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Vacuum drying of advanced gas reactor fuel

James B. Goode, David Harbottle, Bruce C. Hanson*

School of Chemical and Process Engineering, University of Leeds, Leeds, LS2 9JT, United Kingdom

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ABSTRACT

The UK will shortly cease reprocessing spent advanced gas reactor (AGR) fuel in favour of direct disposal, however since a permanent geological disposal facility is not envisaged as being available until 2075 interim storage will be required. The initial intention is to continue wet storage but it is possible that this may not be viable for as long as is hoped. Dry storage is commonly used worldwide for the interim storage of zirconium clad spent nuclear fuel however AGR fuel is stainless steel (SS) clad and as such a new safety case will be required to ensure that fuel can be adequately and safely dried.

A rig has been designed to allow a comparison of the two main drying techniques in use; vacuum drying and flowed gas drying. This paper looks primarily at the design and development of the rig. Some of the initial data is presented to indicate how the rig was developed as a result of early results and is followed by some of the later test data to illustrate the improvements made.

1. Introduction

In 1956 the United Kingdom opened Calder Hall the worlds first commercial nuclear power plant. The Calder Hall plant utilised a graphite core as the moderator, natural uranium fuel and pressurised carbon dioxide as the coolant with the name, Magnox, being derived from Magnesium Non-Oxidising in reference to the special magnesium alloy used for the fuel cladding. The design was very similar to the first reactors built in France, the UNGG (Uranium Naturel Graphite Gaz) with the key difference being the use of a magnesium-zirconium alloy for the cladding. When the second generation of reactors were being designed the CEA and Framatome changed course with France now developing water cooled and moderated reactors which had initially been developed by GE and Westinghouse in the United States, while the British continued with gas cooled reactors developing what is known as the Advanced Gas-cooled Reactor or AGR.

Like Magnox, AGR reactors were graphite moderated and carbon dioxide cooled however the thermal efficiency of the reactor was increased from 32% to 45% by increasing the coolant temperature at the outlet (and in turn the steam temperature) from 370 °C to 650 °C (Brittain, 2012). In order to deal with the increased temperatures metallic uranium was replaced with ceramic uranium dioxide and magnesium alloy cladding was replaced with stainless steel (SS).

In order to prevent radiolytic oxidation of the graphite core by the carbon dioxide coolant corrosion inhibitors were used. In the early Magnox reactors the addition of carbon monoxide was sufficient however as the coolant pressure was increased in the later Magnox reactors it was found that hydrogen was more effective. The AGR's required yet another change and the addition of small quantities of methane was adopted alongside carbon monoxide and water (Best et al., 1985). Unfortunately the use of inhibitors leads to carbon deposits on metal surfaces such as fuel cladding leading to a reduction in heat transfer, however to prevent core damage such deleterious effects must be accepted.

A fuel element used in the AGR reactors is shown in Fig. 1a. Each element consists of thirty six pins held together by SS grids and surrounded by a graphite sleeve. A SS tie bar is threaded through the guide tube of eight elements (seven in the case of Dungeness B) to produce what is known as a stringer and these are in turn lowered into one of 308 channels in the graphite core (Best et al., 1985). Each pin is approximately 1 m in length and 15.5 mm in diameter. The pins are manufactured from 20 wt% Cr, 25 wt% Ni and 2 wt% Nb stainless steel (England et al., 1986) and are machined to form grooves on the surface to increase heat flow leaving a wall thickness of 400 μm. The fuel pellets are annular with an outside diameter of around 14.5 mm and an inner diameter 6.4 mm. The pellets are fed into the pins, which are backfilled with helium and end caps are welded in place. Following welding the pins are annealed in hydrogen at 980 °C.

Following irradiation and removal from the core the spent nuclear fuel (SNF) is initially held in cooling ponds at the reactors for a short period, typically six month (based on the safety case for fuel acceptance) before being transferred to Sellafield for reprocessing. Upon

* Corresponding author.
E-mail address: B.C.Hanson@leeds.ac.uk (B.C. Hanson).

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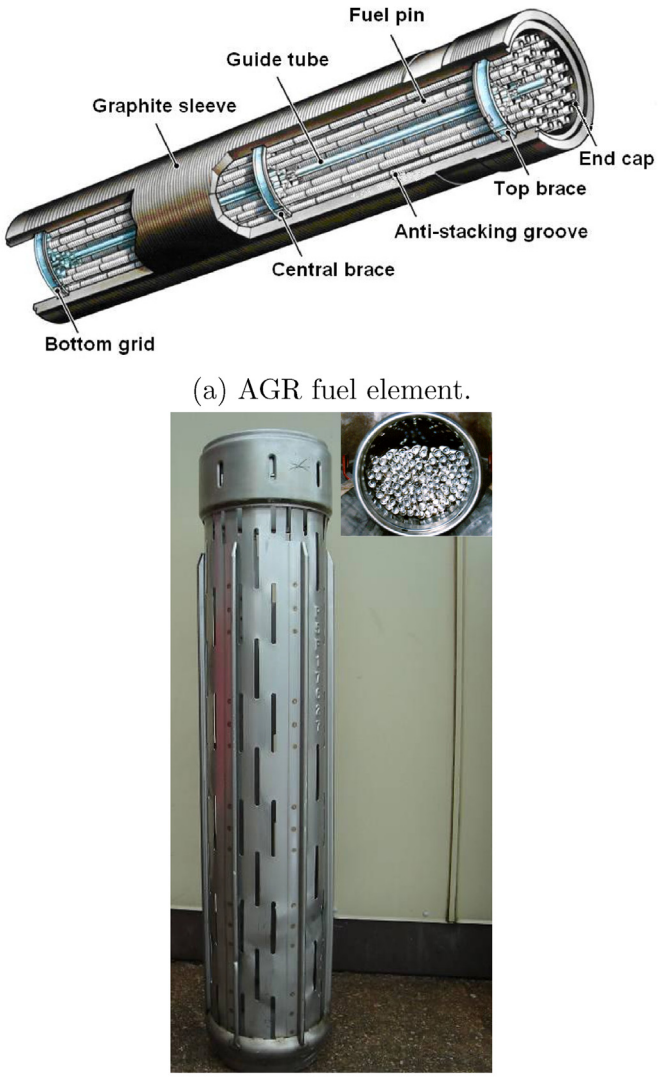

Fig. 1. An AGR fuel element and slotted can (taken from (Kyffin, 2015)).

arrival at Sellafield the graphite sleeve is removed and the individual pins are removed from the grids. The pins from three elements are placed into a slotted can and then transferred to cool before reprocessing.

The cooling ponds at Sellafield were initially filled with demineralised water, however in the early years of operation (from 1978) it was found that failures were taking place (see Fig. 2) (Hambley, 2013) leading to the release of soluble caesium and other radionuclides. An investigation into this found that such failures were due to intergranular attack (IGA) combined with stresses within the cladding leading to intergranular stress corrosion cracking (IGSCC) and that in demineralised water failures would occur within 200 days (Hambley, 2013).

IGA normally occurs due to thermal sensitisation, when chromium carbides form at grain boundaries leading to localised chromium depletion, leaving the SS more susceptible to corrosion (Intergranular Corrosion). In AGR fuel cladding the niobium is present to effectively mop up carbon by preferentially forming niobium carbides thus preventing chromium carbide formation and chromium depletion. Consequently chromium depletion in AGR fuel cladding is attributed to radiation induced segregation (RIS) (Al-Shater et al., 2017). RIS is the diffusion of an element, in this case chromium, against the concentration gradient when in the presence of radiation (Bruemmer et al., 1999; Little, 2006) and has been found to be most serious between 400 °C and 420 °C (Taylor, 1986). Temperatures in this range are experienced by the cladding of the first two elements on each stringer (at the base of the core) (Kyffin, 2014) and in testing 50% of pins from elements 1 and 2 were found to fail by IGSCC (Hambley, 2013; Kyffin, 2015).

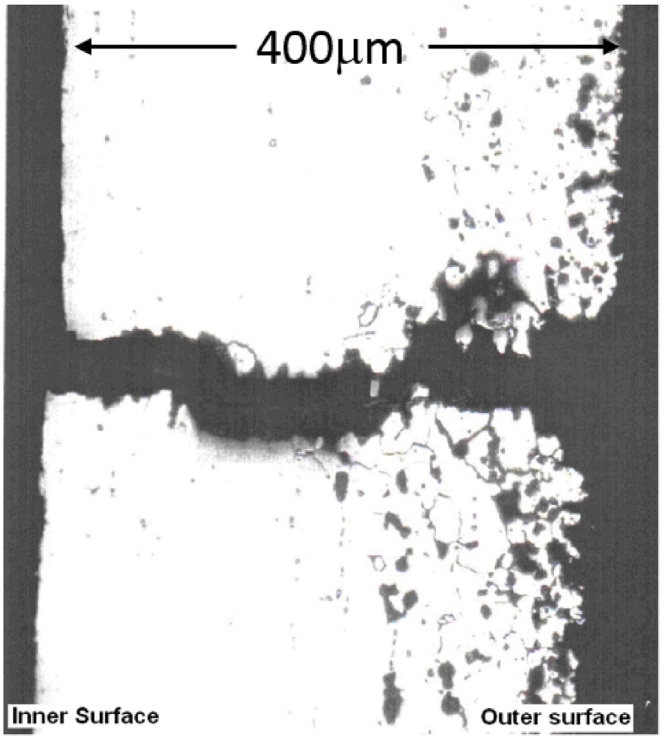

Fig. 2. Failed cladding pre caustic dosing with significant IGA on the outer surface. The crack width is approximately 50 μm (taken from (Kyffin, 2015)).

In order to address this problem a series of corrosion tests were undertaken in the early 1980's to find a corrosion inhibitor and sodium hydroxide (caustic) was identified as most suitable (Hambley, 2013). This led to the dosing of the AGR storage pond to pH 11.4 since when there have been no reported failures. Up until 1993 post storage examination (PSE) was carried out regularly and found evidence of limited IGA (Kyffin, 2014). Since then there has been only limited PSE and that has found no significant degradation beyond that found upon removal from the reactor (Kyffin, 2015).

In recent years the decision has been made by the Nuclear Decommissioning Authority (NDA) that reprocessing of AGR fuel will cease with the fuel being sent for direct disposal to a geological disposal facility (GDF). The expectation is that a GDF will not be available until 2075 (Nuclear Decommissioning Authority, 2012). Sellafield Ltd intend to continue reprocessing until 2018 with future arisings being put into interim storage. Operating experience has shown that fuel can be stored safely for 25 years if caustic conditions are maintained, however it is unknown how fuel behaves beyond this or whether the higher burnup fuels of recent and future years will be suitable for extended pond storage. Consequently Sellafield Ltd will try to extend pond storage beyond this time frame. If this is not possible a second option should be available and the next best option is dry storage.

When spent fuel is placed into storage, either wet or dry, the conditions must be controlled to prevent negative impacts on criticality, general containment of radionuclides, the ability to retrieve the fuel at the end of the storage period and final disposal options (Sindelar et al., 2010). The geometry of fuel is such that without a moderator, criticality is not possible, however in extreme cases when temperatures escalate there is a minor chance of criticality due to changes in fuel geometry due to creep. Such changes may also lead to cladding damage releasing otherwise contained radionuclides, or a change in shape that prevents