ARTICLE IN PRESS

Nuclear Engineering and Design xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

The development of a physical model of an Advanced Gas Cooled Reactor core: Outline of the feasibility study

Luiza Dihoru [a,*], Olafur Oddbjornsson [a], Panos Kloukinas [a], Matt Dietz [a], Tony Horseman [a], Elia Voyagaki [a], Adam J. Crewe [a], Colin A. Taylor [a], Alan G. Steer [b]

[a] University of Bristol, University Walk, Bristol BS8 1TR, United Kingdom
[b] EDF Energy Generation, Barnett Way, Barnwood, Gloucester GL4 3RS, United Kingdom

HIGHLIGHTS

- Validation of computer models for seismic resilience assessments of nuclear power stations.
- Feasibility study of a quarter scale model rig of an Advanced Gas Cooled Reactor core.
- Principles of scale modelling, material selection, component and instrumentation design.
- Relevant examples of dynamic response of AGR core models.

ARTICLE INFO

Article history:
Received 24 June 2016
Received in revised form 10 January 2017
Accepted 12 January 2017
Available online xxxx

Keywords:
Advanced Gas Cooled Reactor
Seismic resilience
Physical model

ABSTRACT

The ageing issues of the Advanced Gas Cooled Reactor (AGR) cores need addressing to maintain their safe and reliable operation, hence the requirement for the computer models of the cores used for the seismic resilience assessments to be conservative and to represent larger percentages of damaged graphite components. The current models have undergone limited experimental validation for high levels of degradation, so there is a need to validate those numerical models and also to enhance the understanding of core dynamics by physical modelling and testing. This paper outlines the feasibility study of a quarter scale model rig of an AGR core developed by the University of Bristol. The damage scenarios to be considered in demonstrating the core seismic tolerability were defined. The principles of scale modelling were put under scrutiny in parallel with several practical aspects of material selection and component design and manufacturing. Several variants of physical models of different size and shape were proposed and their merits with respect to their feasibility and outcomes were discussed. Aspects of instrumentation design are presented together with relevant measurement results. The rig is a viable experimental tool whose outputs can be employed directly in computer model validation.

1. Introduction

The Advanced Gas Cooled Reactors (AGR) are the second generation of British gas-cooled nuclear reactors, using graphite as the neutron moderator and carbon dioxide as the coolant. In the United Kingdom, EDF Energy Generation operates seven AGR power stations, each with two identical reactors. It is a requirement that the reactors should be safely shut down, held down and cooled down in the event of an earthquake with a probability of exceedance of 10^{-4} per annum. This seismic capability needs to be demonstrated throughout the stations' lives and to take account of the consequences of fast neutron irradiation and radiolytic oxidation for graphite component behaviour. These degradation processes, which include changes in geometry, strength and the possibility of differential shrinkage induced cracking have been well documented for a number of years and have been the subject of a number of conferences addressing the issues (Neighbour, 2007, 2013; Flewitt and Wickham, 2015). It is therefore important for such degradation processes to be captured in the numerical reactor core models used to assess seismic capability and, where practicable, in the physical array models. Important whole core modelling work has been performed in both industry and academia over the last three decades. One of the earliest physical models for seismic behaviour was a 9×9 brick array (Fig. 1), employed by the National Nuclear Corporation (NNC) in 1985 as part of the seismic endorsement of the AGR core

* Corresponding author.
E-mail address: Luiza.Dihoru@bristol.ac.uk (L. Dihoru).

http://dx.doi.org/10.1016/j.nucengdes.2017.01.012
0029-5493/

Please cite this article in press as: Dihoru, L., et al. The development of a physical model of an Advanced Gas Cooled Reactor core: Outline of the feasibility study. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.01.012

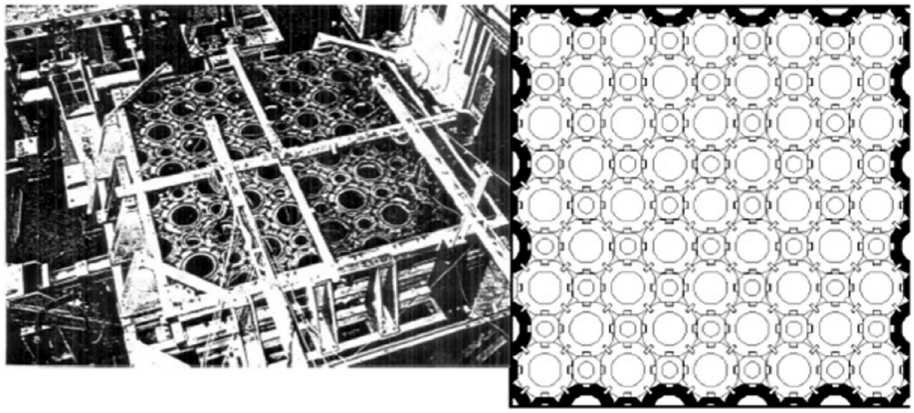

Fig. 1. The 81-brick test arrangement employed in the NNC's seismic assessments of AGR design (left: photograph of test rig, right: diagram of array: motion applied via shaded partial bricks on boundary) (courtesy: EDF Energy).

design (Rogers, 2012). The array was enclosed in a rigid frame on a simple shaking table and was subjected to synthesised seismic or swept-sinusoidal input motions on either one or both horizontal axes simultaneously. The main experimental outputs were velocity at selected locations (inferred from acceleration data) and force within the keying system (using load cells built into some of the components).

A whole core array model was first developed at 1/8th scale by AMEC, to test potential fuel channel displacements (Castro, 2005). The rig contained simplified fuel, interstitial bricks and doubly cracked bricks (scaled 1:8). However, the clearances were maintained at full scale (to facilitate displacement measurements) and that meant that the rotational and the key engagement effects were not represented in the rig. A new scale whole core rig was built at 1/4th scale to replace the 1/8th scale rig, in order to replicate all the salient features seen in the full scale core and to represent key disengagement and rotation. The 1/4th scale rig (Fig. 2) is a rigid boundary model that contains model fuel bricks, interstitial bricks and loose keys. The clearances between components are scaled. However, the rocking features were omitted from the scaled fuel brick and the model material was chosen only on dimensional stability grounds, and not on material scaling grounds (i.e. no link with the prototype material for density and stiffness). The 1/4th scale rig is a purely geometrical model used for static testing, representing well the upper limits of displacement. Fig. 2 right, shows the rig tilted at 40°, modelling the quasi-static end conditions.

The whole core modelling activities for dynamic behaviour were continued at the University of Bristol (UOB), where the largest earthquake simulator in the UK resides. In 2008, the UOB started a phased-approach of physical modelling, investigating the dynamic behaviour of two simple models: a 4×4×8 array ('the Minicore') and a single layer 20-brick-across-array ('the Single Layer Array') (Fig. 3). These two models include 1/4th scale model components (fuel and interstitial bricks, loose, spacer and filler keys) made of a rigid engineering plastic (acetal). The model components represent all the geometrical features of the prototype (i.e. rocking features of the fuel bricks, 'dovetail' shaped keyways). The brick-to-brick clearances are also scaled. The model material was chosen based on scaling laws considerations for density and stiffness and based on friction coefficient considerations. The Minicore and the Single Layer Array were useful for understanding the basic interactions in the core and contributed to component and instrument design verification for the future multi-layer rig (Dihoru et al., 2011).

The experimentation work has run in parallel with the numerical activities. For the dynamic behaviour, the most capable numerical tool is the GCORE finite element (FE) model (Kralj et al., 2005) that uses the explicit dynamic solver, LS-DYNA (© Livermore Software Technology Corporation). GCORE is a 'stick and spring' model, in which the bricks are represented by rigid bodies with assigned mass properties. The interactions between bricks (both through direct contact and via the keying system and end-face features) are modelled using parallel spring/damper pairs. These springs and dampers are assigned non-linear properties which include the 'lost motion' due to the clearances in the system. GCORE does not model the keys explicitly, but evaluates key-keyway

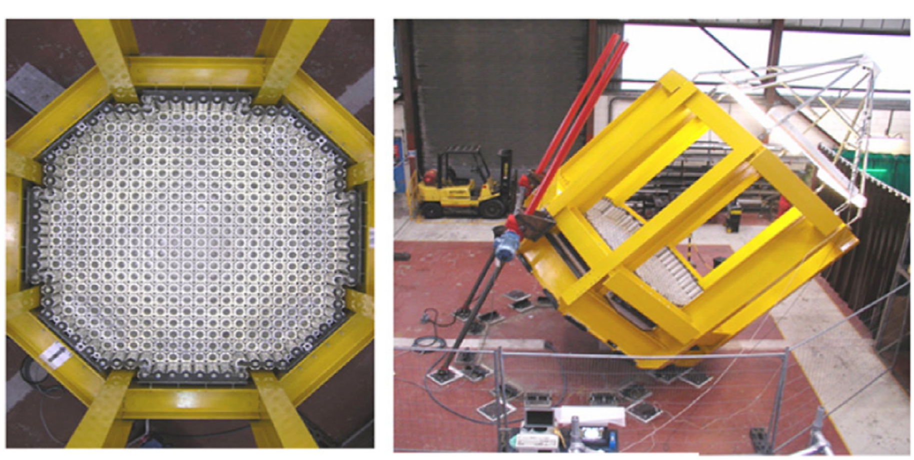

Fig. 2. The 1/4th scale static rig (left: plan view, right: 40° tilt (courtesy: AMEC).

Please cite this article in press as: Dihoru, L., et al. The development of a physical model of an Advanced Gas Cooled Reactor core: Outline of the feasibility study. Nucl. Eng. Des. (2017), http://dx.doi.org/10.1016/j.nucengdes.2017.01.012