Finite Element Stress Analysis of a Gas-Cooled Reactor for Its Reassessment After 25 Years' Operation

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SUMMARY

The ability to analyse the performance of complex structures has improved considerably over the last quarter-century, particularly with the availability of computers and the finite element system. This paper presents a series of finite element analyses undertaken as part of a programme of reassessment of a gas-cooled nuclear power station commissioned over 25 years ago.

The aim of the analyses was to evaluate the general stress levels in the reactor shell and primary cooling circuit under various loading conditions and then to carry out more detailed studies of areas of particular interest, where high localised stresses were expected. The results for this 25 year old design were then assessed in the light of modern acceptable stress limits, and compared with anticipated values where possible, such as strain gauge readings for the initial proof testing of the vessel.

Good agreement was obtained between the calculated and expected results and the code comparisons showed considerable redundancy in the original design.

1. INTRODUCTION

The Calder Hall and Chapelcross nuclear power stations were designed and constructed in the 1950s, and after 25 years' successful service, the operators were required to carry out a comprehensive safety review for their licensing authorities. As part of this review, British Nuclear Fuels Limited have undertaken a programme of reassessment including a study of stress levels in the reactor vessels and primary cooling circuit, as well as comprehensive safety appraisals and NDT inspections.

Analysis capability as well as nuclear codes of practice have changed considerably since commissioning of these reactors, and in order to evaluate operating stresses in greater detail, and to see how the design compares with present allowables, Atkins Research and Development have carried out a series of finite element analyses of vessel and cooling circuit components.

2. THE REACTORS AND COOLING CIRCUITS

Each of the two stations is made up of four carbon dioxide cooled Magnox reactors of very similar design, rated to produce approximately 240 MW of electricity. Figure 1 shows a reactor vessel and Figure 2, one of its four identical cooling circuits.

Each reactor vessel is 37 feet in diameter and 70 feet high, and is constructed mainly of two inch thick low carbon mild steel. It is basically axisymmetric with the exception of the inlet and outlet areas and the supports. The four inlets have their own manifold projected beneath the bottom dome in order to avoid heavy plate reinforcement. At the top of the vessel this was not possible and the four outlet ducts are reinforced locally with three inch and 4.5 inch thick plates. The gas sampling tubes also penetrate the vessel here. At the level where the inlet manifold joins the bottom dome, reinforcement is required, and this is done by using a much thicker section, formed from a forged ring.

The vessel is supported on 20 brackets spaced around the circumference of the lower dome. Matching each of these brackets on the inside of the shell is another bracket supporting the 1400 ton weight of the reactor core. In this way, the core weight does not have to be carried any distance by the shell. The support legs are arranged such that they can deflect freely in the radial direction in order to cope with thermal expansion.

Access for charging and discharging fuel elements and for positioning control rods is achieved through the top dome. There are 112 charge tubes, set in a square matrix, and these rest on, and project up from, the top dome. Beneath them, inside the vessel, a framework supports the sampling tubes and keeps them clear of the charge and discharge operations.

The complete vessel is covered with nine inches of lagging topped with aliminium plate.

Each of the four identical cooling circuits (Figure 2) for the reactor has a heat exchanger and circulating pump (blower) sited separately.

Linking the components to complete the circuits are three 54 inch bore 3/8 inch thick ducts. These are constructed with 90° cascade bends and expansion bellows in such a way as to allow thermal expansion of the system without producing large stresses in the ductwork or the points of attachment to the main components. The duct sections are joined by seal welded flanges designed to minimise the amount of on-side welding and 24 constant load hangers are used to support their weight. Cold draw was used at the initial installation to ensure an optimum distribution of stress under the cyclic loading conditions, but these have relaxed during service.

Under normal operation, the vessel and cooling circuit have an internal pressure of 100 lb/in^2 The CO_2 coolant enters the bottom of the reactor vessel at 150°C and leaves at the top at 345°C.

3. SUMMARY OF ANALYSES

The Reactor Components were analysed using the Atkins finite element program ASAS and its associated post-processors. The analyses covered three loading conditions: normal operation, overpressure test condition and initial proof test condition. In the first condition, the reactor is subjected to a working pressure of 100 lb/in^2 and inlet and outlet gas temperatures are 150°C and 345°C respectively. The second case investigates the effect of increased pressure at reduced temperatures, and here the pressure is 112.5 lb/in^2 and the temperatures 100°C and 140°C. The third case was considered to simulate the initial proof testing of the vessel and cooling circuit components. This not only indicates the largest mechanical stresses imposed during the life of the reactor, but also enables direct comparison to be made with strain gauge readings taken during testing. Initial proof pressure on the reactor vessel was 135 lb/in^2 whilst the duct components and heat exchangers were tested to 237.5 lb/in^2, all at room temperature.

In order to evaluate general stress levels in the reactor and cooling circuit, as well as detailed studies of highly stressed areas, a sequence of analyses was necessary, the detailed analyses relying on previous results for their boundary conditions.

The first analysis was of the cooling circuit. This was a simple model of the three parts of the circuit, with expansion bellows and stiffened bends, and it provided the duct forces necessary to form the loading in detailed analyses of the ductwork components, as well as the heat exchangers and reactor itself.

The first model of the reactor idealised a quarter-symmetric section of the complete vessel shell, though fairly coarsely since, again, this was done to produce the boundary forces for the detailed examinations. This model used the ductwork forces evaluated in the first analysis at the inlet and outlet duct attachment positions. The mesh for this is shown in Figure 3. As well as providing boundary conditions, this model was also useful in establishing general stress levels in parts of the vessel which were not analysed in detail.

Having run these two simple models, boundary conditions were established for all of the detailed analyses of the vessel and cooling circuit.

The first detailed analysis to be carried out was of the outlet region. A quarter-symmetric model (Figure 4) of the top of the cylindrical part of the reactor was chosen, using thin shell elements to model the vessel wall as well as the thickened reinforcing plates and the stub ends of the outlet duct. This anlaysis is discussed in more detail in Section 4.

The second detailed analysis was of the reactor support region, where not only must the weight of the vessel shell be carried without local overstressing, but also the weight of the core must be transferred and thermal expansion of the complete vessel accommodated without adding to stresses in the shell. A thin shell element model (Fig. 5) of a 9° sector was used to assess this, idealising half of one of the 20 support arrangements, and taking advantage of the 1/40th cyclic symmetry that exists here.
Just below the support region, there is a severe discontinuity in the vessel profile where the inlet manifold is attached to the bottom dome and an axisymmetric analysis was carried out of the large forging used to stiffen this section. This forged ring is 12 feet in diameter and is designed to be stiff enough to prevent unacceptable bending stresses which would otherwise occur here due to the internal pressure. Figure 6 shows the mesh for this analysis.

The diagrid carrying the 1,400 ton core is itself supported from adjacent to the main reactor supports. The diagrid is a rectangular grid framework, lying horizontally across the full diameter of the vessel. At its outer extreme is a circular ring girder resting on support brackets which transfer the load directly through the vessel shell into the support columns. Assuming 1/8 symmetry (45° sector), a beam model of this component was used to check that deflections were within limits required for the graphite moderator.

Above the moderator, charging and discharging takes place through the 112 charge tubes set in a square matrix in the top dome, and a portion of this was modelled with shell elements in order to establish the severity of local stresses in the hemispherical shell created by the weight of the tubes in combination with the internal pressure and thermal gradients.

Outside the reactor, two analyses were carried out of cooling circuit components. Quarter-symmetry was assumed for models of both top and bottom halves of a heat exchanger (Figure 7), and a 90° cascade bend in the cooling circuit ducting was idealised with a fairly detailed shell model (Figure 8), utilising one plane of symmetry.

4. ONE ANALYSIS IN MORE DETAIL

One of the earliest models of the outlet region (Figure 4) was typical of the analyses undertaken, and is described in a little more detail here.

At the top of the cylindrical part of the vessel, the two-inch thick shell is replaced by a 4.5" thick plate, approximately square, at each of the outlet ducts. At the same height, eight 12 inch diameter tubes carry the gas sampling pipes through the vessel wall and these are located in two groups of four on opposite sides of the vessel, mid-way between pairs of outlet ducts. To reinforce these penetrations, three inch thick plate replaces the two inch shell, extending to meet the adjacent outlet plates. All plates have their edges tapered on the outside to meet the adjoining shell (they are flush inside) and the 42" outlet duct nozzles have their ends thickened to 1.75" where they penetrate the vessel. Almost immediately above the reinforcing plates, the cylindrical part of the vessel ends and the hemispherical dome begins.

Thin shell elements were used to model a 90° sector, extending sufficiently above and below to cover the discontinuities. Circumferential boundaries were restrained quarter-symmetrically and forces from the "Quarter-Symmetry" model applied at the upper and lower edges. Forces from the ductwork analysis were applied to the duct stub and internal pressure, self-weight and temperatures applied in the three complete load cases considered.

After the finite element run, post-processors were used to calculate average nodal stresses, both direct and principal, and to plot contours of these for inner, middle and outer surfaces.

The results showed a combination of effects. Temperature variation and duct forces caused some local bending with self-weight being almost insignificant. Internal pressure, however, was dominant. This caused considerable bending stresses in the 2" thick shell horizontally adjacent to the reinforcing plates from two effects: the greater stiffness of these plates tended to increase deflections next to them and also, the radially eccentric positioning of the plates combined with the circumferential stress to create a local moment. Fairly high bending stresses were also obtained in the knuckle region above the plates

5. ASSESSMENT OF RESULTS

Apart from hand calculations to confirm general stress levels and check loading and reactions, results were assessed in two ways.

Firstly, maximum stress intensities were evaluated from the principal stresses and checked against the ASME III allowables. These are not strictly relevant of course, since this code was not used for the original design, but they served as an indication of the significance of the highest stresses in the light of modern standards. In the absence of a specified design condition, normal operating stresses from primary loading were checked against the design allowables of S_m and 1.5 S_m for membrane and surface respectively; and both complete operating cases were checked against normal 3 S_m limits. In all cases, stresses were within the allowables, and at the majority of discontinuities, secondary stresses were within primary stress limits.

The other assessment made was the comparison of results with strain gauge readings taken during initial proof testing of the vessel and ductwork components. Many strain gauge readings were taken at this stage, particularly where high stresses were anticipated, and inner and outer surface direct stresses from the initial proof test load cases in the finite element analysis were compared directly with these measurements. Good agreement was obtained at the positions considered, indicating satisfactory representation of the structure and loading.

6. CONCLUSION

A number of detailed analyses were successfully carried out of parts of the reactor vessel and cooling circuit components, based on boundary conditions established with two coarse models. Results were compared with strain gauge readings and with the ASME III allowables. Good agreement was obtained between the calculated and expected results and the code comparisons showed considerable conservatism in the original design.

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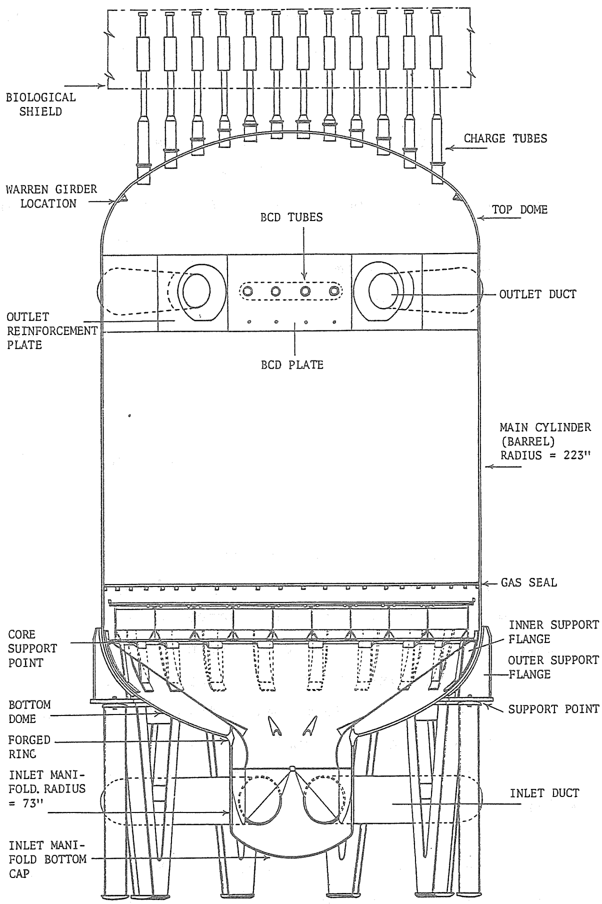

FIGURE 1 The Reactor Vessel

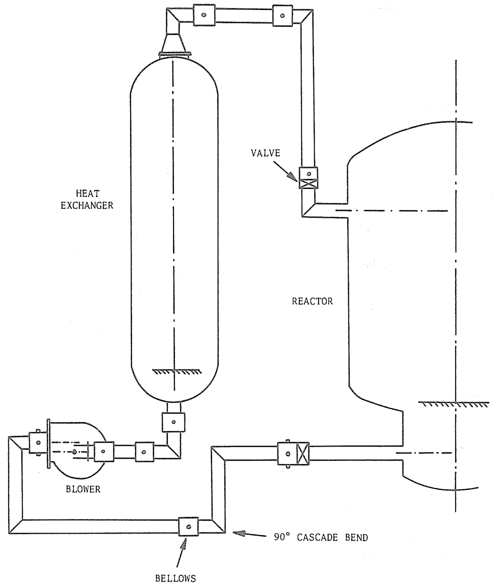

FIGURE 2 Primary Cooling Circuit

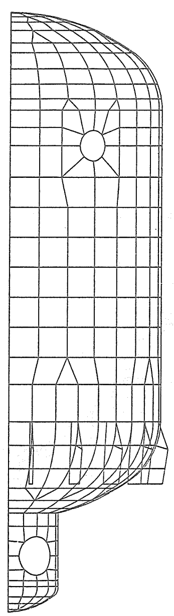

FIGURE 3 Quarter-Symmetry Model

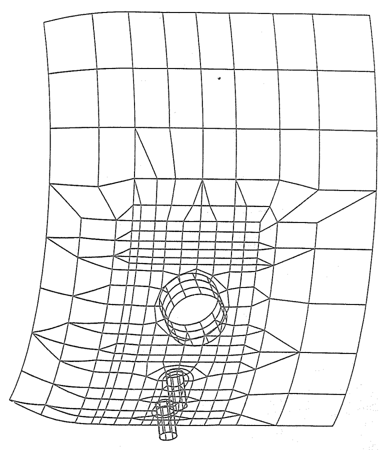

FIGURE 4 Outlet Region Model

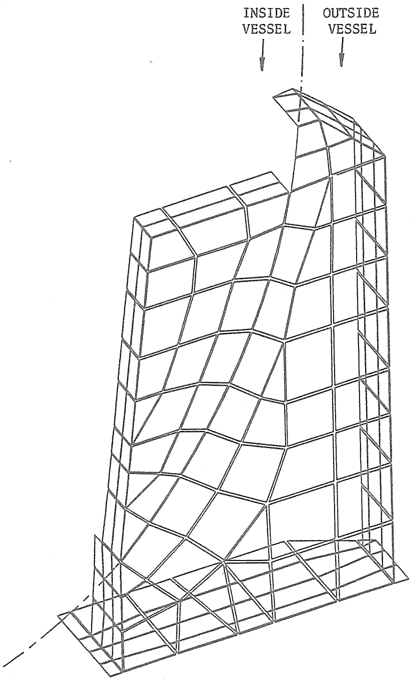

FIGURE 5 Support Model

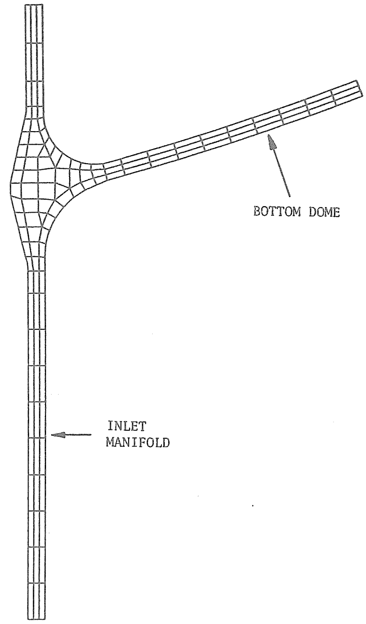

FIGURE 6 Forged Ring Model

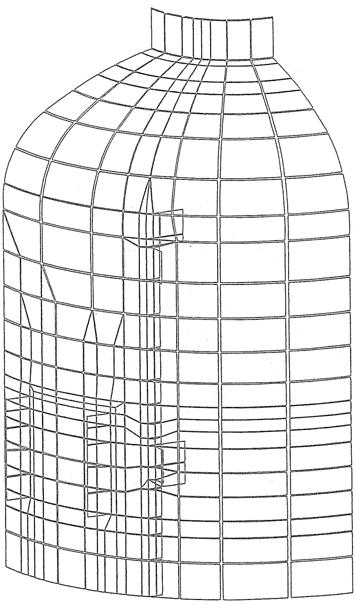

FIGURE 7 Heat Exchanger Model

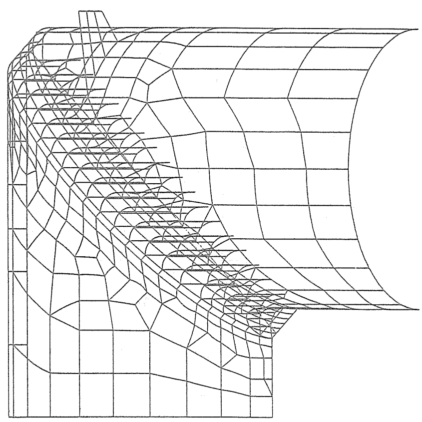

FIGURE 8 Cascade Bend Model