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# HEYSHAM II/TORNESS POWER STATIONS: SEISMIC QUALIFICATION OF CORE STRUCTURES AND BOILERS

D.J. SHEPHERD
National Nuclear Corporation Limited,
Knutsford, Cheshire,
United Kingdom

**Abstract**

For the advanced gas cooled reactors at Heysham II and Torness the seismic qualification of the core and support structures and boilers posed special problems. In each case the response was highly non-linear due to impacting. Within the core itself there are many thousands of degrees of freedom each dominated by impacting during the seismic event and these impact forces are transmitted to the support structure. The boilers, although supported and located in the design case by linear systems, have their motion during the seismic event controlled by seismic restraints and other components which introduce substantial impacting during seismic excitation.

For both these important components a substantial programme of testing was carried out to validate an analysis approach. This testing and correlation with analysis is described in detail for both components. In the case of the core the qualification was based upon a non-liner code AGRCORE which was specifically developed to handle the large number of impact degrees of freedom for this component. The implementation of this code is also described together with a brief summary of results. The boiler analysis was ultimately carried out using conventional finite difference codes and the implementation of these together with a summary of results is also presented.

## 1. INTRODUCTION

For the AGRs at Heysham II and Torness the seismic qualification of the core and support structures and of the boilers posed difficult analytical problems because the responses are highly non-linear due to impacting. In each case a substantial amount of physical testing was required in order to identify parameters for analysis and to provide validation. These interrelationships between test and analysis are described below, together with the approach finally adopted for the qualification and a brief summary of results.

## 2. BOILERS

### 2.1 Description

The boilers comprise twelve individual units, each with its own reheater, installed within the pre-stressed concrete pressure vessel, spread around an annulus between the vessel and the PCPV, Figures 1 and 2. The weight of each unit is carried by an arrangement of hinged steel slings at the base of each unit which allows radial movement to accommodate thermal expansion through thermal distortion of the laminated strips and tangential movement through a pinned detail. All the units are connected together at the base but are otherwise unrestricted except for the upper and lower seismic restraints which provide tangential restraint with a nominal clearance of ± 30mm and the superheater penetrations which are connected to the top of the boiler casing through a gimbal joint. In each case the outer penetrations have ± 4 mm clearance at the connection to the casing whilst the centre gimbals have no clearance.

One further, significant, feature of the boiler arrangement is an annular seal at the base of the casing which inhibits gas flow over the outside of the casing. Details of the inner (gas baffle side) and outer (PCPV side) seals are shown in Figure 3. The reheaters are suspended by pinned slings, one above each main unit as shown in Figure 1, and are structurally independent of the main units except for shear stops which engage between each corner of the main unit casing and the reheater casing. The total weight of each main boiler unit is approximately 100 tonnes and each reheater 24 tonnes.

### 2.2 Testing of Boilers

Because of the obviously non-linear nature of the seismic response of the boilers and the necessity to represent features such as friction at the annular gas seals it was decided prudent to establish the characteristics of the dynamic response by testing an existing scale model. The $^1/_5$ geometric scale model of a single main unit together with supports, gas seal, seismic restraints and superheater penetrations was constructed from steel and concrete. Low level impact excitation was used to determine natural frequencies, mode shapes and damping. Higher level sine wave excitation was used to obtain a qualative assessment of the relative importance of gas seal friction and seismic restraint clearances.

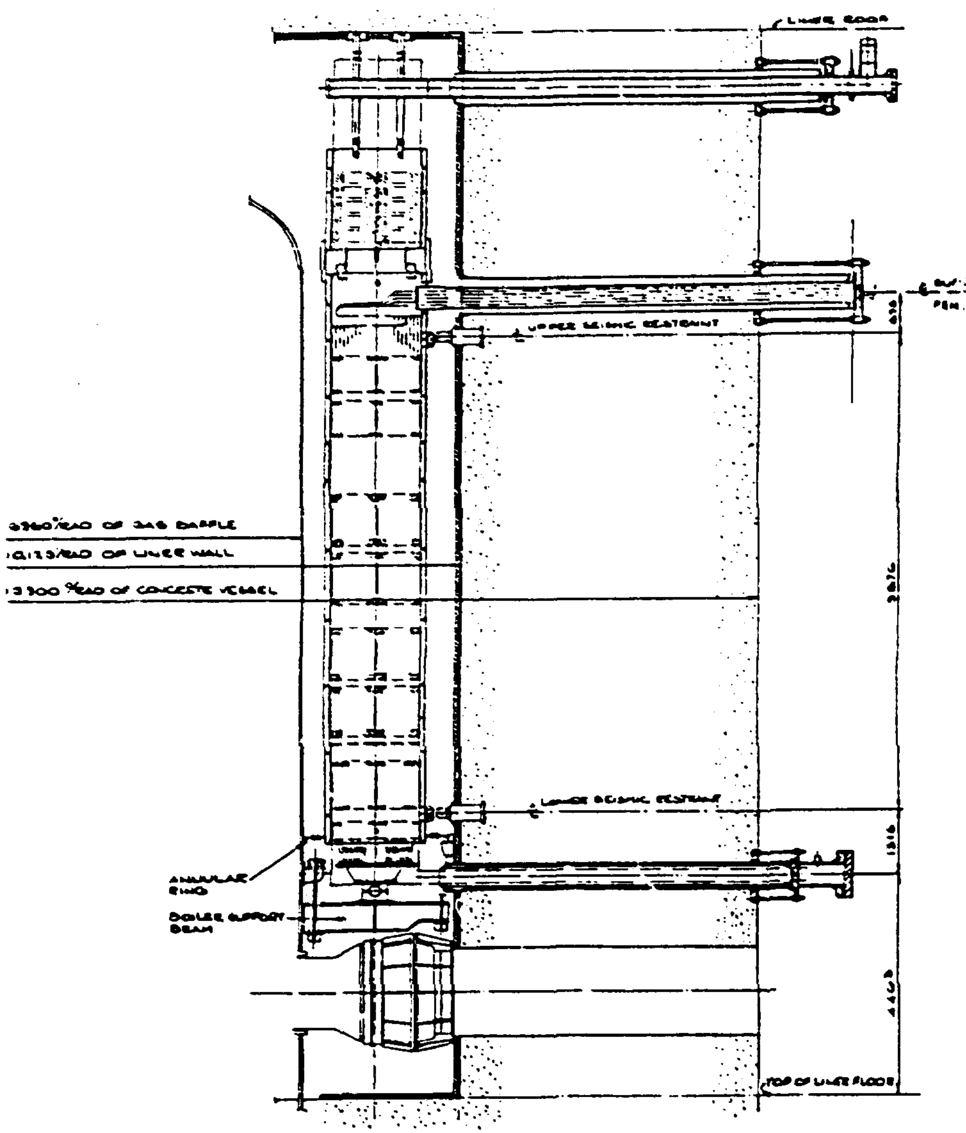

FIG. 1. Sectional elevation through a boiler and outer pressure vessel wall.

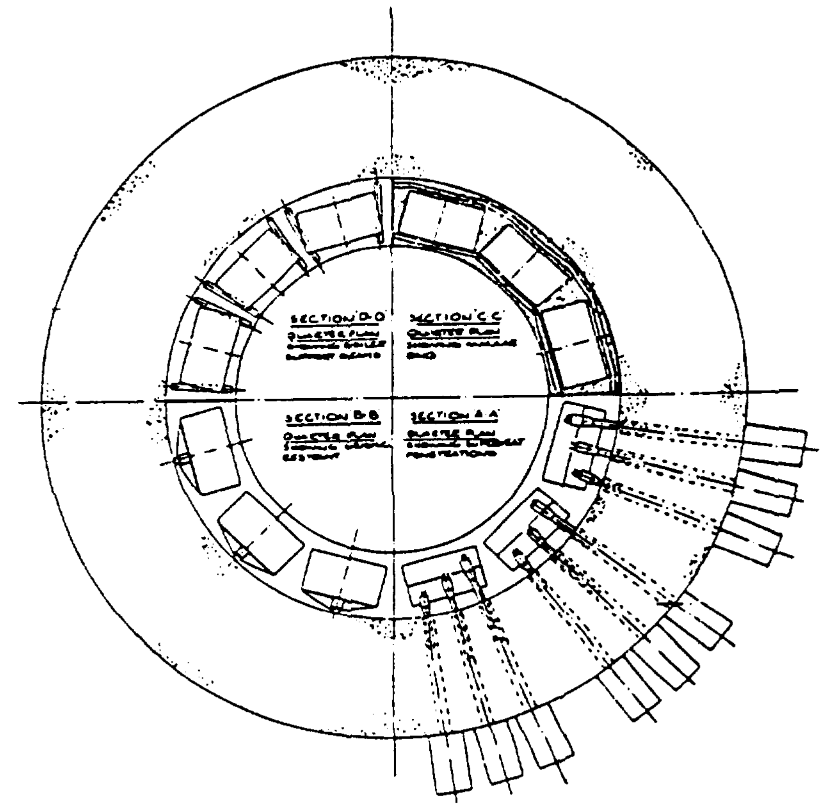

FIG. 2. Plan view of the twelve boilers.

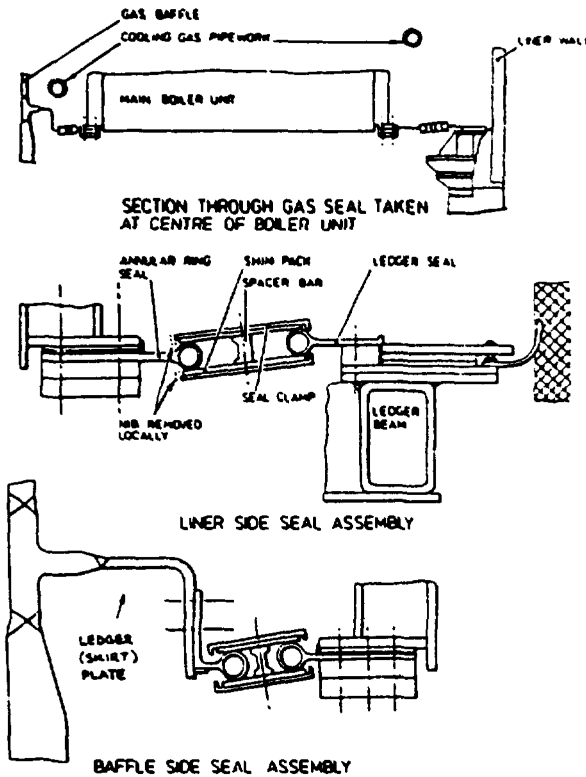


FIG. 3. Arrangement of main boiler gas seal.

A finite element representation of the $^1/_5$ scale model was produced and the comparison between analytical and measured natural frequencies is presented in Table 1 for the rigid body modes of the main unit. The discrepancy in the frequency of mode 1 was attributed to the effect of friction in the laminated hangers. This was confirmed by later tests which exhibited a marked reduction in frequency at higher excitation. The comparison of higher, flexural modes, was found to be very difficult because of the relatively crude representation of the mass of the boiler heat transfer surface. However these modes do not have a significant influence on the overall seismic response of the boiler units.

**TABLE 1**

**SUMMARY OF RESULTS FOR $^1/_5$ SCALE BOILER**

| Mode | Description | Calculated Frequency Hz | Measured Frequency Hz |
|---|---|---|---|
| 1 | Rigid body radial mode | 1.4 | 3.49 |
| 2 | Rigid body tangential mode | 6.1 | 6.61 |
| 4 | Rigid body rotation about vertical axis | 31.8 | 24.94 |
| 5 | Rigid body rotation about horizontal axis | 38.6 | 25.22 |
| 6 | Rigid body vertical mode | 57.5 | 42.88 |

## 2.3 Analysis of Boilers

Having established the validity of the modelling technique a full size, twelve unit, finite element model was constructed, Figure 4. At each gap, location appropriate elements were introduced:

- main unit to reheat casing shear connections
- outer superheater penetrations
- seismic restraints
- gas seals.

In addition, in order to avoid excessive conservatism in calculated impact forces all potential sources of stuctural in-elastic behaviour were modelled with the appropriate non-linear characteristics:

- superheater penetration gimbal brackets
- seismic restraint reaction structures
- gas seal and support structures.

An explicit time history analysis of the resulting model was used to predict maximum forces in each of the boiler components for subsequent seismic assessment. The input was based on artificial time histories which were generated to match PCPV response spectra generated for the SSE level of input (0.25g peak ground acceleration). For illustration of the final calculated response the radial displacement at the bottom of the boiler units and force at the upper seismic restraint are shown in Figure 5 and 6.

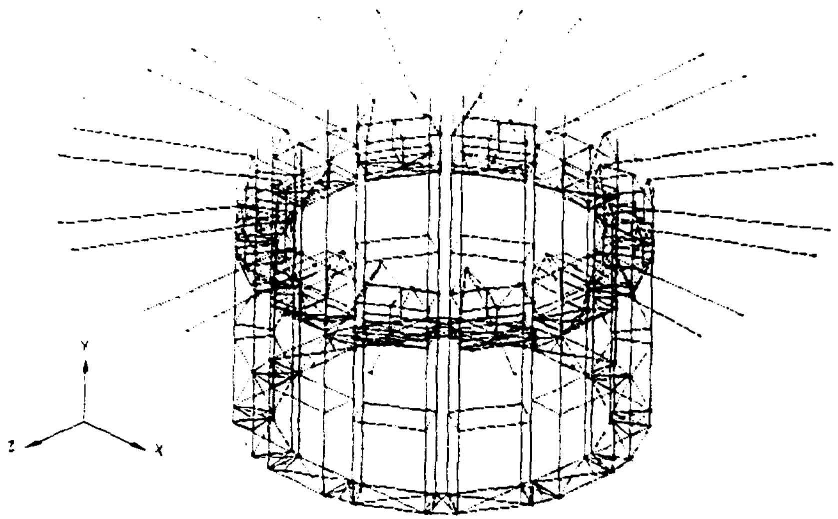


FIG. 4. FE model of boiler ring.

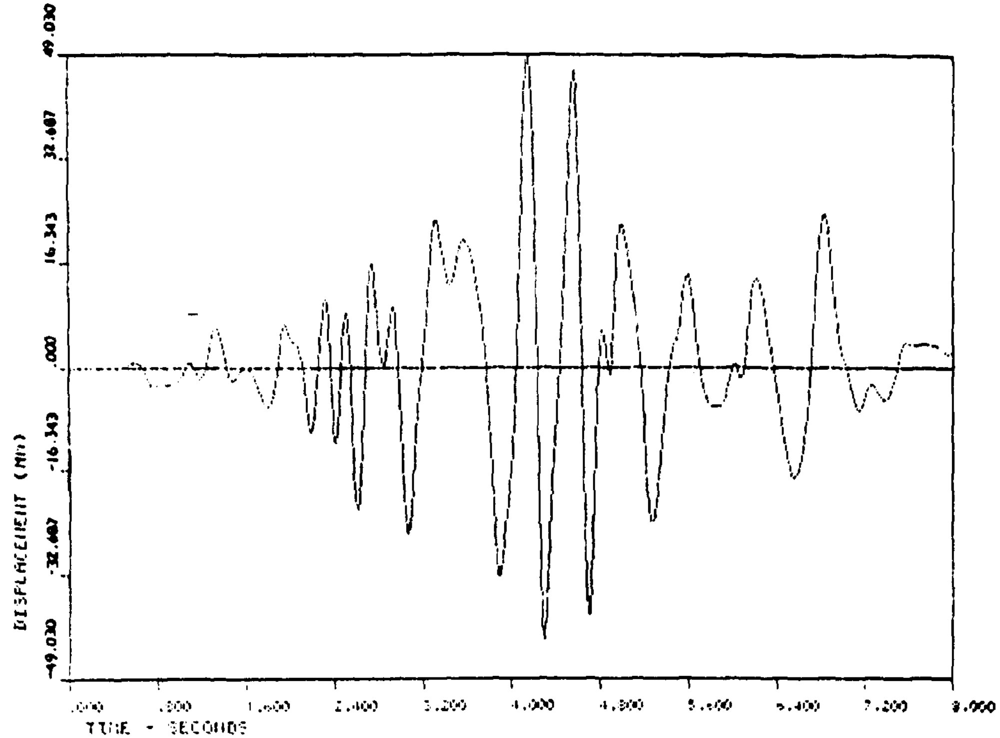


FIG. 5. Radial response at main unit base.

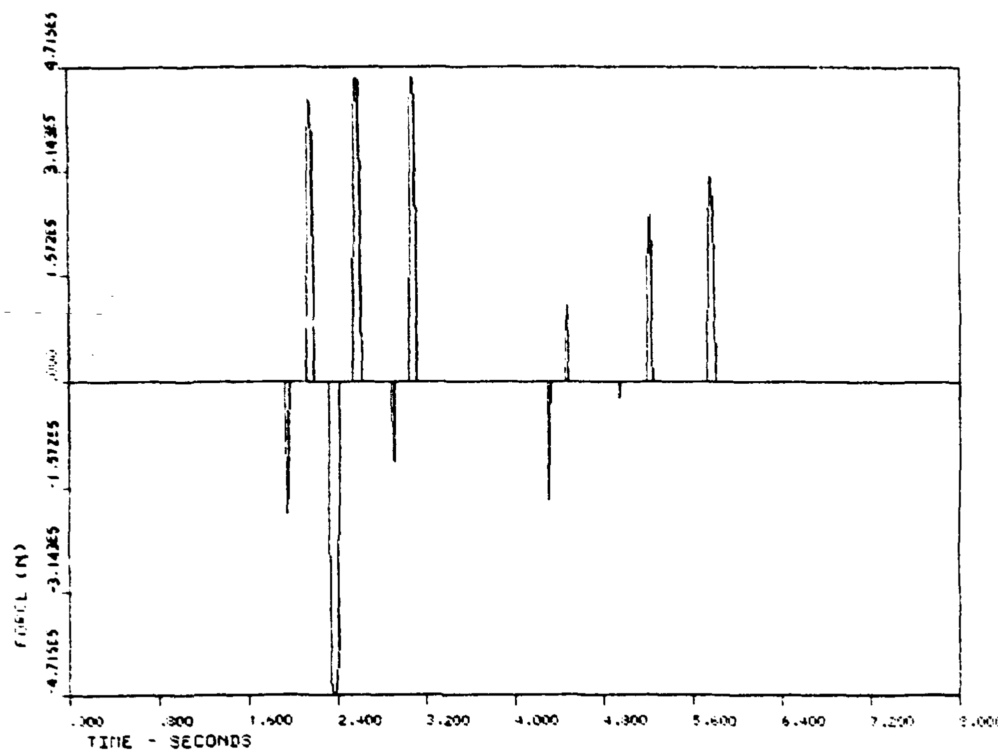


FIG. 6. Top seismic restraint tangential force history.

## 3. CORE

### 3.1 Description

The Heysham II/Torness core can be described approximately as comprising thirteen layers of graphite blocks, each layer being approximately 1400 blocks either fuel, interstitial or shielding, arranged with an octagonal geometry and connected together by rectangular graphite keys. A plan view of one layer of the core is shown in Figure 7. The core is supported by a steel diagrid and restricted laterally by an arrangement of radial links and tangential beams tied back to the gas baffle at each layer, Figures 8 and 9.

The transmission of seismic excitation into the core is therefore through the gas baffle and peripheral support structures into the mass of core blocks where further transmission occurs through friction and impacting at each interface. The final qualification was through an analysis process whereby each impact and friction degree of freedom was individually represented. A substantial amount of experimental validation was required to implement this analysis.

### 3.2 Testing of Core

The analysis approach required the determination of stiffness and damping characteristics for each impact degree of freedom. These were determined from a progressively more complex series of tests starting from effectively a single brick with appropriate boundary conditions progressing to a three layered array of 40 blocks per layer. The test arrays were excited by sine sweeps at various acceleration levels and enabled stiffness and friction parameters to be selected for complementary analyses.

Figure 10 shows typical test arrangement comprising a single layer of full-size graphite blocks. The peripheral row of blocks are only to provide the correct boundary condition. The inner blocks are supported on ball bearings to ensure a free movement at the base. Typical results are shown in Figure 11 which shows the velocity/frequency relationship for a range of peak accelerations. The notable feature, which is seen to be well reproduced in the analytical results, is the "drop-off" in response at higher frequencies which results from the relationship between dynamic displacement and gap size.

In addition to determining parameters for the dynamic analysis it was also necessary to determine integrity criteria for the graphite blocks. Since there would be many impacts on a single block during the seismic event the effect of repeated loads had to be considered. The necessary information was derived from 2-D slices of representative blocks as shown in the typical arrangement in Figure 12. Each impact geometry was represented and numerous impacts at a range of approach velocities were carried out. After each impact the specimen was examined for cracking. By use of the J integral the results of the slice tests were generalised for application to impact forces derived from the analysis applied to the actual brick geometry. A lower bound interpretation of all the data was used for the final assessment, Figure 13.

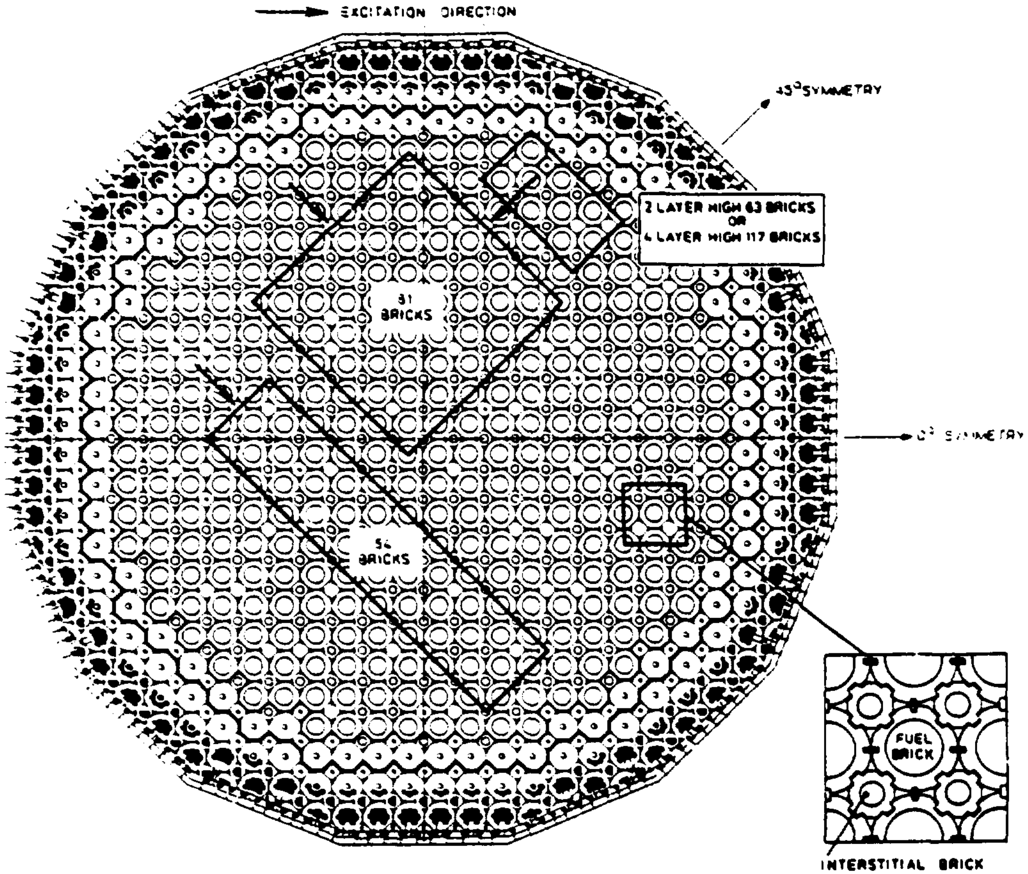


FIG. 7. Comparison between the brick test arrays and a core brick layer.

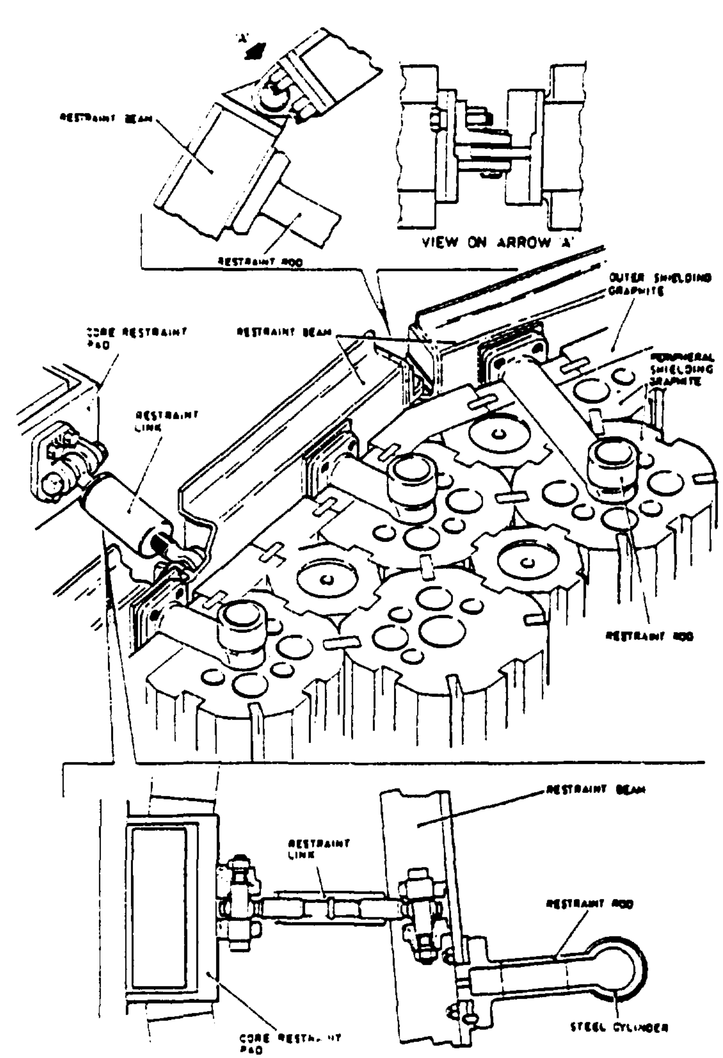


FIG. 8. Arrangement of restraint system.

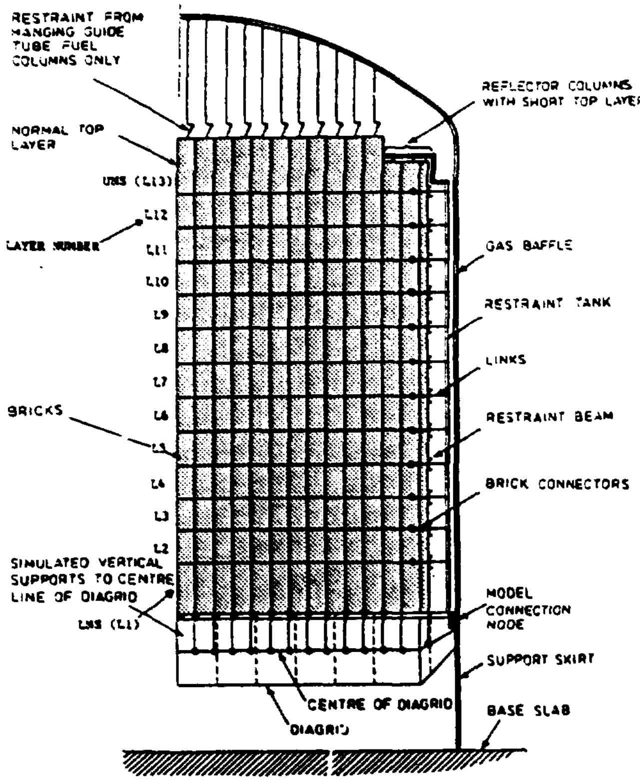


FIG. 9. AGR core vertical plane half-section.

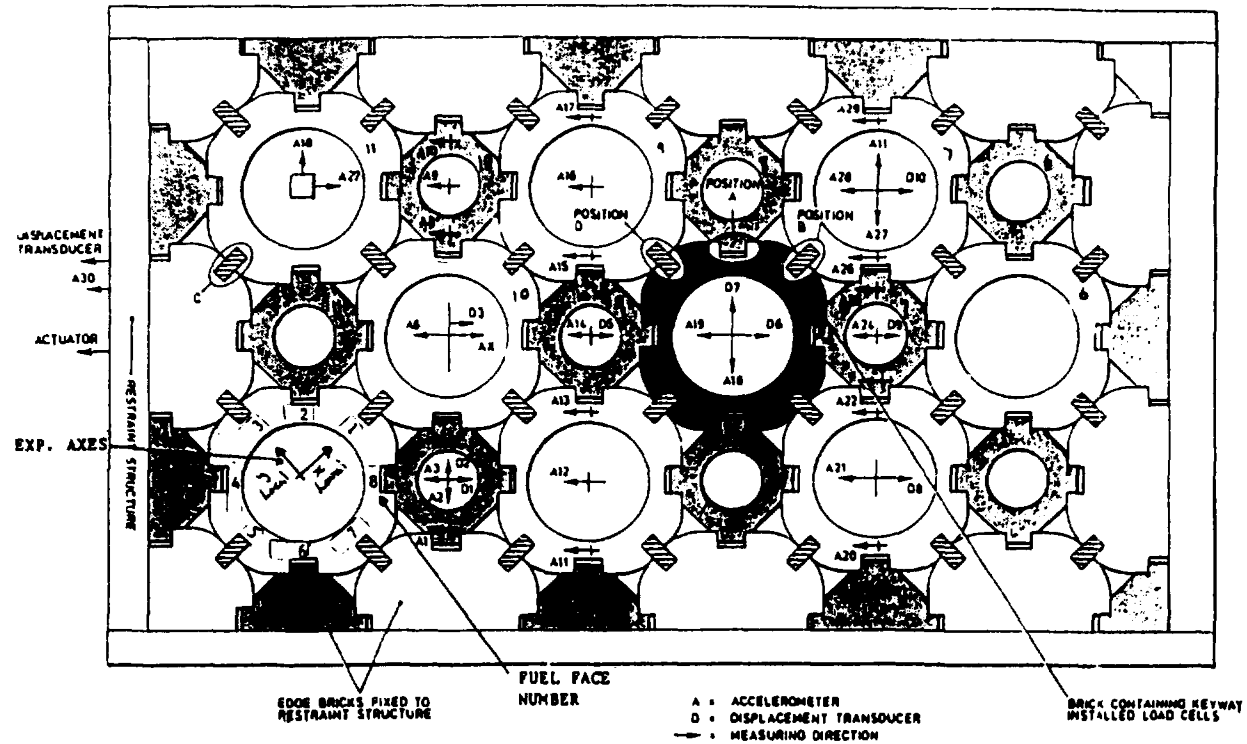


FIG. 10. Core brick slice test assemblages (2 × 1 arrangement).

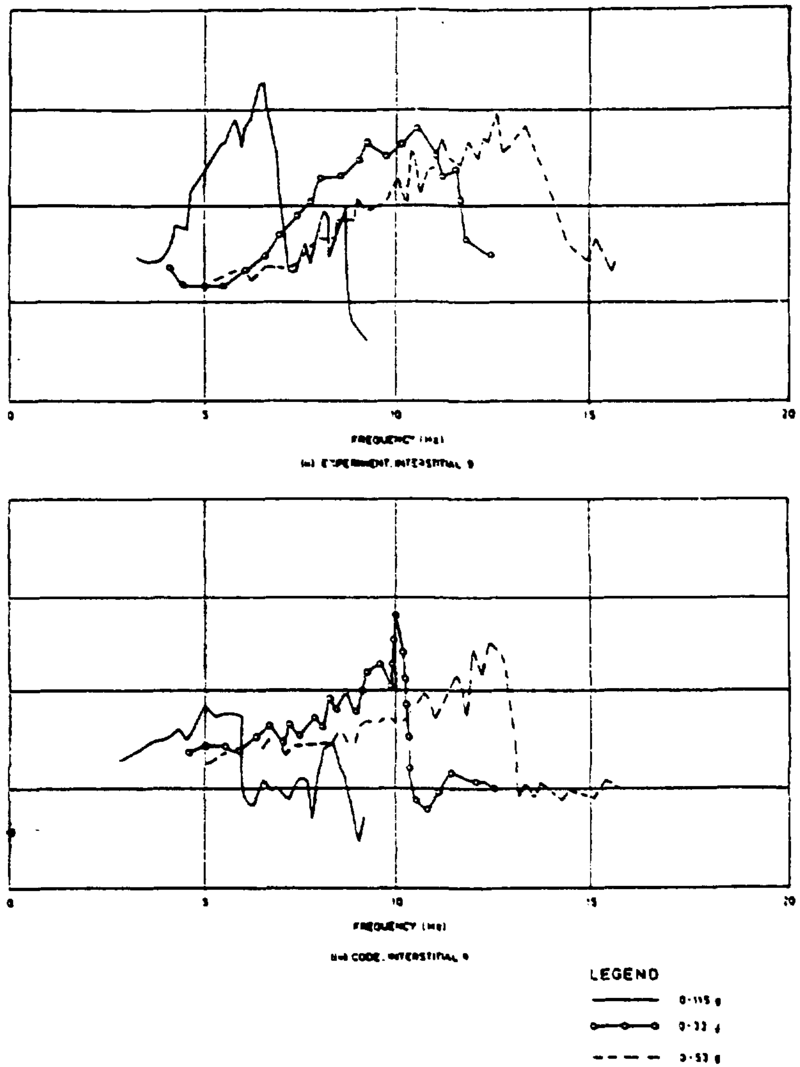


FIG. 11.

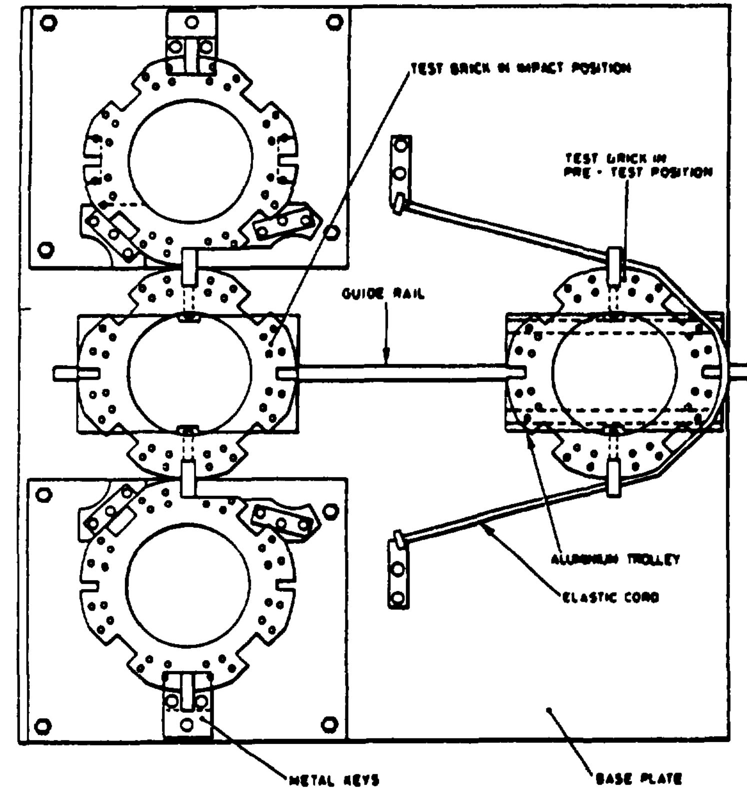


FIG. 12. Impact damage test rig.

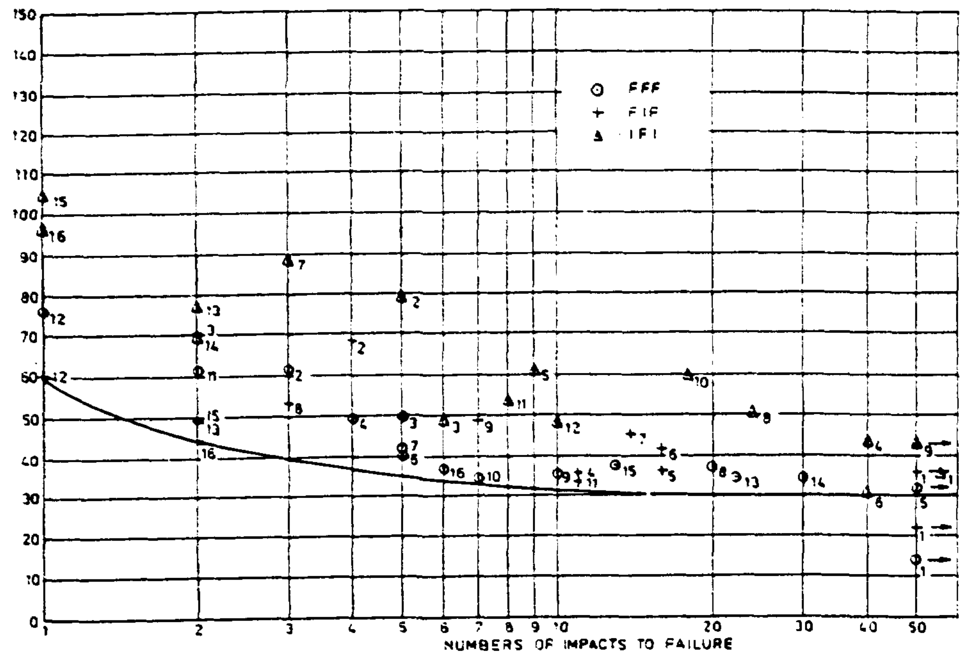


FIG. 13. Impact damage endurance curve.

### 3.3 Core Analysis

A three dimensional rigid mass/contact spring approach was adopted for the core analysis, solved by the specially developed code AGR CORE. For each core brick contact springs were specified at three elevations for each contacting surface. Eleven different types of spring/dashpot element were required to represent the possible contact points, i.e. face to face normal, face to face shear etc. By taking advantage of symmetry only a plan half model of the core was subject to final analysis but, even so, nearly 570000 degrees of freedom were represented.

The excitation was provided by artificial time histories generated to match the PCPV spectra which, as described above, are consistent with a peak ground acceleration of 0.25g.

The results of the analysis indicated that a small number of keyway loads exceeded the peak values which would be acceptable for 30 impacts. By assessing the cummulative damage for these locations it was finally idencified that impacts at the keyway locations of only six bricks exceeded the acceptable load. Because of the high degree of redundancy in the core the consequence of these possible failures at the SSE level was clearly acceptable.

## 4. CONCLUSIONS

A combined test and analysis approach has been used to provide the seismic qualification of both boilers and core structures for the AGRs at Heysham II and Torness. In the case of the boilers the test results enabled a suitable analytical approach to be identified efficiently with the added advantage of test validation, albeit at small scale. For the core the qualification would not have been feasible by analysis alone and substantial testing was required for both validation and integrity demonstration.

## ACKNOWLEDGEMENTS

The work described in this paper was carried out under contract to CEGB and SSEB. The boiler analysis was carried out by Principia Mechanica Ltd. under sub-contract to NNC. The author would like to thank NNC for their kind permission to publish this paper.