BRIEF REVIEW OF THE DOCUMENTS RELATING TO THE GRAPHITE MODERATOR CORES AT HINKLEY POINT B AND OTHER ADVANCED GAS-COOLED REACTORS

DOCUMENT BUNDLE OBTAINED UNDER THE FREEDOM OF INFORMATION ACT 2000

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GRAPHITE MODERATOR CORES AT HINKLEY POINT B AND OTHER ADVANCED GAS COOLED REACTORS

SUMMARY

This review provides a technical interpretation of a bundle of documents recently released under the Freedom of Information Act 2000 (FoI). The documents, in the form of extracts from Assessment Reports of the Nuclear Safety Directorate (NSD), relate the degraded condition of the graphite moderator core in each of the twin, advanced gas-cooled reactors at Hinkley Point nuclear power station.

The graphite core of an AGR is a central nuclear safety component. The core is a loose stack of several thousand graphite bricks assembled to form a facet-sided cylinder of about 12m diameter by 10m height. The core serves to moderate (slow) the neutrons initiating fission in the nuclear fuel, within it are formed about 330 vertical channels that receive stringers of nuclear fuel, it provides for the high pressure flow of the carbon dioxide gas coolant and, importantly, vertical interstitial channels for the entry of control and shut down rods and, if needed, the secondary and emergency reactor close down systems. For nuclear safety it is absolutely essential that the vertical fuel and interstitial channels remain closely aligned during normal service operation and fault conditions under which abnormal forces may arise across the core assembly overall and within the individual graphite bricks.

Loss of channel alignment could result in difficulties in moving the fuel stringers out of the reactor, localised overheating and failure of the fuel because of restricted cooling gas flow, and difficulties in inserting the control rods to shut down the reactor. The nuclear safety case of the AGR system absolutely requires the core assembly to remain intact during all fault conditions, so much so that the designers originally built in sufficient residual strength reserves to accommodate the then expected age-related degradation of the core components.

The extracts from the FoI documents, together with other papers and reports from both British Energy (BE) and NSD, reveal there to be significant uncertainties over the structural integrity and residual strength of the moderator cores in other AGR plants (in addition to Hinkley Point) at Hunterston, Heysham 1 and Hartlepool. Despite heavy redaction, the documents hint that the remaining 6 AGR reactors at Dungeness, Heysham 2 and Torness are also subject of these concerns so, in total, there is uncertainty about the safety of 14 reactors at all 7 UK AGR nuclear power stations.

The nuclear safety issues identified by NSD are:

- A number of the graphite bricks that make up the moderator cores of the Hinkley Point reactors are extensively cracked.
- The operator BE has not yet developed a full understanding of why the cracking is occurring and it is unable to reliably (statistically) extrapolate how many core bricks may be similarly damaged from the limited in-core inspections available during the periodic shut downs of each reactor.
- BE has been unable to establish the level of cracked bricks (numbers and locations) tolerable within the core before the residual strength of the core falls below the minimum required for the reactor nuclear safety case.
- Because of significant uncertainties the Nuclear Installations Inspectorate has, or is about to, impose a requirement for more frequent in-core inspection of a greater number of fuel channels than BE has hitherto agreed to undertake.
- Even with more frequent and probing in-core inspections, there are currently no means of detecting hidden but developing sub-surface cracks, so it is entirely possible that this age-related damage may be much more extensive that presently determined.

The upshot of all of this is that, for the reactors at Hinkley Point B nuclear power station, the NSD has concluded that there is uncertainty about the fault condition performance of the cores. Although the NSD argues against the occurrence of a large radioactive release being triggered by a serious incident, it does acknowledge the possibility of a lesser fault condition may arise in the form of impediment to control rod entry and/or fuel movement.

It is not the purpose of this Review to examine the potential outcomes of the fault scenarios alluded to by NSD. However, the lesser fault condition would more than likely lead to irrevocable damage to the graphite core, long term or permanent closure of the reactor together with its twin reactor at the nuclear power plant affected, and probably most of or the entire AGR series of nuclear power stations – in this lesser fault incident the radiological consequences would most likely be confined to the power plant site. There are a number of possibilities whereby the structurally degraded graphite core of a reactor subject to a serious event, even though within the *'design basis'*,[1] could collapse and trigger a cascade of adverse events that might culminate in off-site radioactive release and serious radiological consequences – this situation might arise if the residual strength or *'redundancy'* of the core had degraded below the minimal level specified in the original design.

The NSD's most recent assessment of the continuing operation of the Hinkley Point reactors concludes unambiguously "*there is I believe an increased likelihood of increased risk should we agree to continued operation*". There can be no other interpretation to this than that, by allowing the AGR reactors to continue in operation under such uncertainties, the

1 *'Design Basis'* accidents and incidents are those that are reasonably foreseeable to occur during the lifetime of the plant so the plant should survive such with acceptable radiological consequences on- and off-site. For example, since it is expected that there is a likelihood that a boiler or superheater pipe will fail, the result of which is that water/steam will burst into the reactor space giving rise to a rapid rise in gas-steam pressure, then the core structure has to have sufficient residual strength or *'redundancy'* engineered in to withstand this *'design basis'* incident.

NSD has deemed, in the absence of any public accountability, that the public are placed at *additional* risk of exposure from a radiological incident.

I consider the decision to permit the Hinkley Point and other AGR reactors to continue in operation to be misjudged: This is because it is not based on the present residual strength of the core structure to withstand a major in-core event since the condition of the core, as the NSD itself admits, is unknown and subject to *"significant uncertainties*" at this time. More so, in promoting the line that only a limited damage (lesser) consequence case is possible, the NSD has to assume that a major but design-basis in-core event (such as a boiler water/steam intrusion, a rapid primary coolant depressurisation, external seismic event, etc) will not be sufficient to overcome the uncertain residual strength of the damaged and degraded graphite core.

Put another way, the NSD's approach relies upon, on one hand, a gamble that a more serious, design-basis event will not occur during the remaining lifetime of each of the AGR reactors but, on the other hand, if it does then as chance would have it the graphite core will remain intact with most of its fuel and control rod channels aligned.

Other issues that arise from the FoI papers reviewed include:

- The NSD has called for more frequent and probing inspections of the graphite cores at Hinkley Point and the other AGR plants at Hunterston, Heysham 1 and Hartlepool – the inspections require shut down of the reactor and removal of a number of fuel stringers from at least 24 channels the core.

Putting aside the public safety issue, the fact that at least 8 reactors (~4,800MWe capacity) are now required to operate with more frequent generating outages for extended core inspection results in a high financial penalty to be borne by BE. If, as implied by the FoI extracts, all 14 AGR reactors are now subject to more frequent inspection outages then about 85% of BE's total nuclear capacity is required to operate at a reduced annual generating output.

- There are a number of instances in the document extracts in which the NSD expresses dissatisfaction with the progress being made by BE in addressing the graphite issue. As late as November 2005, these included charges of the *'lack of clarity'* on the BE proposed strategy and its research projects to understand cracking, *'continuing uncertainty'* of the prediction modelling for the number of cracked bricks in the core, *'lack of evidence'* to demonstrate that improvements had been achieved, and the *'uncertainty'* in successful completion of the monitoring strategy imposed by NSD.
- It seems that as late as April 2006 the NSD was still awaiting a revised nuclear safety case, particularly in account of the high radiolytic weight losses predicted to occur in the AGR cores at Hinkley Point although, now just two months following, both reactors at Hinkley Point B are in full operation.

These last two issues should give rise to considerable public disquiet because:

- here is the operator of 14 nuclear power reactors being criticised on its progress and knowledge of an issue that bears directly on nuclear safety - it does not understand why the cracking is occurring, how extensive it is throughout the moderator cores, and hence what is the level of residual strength of the core to resist an untoward fault condition; with
- this criticism being made by a nuclear regulator who has permitted 2 (Hinkley Point B) or more AGR plants to resume operation in the absence of a fully revised and established nuclear safety case; and, moreover
- the regulator has permitted a resumption of power operation at Hinkley Point, and most likely at the other AGR plants, knowing that this is accompanied by increased risk of accident and radiological incident in the public domain but it has not, apparently, demonstrated and qualified that this additional level of risk is acceptable with the radiological consequences of any incident being tolerable.

Overall, from study of these FoI extracts and reports, albeit in places heavily redacted, the approaches of the nuclear regulator and the plant operator seem to have been disjointed over the last four or so years since the issue has been identified to be a nuclear safety problem. Indeed, since the nuclear safety aspects of the weakening cores became known there seems to have been little progress from both the regulator and the operator, it being almost as if the issue is developing and advancing so fast, that both organisations are scrambling but failing to keep abreast of it.

Whereas I agree with NSD that there are significant uncertainties about the fault condition performance of the graphite cores, I would go further with my opinion that, in view of the increased risk presented by continued operation of these nuclear plants, the reactors should be immediately shut down and remain so until a robust nuclear safety case free of such uncertainties has been established.

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CONDITION OF THE GRAPHITE MODERATOR CORES AT HINKLEY POINT B NUCLEAR POWER STATION

1 INTRODUCTION

I[2] have been instructed by Greenpeace UK to review and comment upon a bundle of documents obtained by the Stop Hinkley campaign group[3] in response to a request to the Nuclear Installations Inspectorate (NII) division of the Health & Safety Executive (H&SE).

2 DOCUMENT BUNDLE

Comprising 14 pages of extracts from 4 Assessment Reports of the H&SE Nuclear Safety Directorate (NSD), the pages are heavily redacted under S38 and S43 exemption criteria of the Act. The Assessment Reports[4] date from September 2003 through to April 2006. The subject matter of the FoI request specifically related to cracking of a number the graphite moderator bricks that make up the core of each of the two advanced gas-cooled reactors (AGR) at the Hinkley Point B nuclear power station.

There is another NSD document, obtained by other means, in the form of a 4 page letter dated December 2004,[5] that relates the cracking of the graphite moderator core blocks in the Hinkley Point B reactors to the graphite cores of other very similar AGR nuclear power stations at Hartlepool, Hunterston, and Heysham 1. In addition, I have accessed and studied further confidential documents comprising a bundle of 94 pages of letters, meeting notes, further NSD Assessment Reports and extracts for the period October 2004 through to February 2005, all of which address the issue of core damage in the AGR series of nuclear reactors in the United Kingdom.

I consider it important to review all of these documents together, particularly in that the earlier documents from October-December 2004 and in June 2005 show that the NII placed a number of mandatory actions on the operator British Energy (BE),[6] and that the later documents of November 2005 and, the most recent, April 2006, provide a telling insight into the NSD's dissatisfaction with BE's progress and, importantly, the NSD's continuing doubts about the nuclear safety case of the graphite cores.

3 ADVANCED GAS-COOLED REACTORS – AGR

Each AGR nuclear power station comprises two identical reactors of 600-660MW$_e$ generating output. British Energy owns and operates all 7 AGR nuclear power stations in the United Kingdom[7] with this capacity being 16% or thereabouts of the total UK generating capacity. The AGR reactor and its moderately enriched (2.5 to 3.5% U-235) fuel system are unique to the UK, there being no other similar plants operating elsewhere internationally.

The AGRs were built during the period 1976 through to 1989, with the first being the twin reactors at Hinkley Point B (commissioned into service in 1976 and 1977), and the last at Torness (1988/89). Dungeness B was scheduled to be the first operational AGR but it run into substantial technical and

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3 Stop Hinkley www.stophinkley.org

4 NSD DIV 1 AR No 44/03, 27/05, 66/05 and 164/05

5 NUC 452/13 P14 E31

6 These actions (a precondition of the Site Licence) required BE to:

- modify the in-core monitoring and inspection arrangements (5 actions);
- prepare and submit new safety cases for all four reactors at Heysham 1 and Hartlepool to account for the graphite core defects not included in the then existing nuclear safety case, included with this a revised Technical Assessment Guide to judge the adequacy of the graphite core safety case;
- studies to determine the long-term hold down requirements at low and zero levels of Xenon present – ie the minimum number and dispersion of control rods to maintain the reactor shut down in the event core distortion barring the entry of a number of control rods;
- application of a proven model to predict the number of 'doubly-cracked' bricks in excess of the 'tolerable' limit of 200 over a the following three-year period (ie until 2007); and
- develop a credible graphite research programme to improve understanding and reduce uncertainty.

The Nuclear Safety Directorate subsequently increased this requirement to 9 actions (June 2005).

7 The AGR units operated by British Energy in the UK. These are Dungeness, Hinkley Point, Heysham 1 and Heysham II, Hunterston, Torness, Hartlepool, that is a total of 14 reactors. BE also operates the single pressurise water reactor (PWR) at Sizewell at ~ 1,300MW so the AGRs provide about 88% of BE's nuclear capacity. The remaining nuclear capacity in the UK operate by Magnox Electric being the Magnox plants totalling about 2,000MW with just (or shortly to be) Wylfa and Oldbury remaining in service and all other plants being shut down.

construction difficulties with its reactors eventually commissioning 11 and 14 years overdue. It is unlikely that further generic AGR plants will be considered for future new nuclear builds in the UK or elsewhere.

Being gas-cooled and graphite moderated, the AGR reactor is relatively bulky compared to the light water reactor designs (PWR and BWR), so large that the reactor core and the concrete pressure vessel had to be fabricated on site. Life limiting factors of the AGR engineered design are the in situ cast concrete pressure vessel that provides the sole containment barrier[8] and the graphite moderator core which degrades over time (neutron irradiation), there being no facility in the core design to replace the thousands of individual graphite bricks that make up the core assembly – for explanation of the terms and jargon used in this Review see APPENDIX I.

On these pressure vessel and core factors alone, the operating life chosen at the design stage is believed to have been 30 years. However, a 35 year target life has recently been identified so the earliest 1976 commissioned AGR reactors at Hinkley Point and Hunterston would be expected to be retired by 2011 or thereabouts.

4 GRAPHITE MODERATOR CORE

Design and Geometry: The purpose of the graphite core is to slow or moderate the active neutrons to improve the efficiency of fissioning the Uranium-235 fuel component, and to provide about 330 individual channels for housing the fuel assemblies (stringers) and routing the carbon dioxide coolant flow through and past the fuel stringers. The core also contains interstitial channels for neutron flux monitoring, entry of control rods deployed for reactor control and close down, and the nitrogen and boron bead emergency purge systems deployed for emergency shut and hold down situations.

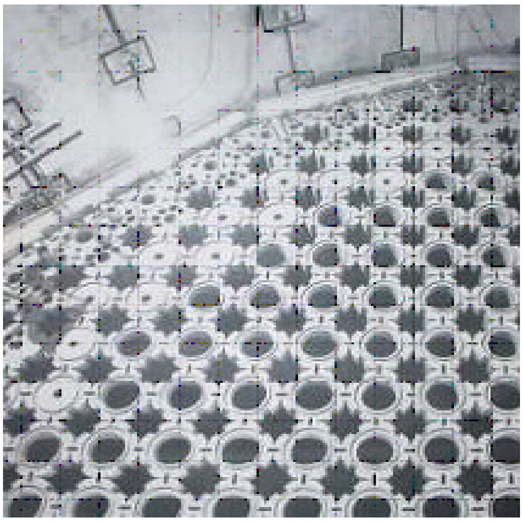
The reactor core is a loose assembly of graphite bricks that are stacked to form a massive, sixteen sided structure that is about 12m diameter by 10m height, all contained within a steel-walled restraint tank. The individual bricks are interconnected with vertically located graphite keys or slats so that columns of hollow bricks form the continuous fuel channels of about 230mm diameter running from bottom to top of the core. The nuclear active section of the core is about 10 brick courses high, adding to this there is a base course of bricks under the active core and, above the core, further courses forming the neutron reflector. Surrounding the active core are solid graphite bricks serving both as shielding and the mechanical linkage to the enclosing restraint tank. Base, neutron reflector, shielding and active core sections comprise, in total, about 6,000 graphite bricks.

The overall core assembly perimeter is restrained laterally by turnbuckle links attached to the core restraint tank. These turnbuckles and the restraint tank accommodate lateral and vertical movements of the core components generated by the temperature and gas pressure reduction across the core when the reactor is in normal operation. In an abnormal fault condition where the core structure is at risk of distortion, the tank should maintain an acceptable alignment of the interstitial control rod, nitrogen gas and boron bead channels to the feed standpipes located overhead in the pile cap.

GRAPHITE BRICK MODULE
NOTE THE KEYWAY GROOVES AND CUT-OUTS FORMING THE INTERSTITIAL CHANNELS – THE FUEL STRINGER IS LOCATED IN THE CENTRAL CHANNEL

Within the core stack, the interbrick keying system provides the horizontal brick-to-brick connection and vertical restraint by the interbrick shear connections. Each column or tier of bricks is supported by a radial-rocking stool which limits the profile distortion of the lower sections of the fuel and control channels, and serves to isolate radial movement of the core from the supporting steel diagrid structure.

8 Effectively, the AGR system has no secondary containment although the primary reinforced concrete pressure vessel is massive thick walled structure.



HEYSHAM II AGR CORE
THE CORE UNDER CONSTRUCTION – THE FUEL CHANNELS ARE THE CIRCULAR BORES AND THE INTERSTITIAL CHANNELS ARE SPANGLED SHAPED MANY OF WHICH WOULD BE FITTED WITH CLOSURE CAPS – THE BRICKS TOWARDS THE CORE PERIPHERY ARE SHIELDING AND SAMPLYING – THE 4 KEYS CONNECTING EACH BRICK TO ITS NEIGHBOURS ARE SHOWN AS STUBBY BARS

Irradiation, Thermal & Material Characteristics: When subject to high levels of neutron bombardment or irradiation, graphite[9] undergoes a number of changes, some of which are irreversible and generally deleterious to the structural performance of the graphite core. Since the changes related to the total number of neutron interactions over time whilst the reactor is in operation, irradiation degradation is referred to as ageing. Also, other changes are generated in the graphite due to thermal cycling and chemical interaction and, similarly, in effect these changes are also age-related.

Of the irradiation changes, at the AGR higher core region temperatures both the modulus of elasticity (E)[10] increases by a factor of two with, similarly, the shear modulus (G) increases by a factor of three, and there occurs significant amendment to the coefficient of friction between contacting graphite surfaces.

Prolonged irradiation also promotes dimensional changes in pyrolitic graphite promoting growth in the basal planes and shrinkage in the direction parallel to the basal planes. This asymmetric dimensional change[11] will subject the individual bricks to a reversal of stress loading, moving the tensile regime towards the root corner of the keyway slot, thereby creating conditions for crack generation and propagation at this localised stress raiser. Also, radiolytic oxidation results in depletion (weight loss) of the graphite and this has been pronounced and a life-limiting factor for the Magnox reactor graphite moderator cores and it will be a consideration in the final shutdown decision for the AGR power stations.[12] Radiolysis will also be important in the structural function of the AGR cores because of the associated increase in porosity of the near surface graphite,[13] all of which could increase the creep rate.[14]

The irradiation (age) related structural performance of the graphite brick components of the moderator core is crucial to the safe operation and ultimate service life of the reactor. This is because it is necessary to undertake engineering analysis at the design stage to determine, amongst other things, the primary and secondary stresses in the graphite components throughout the anticipated life of the reactor, and to determine the levels at which structural failure of the graphite would be predicted to occur – for this analysis the modulus of elasticity (E) relating stress and strain in the graphite is dominant[15] suggesting with its increase a corresponding increase in graphite strength and resistance to cracking as time (irradiation) progresses.

However, irradiation and to a lesser influence thermal and operating pressure conditions running across both the cross section and depth of the core assembly are far from uniform, so much so that the original designers of the AGR system (much of which was undertaken in the 1960-70s) would have made a number of assumptions to

9 So called reactor-grade (pyrolitic) graphite is extruded to maximise the alignment of the basal planes but this results in variation in strength of the binding between the different crystallographic planes – the most obvious difference is the tight binding in the basal planes and the weak binding between the basal planes themselves. This is somewhat analogous to a hank of wool which is strong in the axial direction but utterly weak in the bi-axial direction.

10 Otherwise Young's Modulus, the ratio of stress and strain.

11 Two grades of graphite make up the brick in the core: For the active core and side reflector extruded Grade A anisotropic graphite is used and this which exhibits asymmetric volume changes. The top and bottom neutron shield are moulded to provide more uniform growth properties

12 In the AGR fuel system the fuel modules are held in a graphite cylinder which is withdrawn and disposed of (at reprocessing) after the spent fuel has been withdrawn from the reactor so it serves, to a degree, as a sacrificial element in the graphite moderator system. Nothing is publicly available on the actual and projected rates of radiolytic weight losses for the AGR system, although operating at higher operation pressure it would be expected to be at a higher rate than that the Magnox counterpart. At Hinkley Point B the projected weight loss peak value is expected to about 28% by 2009.

13 The material property changes associated with radiolysis are complex and, perhaps, not fully understood but most likely these relate to changes brought about by radiolysis in the near surface porosity of the graphite brought about by the formation of species of carbon monoxide and methane. The thermal conductivity and Young's modulus (E) and strength decrease with increasing weight loss and the general effect is that of expanding the existing porosity by removal of the surface which may be higher in local situations, such as at the brick keyway root at which the cracking is believed to originate. The extent of weight loss in the longer service AGRs, such as Hinkley Point and Hunterston is not publicly available, although it is believed to be higher than that originally anticipated at the design stage.

14 Changes in the graphite structure which result in a decrease of Young's modulus will alter the creep rate which, in turn, may result in periods of substantial creep strain when the graphite under sustained stress (ie when the reactor is in operation) is followed by an unstressed period (ie when the reactor is shut down and depressurised) and which may contribute to the earlier than expected onset of 'stress-reversal' identified by the NSD in its reasoning as to the cause of the brisk cracking.

15 Young's modulus E increases with irradiation, the strengths in tensile and shear loading conditions increase $\{\sigma \sim (E/Eo)^{0.5}$ where Eo unirradiated and E irradiated$\}$ and the stress at which fractures freely propagate also increases $\{\sigma \sim (E\gamma/C)^{0.5}$ where γ is the fracture energy and C the crack length$\}$.

rationalise the position of the graphite brick within the core and its performance under prolonged irradiation in order to progress the design, although much of this was based on empirical information drawn from irradiation trials at lower temperature and pressure than the operational AGR core – the extrapolation of this data (ie beyond the available data and/or accelerating time) to AGR conditions could have resulted in mismatches of the design and longer term function of the core.[16,17] An important factor that may have not been fully understood at the time, and which probably today still remains subject of some uncertainty, is the role of radiolysis and the local surface conditions created at crucial locations in the core components and core structure overall.

In fact, the H&SE have raised a number of reviews and development issues relating both generally and directly to the AGR graphite core degradation although, that said, many of the AGR specific issues were not raised until autumn 2005 or have yet to be implemented.[18] In one important respect, the H&SE's issues list provides an insight into what it does not know, but what it now needs to know to address the AGR core nuclear safety issue.

Fault Scenarios of Core Multiple Brick Failures: Loads and forces acting on the core during normal service operation, and hence transmitted through the individual graphite bricks, include the self-weight of the bricks acting in columns; the reactive thrust of the main gas flow (pressure drop) up through the individual fuel and operational interstitial channels which results in both vertical and lateral thrust components; the thrust from the interbrick gas distribution that flows down through and across the core; undissipated forces from thermal expansion of the core from its 'cold' shut down state and those arising from time-to-time power transients; and displacement related forces transmitted through brick-to-brick contact surfaces, particularly, at the keys and keyways.

Normal operational service forces are constrained by the self-weight of the core, a layer of steel neutron shielding plates placed at the top level of the core, and by the radial restraint tank. The main operational requirements of the core, apart from its nuclear moderation properties, is that the fuel and control rod channels remain aligned with the overhead standpipes set into the pile cap through which the fuel stringers are charged and discharged and the control rods operate.

Fault conditions are those that abnormally challenge or threaten the continuing alignment of the fuel and interstitial channels, thereby impeding the entry of control rod absorbers for reactor closedown and hold down, and safe removal of the fuel. These fall into two general groups:

1) **Internal Displacement/Misalignment of Core Channel or Channels**

A recognised ('design basis') fault is where a single or limited number of bricks in a tier or column collapses barring fuel stringer and or control rod movement. This loss of a single fuel and/or control rod channel is within the design basis and is handled by automatic reactor SCRAM, with sufficient surplus control rod absorption to bring the reactor out of operation. This fault is likely to be accompanied by restriction of the gas flow in the affected fuel channel, with risk of fuel cladding failure due to overheating of the individual fuel pins during and in the hours following the initiation of the fault sequence. The release of fuel fission product into the primary circuit would normally be contained, although the boiler and circulator gas paths would become heavily contaminated

If the failure of the core bricks spread beyond the single column or channel then the number of fuel pins at risk would be correspondingly higher. In the extreme, where brick failure cascades across a region of the core but providing that this is contained within a single quadrant of the core, then the reactor safety, close

16 My personal recollection when completing research on the AGR fuel stringer charge route, was that the non-linear stress-strain characteristics were approximated with a linear ratio using a Young's Modulus slightly smaller than the small strain values, that is at about 0.8 – much of the graphite material characteristics were extrapolated from the lower temperature DIDO research reactor and from samples extracted from the operational Magnox reactors operating at lower temperatures and pressure.

17 It is not the purpose of this Review to postulate the cause of the cracking, although that said, it does seem that a combination of weight loss and dimensional change, particularly in the areas of the keyways could have resulted in undue levels of stress sufficient to prompt cracking, even though the keys were designed to be 'loose' to accommodate movement and seismic induced movement. Weight loss may be more significant in the inner portions of the brick because of uncertainties about methane (a oxidation inhibitor) delivery via the interbrick flows and methane injection bores (which might themselves be one source of crack initiation) and the ageing effects on diffusion and permeation of the gas through the graphite due to the build up of carbon deposition over the longer term operation.

18 Graphite Strategy Statement, undated, H&SE www.hse.gov.uk/reseacrh/nuclear/nri/open/graphite15.pdf

down and post-trip cooling systems should contain the fault with no radiological consequences occurring beyond the plant boundary.

2) **External Events – Rapid Depressurisation and/or Boiler Injection, Seismic Event**

There are a number of more severe transient and fault condition events that could test the residual strength of the entire core leading to its displacement and thence loss of close and hold down control of the reactor.

These include rapid depressurisation of the reactor containment, for example, by ejection of a feedwater pipe from its pressure vessel entry sleeve, or a circulator fault, the result of which is a sudden and marked increase of pressure drop and force across the core, either laterally or vertically, or both depending on the fault situation, sufficient to displace or corrupt the symmetry of the core channels. Similarly, a sudden increase in pressure, caused by a superheater tail failure and the injection of the higher pressure boiler steam into the reactor space, again developing extraordinary thrusts within the core stack. Another possibly disruptive event is a sufficiently severe seismic incident that could transmit sufficient lateral acceleration into the core, via the supporting diagrid and constraint tank.

Such severe events are within the design basis, that is with the strength of the core as designed being capable of maintaining its integrity and alignment throughout the fault sequence – this being so, the reactor would close down using the control rods or, in the extreme, its nitrogen purge and boron bead standby systems.

However, if the residual strength of the core, or sections of the core, falls below this requirement the thrust and other forces imposed upon the core stack might be sufficient to cause lateral displacement or disruption of the core to the extent that difficulties would arise in closing down the reactor by control rod insertion. In this case, the secondary nitrogen purge system would have to be deployed but this requires frequent replenishment to maintain the hold down of the nuclear processes. The final close down system, the injection of neutron absorbing boron beads, requires a degree of reasonable channel alignment in order to direct the externally sourced beads to the active sections of the core.

Failure to close down and then hold down the reactivity following such a severely damaging incident could result in multiple fuel pin cladding failure, heavy primary circuit fission product contamination and loss of the reactor.[19] My understanding is that large scale disruption of the graphite core and its constraint and supporting structures is not within the design basis and, thus, the reactor would not provide a specific defence, other than designed-in capability, against the consequences of such an extreme failure.

5 CRACKING AT THE HINKLEY POINT AND OTHER AGR REACTORS

In September 2003 NSD reported that a full length, single axial crack had been discovered in the core of one of the Hinkley Point B reactors, comparing this to two other brick cracks that had been discovered sometime (unknown) earlier at another AGR plant. Over the following year NSD reported a number of other failed bricks in the Hartlepool and Heysham 1 reactor cores noting in December 2004 its concern that, at Hartlepool, two 'doubly cracked' bricks[20] had been located in layers (brick courses) 8 and 11 of the core. However, one of these doubly cracked bricks had been observed in a previous periodic shut down of the reactor in 2001 with only a single, partial height crack present. This discovery gave rise to NSD's concern that brick cracking at Hartlepool was ongoing.

19 *'Loss of the Reactor'* means that the reactor could never be restarted because it is simply not practicable to replace the graphite core if it is extensively damaged (say a region of than 5 or so channels) whereas if a lesser fault incident resulted in damage to a single channel this channel might be plugged, the reactor circuit decontaminated for eventual restart.

20 'Doubly Cracked' is a brick where there are two cracks running down the full height of the brick, being located opposite to each other with each crack assumed to have originated in a corner of its respective key channel – in other words, the brick has been cleave in two down its length – see APPENDIX I illustration.

This, reasoned NSD, challenged BE's statistical model[21] for assessing the number of doubly cracked or cleaved bricks in the core, with NSD noting that (direct text quotes from the FoI extracts are *italicised*, explanatory additions *(. .)* and with redacted text enclosed *{. . .}*):

> *'achieving independence (of BE's revised core nuclear safety case) has not been successful in a number of areas'*
>
> *'Many of the judgements made (by BE) in the (core safety) case rely upon a paucity of data and a lack of understanding that the case duly recognises'*
>
> *'There is a lack of predictive capability for crack initiation and propagation leading to significant uncertainty in the prediction of the rate of crack development in the future and that the number of doubly cracked bricks in three years time may be significantly different than that presented in the safety case'*

NSD concludes that

> *'. . . the detailed morphology of the cracks observed in the 2004 periodic shutdowns has challenged the ability to predict future cracking behaviour from modelling work and materials properties data. The safety case for return to service places more reliance on current and future channel inspections than the existing safety case, with the proposed period between inspections being significantly less than the current 3 years between periodic inspections'.*

In the following February (2005)[22] NSD informed BE that its concern on the core safety case extended to the four AGR reactors at Hinkley Point and Hunterston. There is also a reference to a core safety campaign at Dungeness B[23] so, it follows, that revised safety cases are required (with Hartlepool and Heysham 1) for ten reactors in total.

In fact, NSD clearly considers the graphite brick cracking to apply to all of the AGR reactors, that is including Heysham 2 and Torness, itself noting in June 2005 that:

> *'The Nuclear Installations Inspectorate (NII) is faced with significant regulatory issues and decisions to make between now and the end of generation for all of the remaining operating gas-cooled graphite-moderated reactors. This is due to:*
>
> - *The continued observation of unpredicted cracking.*
> - *The prediction of further widespread cracking in the AGRs as a result of ageing processes.*

So, almost two years[24] following the date when NSD had first expressed reservations about the adequacy of the BE's core nuclear safety case, and at a time when most of the ten AGRs first identified to have core problems had been returned to service, and over six months following the NSD pronouncement that BE's modelling and analysis of the issue relied'. . *upon a paucity of data and a lack of understanding*. . ' NSD concluded that:

> *'. . . there is significant uncertainty in the likelihood and consequences for core safety functionality posed by graphite component and core damage. As a result the assessor needs*

21 To undertake a fuel channel accessed inspection of the individual bricks the reactor has to be closedown and cooled so that the gas flow through the channel is minimal and the highly radioactive fuel stringer completely removed. Thus, only a relatively few channels can be practicably inspected during the periodic shut down and, hence, the probability of brick failure numbers has to be projected by statistical means.

22 NII Contact Report, 1 February 2005 Ref No 017/05.

23 The graphite bricks used in the Dungeness (Heysham and Hartlepool) cores have a slightly different keyway design.

24 Two years as referred to in the FoI extracts but it may have been several years earlier that the AGR cracking was been considered to be a significant safety issue. Also, it is doubtful that the original design intent was for the core to tolerate any cracked bricks.

to assume worst case consequences of graphite component and core damage unless the licensee (BE) is able to provide robust arguments.

I judge that due to significant uncertainty that the Precautionary Principle should be adopted for assessment of graphite core safety cases.'

A direct interpretation of this conclusion is that both the risk (of occurrence) of core movement due to a cascade failure of a region of cracked bricks and the radiological consequences of such an event could not be reliably predicted.

NSD returns to this specific conclusion in November 2005 commenting somewhat caustically *'British Energy had provided two responses, which I judged did not fully address the issues'*, going on elucidating how BE had failed earlier actions:

' . . .

- *lack of clarity on how and when BE will address its proposed strategy . . .*
- *continued uncertainty in prediction of the behaviour of Hinkley Point B {and other AGR} cores . . .*
- *lack of clarity in the research in the research projects being undertaken by British Energy to address the understanding of cracking . . .*
- *lack of progress made by British Energy in addressing all issues . . .*

. . .

- *uncertainty in successful completion of British Energy's proposed monitoring strategy'.*

In fact, the latest available report of NSD (April 2006) makes it quite clear that little progress has been made and, indeed, NSD questions the adequacy of BE's revised graphite core nuclear safety case whilst awaiting another safety submission from BE.

The salient conclusions reached by NSD in April 2006 centre about the following issues:

Uncertainties in Core Condition: There still remains considerable uncertainty in the methodology being applied by BE to predict the condition (ie number of cracked bricks) of the AGR cores:

'. . .

there are significant uncertainties in the predictions of the . . . core condition, primarily due to the absence of materials properties data and knowledge as to the cracking behaviour of irradiated graphite . . . whilst keyway-initiated cracking . . . is one possible outcome . . other defect morphologies may be equally likely'.

In other words, now almost three years (although it may have been even earlier) since the cracking damage was first formally raised as a nuclear safety issue, the nuclear safety regulator remains unsatisfied that the operator BE actually understands the degradation mechanisms involved. Clearly, the cracking is the outcome of an ageing process that relates to physical changes to the graphite, but it has not been established exactly what factors are involved – candidate factors include changes in brick shape due to irradiation induced shrinkage and the so-called 'stress-reversal' that places the root of the keyway slot in tension from which cracking may initiate and propagate.

AGR Reactor System Tolerance to the Number of Cracked Bricks: Also, it is clear that there remains doubt about BE's understanding of the core performance in response to fault conditions when cracked bricks are present and, importantly, if and what is the limit to the number of cracked and damaged bricks before the core performance under fault conditions is seriously impaired (ie that is when will the core have insufficient residual strength to withstand the more severe design basis faults outlined previously):

‘. . .

> *[although the BE analysis demonstrates sufficient tolerance to single and doubly cracked bricks] . . . it is not possible to bound all possible component defect morphologies and configurations. Other configurations of defective graphite components may present a greater challenge to core safety functions than singly or doubly cracked bricks ’.*

At this time NSD continues to accept a limit of 10% of brick failures predicted to be within the higher course of the active core (about 200 bricks) but this seems to be based on BE’s analysis of the upper limit for cracked bricks, even though NSD reckon this might not be reliably applied.

Advanced State of Degradation of the Hinkley Point Cores: Conditions leading to further cracking within the bricks of the Hinkley Point reactor cores is specifically identified:

‘. . .

> *Recent core inspection data at Hinkley Point B and {at other AGR reactors} suggest, based upon brick shape change with irradiation shrinkage, that some bricks in the flattened region*[25] *of the core are already at stress-reversal. Sensitivity studies indicate that at this stage some bricks may have passed stress reversal {redacted} and keyway-root initiated cracking is predicted to occur {redacted}’.*

Here NSD’s opinion is that further bricks, in addition to those detected by previous in-core inspections, have commenced the cracking process adding that

‘. . .

> *I judge the likelihood of a challenge to core safety functions over an operating period of 3 years is highly uncertain . . . it is reasonably practicable to increase the core inspection frequency in response to stress-reversal to mitigate (this) uncertainty . . . this will ensure that any component and core degradation this is significantly different to that predicted by British Energy may be detected, an appropriate response developed, before core safety functions are degraded’.*

This conclusion might be considered to be at odds with NSD’s criticism and rejection of BE’s analysis, understanding and its prediction of the cracking, particularly when the same Assessment Report rejects BE’s proposal to reduce the number of cctv in-channel inspections to 18 from a minimum NSD requirement of 24 channels. Indeed, the validity of relying on so few inspections[26] of the many channels in the flattened area of the core relies upon confidence in statistical analysis and prediction which has also been subject to much NSD criticism, particularly in that:

‘. . .

> *There are currently no means of detecting sub-surface keyway-initiated cracks. . . This is a significant shortfall in the safety case.*
>
> *. . . it is essential to develop a means to detect sub-surface cracking from the periphery of the bricks before it is through thickness . . . if this is not achieved there is a reasonable likelihood that extensive sub-surface cracking may be present and subsequent propagation to the surface may occur over as relatively short time period . . .’.*

This NSD opinion casts considerable doubt over the integrity and soundness of the graphite core structure to function under normal service and, particularly, abnormal fault conditions - it is clearly stating that the extent and severity of hidden cracking[27] is unknown and that, if the graphite is in a weakened state, then rapid crack propagation could occur under fault conditions.

---

25 The flattened area is in the central area of the core around the higher levels at courses 7 through to 11 where cracks have already been recorded.

26 A total of at least 24 channels by cctv and 14-15channel bore dimension measurement (ie ovality) – it is not clear from the extract if the bore dimension measurement is to be completed on the channels vacated for cctv inspection or if these are in addition (ie 24 + 15 channels in total).

27 This concern is that upon stress-reversal the crack initiation is from the roots of keyways located on the outside of brick, thus inaccessible to cctv inspection. Since the only other non-destructive examination technique available is measuring the circularity of the channel bore (CBMU), detection is too late and only yields bricks that have actually cracked and cleaved.

The NSD endorses this risk with some caution:

'. . .

> *if inspection is not undertaken at this or similar frequency, whilst I do not believe that a large {radioactive} release due to failure to shut down on demand is a likely scenario, some lesser event (such as impairment of control rod insertion or fuel movement) is I believe inevitable at some stage if a vigilant precautionary approach is not adopted.'*

And, hinting at a 'cliff-edge' situation:

> *'Furthermore, if there are no historical data to indicate how degradation develops with time there is I believe an increased likelihood of increased risk should we agree to continued operation'.*

In other words, here is example of the nuclear regulator acknowledging an increased risk of accident that is, it seems, beyond the risk adopted in the present licensed safety case for the two AGR reactors at Hinkley Point and, most probably, for all of the other AGR nuclear power plants in the UK.

6 IN CONCLUSION

From the evidence I have reviewed it is quite clear that the graphite cores of Hinkley Point and at least a further 6 reactors, possibly all 14 AGR reactors, have developed and continue to develop structural damage to individual bricks in the fuelled section of the reactor.

It is also clear that the cause(s) of the damage is not fully understood by both NSD and BE; that BE are unable to accurately extrapolate from limited core inspections just how many bricks are in a damaged state; that the inspection methods only locate cracks that have fully developed thereby leaving cracks under development undetected; and that BE are unable to determine the limit to the number of cracked bricks present before the core residual strength is below that required to withstand serious and lesser fault events, all of which leads NSD to opine that there is significant *'uncertainties'* about the structural condition of the graphite core and in continued operation the reactors (at least) at Hinkley Point present an *'increased likelihood of increased risk'*.

I agree with NSD that there are significant uncertainties about the fault condition performance of the graphite cores but, that said, I would go further with my opinion that, in view of the increased risk presented by continued operation of these nuclear plants, the reactors should be immediately shut down and remain so until a robust nuclear safety case free of such uncertainties has been established.

JOHN H LARGE

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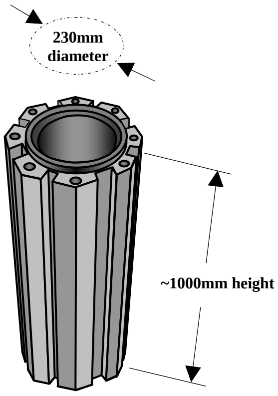
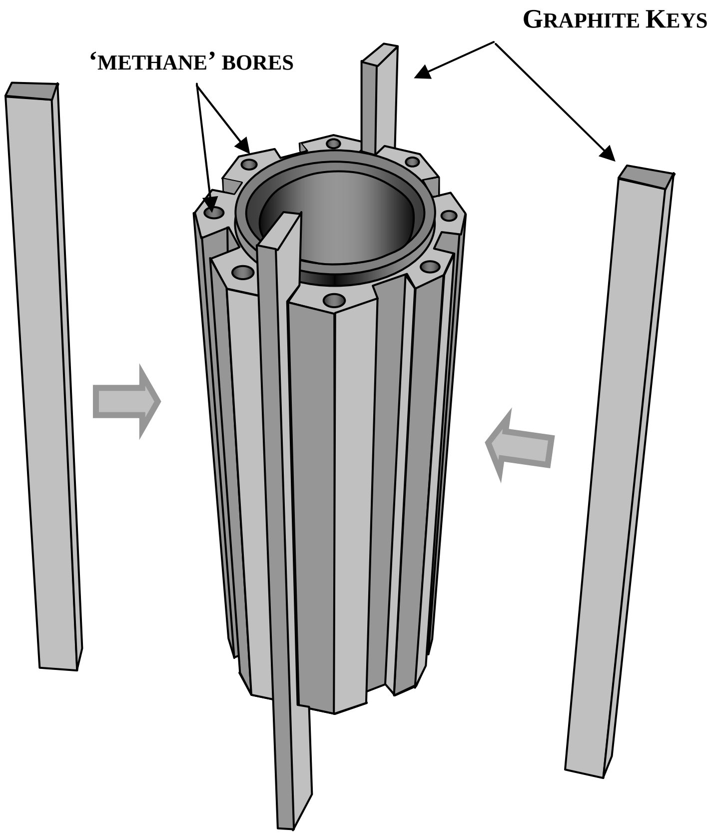
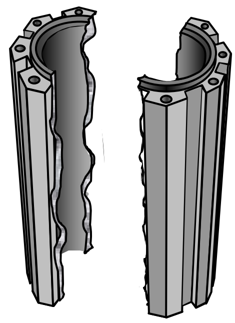
APPENDIX I – TERMS AND JARGON

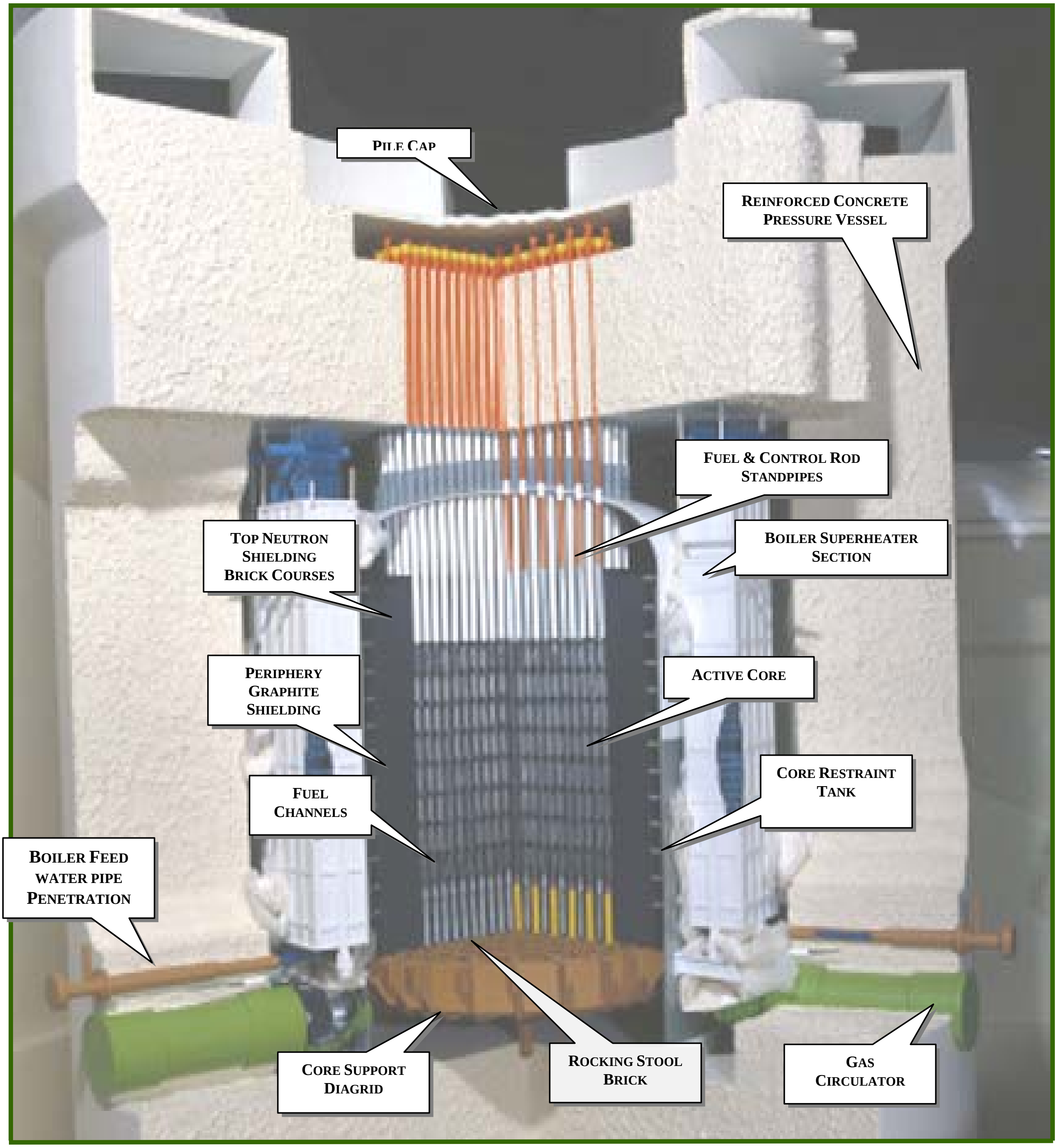




GRAPHITE CORE BRICK – ACTIVE CORE



PLANE & SYMMETRY OF CRACKING



SCHEMATIC OF TORNESS AGR
LOCATION OF COMPONENTS REFERRED TO IN THIS REVIEW