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THE DEVELOPMENT OF A PHYSICAL MODEL OF AN ADVANCED GAS COOLED REACTOR CORE: OUTLINE OF THE FEASIBILITY STUDY

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ABSTRACT

The graphite components in the Advanced Gas Cooled Reactor (AGR) cores are subject to degradation processes that are predicted to lead to greater numbers of weakened and cracked components. These ageing issues need addressing to maintain their safety 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 to provide validation to the computer models. The damage scenarios to be considered in demonstrating the core seismic tolerability were defined. Exploratory work on small arrays of components was carried out to inform the conceptual design of the rig components. 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. The phased decision making process that lead to the development of an 8-layer-20-bricks-across model is explained. Relevant aspects of instrumentation design and general requirements of dynamics and geometry are also presented.

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 UK, 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, need to be captured in the numerical reactor core models used to assess seismic capability and, where practicable, in the physical array models. At present, seismic responses are computed by GCORE-generated, LS-DYNA finite element (FE) "stick-and-spring" models (Kralj et al 2005).

This paper outlines a feasibility study carried out by the University of Bristol (UOB) for a model rig suitable for validation of computer models which are used to predict the seismic behaviour of aged cores. The reasoning process underpinning the design, build and testing of the rig is presented together with relevant aspects of instrumentation and rig operation.

The model rig has increased potential for brick displacements due to component degradation or increased brick-to-brick clearances arising from advanced shrinkage. It was designed to be tested on a dynamic simulator ('shaking table') at UOB, with the following objectives set for the experimental and the numerical work:

- Investigate the dynamic behaviour of graphite brick arrays in AGR cores.
- Determine the limits of validity for the current numerical seismic modelling approach under a range of postulated core damage scenarios.
- Quantify the level of margin within the computational assessments.
- Explore the phenomenological behaviour of the graphite components beyond the perceived assessment limits.

FEASIBILITY STUDY AND RIG DESIGN

Overview

The AGR cores consist of thousands of graphite moderator bricks interconnected through a graphite keying system which acts to resist relative motion between bricks. The graphite components are stacked together in vertical columns that provide the channels for fuel assemblies, control rods and coolant flow (Figure 1). The core columns must remain vertical within tight tolerances so that the control rods and the fuel stringers have a secure and unimpeded travel in and out the channels. The vertical faces between neighbouring bricks are separated by gaps to allow for graphite expansion during reactor operation. The radial keying system allows free radial movement of the bricks during thermal expansion and contraction of the surrounding steel structures, and provides reaction forces to lateral movement once the clearances between the keys and the keyways have been taken up (Figure 2).

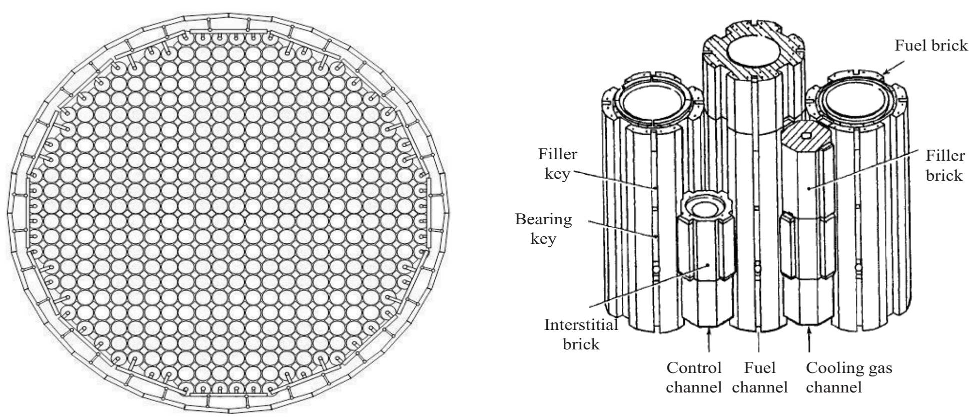
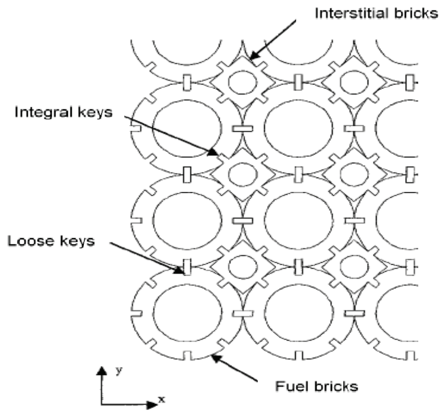


Figure 1. Plan view of AGR core and core restraint (left) and columns of bricks and keys (right).

The rig model for seismic testing is based upon the most highly irradiated AGR cores late in life.



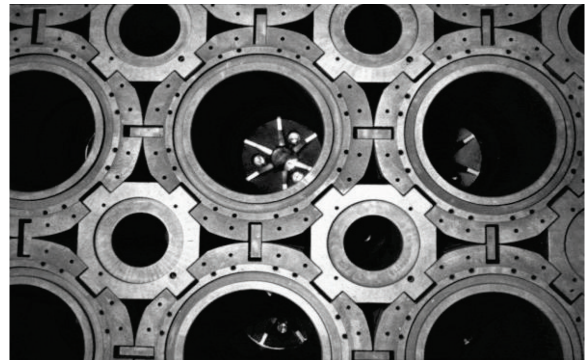


Figure 2. Layout of graphite core components in an AGR core showing the radial keying system.

While the degree of representation of the model for the aforementioned AGR cores is important, the physical model design was primarily guided by the objectives set out by the computer modellers for the validation work. The following aspects of damaged core behaviour have been identified as targets for experimental investigation and such aspects will provide the relevant inputs to the computer model validation work:

- Shape distortion of control channels and fuel channels.
- Core distortion due to variation of horizontal direct clearance between bricks brought about by advanced shrinkage.
- Core distortion due to large percentage of singly and/or doubly axially cracked bricks.
- Core distortion due to displaced / locked / failed graphite keys.
- Core distortion from crack opening, even if adjacent keys are not damaged.

Components And Mechanisms For Modelling

The complexity of the physical model is generally determined by its number of components and level of precision in reproducing the geometry and scaled dimensions. The more complex the scale model, the higher its level of representation for the dynamic behaviour of a 'generic' prototype. The simpler the physical model, the more sophisticated the mapping software that extrapolates the experimental results should be for a realistic prediction of the prototype response. UOB conducted a study that investigated several candidate rigs from the point of view of their feasibility and from the point of view of their experimental outcomes. Rig feasibility involved aspects such as manufacturing costs, manufacturing time, challenges of design and manufacturing, number of personnel required for handling and testing, complexity and convenience of the measurement system. Out of the possible combinations of components that can be used (Table 1), the single layer array and the hybrid array rigs (Variant No. 3) have been selected for the feasibility study. The component interactions and mechanisms relevant for their seismic behaviour are also presented in Table 1.

For the model array, the horizontal restraint system could either be very simply modelled via a ring with various stiffness values or be modelled in a more detailed way to emulate the restraint rod and restraint beam connections. It is important to note that, for a fully representative rig, the provision of a realistic boundary would need additional components and extra space to connect the array bricks to the frame. These additional complications would lead to a loss of focus on the dynamics of the array while increasing assembly and dismantling times. For validation purposes only, the choice of boundary is less constrained as the computer model just needs to represent the rig. Furthermore, for a fully representative rig, a top restraint system would be needed to emulate the behaviour of the missing top layers of bricks and guide tubes, and this would preclude the use of a visual measurement system.

Table 1: Component combinations considered for physical modelling

Variant No.	Components	Interactions/Mechanisms	Observations
1	<u>One control channel rig</u> Fuel bricks (uncracked, singly cracked and doubly axially cracked). Interstitial bricks Keys (loose, filler) Filler bricks Model restraint system	Interstitial channel distortion Key-keyway disengagement* Key locking* Key failure* Post-disengagement behaviour* Post-locking behaviour*	This arrangement is mainly to demonstrate the safe control rod insertion by monitoring the '3-point-angle' of the channel. *Modelling these aspects is limited by the insufficient number of components and oversimplified boundary conditions
2	<u>One control channel with control rod rig</u> Fuel bricks (uncracked, singly cracked and doubly axially cracked). Interstitial bricks Keys (loose, filler) Filler bricks Control rod Model restraint system	Interstitial channel insertion Key-keyway disengagement* Key locking* Key failure* Post-disengagement behaviour* Post-locking behaviour*	This arrangement is mainly to demonstrate the safe control rod insertion by modelling explicitly the control rods. *Modelling these aspects is limited by the insufficient number of components and oversimplified boundary conditions
3	<u>Hybrid Array or Single Layer</u> Fuel bricks (uncracked, singly cracked and doubly axially cracked). Interstitial bricks Keys (loose, filler) Filler bricks Model restraint system	Key-keyway disengagement Key locking Key failure Post-disengagement behaviour Post-locking behaviour Interstitial channel distortion Fuel channel distortion Effect of crack alignment on brick column stability and key system functionality. Variation of gaps between restraint system and graphite core during thermal cycling Variation of brick to brick gaps as a result of shrinkage.	Getting closer to the true prototype behaviour is dependent on the number of model components and the design of the boundary system. Control rods need not be explicitly modelled. Safe control rod insertion demonstrated via monitoring the '3-point-angle' of the channel. This rig can also investigate the fuel stringer '3-point-contact'.

It is recognized that adapting the restraint stiffness in the computer model is far simpler than trying to emulate physically such variation. Therefore, it has been decided that the restraint system of the physical rig will be of constant stiffness and sufficiently high for the restraint frame to behave rigidly in the range of frequencies and displacements employed in seismic testing.

Model Scaling Considerations and Material Selection

In general physical modelling seeks an adequate approximation of the similitude relations between model and prototype. In this particular case, the following basic prototype and model facts have been considered:

- A graphite density of 1.8 g/cm^3 has been historically assumed.
- An unirradiated Young's Modulus of 9.6 GPa has been assumed.
  The prototype Gilsocarbon compressive strength is about 80 MPa.
- The point contact collisions between components are considered rigid.
- Geometrical similitude is required, including rocking features of model fuel bricks, parallel walls for keys and a dovetail shape for keyways.
- Dimensional precision required (i.e. tolerance of 0.1 mm or smaller for linear dimensions).
- Key-keyway clearances are scaled for the correct reproduction of rotational and translational movements of the key in the keyway (prototype clearance: 1.04 - 1.52 mm).
  The smallest practical scale for the model is a quarter scale, because of the required manufacturing tolerances, the instrumentation deployment issues and the size and capacity of the shaking table.
- Mechanical properties of the model material should be stable with time, under normal environmental conditions.
- The ideal scaling factor for Young’s modulus is 1. However, this poses severe restrictions on material properties and probably cannot be achieved in practice.
- The scaling factor for gravity is 1.
- The maximum dimension of model rig is dictated by the size of the shaking table (3m x 3m).
- The maximum weight of model rig is dictated by the capacity of the shaking table (15 tonnes).

In principle, the models have to be easy to manipulate and to monitor. The larger the scale of the model, the more time is needed to assemble and more effort is required in handling. On the other hand, in smaller scale models the measurements are more difficult to make (i.e. limited space for transducers) and the signal/noise ratio becomes smaller. It is also important to note that the dynamic behaviour of large arrays may be significantly different to that of smaller ones and that a higher degree of sophistication would be required for computer model validations for smaller arrays. Overall, the above arguments are driving the physical modelling choice towards the models with a larger number of components but relaxing the requirement for full AGR core representation.

A summary of scaling factors for earthquake response of structures can be found in (Crewe 1998). In general, a true replica model implies simultaneous duplication of inertial, gravitational and restoring forces and full compliance with the similitude laws. Such a model would require scaling of density and stiffness at the same time. Finding a material whose properties satisfy scaling requirements simultaneously is practically impossible, therefore, an adequate approximation has to be sought. Another method employed in physical modelling is the artificial mass simulation method. It implies the presence of additional material of a non-structural nature to simulate the required density of the model. Such mass can be lumped or distributed. This method is difficult to apply to the scaled AGR core model because of the large number of components that have a role in system’s dynamics. Distributing an artificial mass within such a complex array of rigid blocks would be technologically impractical. The third type of modelling applies to cases where gravity forces can be neglected. In the particular case of a graphite core under seismic loading, the gravitational forces cannot be neglected, therefore, using the third type of scaling law is out of the question. It was therefore proposed that the graphite core model should be an ‘adequate model’ which maintains ‘first-order’ similarity. ‘First-order’ similarity implies that the physical parameters with significant influence on the seismic response are accurately scaled, while the ‘second-order’ parameters are only be approximately scaled. In this way a modified version of a true replica model will be created. For this research programme it was proposed that the geometrical properties of the core would be scaled, as the channel shapes and the general distortion of the core are governed by the brick-to-brick and the key-keyway clearances. It has been decided that the brick and key design will be a quarter scale design based on that of the most irradiated cores. All the clearances in the model will be quarter scaled and determined from those predicted late in their lives. The scaling of material properties has also to consider the dynamic problem that is at the centre of this investigation. During a seismic event, the core will behave as an array of rigid bodies in which the relevant forces are the impact forces generated during the collisions between the components, the gravitational and the restoring forces. As impact forces depend on the local contact properties (i.e. contact stiffness and coefficient of restitution), then the Young’s modulus of the component material becomes relevant in scaling. It is important to observe, that the contact properties are different for the normal and for the shear contact. The energy restitution after a brick-to-brick collision depends heavily on the actual layout of components in a zone of investigation (i.e. presence or absence of bearing key, presence or absence of integer key, locking of key, etc). Brick-to-brick testing of model components have been carried out to determine the values of contact properties for various component combinations. The selection of the model material has to seek a reasonable approximation for the ratio between the scaling factor for density (S_r) and the scaling factor for stiffness (S_E) of the model component. This ratio is described by the basic scaling law in Equation 1:

$$S_{\rho} = S_E / S_L \tag{1}$$

where S_L is the scaling factor for length. For a quarter scale model, Equation 1 becomes:

$$S_{\rho} = 4 \times S_E \tag{2}$$

Table 2 presents the results of Equation 2 for a number of candidate materials.

Table 2: Scaling factors for density and stiffness for candidate model materials

Material	**Density (kg/m^3)**	**Young’s Modulus (GPa)**	**Compressive Strength (MPa)**	**S_ρ**	**S_E**	**S_ρ/ S_E**
Commercial Graphite	1800	9.60	70	1.00	1.00	1.00
Nylon 12	1020	1.80	75	0.57	0.19	3.02
POM	1410	2.70	90	0.78	0.28	2.79
Reinforced POM	1580	9.00	100	0.88	0.94	0.94
PPS(Fortron)	1600	13.00	93	0.89	1.35	0.66
LCP(Vectra)	1610	13.00	90	0.89	1.35	0.66
Aluminium Alloy	2700	70.00	110	1.50	7.29	0.21

Note: Property values are indicative. POM is the DIN abbreviation for polyoxymethylene. PPS (Fortron®) is polypheniline sulphate with 40% glass reinforcement. LCP(Vectra®) is a liquid crystal polymer with 30% glass reinforcement (supplier: Ticona Ltd).

The friction between the surfaces in contact within the array is another property of interest. Table 3 presents the static and the dynamic coefficient of friction for various combinations of candidate materials that were investigated. Based on these results, the engineering thermoplastic polyoxymethylene (DIN-abbreviated POM) has been identified as the strongest candidate for the array component manufacturing.

POM exhibits a reasonable density/stiffness ratio and high rigidity which makes it suitable for precision machining. POM is catalogued as non-hygroscopic, therefore the component dimensional tolerances are likely to be stable with time in normal environmental conditions. POM also exhibits comparable friction coefficients with the graphite bricks at reactor operating temperature (Table 3).

Table 3: Friction coefficients for selected pairs of materials

No.	Material 1	Material 2	μ_{static}	$\mu_{dynamic}$
1	POM	Steel	0.14	0.21
2	POM	POM	0.19	0.15
3	POM	PA (Polyamide)	0.04	0.06
4	POM+20% PTFE	PA + 20% PTFE	0.03	0.04
5	Graphite (temp 20 deg C)	Graphite (temp 20 deg C)	0.10	0.10
6	Graphite (temp 350 deg C)	Graphite (temp 350 deg C)	0.20	0.20
7	Aluminium (dry)	Aluminium (dry)	1.05	1.40
8	Aluminium (greasy)	Aluminium (greasy)	0.30	0.32

Note: Property values are indicative. POM is the DIN abbreviation for polyoxymethylene.

Two colours, natural and black, were available and the choice of which components would be white and which black was made so as to minimise assembly errors by differentiating components of similar but different shapes, and to provide visual contrast when observing the experiments. A matte finish was chosen to minimise reflections which could affect the performance of the measurement vision systems that work best under low light noise conditions.

Considerations of Dynamic Behaviour

The smaller and stiffer the array, the smaller the relative displacements between the components, making measurement more challenging. Previous measurements on small array tests (Roscow et al 2010) show that the displacements in a 10x10x1 section are ~10mm maximum for the 100% cracked core, but only ~5mm for the 50% cracked core, and as small as ~1mm for the intact core. It is also important to note, that smaller and stiffer models are likely to respond at higher frequencies and that such behaviour would be a departure from the actual prototype for which a 'natural frequency' of 2-3Hz has been historically assumed. Lowering the 'natural frequency' of the model can be done via increased slackness in the system. As the horizontal clearance value should be representative of late life operations (i.e. it has a well-defined scaled value), then slackness can be increased via increased key-keyway clearances and/or via increased area section of the model. If the key-keyway clearances are to be kept quarter-scale of the prototype value, then the only route for increasing slackness is via a larger model section. This has lead to the decision to design and build a near-full core multi-layered array rig (MLA) with the following characteristics: quarter scale, octagonal shape, 20 bricks across the horizontal cardinal dimension and 8 layers. The model components and their layout in the horizontal plane are shown in Figure 3. The base of the rig (Layer 1) (Figure 4) is a seating assembly of plastic plates that allow only radial rocking. More than one such grid bases may be used in the future, to emulate several values of horizontal direct clearance between bricks. The model represents the inner-most 10 rings of the AGR core (Figure 4). Because the experiment was intended to study the dynamic behaviour of the array, the flexibility and dynamics of the actual core restraint mechanism was not represented. The boundary frame was designed to be dynamically rigid within the seismic test range (i.e. natural frequencies above 35Hz). The lateral boundary restraint arrangements provides the required rigidity of the perimeter model bricks, while allowing for sufficient adjustment to accommodate the required brick pitches and gaps. The restraint base frame is rigid and allows for precise levelling of the base plastic plate assembly on which the model bricks are founded.

Figure 3. Quarter scale POM components in the MLA rig (left: columns, right: top layer).

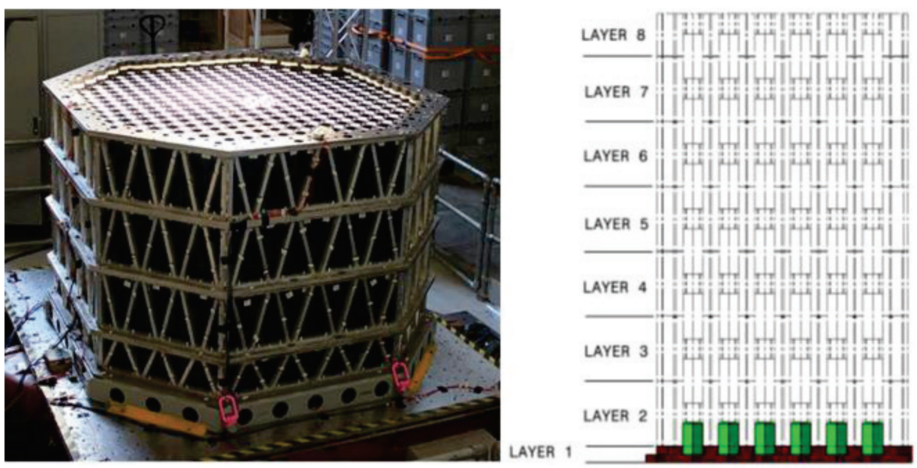


Figure 4 The ML restraint (left). Layer layout in the MLA rig (right). Layer 1 is an assembly of plastic plates. Layers 2-8 are active. (courtesy Atkins).

Array Component Design and Manufacturing

The MLA rig contains quarter scale model components of fuel bricks, interstitial bricks, loose bearing keys, filler keys and spacer keys, and takes into account the effects of the core late in life and the associated changes in graphite component geometries. The array components were manufactured via a combined process of extrusion, machining of stock shapes, annealing and precision machining that can secure linear tolerances down to 0.05mm. The rig must also take into account the effects of keyway root cracking resulting in singly and doubly-cracked bricks. Arrays with up to 30% doubly cracked bricks in Layers 4-7 and up to 10% doubly cracked bricks in Layer 8 can be currently built in the MLA rig. The level of cracking can be increased according to the numerical validation needs. Initial experimentation involved only intact arrays that will provide reference results for future studies with cracked arrays.

Measurements and Instrumentation

The MLA testing programme consists of one-axis shaking table tests in the horizontal plane. The physical parameters that are measured in the rig and the instrumentation employed for this purpose are given in Table 4. A summary of rig component and instrument numbers deployed in the rig is presented in Table 5, and the rig data flow and data acquisition are explained in Figure 5.

Table 4: Instruments and measurands in MLA rig testing

Instrument/ Measurement System	Measurands
Infrared Vision System (IRVS)	Displacement of array components, ML restraint frame, shaking table
High Speed Video System (HSVS)	Displacement of array components in top layer
Accelerometers (SETRA type)	Acceleration of shaking table and ML restraint frame
Accelerometers (MEMS* type)	Acceleration of interstitial/filler/fuel bricks
Hall Effect Sensors	Interstitial channel profile and loose bearing key position in the keyway
Linear Potentiometric Transducers	Fuel channel profile

Note: MEMS* stands for Micro-Electro-Mechanical-System

Table 5: Summary of component and instrument numbers in the MLA rig.

	Number
Model Acetal Components	~ 44000
Sensors for One Lattice Column Profile	82
Sensors for One Interstitial Column Profile	195
Sensors for One Loose Bearing Key Monitoring	12
Sensors for One Cracked Brick Monitoring	32
Expected Number of Sensors in the Rig for 10 Pairs of Instrumented Columns, 10 Instrumented Cracked Bricks, 10 Instrumented Keys	3210

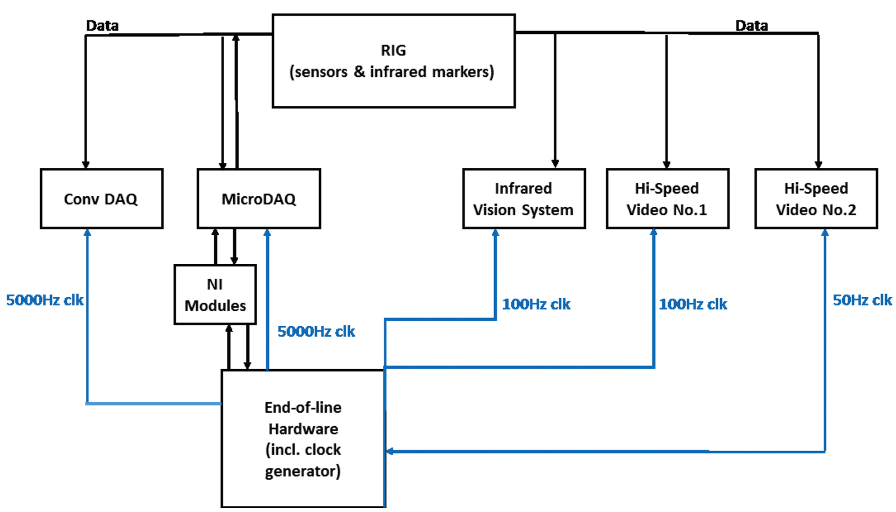


Figure 5. Diagram showing MLA rig data acquisition systems and data communication.

CONCLUSIONS

The development of a quarter scale physical model of the array of graphite bricks in an AGR core has been presented. The MLA rig is a tool of high complexity, unique in the world: its number of model components (> 44000) and the number of measurement sensors (> 3000) are pushing the boundaries of design in instrumentation, data acquisition and data processing. The decision making process that underpinned the rig design and build, which included investigations of model scaling, material selection and instrumentation design, has been described. The rig can provide displacement and acceleration data for the array components, as well as channel profile measurements. The rig presents sufficient embedded versatility for a wide range of scenarios of brick cracking and key disengagements to be modelled. The MLA rig data will be employed directly for computer model validation.

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