proton-stripped electron current density volume integral is as follows:

$$J_s = \sum_{energies} \frac{I}{2\pi} \int_{r=0}^{R} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \phi_p \sin\theta \cos\theta d\theta d\phi e^{-\mu r} dr$$

where I is the average number of ion pairs created in a target material by an average energy proton,

ϕ_p is the average proton flux within the volume of interest, and

μ is the linear attenuation coefficient for an average energy stripped electron in a given material.

Recoil proton and stripped electron dose rate distributions around the SLOWPOKE-2 reactor vessel can be seen at Figures 5 and 6 respectively.

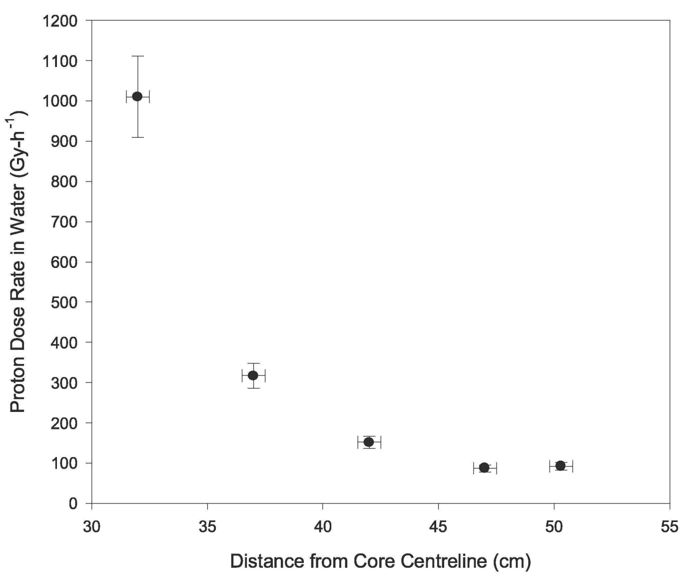

Figure 5
SLOWPOKE-2 Proton Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

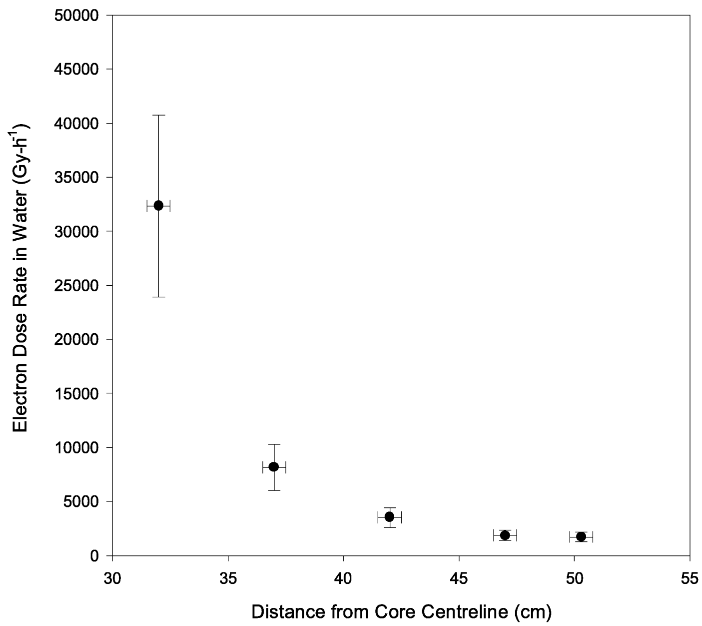

Figure 6
SLOWPOKE-2 Electron Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

The final task of this work was to sum the dose rate contributions from each of the particles of interest (neutrons, gammas, recoil protons, and stripped electrons) to obtain a total dose rate mapping around the SLOWPOKE-2 reactor core. MS 5 analytical gamma dose rate values were used in the calculation of total dose rates. The total dose rate distribution in water around the SLOWPOKE-2 reactor vessel can be seen at Table I and Figures 7 and 8.

Discussion and Conclusions

This work resulted in detailed neutron, gamma, and charged particle dose rate mappings around the core of the SLOWPOKE-2 at RMC and is reported in full detail at Ref. 7. The thermal neutron dose rate distribution is considered accurate given the strong correlation between WIMS-AECL and experimental NAA thermal neutron flux values. Given this strong correlation, the total neutron dose rate distribution is also assumed accurate. The results for the electromagnetic radiation show a significant discrepancy between experimentally-determined and calculated dose rates, the TLDs always over-predicting the rates (see Figure 4). It is believed that the TLD dose response is affected by the presence of radiations other than gammas (such as neutrons, energetic beta particles, and x-rays), and additional work is needed to sort out the various effects individually. In addition, the inherent over-response characteristics of CaF_2:Mn TLDs to low-energy photons no doubt affected the TLD dose response. The analytical approach to gamma dose rate determination using MS 5 could not possibly account for all secondary gamma effects. It is believed that the "true" gamma dose rate distribution lies somewhere between these two curves. The charged particle dose rate distributions represent a reasonably accurate estimation of their contributions. In general, the data

TABLE I
Total Dose Rates Around the SLOWPOKE-2
Steady-State Half Power Operation (10 kW_{th}) at Reactor Core Mid-Height

Distance from the Core Centre-line (cm)	Total Dose Rate ($Gy\text{-}h^{-1}$) ($\pm$28% to $\pm$40%)
15.2 (inner irradiation site)	3.7×10^4*
23.6 (outer irradiation site)	1.2×10^4*
32.0	3.7×10^4†
37.0	1.0×10^4†
42.0	4.9×10^3†
47.0	2.7×10^3†
50.3	2.4×10^3†

Note: * Dose in air
† Dose in water

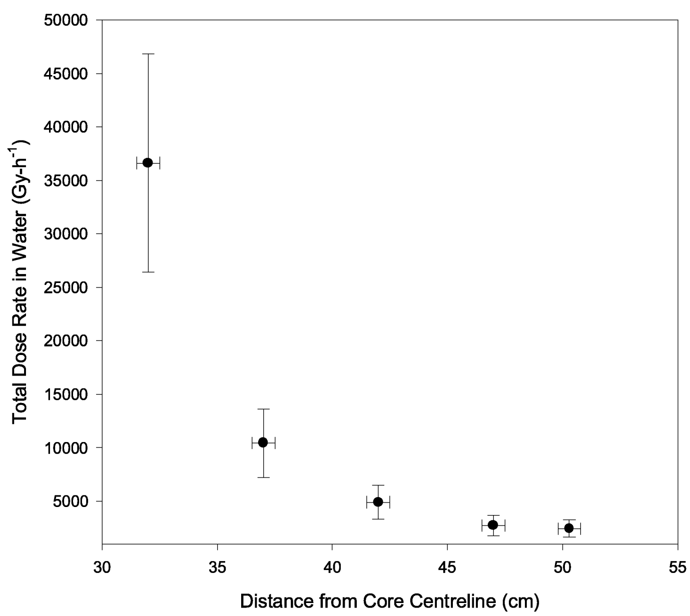

Figure 7
SLOWPOKE-2 Total Dose Rate Distribution
Steady-State Half Power Operation (10 kW_{th}, ϕ_{th}=5 x 10^{11} $n\text{-}cm^{-2}\text{-}s^{-1}$) at Core Mid-Height

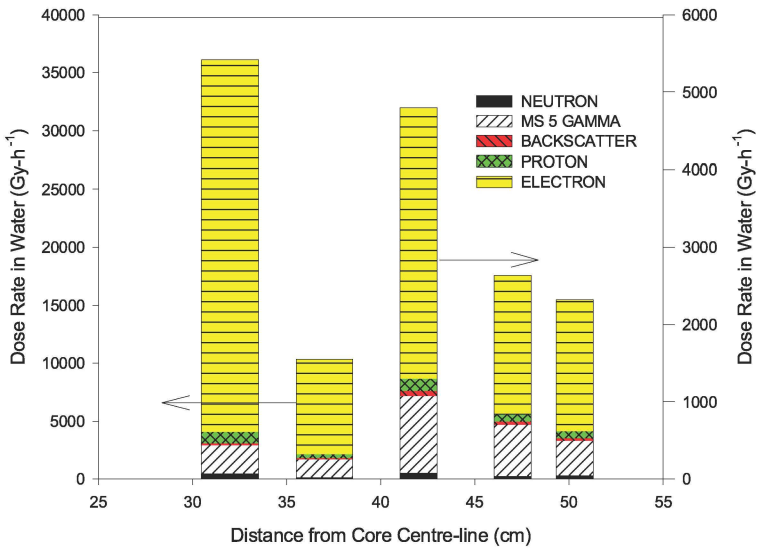

Figure 8
SLOWPOKE-2 Particle Dose Rate Distribution
Steady-State Half Power Operation (10 kW$_{th}$, ϕ_{th}=5 x 10^{11} n-cm^{-2}-s^{-1}) at Core Mid-Height

obtained from the present research represents a significant improvement in the quality and the quantity of the knowledge on the dose rates in the SLOWPOKE-2 reactor vessel and pool. Continuation of this research could involve gamma detectors with higher total dose capabilities permitting longer residence times in the reactor and pool, in order to reduce the relative errors due to the positioning and retrieval of TLD's.

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