

# THE SIGNAL AND NOISE IN THE VALIDATION OF COMPUTATIONAL REACTOR MODELS

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## ABSTRACT

Computational models are essential to understanding a reactor's structural mechanics, including its behaviour under normal operation, fault conditions and seismic events. The validity of a given model to assess a given scenario is typically evaluated through comparison to a physical test rig. A test rig is a different kind of model, with its own assumptions and limitations, as well as measurement error and manufacturing tolerance.

A test rig of a large part of a reactor core is necessarily large and expensive. Therefore, the number of experiments is often limited. Furthermore, the complexity can make the results unclear. Therefore, it is important to design rig tests and choose comparison methods to give a clear signal that can be discerned from the noise to determine the validity of the computational model. Typically, this means an experiment with a large change in the input, to give a large change in the output. This paper gives examples from the AGR graphite core programme to illustrate how this can be achieved: the quarter-scale core rig (Roscow et al., 2010) used to validate the AGRIGID whole-core model (McLachlan et al., 2007)(Shaw et al., 2007, 2010) and full-scale channel rigs used to validate LEWIS (Crawford, 2013, 2015).

## MOTIVATION

Computational models are essential to understanding a reactor's structural mechanics. Safety necessitates considering scenarios that have not happened to a specific reactor, or potentially in any reactor. While test rigs can help, practicalities may limit the scope of the scenarios considered. Simple calculations can also help, but computational models allow modelling in more detail and with fewer simplifications, as well as numerical calculation that is not practical by hand.

While greater complexity can give more accurate models, it also gives less accurate results, through more opportunities to miss important differences between the model and reality. Where model parameters have been tuned to give a good match for existing data, there is also the danger of over-fitting and so giving inaccurate results outside the range of the existing data while giving false assurance from a good match where a comparison is made. This is why models must be validated. This comes from comparing model outputs to independent data, such as alternative calculations, or measurements from an existing reactor or a specially designed test rig. Of these, the test rig is often the best option, but again practicalities can limit the scope of the scenarios considered, so we must be aware both that not all aspects are modelled by the rig and that the data set will be limited.

As with computational models, the more aspects covered by a test rig, the greater its complexity and the more opportunity for it to differ from the reactor in a way that we don't expect. Furthermore, manufacturing tolerances and measurement errors can give results that differ from a model for reasons unrelated to the validity of the model.

Nate Silver (2012) applied the terms signal and noise – common in communication and signals processing – to statistical modelling and prediction. According to Silver, to make a good prediction requires discerning the signal from the noise in the data. Silver's book did not consider experiments, which can be designed such that the signal can be discerned from the noise. While Silver focused on analysing existing

data, the same principle applies to experimental design: well-designed experiments should maximise the signal while minimising the noise.

In pharmaceutical research, a phase 3 clinical trial is designed to test the effectiveness of a treatment and uses a larger number of patients than earlier trials. It will typically consider a dose at or close to the maximum tolerable dose (which would have been shown in an earlier phase). If only smaller doses are tested there is an unnecessary risk of an inconclusive study where a larger dose might have been conclusive. The signal of a statistically significant treatment effect could be lost in the noise of variability between patients.

Similarly, in validating computational models, small experimental inputs, such as loads and displacements, may lead to ambiguous results, where manufacturing tolerances, measurement errors, or unanticipated aspects of the rig obscure meaningful conclusions about model validity. To avoid this, rig tests must apply large inputs to generate a signal that can be discerned from the noise. This paper will illustrate this with two case studies related to the graphite core of the UK Advanced Gas-cooled Reactor (AGR).

## **VALIDATION OF AGRIGID WITH QUARTER-SCALE CORE RIGS**

AGRIGID (McLachlan et al., 2007; Shaw et al., 2007, 2010) has been used for many years to model the whole AGR graphite core. It is a Fortran program that generates an input deck for Abaqus, modelling each brick as a rigid body and modelling each interaction between bricks using bi-linear and tri-linear springs. By changing the inputs, a user can model the different designs of AGR, different configurations of damage to the graphite bricks, and different operating and fault conditions.

AGRIGID has been validated by comparison to a quarter-scale rig (Roscow et al, 2010). At first this was done using “maximum displacement by tilt”. Arrays of bricks were built up in the rig and the rig was tilted by up to 30°, as shown in Figure 1. An equivalent array was built in AGRIGID, with a horizontal force applied to each brick, equivalent to the component of gravity in the tilted rig. This gave a good match, which was sufficient to validate AGRIGID at the time.

However, the use of AGRIGID became more sophisticated. LEWIS (Crawford, 2013, 2015) was used to analyse individual channels from AGRIGID for their ability to allow the movement of control rods and fuel stringers, as well as their ability to allow the cooling of fuel. As such, a more detailed validation of AGRIGID was required.

To enable a more detailed validation, the quarter-scale rig was improved. A system was developed using a camera and targets on each brick, as shown in Figure 2 and Figure 3. It measured the displacement of each brick to a fraction of a millimetre. It could measure displacement of bricks at different layers by changing the focal length of the camera. Arrays were built that included doubly cracked bricks, where the two halves can move independently. Replicas of singly cracked bricks were also made, which could push neighbouring bricks as the crack was opened with a wedge. Shims were added to some of the bricks, to replicate the rocking flats seen in some channels in some AGR designs. The intention was for these brick changes, rather than tilting the rig, to lead to displacements. The displacement of the bricks was measured with the camera system and compared to the displacements in an AGRIGID model of the same array.



Figure 1. Quarter-scale rig undergoing tilt



Figure 2. Array of quarter-scale bricks with targets



Figure 3. Camera system on quarter-scale rig

Initially, there were many challenges. For some bricks, the match between the rig and the AGRIGID model was poor. Improvements to the camera system were identified and implemented. The imperfections in the base – previously irrelevant as the base was tilted by  $30^\circ$  – were measured and input into AGRIGID. The match between the rig and the model improved. Overall displacements in AGRIGID were bounded by those in the quarter-scale rig. Comparing on a brick-by-brick basis, some channels matched quite well, but there were still some channels within the array where the match was poor. One theory considered was that the weight of the bricks was causing the base to sag. Attempts were made to model this, but it was hard because it could not be measured since there was no way to access the base under the bricks and the camera system only measured horizontal displacement.

AGRIGID does not usually model friction between bricks since it is concerned with the static equilibrium, reached after months of the core operating and vibrating. Friction was introduced to the model and found to improve the match of individual channels with the test rig, which was not subject to vibration. Friction also reduced the overall displacement, confirming that not modelling friction is conservative.

Eventually, a much better match was achieved, partly by reducing the number of bricks, and so the weight on the base, and partly by introducing a better replica of a singly cracked brick. This new brick could open much wider than previous replicas. As the crack width increased, the diameter increased and the keyways moved, forcing neighbouring bricks to move. This led to a greater displacement, which was easier to distinguish from the noise of measurement error, manufacturing tolerances and unmeasured changes to the base. With all these changes, the quarter-scale rig still had much more realistic mechanisms for driving brick displacements, which were still measured in detail, meeting the design intent of the changes to the rig, away from maximum displacement by tilt.

## VALIDATION OF LEWIS WITH FULL-SCALE CHANNEL RIGS

The LEWIS method (Crawford, 2013, 2015) calculates a measure of the functionality of channels in the AGR core. As mentioned above, it is used to analyse individual channels from AGRIGID for their ability to allow the movement of control rods and fuel stringers, as well as their ability to allow the cooling of fuel. It is also used similarly for GCORE, a seismic model of the core. The main output from LEWIS is the maximum distortion scale factor, the largest factor by which distortions of the channel can be multiplied and still allow movement of a control rod or fuel stringer, or cooling of the fuel. A maximum distortion scale factor above one shows that a channel performs its function. The closer the factor is to one, the closer the distorted channel is to not being shown to function by LEWIS. While assembly movement or cooling

may be possible, it would rely on aspects not modelled by LEWIS, such as assembly segments bending or a brick moving to the side in response to contact from the assembly.

Figure 4 and Figure 5 show two of the full-scale rigs used to validate LEWIS. For all rigs, an assembly (a replica fuel stringer or control rod) was moved in and out of the channel, measuring the load on the chain from which the assembly is suspended.

The rig tests used multiple amplitudes of given shapes. Plotting the peak change in the chain load (both positive and negative) against the shape amplitude gives figures such as Figure 6 (Crawford, 2015). Comparing the amplitude required to increase or decrease the chain load by 50% to the amplitude calculated by LEWIS showed that the maximum distortion scale factor calculated by LEWIS is conservative. It would be more conservative still relative to a load that would prevent assembly movement, giving confidence that a distortion scale factor of one or more confirms that a channel can perform its function.



Figure 4. Replica control rod (top) before being lowered into a control channel rig



Figure 5. Replica fuel stringer, partially inserted into a fuel channel rig

This conservatism was expected, given the conservative assumptions of LEWIS. However, as with the AGRIGID example above, looking in more detail initially seemed to show an unexpected result. Fuel stringers have a series of fuel sleeves. Channel distortion can cause articulation of the stringer, which results in gaps between adjacent sleeves. These gaps were measured in the rig using linear variable differential transformers (LVDTs) as shown in Figure 7. At first, there was concern that at low amplitudes there was some gapping at some insertion depths that was not seen in the LEWIS results.

Investigation showed that this was due to the swaying of the stringer as it was being lowered or raised. Where the channel amplitude was greater, the channel distortion determined the gapping and there is no scope for the stringer to sway. In this situation, LEWIS gapping exceeds that observed in the rig.

Gaps between fuel sleeves are only of concern during operation, when the fuel stringer is fully inserted in the channel (and is loaded from above to reduce gapping). Such in-situ stringers do not exhibit the swaying that was observed in a moving stringer in the test rig. As such, gapping is only a concern if it is forced by the channel distortion, i.e. with large shape amplitude. This is the situation which the rig has shown that LEWIS is conservative, i.e. it overestimates gapping. When there is sufficient signal from a large shape amplitude, the noise from the swaying no longer obscures the validity of the model.

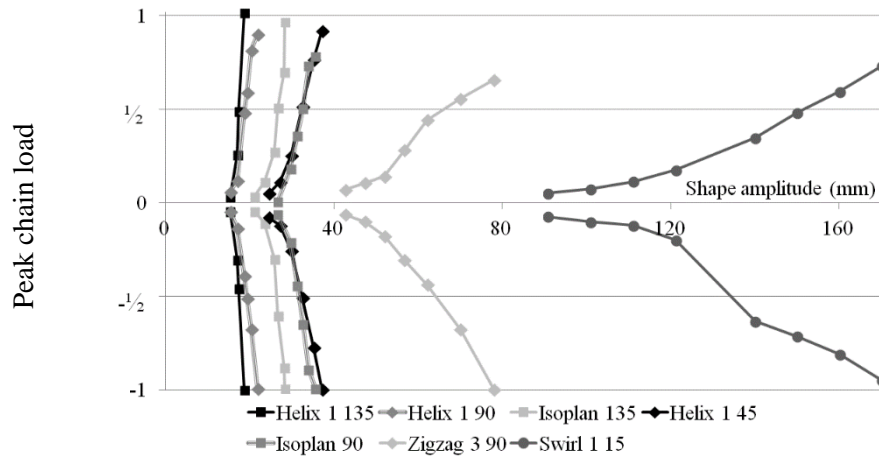


Figure 6. Peak chain load as a function of amplitude for 7 different channel shapes. Peak chain load is given in the form of the difference from assembly weight, as a proportion of assembly weight.

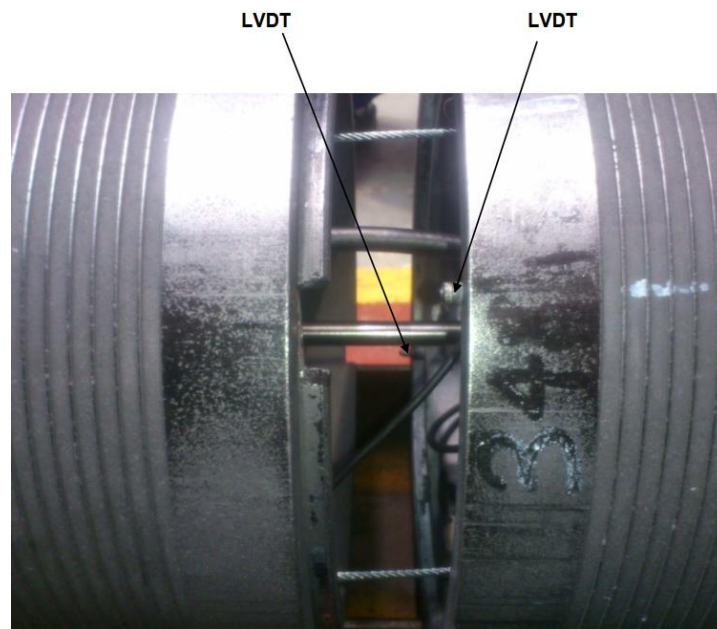


Figure 6. Fuel sleeves in the replica fuel stringer, separated to show the LVDTs.

## CONCLUSIONS

Of all methods of validation, comparison to rig tests often gives the most confidence because it relates the computational models to something physical, while allowing scenarios to be considered that have not presented in a reactor. However, the above examples show that the design of the rig and the choice of tests can lead to the validity of the model being obscured. Measurement error and manufacturing tolerances can play their part, but in the two examples above, the biggest issues were related to phenomena that were not relevant to the modelling of the reactor and/or hard to measure on the rig: the distortion of the base under the weight of the quarter-scale bricks, friction in a non-vibrating system, and the swaying of the replica stringer inside the channel. In both examples, a more relevant comparison and successful validation was achieved by using larger displacements, whether through the opening of a singly cracked brick in the quarter-scale core rig, or distortion of channels in the channel rig. Any scenario that could challenge the functionality of an AGR channel will ultimately involve large displacements, and so large displacements are most relevant to the validity of the models discussed here. These large displacements generated a sufficiently large signal that can be detected through the noise of inaccuracies in the test rig, ultimately giving confidence in the computational models.

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