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An investigation towards real time dose rate monitoring, and fuel rod detection in a First Generation Magnox Storage Pond (FGMSP)

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HIGHLIGHTS

- Sludge (CMS) composition and radiological makeup within Sellafield legacy storage pond are detailed.
- Instrumentation to detect spent fuel within CMS and provide real time dose rate monitoring.
- RadLine® is a sub-aquatic gamma detector consisting of a scintillator and long range fibre optic cable.
- MCNP study finds the dose rate threshold at which a fuel rod is detected and instrumentation range.

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ABSTRACT

The First Generation Magnox Storage Pond (FGMSP) is located on the Sellafield Nuclear Site, housing legacy spent Magnox nuclear fuel. Some of which has since corroded, forming a layer of Corroded Magnox Sludge (CMS) creating one of the largest decommissioning challenges the UK has faced. In this work the composition, physical properties and potentially high hazard nature of CMS are discussed, as are the gamma emission spectra of spent Magnox fuel rods typical of the ilk stored. We assess the potential use of a RadLine gamma detector to dose rate map this area and provide fuel rod detection. RadLine consists of a small scintillator, fibre optic cable and photon counter. The probe has the unusual advantage of not being electrically active and therefore fully submersible underwater, with the option to deploy hundreds of metres in length. Our experimental method encompasses general purpose Monte Carlo radiation transport code, MCNP, where we describe the modelling of CMS and pond liquor in comprehensive detail, including their radiological spectrum, chemical composition data, and physical properties. This investigation concludes that the maximum energy deposited within the scintillator crystal due to ambient CMS corresponds to a dose rate of 5.65 Gy h^{-1}, thus above this value positive detection of a fuel rod would be anticipated. It is additionally established that the detectable region is within a 20 cm range.

1. Introduction

The name ‘Magnox’ is widely used to refer to the early gas cooled reactors and it is also the name of an alloy, mainly of magnesium with small amounts of aluminium, used in cladding natural uranium metal fuel with a non-oxidising covering. The first Magnox reactors started operation in the 1950s, by the mid-1960s there were eight MK 1 nuclear power stations operating the across UK. The Magnox alloy cladding has the advantage of a low neutron capture cross section, a primary selection criterion for natural uranium reactors; however a major disadvantage is that it reacts with water, making it susceptible to corrosion and prohibiting long term storage of spent fuel under water. After removal from a reactor, the irradiated elements are lowered into an on-site fuel storage pond. The used fuel remains in the cooling ponds for about 100 days so that the inventory of the short lived fission products is sufficiently reduced, after which it is then transported to the Sellafield Nuclear Site for mid-term storage before reprocessing, in a pond now known as the First Generation Magnox Storage Pond (FGMSP).

The FGMSP at the Sellafield Nuclear Site (Cumbria, UK) was constructed in the 1950s as an open air structure (Fig. 1) designed to receive and store irradiated fuel from Magnox reactors, and to

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Fig. 1. First Generation Magnox Storage Pond (Hastings et al., 2007).

remove the fuel rod cladding prior to the fuel being processed. After a long period of shutdown in the 1970s the fuel rods, primarily their cladding, started corroding in the pond, which gave rise to increased radiation levels and poor underwater visibility. Fuel continued to be sent to the pond until 1992. Over the years the pond has accumulated significant quantities of waste materials amongst the skips of fuel including; Corroded Magnox Sludge (CMS) the product of the corroded cladding, fuel fragments and other wind-blown debris (Sellafield Ltd., 2011). As such the UK government has pledged to spend £7 billion on decommissioning this challenging facility (Nuclear Decommissioning Authority (NDA), 2011) and the UK's Nuclear Decommissioning Authority (NDA) state that the FGMSP ‘remain one of their main priorities’. The export of fuel and skips is scheduled to begin in 2016 with bulk desludging complete by 2019 (Nuclear Decommissioning Authority (NDA), 2012).

It is expected that a system providing real time, reliable and accurate sub-aquatic dose monitoring would assist with current efforts to detect and map radiation ‘hot spots’ around a complete fuel skip or even a single fuel rod. For this investigation the National Nuclear Laboratory's RadLine gamma radiation detector is proposed. It consists of a scintillation crystal coupled to a fibre optic cable, which transmits scintillation light to a photon counting device (PMT, CCD, or SiPM (Jackson, 2013)). The number of photons detected is processed by software which measures the strength of the dose by means of an initial calibration. For this work it is assumed that there is 100% photon detection efficiency (PDE) in the photon counter. PDE can range dramatically from 90% for a CCD (Jackson et al., 2013) to 20% for a PMT (Sens-Tech, 2010). In order to quantify dose rate the PDE and losses must be taken into account, here however the dose levels are compared as a ratio against each other.

The RadLine detector has several advantages over conventional devices such as Geiger–Müller (GM) counters or Cadmium Zinc Telluride (CZT) devices when performing in aquatic environments. GM and CZT devices perform well over short ranges, whereas the RadLine is designed for intermediate and long range (≤ 1 km) radiation dose rate monitoring; the optical fibre can be up to a kilometre long without significant data transmission losses, and is sheathed in aluminium to provide radiation resistance (above 1000 Sv h^{-1} (Stanley, 2012)) and Kevlar for damage resistance during deployment. Secondly the RadLine's probe (scintillation crystal and housing) do not require power or any electrical input to function, unlike GM and CZT devices which require an electrical cable to be submerged in the water. The small dimensions of the RadLine, both the probe and the rest of the set-up, are compact in comparison to opposing systems (Jackson et al., 2013). The probe's small dimensions and simple sleek design make it advantageous for deployment at the FGMSP where sludge disturbances must be kept to a minimum. The RadLine is also safe to use in harsh environments (tested up to a working temperature of 100 °C (Stanley, 2012)) with no moving parts and inexpensive enough to be made sacrificial. The flexibility of the optical fibre lends itself for further deployment applications in small and difficult to access areas such as pipe work, liquid filed or otherwise.

In order to assess the feasibility of using the detector to dose rate monitor the FGMSP and provide spent fuel rod detection, the RadLine is modelled with spent Magnox fuel and CMS using general purpose Monte Carlo radiation transport code, MCNP, thereby allowing a thorough evaluation of its potential to perform in this hazardous environment where physical ad-hoc testing without such simulation back up is prohibited.

2. FGMSP materials

2.1. Corroded Magnox Sludge (CMS)

Due to the corrosion of Magnox fuel elements FGMSP contains large inventories of sludge which consists of tiny fuel corrosion particles, fuel rod fragments, metal fragments (from fuel skips), concrete degradation products (from the pond infrastructure), wind-blown sand, and other materials such as bird guano and animal remains.

When the pond water is stagnant the sludge settles to a grey bed layer (Fig. 2). However when the water is disturbed the sludge becomes mobile and turns the water cloudy this together with the growth of micro-organisms leading to frequent seasonal algae blooms (encouraged by CO_2 ingress) obscuring pond clarity, and hindering decommissioning operations.

The Magnox cladding alloy is mainly comprised of magnesium with small amounts of aluminium; hence the main product of cladding corrosion is magnesium hydroxide ($Mg(OH)_2$) or brucite

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \quad (1)$$

After which parts of the bare uranium fuel will inevitably become exposed. Uranium metal reacts with water to form uranium hydride (UH_3), uranium dioxide (UO_2), and diatomic hydrogen (H_2). Mechanistic studies show that hydrogen radicals ($H^\bullet$) and UH_3 serve as intermediates in the reaction of uranium metal with water to produce H_2 and UO_2. This presents two explosion hazards, firstly flammable H_2 is released into the gas

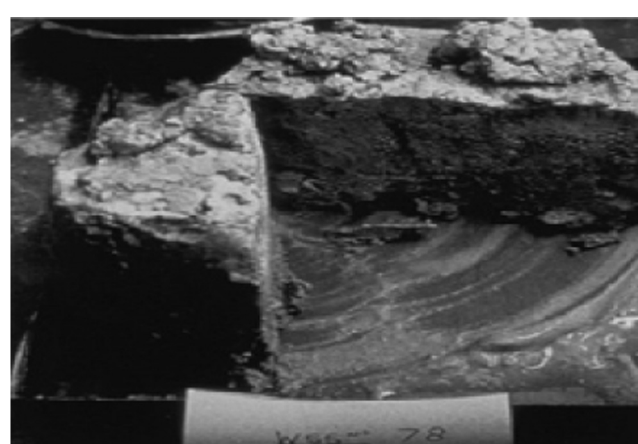

Fig. 2. A Magnox sludge sample, of mainly magnesium hydroxide (Hastings et al., 2007).