LEU-FUELLED SLOWPOKE-2 RESEARCH REACTORS: OPERATIONAL EXPERIENCE AND UTILISATION

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Atomic Energy of Canada Limited designed the SLOWPOKE-2 research reactor [1] based on experience with the SLOWPOKE-1 prototype, which operated for four years at the University of Toronto. Between 1976 and 1984, seven SLOWPOKE-2 reactors with HEU fuel were commissioned in six Canadian cities and in Kingston, Jamaica. They use 93% enriched uranium in the form of 28% uranium-aluminum alloy with aluminum cladding. The core is an assembly of about 300 fuel pins, only 22 cm diameter and 23 cm high, surrounded by a fixed beryllium annulus and a bottom beryllium slab. Criticality is maintained by adding beryllium plates in a tray on top of the core. A schematic drawing of the core with irradiation sites is shown in Figure I.

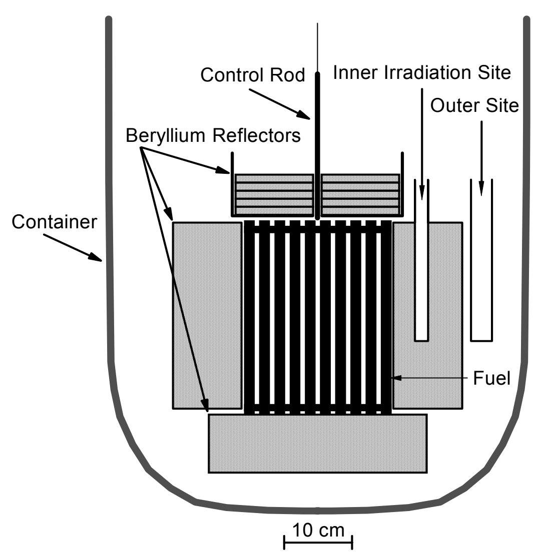

Figure I The SLOWPOKE-2 reactor core

Maximum thermal power is 20 kW and heat is removed by natural convection of the light water moderator. The maximum neutron flux in an inner irradiation site is 1×10^{12} $cm^{-2}s^{-1}$. Excess reactivity is limited to 4 mk. Every two or three years a beryllium shim-plate is added to compensate the loss of reactivity due to U-235 burnup and the production of long-lived poisons.

The reactors are used mainly for neutron activation analysis but also for the production of radioactive tracers and teaching. One reactor is equipped with a neutron beam tube for neutron radiography.

The SLOWPOKE-2 reactor is totally inherently safe due to its very limited excess reactivity and large negative temperature coefficient of reactivity. As a result, an attendant operator is not required and the reactor is licensed for remotely attended operation up to 24 hours. In practice, all licensed operators are primarily researchers as analytical chemists, physicists, professors, etc.

In 1985 the first LEU-fuelled SLOWPOKE-2 reactor was commissioned at the Royal Military College of Canada (RMC) in Kingston, Ontario. The newer LEU fuel is constructed in the same manner as CANDU fuel, Zircaloy-clad, but with 20% enrichment instead of natural uranium oxide [2]. The pool, reactor water container, light water moderator, beryllium reflector, cadmium control rod and irradiation sites are the same as for the HEU-fuelled reactors. The details of the two types of SLOWPOKE-2 reactor cores are given in Table 1.

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

	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 cladding	5.23 mm	5.26 mm
fuel length	225 mm	234 mm
Cladding	Aluminium	Zircaloy-4
Fuel	U-Al 28% alloy	UO_2
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

The reactor at Ecole Polytechnique, Montreal was installed in 1976 and operated with HEU fuel for 21 years. In 1997 the tray of beryllium shim-plates was full and there was no remaining excess reactivity. The exhausted fuel was removed and replaced with LEU fuel in the same beryllium reflector, making it essentially identical to the reactor at RMC.

Operational Experience

The lifetime of a SLOWPOKE reactor core depends on the amount of use and on the amount of reactivity that can be added with beryllium shims. A complete 10 cm thick stack of shims is worth about 20 mk. However, when the HEU cores were installed, at least 1 cm of beryllium was placed in the tray to reach criticality, and this beryllium, being closest to the fuel, had the greatest worth. There was less than 15 mk remaining to compensate U-235 burnup and poisons. With an average operating power of 1.3 kW (11 MWh/year, typical for the more heavily used reactors), this reactivity is used up in about 20 years. At two of the reactors, in Toronto and Halifax, this lifetime was extended by adding more beryllium as a second annulus above the annular reflector. With the LEU cores and increased experience, it is now possible to reach criticality by adding fuel alone, with no beryllium in the shim tray. Thus, there remains a full 20 mk to compensate reactivity losses. This increases the life of the core by more than a factor of 20/15 because the reactivity losses are highest in the first few years until the main poison, Sm-149, reaches its saturation level. The lifetime of the two reactors with LEU fuel is thus expected to be about 40 years.

A very important feature of the SLOWPOKE-2 reactor is its inherent safety due to its limited excess reactivity and large negative temperature coefficient of reactivity. With both the HEU and the LEU cores, power excursions were carried out during commissioning up to the maximum credible reactivity insertion of 4.3 mk. For both types of cores, the power reached about 80 kW after about 2 minutes before levelling off. At lower powers (lower temperatures), the negative feedback with temperature increase is greater with the HEU core and, for reactivity insertions less than 4.3 mk, lower powers are reached with the HEU core. Both cores are highly undermoderated but the HEU core even more so because there is less water in the volume of the core (Table 1). At 80 kW some boiling may take place with both cores, causing rapid negative feedback, and the LEU core has additional negative feedback due to the U-238. Considering all the reactivity feedback effects, the HEU and LEU cores are roughly equivalent from a safety standpoint, since neither can reach temperatures which could cause damage to the fuel after any credible reactivity insertion.

During normal operation the reactor water temperature varies between 20^0C and 60^0C. With the HEU core, the reactor has maximum reactivity at 19^0C and thus reactivity always decreases as temperature increases from room temperature to operating temperature. During early operation of the LEU-fuelled reactor at RMC with low starting temperatures, an increase in reactivity with temperature, as deduced from the control rod movement, was noticed. Subsequent measurements [3] showed that the maximum occurred at 33^0C. The original reactor simulations were not sufficiently accurate to predict this difference between the two reactors, but a more recent thermodynamic model [4] has reproduced the observed variations. This reduced reactivity loss with increasing temperature allows the LEU-fuelled reactor to operate for a longer time at full power. With a starting temperature of 20^0C and excess reactivity 4.0 mk, the HEU reactor will run for 16 h at 20 kW and the LEU reactor for 24 h. The LEU reactor can run continuously for 5 days at 10 kW. The differences in maximum operating time are even more noticeable for lower starting excess reactivities, which are the normal situation between shim additions. With the HEU core, when the excess reactivity for a cold reactor decreases to about 2.5 mk, a shim plate must be added to maintain a reasonable operating margin. With the LEU core, this is typically done at about 1.5 mk. This longer time between shim additions results in significant savings in operating costs.

Another advantage of the LEU fuel is the virtual absence of fission products in the reactor water. When the HEU-fuelled reactors were new, releases from the fuel to the water were low but they increased as the fuel aged. Releases were highest for the noble gases: the Xe-133 concentration in the reactor water reached a maximum of 6 MBq/L at the Montreal reactor in 1996. At the RMC LEU-fuelled reactor the Xe-133 concentration in the reactor water is 5 orders of magnitude lower and is attributed to trace uranium contamination on the surface of the fuel cladding. A visual inspection of the Montreal reactor core in 1991 revealed swelling in the aluminum cladding near the ends of some of the fuel pins around the outside of the core. The fuel pins in the higher power central region of the core could not be viewed. Microfissures in these swellings may contribute to the releases. It has also been theorized [5] that the releases are caused by increasingly exposed uranium in the end-cap welds at the ends of the fuel pins. However, in none of the HEU-fuelled reactors has the release of fission products increased to the point where it becomes a radiation safety problem.

After the Montreal reactor was converted to LEU fuel, the Xe-133 concentration in the reactor water decreased by three orders of magnitude but still remained two orders of magnitude higher than the level at the other LEU-fuelled reactor at RMC. The residual fission products in the water in Montreal are attributed to about 1 mg of U-235, which was released from the original HEU core and plated out on the beryllium reflector and other reactor container surfaces.

With a thermal neutron flux in an inner irradiation site of 1×10^{12} $cm^{-2}s^{-1}$ at an operating power of 20 kW, the SLOWPOKE reactor has an excellent flux/power ratio. While no accurate measurements have been performed of the absolute power of a SLOWPOKE-2 reactor, relative measurements carried out in Montreal allow a comparison of the HEU and LEU cores. In 1996, with the HEU core and a neutron flux of 1×10^{12} $cm^{-2}s^{-1}$, the temperature difference between the water flowing out of the core and the water entering the core was $22^0C \pm 1^0C$. In 1998, with the new LEU core and the same neutron flux, the temperature difference was $24^0C \pm 1^0C$, which implies a higher reactor power. The 9% higher temperature difference produces an approximately 9% higher convection flow rate. The power with the LEU fuel is thus approximately 18% higher than the power with HEU fuel for the same thermal neutron flux in the irradiation sites. However, diffusion calculations [6] have predicted an LEU/HEU power ratio of 1.06. Considering the uncertainties in the temperature measurements and in the diffusion calculations, we now estimate the LEU reactor to have about 10% higher power. This is attributed to the absorption of neutrons by U-238. This absorption by U-238 also results in different thermal/fast ratios in the irradiation sites. In the inner irradiation sites the thermal/fast ratio was measured to be 4.4 with the HEU core and 4.0 with the LEU core [7]. Fast neutrons are generally considered a nuisance in neutron activation analysis, the main use of the reactor, because they cause interfering reactions. These nuclear interferences are 10% higher with the LEU core.

The safety studies for the licensing of these two reactors followed the requirements of the Atomic Energy Control Board (AECB) now the Canadian Nuclear Safety Commission (CNSC).

The conversion of the Montreal reactor to LEU fuel required a new Safety Analysis Report and a license modification.

These reactors are used mainly for neutron activation analysis (NAA), in research and as a commercial service, but also for teaching, training, irradiation studies, neutron radiography (at RMC) and the production of radioactive tracers. Over the years, the SLOWPOKE reactor has proven to be particularly suitable for NAA. The neutron flux of 10^{12} $cm^{-2}s^{-1}$ is sufficient for almost all NAA work, especially when using large samples (up to 10 g in 7 ml vials) and counting them close to the detector. The main advantages are the reliability and ease of use of the reactor and the reproducibility of the neutron flux. Since the fuel is not modified at all for at least 20 years, the neutron spectrum in the irradiation sites does not change and the neutron flux is reproducible to about 1%. This allows convenient NAA without the need to continually repeat the standardization measurements for all elements [7].

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