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OPERATIONAL EXPERIENCE FROM THE ADVANCED GAS-COOLED REACTOR (AGR) GRAPHITE CORES USEFUL TO THE DESIGN OF FUTURE HIGH TEMPERATURE REACTOR (HTR) GRAPHITE CORES

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ABSTRACT

Many lessons can be learned from the operational experience gained from the graphite cores of the 14 Advanced Gas-cooled Reactors (AGRs) of the United Kingdom, intended to remain intact through-out their design lives, the first running commercially since 1976, of which 8 are planned to still be generating beyond 2023. The aim here is to highlight some of that operational experience, where the broad principles may be helpful to the design of graphite cores in future high temperature reactors (HTRs), and hence avoid unnecessary additional work to justify safety cases for continued operation.

This overview of operational experience and lessons learned from the graphite cores of the Advanced Gas-cooled Reactors covers:

- an appreciation of both non-uniform irradiation-induced shrinkage and thermal strains as a source of significant component brick self-stress,
- opportunities to reduce non-uniform irradiation-induced shrinkage and thermal strains as a source of significant component brick self-stress by design,
- recognition of the variable nature of as-manufactured graphite material properties, and the possibility of defects arising during material manufacture,
- the benefits of a radial key/keyway system to accommodate differential core and support/restraint thermal movements and reduce external loads by design,
- opportunities to avoid stress-raising features by design,
- the benefits of considering the consequences of damaged components were they to crack, and of having a core tolerant to cracked components by design,
- the benefits of marking plain brick bores circumferentially so that crack locations can be easier to identify in inspections,
- an appreciation of the significance of the seismic hazard,
- minimising undesired behaviour, mitigating undesired behaviour, enabling repair or reversal of undesired behaviour.

Each of these topics is covered in turn, with the consequences of not taking such subjects into account illustrated by examples from the graphite cores of the Advanced Gas-cooled reactors.

Since the late 1980s substantial work has been performed which demonstrates tolerability to a large extent of cracked graphite core components in the AGRs, beyond the design intent of having no cracked components, and to support safety cases which justify safe operation well beyond their original design lives.

Although it has been possible to continue operation of the AGRs by performing substantial additional work to justify future safety cases, a slightly different original design of the graphite cores would have reduced, or even avoided the need for, the work involved to provide such justification and recover operation.

OVERVIEW OF OPERATIONAL EXPERIENCE AND LESSONS LEARNED FROM THE GRAPHITE CORES OF THE ADVANCED GAS-COOLED REACTORS

Brief Description Of The AGR Graphite Core Design

AGR graphite cores, Steer (2007), of which there were four designs, are structures ~10m in diameter by ~10m in height, weighing ~2000te, and comprise ~12 layers of ~500 large "circular", ~460mm diameter, bricks, with smaller "square", ~180mm side, interstitial bricks, forming ~12 "rings" of large-brick columns. Lower and upper layers form the bottom and top reflectors and neutron shields, while the 2-3 outer rings form the side reflector. Neighbouring bricks are located horizontally and vertically using a system of rectangular cross-section slots ("keyways") and graphite cuboids ("keys") which span the slots, with keys typically integral to the interstitial bricks and separate "loose" entities between large bricks, Figure 1.

The inner ~300 large-brick columns each have a ~260mm diameter channel to accommodate an AGR fuel assembly, while the inner ~300 interstitial brick columns each have a smaller channel of various sizes for various purposes, including ~80 of ~120mm diameter each accommodating a control rod assembly.

The core is supported vertically by, and "keyed" into, a steel structure and restrained laterally (but not vertically) by a separate steel structure connected to each large brick in the outer ring. The core "radial keying system" allows horizontally neighbouring bricks to separate and come together in a controlled manner, and the graphite core to expand and contract in the horizontal plane to match thermal movements of its steel boundaries, while maintaining the core's horizontal lattice and vertical continuity and adequate straightness of the channels.

More generally, the AGRs were designed for electrical power generation, and produce essentially the same steam raising conditions as conventional fossil-fuelled power stations. Unlike many other nuclear reactors for power generation, an important feature of the AGRs was that they were designed to be continually re-fuelled at full power, with a reactor refuelling cycle lasting a period of ~5years.

The design intent for the AGR cores was that the core components would remain intact throughout their lives, where their design operating life was 30 years at full power with 85% availability. The bricks and keys of the AGR cores cannot be repaired or replaced. However, as will be seen, substantial work has been performed to support safety cases which justify their safe operation well beyond their original design lives, and which demonstrate tolerability to a large extent of cracked core components.

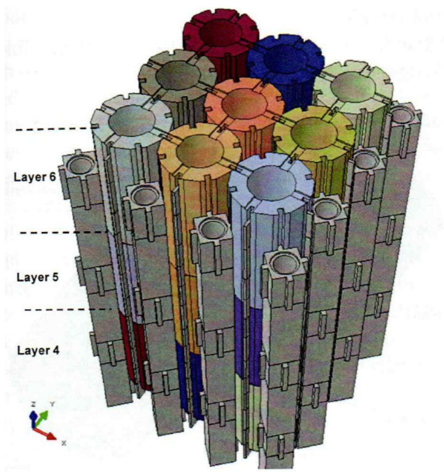

Figure 1. Typical core design, Teng et al. (2020).

An Appreciation Of Both Non-Uniform Irradiation-Induced Shrinkage And Thermal Strains As A Source Of Significant Component Brick Self-Stress

As late as the final commissioning stages of the last AGR stations to be built, Heysham 2 and Torness, the significance of self-stresses in the graphite core bricks from late-in-life thermal strains arising during the shutdown transient, adding to known self-stresses from irradiation-induced / irradiation-creep-offset shrinkage strains arising at power, had not been fully appreciated. Instead, the principal challenge to AGR core brick integrity had been considered, during design, to be external loads arising from differential thermal movement of the graphite core steel support and lateral restraint in a shutdown following a reactor fault, leading to distortion of the core brick columns and associated loads on the keying system, and potentially consequent key or keyway failures.

Irradiation-induced shrinkage stresses, late in life, were known to be tensile at the outside of the large “fuel” bricks and to concentrate stress at their keyway roots, Figure 2. Graphite brick keyways and keys were sized during design to tolerate such external brick loads in faults in combination with the late-life tensile shrinkage stresses. However, late in life the coefficient of thermal expansion of graphite under the highest irradiation reduces to ~40% of its initial value, such that material at the bore of fuel bricks undergoes less thermal strain than that at the outside of the brick, and thermal tensile stresses arise at the fuel brick outside and keyway roots on cooling without irradiation creep (e.g. shutdown), Figure 2.

The tensile thermal stresses add to the tensile shrinkage stresses during shutdown, and were predicted, in the mid-1980s, to potentially cause spontaneous cracking of fuel bricks which could challenge the AGR design principle of having intact components throughout their lifetime. This finding led to the substantial programme of work to demonstrate tolerability to a large extent of cracked graphite core components in the AGRs, and to support safety cases which justified safe operation.

Now, even in the absence of external loads due to faults, some of the highest-rated fuel bricks in the AGRs have been observed to experience cracks running from their horizontally connecting keyways and penetrating to their bores late-in-life.

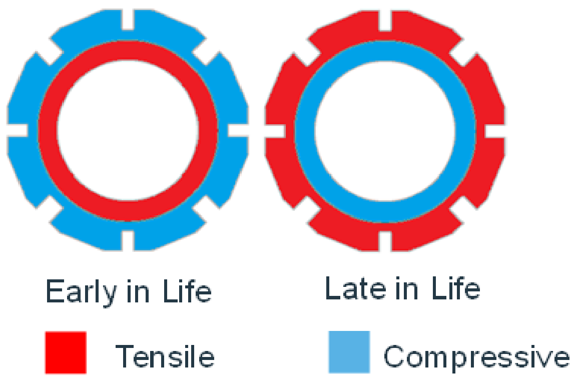

Figure 2. Shrinkage/thermal stresses, Booler (2023).

Opportunities To Reduce Non-Uniform Irradiation-Induced Shrinkage And Thermal Strains As A Source Of Significant Component Brick Self-Stress By Design

The principal source of brick self-stresses that challenge fuel brick integrity are spatially non-uniform irradiation-induced shrinkage and thermal strains. Spatial non-uniformity arises due to attenuation of fast neutrons, which are the source of "damage" to, and restructuring of, the crystals that form nuclear graphite and associated changes to material properties. The attenuation is a function of distance from the fuel and also moderation by the graphite to thermal neutrons. Self-stresses arise because the spatial non-uniformity of those inelastic strains cannot be fully accommodated by simple distortion of the fuel bricks; i.e. gradients in inelastic strain through the wall of fuel brick (between its bore and outside) cannot be relieved by bending about the vertical or horizontal since the brick is a continuous body around the fuel, taller than its diameter, and rotationally symmetric, and instead lead to hoop and axial stresses.

The magnitude of spatial non-uniformity of irradiation-induced shrinkage and thermal strains, and associated stresses, could therefore have been reduced in design by using graphite components with smaller dimensions in the direction of the fast neutron dose gradient, for example concentric rings of graphite for each AGR fuel brick, Figure 3. Such a design may even have admitted the possibility of replacement of the highest irradiated inner ring of material surrounding the fuel, if necessary.

Hoop and axial stresses could also have been reduced in design by introducing slots in the bores of the bricks, wide enough to accommodate non-uniformities in inelastic strains, essentially interrupting the continuity of the body; thus axial slots to reduce hoop stresses and horizontal slots to reduce axial stresses, Figure 3. The slots could be at an inclined angle to radial and horizontal to reduce the "shine" of unmoderated fast neutrons into the brick body. The principle could also be applied to side reflector bricks.

Again, as above, without such relief of the magnitude of non-uniformities in inelastic strains, some of the highest-rated fuel bricks in the AGRs have been observed to experience cracks running from their horizontally connecting keyways and penetrating to their bores late-in-life.

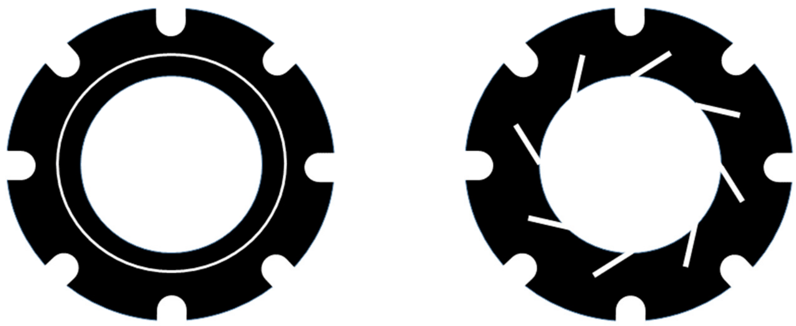

Figure 3. Opportunities to reduce self-stress (slot angles / corners would be smaller in practice).

Opportunities To Avoid Stress-Raising Features By Design

During the design of the AGRs, it was considered that AGR nuclear graphite was "notch insensitive", i.e. the presence of a "sharp" internal corner did not unduly reduce the load bearing capacity. This may have been associated with the granular nature of AGR nuclear graphite, having spherical filler particles ~0.5mm in diameter, such that internal corners with smaller dimensions were "blurred" by the granularity; or, alternatively, that the granularity essentially means that the geometry is "pre-cracked" regardless of any surrounding notch width. As a consequence, although the core brick keying system was expected to be capable of tolerating external loads, in combination with irradiation-induced shrinkage stresses in the fuel bricks, the internal corners of graphite keyways and keys were machined with a radial or "45° chamfer" dimension of ~1-2mm.

Despite the prevailing views, it would have been simple and prudent to design the key and keyway internal corners with a substantially larger radius, which did not concentrate stresses so greatly, Figure 4.

Again, as above, some of the highest-rated fuel bricks in the AGRs have been observed to experience cracks running from their horizontally connecting keyways and penetrating to their bores late-in-life.

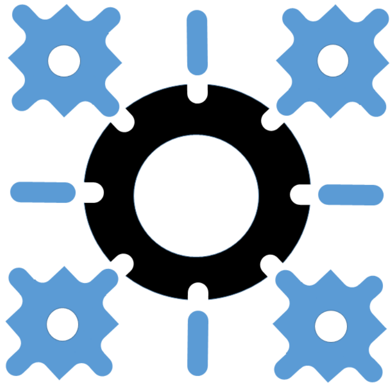

Figure 4. Opportunities to avoid stress raising features.

The Benefits Of A Radial Key/Keyway System To Accommodate Differential Core And Support/Restraint Thermal Movements And Reduce External Loads By Design

This design feature of the AGRs, building from the experience of core designs in the Magnox reactors, moving from "brick and tile" to "radially keyed", has been a considered success. As mentioned already, the design facilitates horizontal separation and coming together of columns in a controlled manner, allowing the graphite core to expand and contract in the horizontal plane to match thermal movements of its steel boundaries, while maintaining the core's square horizontal lattice, and vertical continuity and adequate straightness of the channels. The radial keying system also accommodates the ~3% shrinkage of graphite components caused by fast neutron irradiation over AGR lifetimes, without affecting the lattice pitch.

In addition, loads in the radial keying system caused by differences in core support and restraint steelwork temperatures, which can arise in the thermal transients of shutdowns and faults, and which lead to differences in core-radial movements, are often reduced in the AGR core design by various narrow "rocking" features of an appropriate direction, or combinations of directions, machined on the brick ends.

Recognition Of The Variable Nature Of As-Manufactured Graphite Material Properties, And The Possibility Of Defects Arising During Material Manufacture

Nuclear graphite is a manufactured material, initially comprising a mixture of filler particles and pitch, which is then moulded into billets by extrusion or pressing. The billets are baked (carbonised) at ~1200°C, and sometimes re-impregnated with pitch and re-baked several times. Finally, the billets are graphitised in a furnace at ~3000°C. The billet is composed of many differently oriented graphite crystals, where the original filler particles are often visible using microscopy. Graphite crystals are transversely isotropic, and as their coefficient of thermal expansion is substantially different in the two graphite crystal axes, cooling from graphitisation leads to stresses within the material, and micro-cracking between crystals and between larger zones. The material is also typically ~20% porous, as a consequence of voids, having only ~80% of the crystal density. Billets can be machined to the desired component shape with normal tooling.

As a consequence of the manufacturing process, the material has considerable variability in most physical properties, both within billets, as well as between billets of nominally the same mixture and baking/impregnation/graphitisation history. Furthermore, the material can contain flaws that are a significant fraction of the billet dimensions, usually associated with poor mixing or poor bonding, e.g. between consecutive mixes used to fill the mould of a billet. Although billets were inspected before machining, and components after machining, it is still possible for flaws to be revealed during commissioning and during operation.

Now there are rare instances within the fleet of AGR cores where material manufacturing flaws have been revealed in components early in their design lifetimes. These include axial and circumferential cracks in a very few fuel brick bores prior to the first power-raising, in the outside of a very small fraction of shielding bricks (narrow columns outside the side-reflector in one AGR design) which have negligible irradiation dose and hence negligible associated changes to material properties, and in a small fraction of fuel brick bores which have substantial irradiation-dose associated changes to material properties and shrinkage and thermal stresses early in life before "stress-reversal" (Figure 2).

Furthermore, graphite is also used as a structural (outer wall or "sleeve") feature of the fuel stringer elements, which also provides a coolant flow boundary, and is an important feature of the AGR design which separates the gas flows that keep the moderator cool (~300-450°C) from the gas flows that pass over the fuel on their way to the boilers (~650°C). Early operation of the AGRs discovered that flow-induced vibration during full-power refuelling, potentially together with variability in material properties and flaws in sleeves, led to rare instances of sleeve cracking. Since then, the design of the AGR fuel sleeves has been changed to make them more robust, and the AGRs are either re-fuelled at ~30% power, or even, for some designs, off-load. A further significant improvement in maintaining the robustness of fuel sleeves has been the implementation of "proof testing", where all sleeves, not just an occasional sample, are pressurised following their manufacture to eliminate weaker components. It may have been beneficial to have performed an appropriate form of proof testing on core bricks and keys after their manufacture.

The Benefits Of Considering The Consequences Of Damaged Components Were They To Crack, And Of Having A Core Tolerant To Cracked Components By Design

As described above, the AGR cores have experienced some fuel bricks with axial cracks running from their horizontally-connecting keyways through to the bores. Such cracks have arisen at burnups around or beyond the AGR designed lifetimes, Table 1. Also, as described above, the AGRs have experienced axial and circumferential cracks in the bores of a small fraction of fuel bricks, and these occurred early in life when irradiation-induced shrinkage and thermal stresses were tensile at the brick bore. Axial cracks in fuel bricks are of particular interest, as bricks with single fully-through full-height axial cracks may open up as "C-rings" with further late-life irradiation, providing a source of distortion to neighbouring fuel and control rod columns, and those with more than one such axial crack reduce the stiffness of the brick, column and core to resist such distortion. The associated current and future core distortions are regularly assessed and determined to be tolerable in safety cases, and hence, although not the design intent, the core radially keying system has been found to be a design that is tolerant of brick cracking, to a high degree.

Graphite in the AGRs is susceptible to oxidation by their carbon dioxide coolant, activated by the irradiation environment, leading to "weight loss" and associated changes in material properties, including reduction in moderation, stiffness and strength. The AGR's design naturally induces a pressure drop between the outside and bore of fuel bricks in normal operation, that impresses flow of oxidation inhibitor in the coolant into the bricks, and reduces the rate of weight loss. Although through cracks in the fuel bricks reduce the pressure drop and effectiveness of the inhibitor, they do not significantly affect the cooling of the core and fuel, since the principal coolant flow boundary is provided by fuel stringer sleeves within.

Table 1: Significant events in the AGR core lifetimes.

	Core Burnup (BU) (terra-watt days, TWd, (thermal))						
Event	Dungeness	Hinkley Point B	Hunterston B	Hartlepool	Heysham 1	Heysham 2	Torness
Design Life	14.0	14.0	14.0	14.0	14.0	15.8	15.8
Onset of radial keyway cracking - earliest BU	None	16.0	15.2	None	None	15.3	15.3
Current - greatest BU at 2023 outage	N/A	N/A	N/A	14.2	13.8	16.1	16.1
At closure - greatest BU	9.1	17.2	16.4	N/A	N/A	N/A	N/A

In the last of the four AGR designs, the end-face keying system was “turned 90°”, becoming a single circumferential keyway housing four quadrant keys, Figure 5, rather than four radial key/keyways, thereby providing a gas-seal resistant to column distortion from straight and allowing an increase in the pressure drop, impressed flow and inhibition of weight loss. The circular keyway wall nearest the brick bore, however, is affected by axially-cracked bricks, since if a cracked brick is increasing its radius by opening at a greater rate than a vertically-adjacent brick, e.g. because the latter is not cracked, the circular keyway wall of the first brick cannot accommodate the opening and may crack through to the bore. Work is currently ongoing to establish whether such cracks will result in debris which may potentially impede fuelling and defueling, though there is no concern with fuel cooling or any effect on control rod movement.

Incidentally, the original AGR design intended operating with ~double the current equilibrium methane concentration as an oxidation inhibitor, but the prospect of carbon deposition on the fuel led to its’ reduction. To offset this reduction, narrow holes penetrating the full height of the bricks were drilled during manufacture to facilitate diffusion of inhibitor into the bricks, increasing in number over the first three AGR designs, before reducing in number with the last design having an increased impressed flow.

Though operating with cracked fuel bricks was beyond the original design basis, this illustrates why establishing the effects of cracking and designing tolerance to cracked components is desirable.

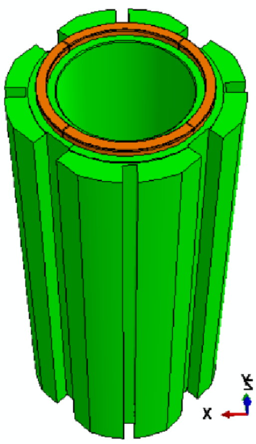

Figure 5. Circumferential end-face key/keyway.

More generally, it would be desirable to establish the load bearing capacities of (i) all component features potentially loaded by design and (ii) component features which could potentially become loaded in the event of failure of the former features or themselves. The load bearing capacity may be established theoretically, or, ideally, be based on physical testing of the component features under simulated reactor loading, as described in McLachlan (2023). Without proof testing of every component, the limited numbers of components that can be physically tested to failure, and hence associated validation of theoretical models, means that failure, or even crack initiation, cannot be wholly discounted, even at a low probability, as the frequency of outliers to the underlying statistical distribution is the concern. Therefore, the tolerability to crack initiation, and even failure, should be taken into account in the core design, e.g. by redundancy and diversity of connectivity and means of maintaining adequate core geometry.

The Benefits Of Marking Plain Brick Bores Circumferentially So That Crack Locations Can Be Easier To Identify

Although the fuel and control rod channel bores are regularly inspected using TV equipment, there are few features on the brick bores to help identify the height and circumferential location of cracks (or other observations), and how they relate to the brick outside geometry, e.g. keyways and keys. Though inspection equipment has been developed which allows the height and circumferential location to be determined, it may have been prudent to have marked the brick bores in some way during manufacture to help such location of cracks.

An Appreciation Of The Significance Of The Seismic Hazard

Only the last of the AGR core designs was seismically qualified by design, while all three other AGR core designs were seismically qualified retrospectively. In practical terms, for the last of the AGR designs, this meant that the interstitial bricks were made wider to provide thicker walls, with the "circular" fuel bricks having "flats" machined on their adjacent sides to accommodate the increased interstitial width, and both "loose" and interstitial keys were made thicker, at the expense of having wider keyways in the fuel bricks.

It would be prudent to seismically qualify any new cores by design, rather than retrospectively.

Minimise Undesired Behaviour, Mitigate Undesired Behaviour, Enable Repair Or Reversal Of Undesired Behaviour

During the operation of the AGRs, the experience gained has suggested that there was potential to improve the original designs, for example to minimise undesired behaviour by delaying or eliminating the occurrence of cracks, or to mitigate undesired behaviour by tolerating cracks should they arise by reducing their consequences.

Consideration has since been given, during the operational lives of the AGRs, to modifying the cores, by re-machining bricks in-situ in the cores, so that the likelihood of cracks is reduced, or that cracks grow in a preferred shape or size, or to better tolerate any fragments or debris arising.

For example, some of the design improvements mentioned earlier in this paper could have been implemented, albeit not without considerable effort, after the cores had been built and during their operating lives. In particular, hoop and axial stresses could also have been reduced during reactor lives by introducing slots in the bores of the bricks, wide enough to accommodate non-uniformities in inelastic strains, essentially interrupting the continuity of the body; thus axial slots to reduce hoop stresses and horizontal slots to reduce axial stresses. The slots could be at an inclined angle to radial and horizontal to reduce the "shine" of unmoderated fast neutrons into the brick body.

Consideration has also been given to the possibility of partially mitigating the undesired behaviour of an opening singly-axially cracked brick causing displacement of surrounding channels, by cutting those bricks in-situ so that they are doubly-axially cracked, where the distortion of the halves is more tolerable, albeit at the expense of having less stiff columns and cores to resist distortion.

Although not the original intention, the design of the AGR cores has since been established to be tolerant to large numbers of axially and circumferentially cracked fuel bricks, and as such mitigates the consequences of the undesired cracking behaviour in terms of channel distortions that could affect the fundamental nuclear safety requirements for the AGR cores of uninhibited control rod movement, cooling of the fuel and uninhibited fuel movement.

In the Hinkley Point B and Hunterston B reactors, plant modifications were made to mitigate the potential of undesired control channel distortions by replacing a number of control rods with a modified design incorporating more joints and shorter segments over the same total length, enabling substantially more opportunities for articulation over shorter distances, and with a substantially greater range of articulation at any given joint.

Furthermore, for the last of the AGR designs, consideration is being given to mitigating the potential consequences of cracking of the circular end-face keying system wall nearest the brick bore, as a result of differential opening of axially-cracked vertically-adjacent bricks, by re-machining the features. Various modifications are being explored, e.g. to increase the clearances in the end-face keying system and hence delay or even prevent such cracking and its potential consequences, but also, as an alternative, to change the end-face geometry so that any debris is of a preferred size, and even to direct the crack paths so that any fragment has a preferred less-mobile shape, and less likely to become debris.

No repairs or modifications to reverse undesired behaviour have yet been attempted in the AGR cores.

CONCLUSION

The design intent for the AGR cores was that the core components would remain intact through-out their lives, where their design operating life was 30 years at full power with 85% availability. The bricks and keys of the AGR cores cannot be repaired or replaced.

However, since the late 1980s, substantial work has been performed which demonstrates tolerability to a large extent of cracked core components in the AGRs, beyond the design intent of having no cracked components, and to support safety cases which justify their safe operation well beyond their original design lives.

An overview is given of lessons learned from the operational experience gained from the graphite cores of the 14 Advanced Gas-cooled Reactors (AGRs) of the United Kingdom. The operational experience is highlighted in the hope that the broad principles may be helpful to the design of graphite cores in future high temperature reactors (HTRs), and hence avoid unnecessary additional work to justify safety cases for continued operation.

ACKNOWLEDGEMENT / DISCLAIMER

The views expressed here are those of the author and not necessarily those of EDF Energy Nuclear Operations.

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