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Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRTs)

Volume 5: Graphite PIRTs

OAK RIDGE NATIONAL LABORATORY

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ABSTRACT

Here we report the outcome of the application of the Nuclear Regulatory Commission (NRC) Phenomena Identification and Ranking Table (PIRT) process to the issue of nuclear-grade graphite for the moderator and structural components of a next generation nuclear plant (NGNP), considering both routine (normal operation) and postulated accident conditions for the NGNP. The NGNP is assumed to be a modular high-temperature gas-cooled reactor (HTGR), either a gas-turbine modular helium reactor (GT-MHR) version [a prismatic-core modular reactor (PMR)] or a pebble-bed modular reactor (PBMR) version [a pebble bed reactor (PBR)] design, with either a direct- or indirect-cycle gas turbine (Brayton cycle) system for electric power production, and an indirect-cycle component for hydrogen production. NGNP design options with a high-pressure steam generator (Rankine cycle) in the primary loop are not considered in this PIRT. This graphite PIRT was conducted in parallel with four other NRC PIRT activities, taking advantage of the relationships and overlaps in subject matter.

The graphite PIRT panel identified numerous phenomena, five of which were ranked high importance–low knowledge. A further nine were ranked with high importance and medium knowledge rank. Two phenomena were ranked with medium importance and low knowledge, and a further 14 were ranked medium importance and medium knowledge rank. The last 12 phenomena were ranked with low importance and high knowledge rank (or similar combinations suggesting they have low priority). The ranking/scoring rationale for the reported graphite phenomena is discussed.

Much has been learned about the behavior of graphite in reactor environments in the 60-plus years since the first graphite rectors went into service. The extensive list of references in the Bibliography is plainly testament to this fact. Our current knowledge base is well developed. Although data are lacking for the specific grades being considered for Generation IV (Gen IV) concepts, such as the NGNP, it is fully expected that the behavior of these graphites will conform to the recognized trends for near isotropic nuclear graphite. Thus, much of the data needed is confirmatory in nature. Theories that can explain graphite behavior have been postulated and, in many cases, shown to represent experimental data well. However, these theories need to be tested against data for the new graphites and extended to higher neutron doses and temperatures pertinent to the new Gen IV reactor concepts. It is anticipated that current and planned future graphite irradiation experiments will provide the data needed to validate many of the currently accepted models, as well as providing the needed data for design confirmation.

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FOREWORD

The Energy Policy Act of 2005 (EPAct), Public Law 109-58, mandates the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department of Energy (DOE) to develop jointly a licensing strategy for the Next Generation Nuclear plant (NGNP), a very high temperature gas-cooled reactor (VHTR) for generating electricity and co-generating hydrogen using the process heat from the reactor. The elements of the NGNP licensing strategy include a description of analytical tools that the NRC will need to develop to verify the NGNP design and its safety performance and a description of other research and development (R&D) activities that the NRC will need to conduct to review an NGNP license application.

To address the analytical tools and data that will be needed, NRC conducted a Phenomena Identification and Ranking Table (PIRT) exercise in major topical areas of NGNP. The topical areas are: (1) accident analysis and thermal-fluids including neutronics, (2) fission product transport, (3) high temperature materials, (4) graphite, and (5) process heat and hydrogen production. Five panels of national and international experts were convened, one in each of the five areas, to identify and rank safety-relevant phenomena and assess the current knowledge base. The products of the panel deliberations are Phenomena Identification and Ranking Tables (PIRTs) in each of the five areas and the associated documentation (Volumes 2 through 6 of NUREG/CR-6944). The main report (Volume 1 of NUREG/CR-6944) summarizes the important findings in each of the five areas. Previously, a separate PIRT was conducted on TRISO-coated particle fuel for VHTR and high temperature gas-cooled reactor (HTGR) technology and documented in a NUREG report (NUREG/CR-6844, Vols. 1 to 3).

The most significant phenomena (those assigned an importance rank of “high” with the corresponding knowledge level of “low” or “medium”) in the thermal-fluids area include primary system heat transport phenomena which impact fuel and component temperatures, reactor physics phenomena which impact peak fuel temperatures in many events, and postulated air ingress accidents that, however unlikely, could lead to major core and core support damage.

The most significant phenomena in the fission products transport area include source term during normal operation which provides initial and boundary conditions for accident source term calculations, transport phenomena during an unmitigated air or water ingress accident, and transport of fission products into the confinement building and the environment.

The most significant phenomena in the graphite area include irradiation effect on material properties, consistency of graphite quality and performance over the service life, and the graphite dust issue which has an impact on the source term.

The most significant phenomena in the high temperature materials area include those relating to high-temperature stability and a component’s ability to withstand service conditions, long-term thermal aging and environmental degradation, and issues associated with fabrication and heavy-section properties of the reactor pressure vessel.

The most significant phenomenon in the process heat area was identified as the external threat to the nuclear plant due to a release of ground-hugging gases from the hydrogen plant. Additional phenomena of significance are accidental hydrogen releases and impact on the primary system from a blowdown caused by heat exchanger failure.

The PIRT process for the NGNP completes a major step towards assessing NRC's research and development needs necessary to support its licensing activities, and the reports satisfy a major EPAct milestone. The results will be used by the agency to: (1) prioritize NRC's confirmatory research activities to address the safety-significant NGNP issues, (2) inform decisions regarding the development of independent and confirmatory analytical tools for safety analysis, (3) assist in defining test data needs for the validation and verification of analytical tools and codes, and (4) provide insights for the review of vendors' safety analysis and supporting data bases.

Farouk Eltawila, Director
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ACRONYMS

AGR	advanced gas-cooled reactor
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing & Materials
AVR	Atomgeneinschaft Versuchs Reaktor
B&PV	Boiler and Pressure Vessel (Code)
CFC	carbon-fiber composite
CFRC	carbon-fiber reinforced carbon
CTE	coefficient of thermal expansion
DOE	Department of Energy
DSC	differential scanning calorimeter
EPRI	Electrical Power Research Institute
FOM	figure of merit
FP	fission product
FPT	fission-product transport
GA	General Atomics
GT-MHR	gas turbine-modular helium reactor
HTR	high-temperature reactor
HTGR	high-temperature gas reactor
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
LBE	license basis event
NDE	nondestructive examination
NGNP	next generation nuclear plant
NRC	Nuclear Regulatory Commission
PBR	prismatic block reactor
PBMR	pebble-bed modular reactor
PCR	passive cooling requirement
PIRT	phenomena identification and ranking table
PMR	prismatic-core modular reactor
THTR	thorium high-temperature reactor
UK	United Kingdom
U.S.	United States
VHTR	very high temperature gas-cooled reactor
XRD	x-ray diffraction

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1. INTRODUCTION

Here we report the outcome of the application of the Nuclear Regulatory Commission (NRC) Phenomena Identification and Ranking Table (PIRT) process to the issue of nuclear-grade graphite for the moderator and structural components of a next generation nuclear plant (NGNP), considering both routine (normal operation) and postulated accident conditions for the NGNP. The NGNP is assumed to be a modular high-temperature gas-cooled reactor (HTGR), either a gas-turbine modular helium reactor (GT-MHR) version [a prismatic-core modular reactor (PMR)] or a pebble-bed modular reactor (PBMR) version [a pebble-bed reactor (PBR)] design, with either a direct- or indirect-cycle gas turbine (Brayton cycle) system for electric power production, and an indirect-cycle component for hydrogen production. NGNP design options with a high-pressure steam generator (Rankine cycle) in the primary loop are not considered in this PIRT.

This graphite PIRT was conducted in parallel with four other NRC PIRT activities, taking advantage of the relationships and overlaps in subject matter. The five NRC PIRT topical panels in this exercise are

- nuclear-grade graphite,
- accident and thermal fluids analysis (with neutronics),
- high-temperature materials (metals),
- process heat with hydrogen cogeneration, and
- fission product transport and dose.

The graphite PIRT panel maintained communications and coordination with the other PIRT groups throughout the exercise.

The NGNP will use either a pebble-type fuel element made from powdered graphite and carbonized resin or a graphite fuel element of prismatic geometry. United States designs have historically favored the prismatic core, while the PBMR and the high-temperature reactor (HTR-10) of China have adopted the German pebble fuel element. There are significant differences in the materials in each of these fuel element types. The prismatic-core modular reactor (PMR) utilizes nuclear-grade graphite block fuel elements, whereas the PBR fuel pebbles are formed from a mix of artificial graphite, natural flake graphite, and resin. The final processing temperature is limited in the fuel pebbles by the presence of the coated particle fuel so the resin-derived carbon (glassy) carbon is only processed to 1800–1900°C.

The two reactor concepts (PMR and PBR) both utilize nuclear-grade graphites for the moderator and core structural material. The temperature ranges for the two concepts are broadly similar, but the graphite core component peak neutron dose in a PBR is substantially in excess of those in a PMR.

The graphite PIRT was conducted according to the eight-step PIRT process:

1. identification of issues,
2. define PIRT objectives,
3. hardware and scenario,
4. evaluation criteria,
5. knowledge base,
6. identify phenomena,
7. importance ranking, and
8. knowledge level ranking.

After deliberation, the panel concluded that the figures of merit (FOM) for graphite should be split into three categories: regulatory, system, and component. The graphite-related phenomena were evaluated against these FOMs. The primary FOM for the graphite phenomena was the regulatory FOM for maintaining the dose at the site boundary within regulatory limits.

2. GRAPHITE PIRT BACKGROUND

Graphite will be used as the structural material and neutron moderator for HTGR cores, permanent side reflectors, and for the core support structure. A significant challenge related to graphite for HTGRs in the United States is that the previous graphite grade qualified for nuclear service in the United States, H-451, is no longer available. The precursors from which H-451 graphite was manufactured no longer exist and, furthermore, the present understanding of graphite behavior is not sufficiently developed to enable the H-451 database to be completely extrapolated to nuclear graphite grades currently available. Hence, it will be necessary to qualify new grades of graphite for use in the NGNP. It will be necessary to qualify the new graphite(s) with regard to both non-irradiated and irradiated performance. In reactor designs that impose large irradiation damage doses (i.e., beyond volume change turnaround) it may become necessary to replace cores, components, and structures during the lifetime of the reactor, with associated in-service inspection and assessment of the structural integrity of these structures. Thus the operators will require data and understanding for decisions to be made on replacement timing.

In qualifying new grade(s) of graphite, it would be highly desirable to gain a more robust fundamental understanding of irradiated graphite behavior to ensure that new theories and models have a sound, in-depth, scientific basis. To the extent that this is achieved, it would provide increased confidence for design and licensing and reduce the extent of experimental verification that is required when additional new graphite grades must be qualified in the future. Because of the inherent variability in the important properties of graphite, a good understanding of the variability of the physical, mechanical, and thermal properties for a given graphite grade within billet, between billets, and between lots is needed to establish behavioral models of (degradation) phenomena during reactor life. Moreover, the effects of reactor environment (temperature, neutron irradiation, and chemical attack) on the physical properties must be elucidated. Finally, for each grade of graphite the irradiation- induced dimensional change (which drives the generation of graphite component stresses) and irradiation creep behavior (which relieves graphite component stresses) must be determined over a representative temperature and fluence range.

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3. GRAPHITE PIRT PROCESS

The graphite PIRT panel used the specified PIRT process in their deliberations. Specifically, the panel first discussed the PIRT process, establishing an understanding of the various steps and requirements. These are given below:

1. identified the FOM;
2. defined the phenomena that affect FOM;
3. organized the phenomena at component level;
4. individually established the importance and assigned rank of high (H), medium (M), or low (L) based upon the phenomenon influence on the FOM;
5. individually established the knowledge base and rated it as H, M, or L and identified pertinent literature; and
6. reconciled rankings and collectively recommended panel rankings.

3.1 Step 1—Potential Graphite Issues

Specific phenomena that will need to be evaluated related to graphite are itemized in the list that follows. Note that all artificially manufactured graphite exhibits some degree of anisotropy. Although near-isotropic graphite is expected to be used in critical components, there are other components where some isotropic behavior may be encountered. In such cases, the listed properties must be determined in several directions of the billet.

- Property variations
  - The physical, mechanical, and thermal properties of graphite vary within a billet due to process-induced texture and density gradients.
  - The properties vary from billet to billet within a given production lot, and between lots and batches.
  - These statistical variations must be quantified and modeled.
- Temperature
  - The physical properties of graphite are temperature-dependant. The effect of temperature must be quantified and modeled.
- Neutron irradiation
  - Graphite undergoes dimensional change when subjected to neutron irradiation. The rate of change is temperature dependant. Initial shrinkage “turns-around” into growth.
  - The dose and temperature dependency of dimensional change must be determined and mathematical models developed.
  - Dimensional change under stress (irradiation creep) must be elucidated and irradiation creep models developed. (Note graphite thermal creep is negligible below 1800°C.)
  - The effect of fatigue on graphite needs to be assessed. Historically, fatigue failures have not been observed, but limited experimental data show that a fatigue failure can occur in graphite.
  - Graphite physical and thermal properties are altered by neutron irradiation, and thus the effects of neutron dose on properties and the temperature dependency of these effects must be determined.
- Thermal oxidation
  - Helium coolant gas impurities (H_2O, O_2, CO_2, CO) will cause thermal oxidation of graphite at temperatures above ~300°C. Similarly, air oxidation will occur during air-

ingress accidents. The kinetics of the oxidation reactions must be determined as a function of temperature, pressure, reactant concentration, and gas flow rate.
    - The effect of oxidative weight loss on the physical properties of graphite must be determined.
    - Because neutron irradiation causes damage to graphite microstructure, oxidation studies should be performed on irradiated graphite. The accident conditions of air- and moisture-ingress will most likely occur for irradiated graphites, and thus accident analysis will depend on this information for risk assessment.
- Fracture behavior
    - The fracture behavior of graphite must be elucidated and modeled and the influence of neutron dose and oxidation on fracture determined.

In support of graphite design, manufacturing, qualification, and operation, the following should also be developed and/or integrated within the framework of industrial codes and standards. The following relate to tools that may be used by the designer to mitigate the effects of the phenomena identified above.

- Design codes and standards and material specifications
    - Standard test methods are needed for certain graphite physical, thermal, and mechanical properties (others already exist) and must be developed through a consensus body [American Society for Testing & Materials (ASTM)].
    - Test methods and procedures are required for irradiation testing and oxidation testing.
    - Graphite materials specifications must be developed.
    - Graphite "failure"/"performance" criteria, design codes, and methodologies must be developed and approved via consensus standards bodies [American Society of Mechanical Engineers (ASME)].
- Nondestructive testing
    - Nondestructive examination (NDE) methods must be developed for the inspection of graphite components. These methods should have sufficient range and resolution to image "critical defects."
    - Automated NDE methods are needed.
- Inspection codes and standards
    - Inspection criteria, methods, codes, and personnel requirements need to be developed and approved in consensus manner to examine and approve graphite materials and components for HTGR use.
    - In-service inspection criteria, methods, codes, and personnel requirements need to be developed and approved in consensus manner to examine and approve graphite materials and components for further reactor operation, repair, or replacement.
- In-service inspection
    - In-service inspection methods are needed to assess the condition of systems, structures, and components during reactor operation and during outage. Methodology to further assess the observed condition to the start-up condition is needed to determine any compromise in safety margins and to ensure the adequacy of safety margin.

Additionally, significant activity is required to bring the existing graphite codes and standards to an acceptable condition. The proposed section III Division 2, Subsection CE of the ASME Boiler and Pressure Vessel (B&PV) Code (Design Requirements for Graphite Core Supports) was issued for review and comment in 1992, but only limited action has been taken on this code since that time, and it must be updated and adopted. During 2006, a Special Group (SG) was commissioned under Section III of the ASME B&PV Code Committee to develop codes and standards for the design of graphite components for high temperature gas-cooled reactors. This SG has made significant progress since then, including the development of educational material for introducing those familiar with metallurgy and materials to the unique requirements for intrinsically anisotropic graphite exhibiting nonlinearity in stress-strain response and variability in properties. Since 2004, ASTM has also been developing material specification standards and recommended practices for determining properties of graphite that are important for reactor design. The material specification standard for graphite core components was issued in 2006. Another material specification standard for graphite core support components that are not subjected to high-dose irradiation is under development and is expected to be issued during 2008. A thorough review of the existing properties measurement standards has revealed that many of these standards must be expanded to cover test methods for fracture toughness, lattice parameter determination by x-ray diffraction (XRD), graphite-air oxidation, boron equivalency determination, chemical inventory (for decommissioning considerations), specimen size issues, and overall nuclear-grade graphite material specifications.

3.2 Step 2—PIRT Objectives

The objectives of this PIRT exercise were to

1. identify aspects of the (graphite materials usage) PIRT that impact radiological safety at the highest-level;
2. identify the graphite degradation phenomena for systems, structures, components, in HTGRs that could potentially impact safety by reducing the available safety margin during normal reactor operation, off-normal anticipated occurrences, design basis accidents, and beyond design basis accidents;
3. assess the importance of several phenomena for their relative importance, based on a consensus FOM; and
4. assess the adequacy of the state-of-knowledge of understanding the phenomena to provide technical information for regulatory safety decisions.

3.3 Step 3—Hardware and Scenarios

3.3.1 Hardware

The NGNP is currently in the conceptual design stage, and the Department of Energy's (DOE's) selection of the reactors concept and process heat systems is in progress. Reactor candidates include the direct cycle prismatic-block gas turbine HTGR (such as the GA concept), an indirect-cycle prismatic core version by AREVA, and a pebble-bed version similar to the South African PBMR.

Prismatic fuel elements consist of fuel compacts manufactured from natural flake graphite, synthetic graphite, and a pyrolyzed binder resin, inserted into holes drilled in graphite hexagonal prism blocks ~300 mm across flats and 800 mm long (very similar to Fort St. Vrain reactor fuel elements). Pebble fuel elements, developed in Germany in the late 1960s, are 60-mm-diam spheres containing a central region of TRISO fuel particles in a matrix material comprised of natural flake graphite, artificial graphite, and a pyrolyzed resin binder, surrounded by a 5-mm-thick fuel-free layer of the matrix material. The pebble bed employs continuous refueling, with pebbles recycled approximately six to ten times, depending on measured fuel burnup.

The use of graphite is envisioned primarily as a structural material and neutron moderator for the NGNP core, permanent side reflectors, and core supports. The particular challenges related to graphite for the NGNP relate primarily to the fact that the previous grades of graphite qualified for nuclear service are no longer commercially available. The precursors from which those grades of graphite were made no longer exist. Hence, it will be necessary to qualify new grades of graphite for use in the NGNP. Likely potential candidates currently exist, including fine-grained isotropic, molded, or isostatically pressed, high-strength graphites suitable for core support structures, fuel elements and replaceable reactor components, as well as near isotropic, extruded, nuclear graphites suitable for the above-mentioned structures and for the large permanent reflector components.

Graphite is a composite materials manufactured from a filler coke and pitch binder. Nuclear graphites are usually manufactured from isotropic cokes (petroleum or coal-tar derived) and are formed in a manner to make them near-isotropic or isotropic materials. Figure 1 shows the major processing step in the manufacturing of nuclear graphite. After baking (carbonization) the artifact is typically impregnated with a petroleum pitch and re-baked to densify the part. Impregnation and rebake may occur several times to attain the required density. Graphitization typically occurs at temperatures >2500°C. Additional halogen purification may be required. Typical manufacturing times are 6–9 months.

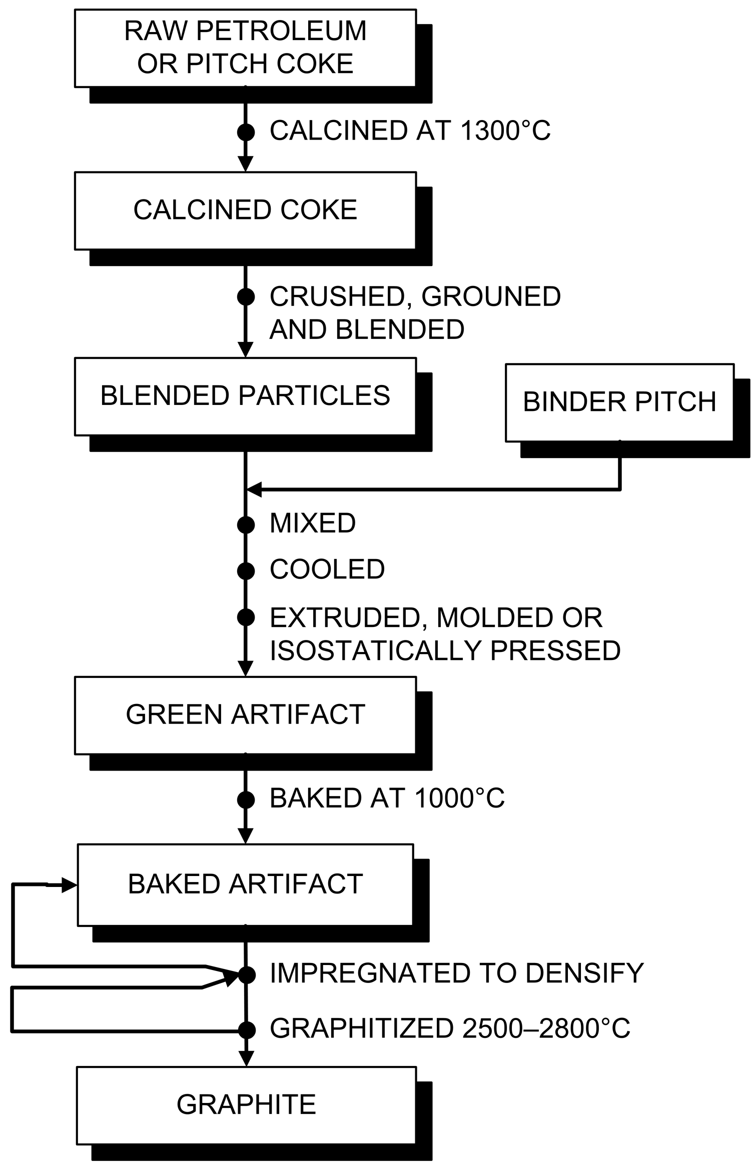

Fig. 1. The process steps in the manufacturing of nuclear graphite.

The forming and densification processes will impart property variation within the billet. The properties will be somewhat different in the forming direction compared to the perpendicular to forming direction. Moreover, a density gradient will exist from billet edge to center. These variations must be quantified for the selected grades of graphite. In addition, variations in property will arise from billet to billet within a batch, and between production lots. Finished graphite is machined to the complex geometries required for the reactor components (fuel elements, reflector blocks, core support post, etc.).

3.3.2 Scenarios relevant to graphite

The panel discussed scenarios that would lead to identifiable phenomena for the graphite components of an NGNP. The following contributing factors to phenomena occurrence were identified.

- effect of air oxidation on properties after air ingress;
- external (applied) load;
- creep strain (irradiation-induced stress-modified dimensional change);
- internal stress (strain) temperature, fluence, coefficient of thermal expansion (CTE), E, dimensional change, f(gradient in temperature, fluence);
- chemical attack (impure helium, graphite purity, for example);
- variability in properties (textural and statistical);
- consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example);
- temperature-induced change in specific heat;
- change in thermal properties due to annealing, including stored energy;
- graphite dust generation (tribological behavior in helium, f(temperature, pressure, fluence);
- graphite specification;
- oxidation of graphite dust;
- emissivity, f(surface roughness);
- cyclic fatigue;
- thermal shock;
- subcritical crack growth;
- component NDE;
- online monitoring;
- in-service inspection;
- irradiation-induced dimensional change;
- irradiation-induced strength change;
- irradiation-induced thermal conductivity change;
- irradiation-induced Young's modulus change;
- irradiation-induced change in CTE;
- irradiation-induced change in shear modulus;
- irradiation-induced change in stress-strain curve; and
- irradiation-induced change in fracture behavior.

3.4 Step 4—Evaluation Criteria

The panel identified three levels of FOM. The top-level FOM was the requirement to maintain dose levels to the public within the regulatory requirements. It was concluded in early discussions that no graphite-specific phenomena (e.g., analogous to primary pressure boundary failure) could directly result in radionuclide release to the environment. On this basis, the focus of the analysis was shifted to identifying phenomena that could potentially lead to increases in the likelihood of radionuclide releases or in the severity of radionuclide releases, should they occur. This led to the identification of Level 2 and Level 3 FOM that relate to that potential. The second level consisted of three "System" FOM that could influence the top-level FOM, and were identified as those (1) leading to increased activity in the helium coolant, (2) leading to challenges to the primary pressure boundary, and (3) adversely affecting the ability to attain and maintain cold shutdown and hold down. These FOMs, in turn, are influenced by and through the third-level "Component" FOM, which were ability to maintain passive heat transfer; maintain ability to control reactivity; ability to protect adjacent components from excessive heat; ability to shield adjacent components; ability to maintain coolant flow path; ability to prevent excessive mechanical load on the fuel; and, ability to minimize activity in the coolant. These FOMs are given in Table 1.

Table 1. FOMs for the graphite phenomena

Level 1	Regulatory		Dose
Level 2	System	1	Increased activity in the coolant
		2	Challenge primary pressure boundary
		3	Degraded ability for cold shutdown and hold down
Level 3	Component	1	Ability to maintain passive heat transfer
		2	Maintain ability to control reactivity
		3	Thermal protection of adjacent components
		4	Shielding of adjacent components
		5	Maintain coolant flow path
		6	Prevent excessive mechanical load on the fuel
		7	Minimize activity in the coolant

3.5 Step 5—Knowledge Base

The panel compiled and reviewed (to some extent) the contents of a database that captured

- recent design information available for both reactor types;
- relevant operational experience from Fort ST. Vrain, the Thorium High-Temperature Reactor (THTR-300) in North Rhine Westaphalia, Germany, the Atomgeneinschaft Versuchs Reaktor (AVR) in Julich, Germany, and from the operation of Magnox and Advanced Gas-Cooled Reactors (AGRs) in the United Kingdom (UK);
- the findings from the NRC preliminary safety evaluation of the steam-cycle MHTGR (NUREG-1338);
- a database of extensive and comprehensive international reports available from the International Atomic Energy Agency (IAEA) Web site (www.IAEA.org);
- a database of irradiated graphite properties available to participating nations from the IAEA Web site; and,
- an extensive set of open literature reports that are listed in the Bibliography section.

3.6 Step 6—Plausible Graphite Phenomena

The panel identified many phenomena that affected the FOMs in various ways and determined which of the component FOM applied to these phenomena. A summary of the number of phenomena associated with each of the FOM is provided in Table 2.

Table 2. Total number of phenomena influencing each FOM

FOM ID	FOM	Number of phenomena
3-1	Ability to maintain passive heat transfer	22
3-2	Maintain ability to control reactivity	25
3-3	Thermal protection of adjacent components	22
3-4	Shielding of adjacent components	11
3-5	Maintain coolant flow path	23
3-6	Prevent excessive mechanical load on the fuel	14
3-7	Minimize activity in the coolant	19

The phenomena identified by the graphite PIRT panel, plus several others that were passed to the graphite panel from the other PIRT panels are listed in Table 3. The relevant FOM are also listed along with a brief comment explaining the relevance of nature of the phenomena.

Table 3. Plausible phenomena

ID No.	FOM	Phenomena	Comment
1	All Level 3	Statistical variation of non-irradiated properties.	The variability in properties of graphite manufactured to given specifications must be accounted for, including the degree of anisotropy. There are implications for mechanical and heat transport properties, as well as for response to chemical attack (purity level), degradation in service and decommissioning. (This aspect is well-understood by the graphite designers and has been implemented in the design code of various HTGR designs in the past. The currently ongoing *ASME Code* development is expected to incorporate these aspects in the design codes and standards.)
2	All Level 3	Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example).	The concern is with variation in the quality of graphite supply over long-periods of time (e.g., the lifetime of any reactor), and with manufacturing levels associated with a multiple reactor fleet.
3	3-2 through 3-6	Graphite contains inherent flaws.	Need improved methods for flaw evaluation.
4	3-2 3-4 3-5	Cyclic fatigue (nonirradiated).	Implications for structural reliability.

Table 3 (continued)

ID No.	FOM	Phenomena	Comment
5(a)	3-1 3-3	Temperature dependence of non-irradiated thermal properties.	Need analytical models that correlate fundamental graphite properties, such as porosity (size, shape, and orientation), distribution, grain (size, shape, and orientation distribution), and density with non-irradiated properties and predictive models for irradiated properties from non-irradiated properties data.
5(b)	3-2 3-5 3-7	Temperature dependence of non-irradiated mechanical properties.	The knowledge level associated with properties influencing these Level 3 criteria was considered higher by one reviewer.
6	All Level 3	Irradiation-induced dimensional change.	Largest source of internal stress. Need predictive models for irradiated properties from non-irradiated properties data.
7	All Level 3	Irradiation-induced creep (irradiation-induced dimensional change under stress).	Could potentially reduce internal stress significantly.
8	3-1 3-3 3-5 3-7	Irradiation-induced thermal conductivity change.	Concern is that thermal conductivity might be lower than required by design basis for licensee basis event (LBE) heat removal due to (a) inadequate database to support design over component lifetime and (b) variations in characteristics of graphites from lot to lot; potential is to exceed fuel design temperatures during LBEs.
9	3-2 3-3 3-5 3-6	Irradiation-induced changes in elastic constants, including the effects of creep strain.	
10	3-2 3-3 3-5 3-6	Irradiation-induced change in CTE, including the effects of creep strain.	
11	3-2 3-3 3-5 3-6	Irradiation-induced changes in mechanical properties (strength, toughness), including the effect of creep strain (stress).	Tensile, bend, compression, shear (multiaxial), stress-strain relationship, fracture, and fatigue strength.
12	3-1	Stored energy release.	Above 150°C, this is considered not to be an issue and above 350^{o}C to be insignificant. Low-temperature release of stored energy is not an issue for HTRs. The reported minimal high-temperature reduction (due to irradiation) of specific heat needs to be confirmed by additional experiments and analyses.
13	3-1	Annealing of thermal conductivity.	During accident improves heat conduction, has beneficial implications for maintaining fuel temperature limit.
14	3-7	Oxidation of graphite dust.	See report: A. Wickham (EPRI report).
15	3-7	Graphite dust generation.	Tribological behavior in helium, f(T, pressure, fluence). Dust particle size distribution.

Table 3 (continued)

ID No.	FOM	Phenomena	Comment
16	3-1	Potential changes in irradiated graphite emissivity.	Emissivity, f(oxidation, surface roughness).
17	3-5	Tribology of graphite in (impure) helium environment.	
18	3-7	Irradiation-induced change in graphite pore structure.	Link to FPT panel.
19	3-7	Temperature-dependent release of fission product (FP) from graphite.	Link to FPT panel.
20	3-7	Oxidation of irradiated graphite, including potential adsorbed/absorbed FP.	Irradiated graphite will have degraded structure, potentially having enhanced oxidation; it will potentially increase the release of FP. Link to FPT panel.
21	3-1	Degradation of thermal conductivity	This has implications for fuel temperature limit for loss-of-forced cooling accident.
21(a)	3-3	Degradation of thermal conductivity	Has implications for maintaining temperature limits for adjacent (metal) components.
22	3-1	Annealing of thermal conductivity	During accident improves heat conduction, has implications for maintaining fuel temperature limit.
22(a)	3-3	Annealing of thermal conductivity	During accident improves heat conduction—detrimental to adjacent metallic component temperature.
23	3-1	Stored energy release	Above 150°C, this is considered not to be an issue and above 350°C to be insignificant. Low-temperature release of stored energy is not an issue for HTRs. The reported minimal high temperature reduction (due to irradiation) of specific heat needs to be confirmed by additional experiments and analyses.
24	3-5	Blockage of fuel element coolant channel (prismatic fuel).	Results in increased fuel temperature in localized areas.
24(a)	3-5	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials [carbon fiber composite (CFC)].
24(b)	3-5	Due to graphite failure, spalling	Debris generated from within the graphite core structures.
24(c)	3-5	Channel distortion	Deformation from individual graphite blocks and block assemblies. There is a link to the metallic core support structure.
26	3-1	Blockage of reflector block coolant channel	Results in reduced thermal capacity of the core during accident conditions.
26(a)	3-1	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Collapse of upper insulation and deposition onto channel (PCR). Tied to high-temperature materials (CFRC hanger rods).
26(b)	3-1	Due to graphite failure, spalling	Debris generated from within the graphite core structures.

Table 3 (continued)

ID No.	FOM	Phenomena	Comment
26(c)	3-1	Channel distortion	Deformation from individual graphite blocks and/or block assemblies. There is a link to the metallic core support structure.
27	3-2, 3-3	Blockage of coolant channel in reactivity control block	Results in damage to the reactivity control components; physical misalignment of channel interfaces.
27(a)	3-2, 3-3	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials [carbon-fiber-reinforced composite (CFRC)].
27(b)	3-2, 3-3	Due to graphite failure, spalling	Debris generated from within the graphite core structures.
27(c)	3-2, 3-3	Channel distortion	Deformation from individual graphite blocks and/or block assemblies. There is a link to the metallic core support structure.
28	3-2	Blockage of reactivity control channel	Results in inability to freely insert absorber materials.
28(a)	3-2	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials (CFRC)
28(b)	3-2	Due to graphite failure, spalling	Debris generated from within the graphite core structures.
28(c)	3-2	Channel distortion	Deformation from individual graphite blocks and/or block assemblies.
29	3-5, 3-7	Increased bypass coolant flow channels by break, distortion, etc.	Due to channel distortion, cracking in graphite bricks, etc. Reduced coolant flow through fuel requires higher fuel temperature to maintain the same core outlet temperature.
30	3-3	Increased bypass coolant flow channels by break, distortion, etc.	If the bypass is near to the adjacent metallic structures, this phenomenon may challenge the temperature limit of metallic structures.
31		Outlet plenum collapse	Gross collapse of structures that define the core outlet plenum.
31(a)	3-1	Outlet plenum collapse	Disrupts heat conduction path.
31(b)	3-2	Outlet plenum collapse	Potentially distortion/displacement of reactivity control channels.
31(c)	3-5	Outlet plenum collapse	Disrupts coolant flow path.
31(d)	3-6	Outlet plenum collapse	Could potentially result in excessive mechanical load in the fuel.
32	3-7	Chemical attack	During air/moisture ingress accident, chemical impurities in graphite have effect on the rate of chemical attack.
32(a)	3-1, 3-2, 3-7	Catastrophic chemical attack.	Excessive change in component geometry, such as reduction in cross section, due to large and sustained chemical attack.

Table 3 (continued)

ID No.	FOM	Phenomena	Comment
32(b)	All Level 3	Effect of chronic chemical attack on properties	Change in graphite internal pore structure due to (slow) chemical attack over long period of time. Degradation of strength, thermal conductivity, Young's modulus. CTE not relevant as per existing data [Hacker, P. J., et al. (1999)]. The consequences have been dealt with for phenomena 12, 13, 14, 15, 16, and 17.
33	3-2, 3-3, 3-4, 3-5, 3-6, 3-7	External (applied) loads	Can become significant if not properly addressed in design. For example, heat up (thermal expansion of core barrel, deformation of the integrated, whole-core graphite structure, dimensional change). Consequences of these phenomena have been addressed in others (e.g., 12 through 17).
34	3-1, 3-2, 3-3, 3-4, 3-5, 3-6, 3-7	Fast neutron fluence	All graphite component life (structural integrity) predictions rely on an accurate time and spatial calculation of fast neutron fluence (data supplied to graphite specialists by reactor physicists).
35	3-1, 3-2, 3-3, 3-4, 3-5, 3-6, 3-7	Gamma and neutron heating	About 5% of the heat in a graphite-moderated reactor is generated within the graphite components due to gamma and neutron heating. Predictions of the graphite temperatures for use in structural integrity calculations rely on this quantity. Accurate calculation of the spatial distribution of gamma and neutron heating is required to be supplied to the graphite specialist by reactor physicist).
36	3-1, 3-2, 3-3, 3-4, 3-5, 3-6, 3-7	Graphite temperatures	All graphite component life and transient calculations (structural integrity) require time-dependent and spatial predictions of graphite temperatures. Graphite temperatures for normal operation and transients are usually supplied to graphite specialists by thermal-hydraulics specialist. Although in some cases gas temperatures and heat transfer coefficients are supplied, and the graphite specialists calculate the graphite component temperatures from these.

3.7 Step 7—Importance Level Ranking

The panel ranked applicable phenomena in each table relative to one or more evaluation criterion or FOM, for example “maintain ability to control reactivity”. Each phenomenon was assigned an importance rank of “High,” “Medium,” or “Low,” accompanied by a discussion and rationale for the assignment. The NRC definitions associated with each of these importance ranks follow:

Importance rank and definition

Importance rank	Definition
Low (L)	Small influence on primary evaluation criterion
Medium (M)	Moderate influence on primary evaluation criterion
High (H)	Controlling influence on primary evaluation criterion

A compilation of the rankings for all the scenarios covered is found in Table 4 and in the PIRT Table in Sect. 5.

3.8 Step 8—Collective (Panel) Knowledge Level Ranking

Panel members assessed and ranked the current knowledge level for applicable graphite phenomena in the PIRT table (Table 5, Sect. 4). Compiled (averaged) values of the panel member's individual rankings are also given in Table 6. High, medium, and low designations were used to reflect knowledge levels and adequacy of data and analytical tools used to characterize the phenomena, using the NRC-supplied definitions shown below.

Knowledge level and definitions

Knowledge level	Definition
H	Known: Approximately 70–100% of complete knowledge and understanding
M	Partially known: 30–70% of complete knowledge and understanding
L	Unknown: 0–30% of complete knowledge and understanding

3.9 Documentation of the PIRT—Summary

The collective PIRT table and panel scoring is in Sect. 4. The panel's phenomena importance and knowledge ranking are summarized in Table 4 below. In the table, "I" refers to the importance of the phenomenon and "K" refers to the present level of knowledge. "H," "M," and "L" refer to high, medium, and low, respectively.

Table 4. Summary of the phenomena importance and knowledge rankings

PIRT rank	Number of phenomena
I-H, K-L	5
I-H, K-M	9
I-M, K-L	2
I-M, K-M	14
I-L, K-H	0
I-L, K-M	2
I-L, K-L	1
I-H, K-H	8
I-M, K-H	1

The phenomena ranked with HIGH importance and LOW or MEDIUM knowledge bases are of the utmost concern. Similarly, phenomena with a MEDIUM knowledge rank and LOW or MEDIUM knowledge base are of concern.

3.9.1 Phenomena ranked I-H, K-L

I.D. No. 7: Irradiation-induced creep (irradiation-induced dimensional change under stress)

Stress due to differential thermal strain and differential irradiation-induced dimensional changes would very quickly cause fracture in the graphite components if it were not for the relief of stress due to irradiation-induced creep. The phenomena and mechanism of irradiation-induced creep in graphite is therefore of high importance. Currently there are no creep data for the graphite grades being proposed for use in the NGNP. However, creep at low dose follows a linear law that can be explained through a dislocation pinning/unpinning model due to Kelly and Foreman [39]. Marked deviation from this law has been observed at intermediate neutron doses. The applicability of the law has been extended by taking into account changes in the pore structure that manifest themselves as changes in the CTE with creep strain [15]. However, the current creep law breaks down at high-temperature, moderate-dose and moderate-temperature high-dose combinations. A new model for creep is needed that can account for the observed deviations from linearity or the creep strain rate with neutron dose. Existing and new models must be shown to be applicable to the currently proposed graphite grades. Knowledge rank was therefore considered as low.

I.D. No. 10: Irradiation-induced change in CTE, including the effects of creep strain

Differential thermal strains occur in graphite components due to temperature gradients and local variation in the CTE. Variations in the CTE are a function of the irradiation conditions (temperature and dose) and the irradiation induced creep strain [20, 33, 15, 10]. Thus the importance ranking is high for this phenomenon. Irradiation-induced changes in CTE are understood to be related to changes in the oriented porosity in the graphite structure. The changes are observed to be different when graphite is placed under stress during irradiation. The direction and magnitude of the stress (and creep strain) affect the extent of the CTE change. Only limited data are available for the effect of creep strain on CTE in graphite, and none of this data is for the grades proposed for the NGNP. Thus, the knowledge rank is low.

I.D. No. 11: Irradiation-induced changes in mechanical properties (strength, toughness), including the effect of creep strain (stress)

The properties of the graphite are known to change with neutron irradiation, the extent of which is a function of the neutron dose, irradiation temperature, and irradiation-induced creep strain. Differential changes in moduli, strength, and toughness must be accounted for in design. The importance of this phenomenon is thus ranked high. Although data exist for the effect of neutron dose and temperature on the mechanical properties of graphite, there are few data on the effects of creep strain on the mechanical properties. Moreover, none of the available data is for the grades currently being considered for the NGNP. Knowledge ranking is therefore low.

I.D. No. 25(b): Blockage of fuel element coolant channel due to graphite failure and/or graphite spalling

Significant uncertainty exists as to the stress state of any graphite component in the core. Moreover, the strength of the components changes with dose, temperature, and creep strain. The combination of these factors makes the probability of local failure, graphite spalling, and possible blockage of a fuel element coolant channel difficult to determine. Consequently the panel rated this phenomenon’s importance as high. Although the changes in properties of graphite have been studied for many years, there are still data gaps that make whole core modeling very difficult (e.g., effect of creep strain on properties). Moreover, data on the grades selected for NGNP are not available. Therefore, the panel rated the knowledge base for this phenomenon as low.

I.D. No. 27(b): Blockage of coolant channel in reactivity control block due to graphite failure and/or graphite spalling.

Significant uncertainty exists as to the stress state of any graphite component in the core. Moreover, the strength of the components changes with dose, temperature, and creep strain. The combination of these factors makes the probability of local failure, graphite spalling, and possible blockage of a coolant channel in a reactivity control block difficult to determine. Consequently the panel rated this phenomenon's importance as high. Although the changes in properties of graphite have been studied for many years there are still data gaps that make whole core modeling very difficult (e.g., effect of creep strain on properties). Moreover, data on the grades selected for NGNP are not available. Therefore, the panel rated the knowledge base for this phenomenon as low.

3.9.2 Phenomena ranked I-H, K-M

I.D. No. 1: Statistical variation of non-irradiated properties

The graphite single crystal is highly anisotropic due to the nature of its bonding (strong covalent bonds between the carbon atoms in the basal in the plane and weak van der Waals bonds between the basal planes). This anisotropy is transferred to the filler coke particles and also to the crystalline regions in the binder phase. Thus, the mechanical and physical properties of graphite vary within a billet due to texture introduced during forming and thermal processing. Moreover, there is statistical variability in the properties between billets within the same lots, between lots, and between batches due to variations on raw materials, formulations, and processing conditions. Therefore, it is necessary to develop a statistical data base of the properties for a given graphite grade. Variations in the chemical properties (chemical purity level) will have implications for chemical attack, degradation, decommissioning). Probabilistic design approaches are best suited to capturing the variability of graphite. The panel rated this phenomenon as high importance. Although other nuclear graphites have been characterized and full databases developed, allowing an understanding to de developed of the textural variations, only limited data exist on the graphites proposed for the NGNP. Therefore, the panel rated this phenomenon's knowledge level as medium.

I.D. No. 2: Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)

Graphite is manufactured from cokes and pitches derived from naturally occurring organic sources such as oil and coal (in the form of coal tar pitch). These sources are subject to geological variations and depletion, requiring the substitution of alternate sources. Therefore, consistency of graphite quality and properties over the lifetime of a reactor, or the reactor fleet (for replacement, for example), is of importance. The panel ranked the importance of this phenomenon as high. Our understanding of this phenomenon is sufficient that we are able to develop generic specifications (ASTM DO2.F, D 7219-05) that should assure quality and repeatability. However, this has not been proven. The panel assessed the knowledge base for this phenomenon as medium.

I.D. No. 6: Irradiation-induced dimensional change

Neutron irradiation causes dimensional changes in graphites. Theses changes are the result of anisotropic crystal growth rates (a-axis shrinkage and c-axis growth), the interaction of crystal dimensional change with porosity, and the generation of new porosity. The amount of irradiation-induced dimensional change is a function of the neutron dose and irradiation temperature. Consequently, gradients in temperature or neutron dose will introduce differential dimensional changes (strains). Irradiation induced dimensional changes are the largest source of internal stress. Because of the significance of dimensional changes in generating core stresses, the panel gave this phenomenon as high importance. Irradiation-induced dimensional changes have been researched for many years, and several dimensional change models have been proposed. However, there is a paucity of data for the dimensional changes of the graphites proposed for the NGNP. Therefore, the knowledge rank was considered as medium.

I.D. No. 8: Irradiation-induced thermal conductivity change

Displacement damage caused by neutron irradiation introduces additional phonon scattering sites to the graphite crystal lattice and consequently reduces the thermal conductivity. The nature of the irradiation-induced damage is sensitive to the temperature of irradiation. Consequently, the extent of degradation is temperature dependant. In addition, phonon-phonon (Umklapp) scattering increases as the measurement temperature increases, and thus the thermal conductivity falls as the temperature increases. At very high irradiation dose, thermal conductivity reduces further, at an increased rate, attributed to porosity generation due to large crystal dimensional change. The thermal conductivity is also subject to some recovery (annealing) on heating above the irradiation temperature (such as during an accident thermal transient). The exact thermal conductivity under all core conditions is therefore subject to some uncertainty. A thermal conductivity lower than required by design basis for LBE heat removal due to (a) inadequate database to support design over component lifetime, or (b) statistical and textural variations in characteristics of graphites from lot to lot have the potential to allow fuel design temperatures to be exceeded during LBEs. The importance of this phenomenon was therefore considered high. Irradiation-induced thermal conductivity changes have been researched for many years and several conductivity change models have been proposed. However, there is a paucity of data for the conductivity changes of the graphites proposed for the NGNP. Therefore, the knowledge rank was considered as medium.

I.D. No. 9: Irradiation-induced changes in elastic constants, including the effects of creep strain

Neutron irradiation induces changes in the elastic constants of graphite. Initial increases in the moduli are attributed to an increase in dislocation pinning points in the basal plane, which reduce the crystal shear compliance, C_{44}. Subsequent changes in the elastic modulus are attributed to pore-structure changes (initial pore closures followed by pore generation). Although the understanding of irradiation modulus changes is plausible behavior, there are no direct microstructural observations or sufficiently well developed models of these mechanisms. Therefore, the knowledge rank was considered as medium.

I.D. No. 17: Tribology of graphite in (impure) helium environment

Graphite is a naturally lubricious material. However, its behavior is modified by the helium environment of the NGNP. The abrasion of graphite blocks on one another or of the fuel pebbles on the graphite moderator blocks may produce graphite dust. Studies are needed to assess the effect of the helium environment on the friction and wear behavior of graphite. The possibility that fuel balls can "stick" together and cause a fuel flow blockage must be explored, although German pebble bed experience was positive in this regard (i.e., no blockages). The consequences of dust generation (possible fission product transport mechanism) and possible fuel ball interactions resulted in the panel ranking the importance of this phenomenon as high. Some literature exists on this subject mostly from the past German program. Consequently, the panel ranked the knowledge level as medium.

I.D. No. 21: Degradation of thermal conductivity (see No. 8 above)

The degradation of thermal conductivity in graphite components has implications for fuel temperature limits during loss-of-forced cooling accidents.

I.D. No. 28(b): Blockage of Reactivity Control Channel due to graphite failure, spalling

Significant uncertainty exists as to the stress state of any graphite component in the core. Moreover, the strength of the components changes with dose, temperature, and creep strain. The combination of these factors makes the probability of local failure, graphite spalling, and possible blockage of a reactivity control channel in a reactivity control block difficult to determine. Consequently, the panel rated this phenomenon's importance as high. Although the changes in properties of graphite have been studied for many years, there are still data gaps that make whole core modeling very difficult (e.g., effect of creep strain on properties). Moreover, data on the grades selected for NGNP are not available. NGNP designs are known to be capable of safe shutdown without control rod entry. Therefore, the panel rated the knowledge base for this phenomenon as medium.

I.D. No. 36: Graphite temperatures

All graphite component life and transient calculations (structural integrity) require time-dependent and spatial predictions of graphite temperatures. Graphite temperatures for normal operation and transients are usually supplied to graphite specialists by thermal-hydraulics specialists. Although, in some cases, gas temperatures and heat transfer coefficients are supplied, and the graphite specialists calculate the graphite component temperatures from these.

3.9.3 Phenomena ranked I-M, K-L

I.D. No. 15: Graphite dust generation

Abrasion between adjacent block, or fuel pebbles and reflector blocks, will cause the formation of dust. This may become a vector for fission products or could possibly impede coolant flow (see below).

I.D. No. 26(b): Blockage of reflector block coolant channel—due to graphite failure, spalling

Blockage of coolant channels by graphite debris could cause local hot spots in the core.

3.9.4 Phenomena ranked I-M, K-M

I.D. No. 3: Graphite contains inherent flaws

Graphite contains a distribution of inherent flaws that control the strength of the material. This flaw population must be established, along with the mechanical properties, in order to design the reactor graphite structures. The flaw structure is one of the components of the graphites texture.

I.D. No. 4: Cyclic fatigue (non-irradiated)

The extent to which a given grade suffers from fatigue reduction in strength must be determined for both unirradiated and irradiated graphite. However, prior data show this to be a small effect.

I.D. No. 13: Annealing of thermal conductivity

When graphite is heated above its previous irradiation temperature by ~50°C, annealing of the defect structure (caused by displacement damage) can occur. Thus, there is some recovery of the thermal conductivity because the internal resistance caused by phonon-defect scattering is reduced.

I.D. No. 21(a): Degradation of thermal conductivity

See I.D. No. 8 (above).

I.D. No. 22: Annealing of thermal conductivity

See I.D. No. 13 (above).

I.D. No. 22(a): Annealing of thermal conductivity

See I.D. No. 13 (above).

I.D. No. 25(c): Channel distortion

I.D. No. 26(c): Channel distortion

I.D. No. 27(c): Channel distortion

I.D. No. 28(c): Channel distortion

Channel distortions may occur because of differential strains. These, in turn, are caused by local differences in dimensional change rates due to temperature and dose gradients.

I.D. No. 29: Increased bypass coolant flow channels by break, distortion, etc.

I.D. No. 30: Increased bypass coolant flow channels by break, distortion, etc.

Channel distortions may occur because of differential strains. These, in turn, are caused by local differences in dimensional change rates due to temperature and dose gradients. Differential strains may eventually cause failure of graphite core components

I.D. No. 32(b): Effect of chronic chemical attack on properties

Oxidation by air of impurities in the helium coolant to chronic levels will reduce graphites mechanical integrity and increase the rate of dust formation. Predictive methods are needed for the extent of weight loss and the effect of weight loss on graphite.

I.D. No. 33: External (applied) loads

Such loads must be quantified and properly accounted for in the design process.

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4. PIRT TABLES

Table 5. PIRT table for graphite material
(Bu = Burchell, M = Marsden, Br = Bratton, P = Panel)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
1	All Level 3	Statistical variation of non-irradiated properties	Variability in properties (textural and statistical); isotropic. Probabilistic approach use is prudent. Purity level; implications for chemical attack, degradation, decommissioning.	H	H	H	H	Graphite has a significant spread in properties; therefore, a statistical approach is essential. That is within block, block to block within the same batch and batch to batch. This has to be known and understood.	M	M	M	M	Statistical methods need agreeing, improving on, and validating. Standards need establishing.
2	All Level 3	Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example).	Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example). Over multiple reactor fleet, and over the lifetime of any reactor.	H	H	H	H	Raw materials and manufacturing techniques may change with resultant change in properties and irradiation behavior.	M	M	M	M	While there is a general understanding of graphite behavior for similar types of graphite, research is required to enable a reasonable prediction of irradiated graphite behavior to be made from knowledge of the microstructure of unirradiated graphite. Thus, reducing the need for large databases which may take many years to carry out.

Table 5 (continued)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
3	3-2 thru 3-6	Graphite contains inherent flaws	Need methods for flaw evaluation.	H	M	H	M *	Available techniques need further development, demonstration, and confirmation. New improved component NDE techniques are desirable.	M	M	L	M	New improved NDE methods require developing.
4	3-2 3-4 3-5	Cyclic fatigue (nonirradiated)	Structural reliability	L	M	M	M	Probably number of cycles too low to be important.	M	M	M	M	Unirradiated data exist, irradiated data required.
5(a)	3-1 3-3	Temperature dependence of nonirradiated thermal properties.		H	H	H	H	Thermal and mechanical behavior different than metals and need to be understood. In particular CTE, thermal conductivity.	H	H	H	H	Empirical data can be easily obtained on unirradiated properties, temperature conversion rules need to be defined in standards.
5(b)	3-2 3-5 3-7	Temperature dependence of nonirradiated mechanical properties.		L	L	L	L	In particular Young's modulus and strength. Could add margin to the safety case at high temperature.	M	H	H	H	Empirical data can be easily obtained on unirradiated properties, temperature conversion rules need to be defined in standards.
6	All Level 3	Irradiation-induced dimensional change	Largest source of internal stress	H	H	H	H	Required for graphite FEM stress analysis, main driver for stresses.	M	M	H	M	Data available or can be measured, but better mechanistic understanding desirable.

Table 5 (continued)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
7	All Level 3	Irradiation-induced creep (irradiation-induced dimensional change under stress).	Could potentially reduce significantly internal stress?	H	H	H	H	Required for graphite FEM stress analysis, acts to reduce stress.	L	L	L	L	It is essential that irradiation creep is better understood, mechanistic understanding essential. There are interaction effects with CTE and maybe dimensional change and modulus. New models are needed along with data on new graphites.
8	3-1 3-3 3-5 3-7	Irradiation-induced thermal conductivity change.	Thermal conductivity lower than required by design basis for LBE heat removal due to (a) inadequate database to support design over component lifetime and (b) variations in characteristics of graphites from lot to lot; potential is to exceed fuel design temperatures during LBEs.	H	H	H	H	Important input to loss-of-coolant accidents and used to define temperatures for FEM irradiated graphite component stress analysis.	M	M	H	M	Low fluence data available and understanding adequate. High fluence data and understanding required. Methodology for temperature dependence requires validation see Kelly (1967).

Table 5 (continued)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
9	3-2 3-3 3-5 3-6	Irradiation-induced changes in elastic constants, including the effects of creep strain.		H	H	H	H	Essential for input into irradiated graphite FEM stress analysis.	M	M	M	M	Data available or can be measured, better mechanistic understanding desirable. Concept of increase in modulus due to "pinning" needs further investigation.
10	3-2 3-3 3-5 3-6	Irradiation-induced change in CTE, including the effects of creep strain.		H	H	H	H	Essential input into irradiated graphite component stress analysis, also affected by irradiation creep.	L	M	L	L	Extensive database, some micro-structural/ mechanistic studies required.
11	3-2 3-3 3-5 3-6	Irradiation-induced changes in mechanical properties (strength, toughness), including the effect of creep strain (stress).	Tensile, bend, compression, shear (multiaxial), stress-strain relationship, fracture, and fatigue strength.	H	H	H	H	Essential input into irradiated graphite component stress analysis.	L	L	L	L	Extensive database, some micro-structural/ mechanistic studies required. Better understanding of fracture process required.

Table 5 (continued)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
12	3-1	Stored energy release	Above 350°C, this is not an issue. Low-temperature release of stored energy is not an issue. The reported minimal high-temperature reduction (due to irradiation) of specific heat needs to be confirmed by additional experiments and analyses.	L	L	L	L	Not an issue. But, high-temperature long-term behavior needs to be confirmed by further experiments.	M	M	M	M	At low temperatures, enough information is available. However, for high temperatures, experimental data and model would be needed.
13	3-1	Annealing of thermal conductivity	During accident improves heat conduction, has implications for maintaining fuel temperature limit.	H	M	M	M	Information on recovery of thermal conductivity during transients will be needed.	M	L	H	M	Physics well-understood. Data lacking for relevant grades.
14	3-7	Oxidation of graphite dust	See report: A. Wickham (EPRI report)	M	M	M	M	Kinetics of graphite dust can be different than bulk graphite; dust adsorbs/absorbs FP and has implications for FP transport and relocation. Additionally, exothermic heat generation from dust oxidation can heat graphite.	H	H	M	H	A significant amount of work has been carried out in this area related to decommissioning.

Table 5 (continued)

Material: Graphite														
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
15	3-7	Graphite dust generation	Tribological behavior in helium, f(temperatures, pressure, fluence). Dust particle size distribution.	M	M	M	M	Potential circulating activity.	L	L	L	L	There appears to be a lot of contradictory statements and evidence as to the level of dust involved and where it comes from, that is, graphite pebbles, blocks. Requires validated evidence.
16	3-1	Potential changes in irradiated graphite emissivity	Emissivity, f(oxidation, surface roughness).	L	L	L	L	Emissivity change probably has low impact on heat transfer.	H	H	H	H	System specific data may be required.
17	3-5	Tribology of graphite in (impure) helium environment		H	H	M	H	Depends on design. Impacts seismic assessments. Whole-core modeling needs these data.	L	M	M	M	Limited data available.
18	3-7	Irradiation-induced change in graphite pore structure.	Link to FPT panel.	M	M	L	M	Related to pore structure of graphite and "tortuosity." Permeability, gas diffusivity, and form and location of impurity within the pore structure may factor into FP transport. May influence the fission product transport. Needs to be coordinated with FP panel. The graphite panel needs more	M	M	L	M	There is a significant amount of UK work on porosity development in radiolytically oxidized graphite, but much less on graphite irradiated in an inert atmosphere. There is empirical data on FP in graphite, little know how they and other impurities are bonded into structure,

Table 5 (continued)

Material: Graphite													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
								information for importance ranking.					this subject is part of EU FP7 Carbowaste program.
19	3-7	Temperature-dependent release of FP from graphite.	Link to FPT panel	L	L	L	L	Stored FP. The graphite panel needs more information for importance ranking.	L	L	L	L	Irradiation high-temperature release mechanism is postulated. No experimental evidence.
20	3-7	Oxidation of irradiated graphite, including potential adsorbed/ absorbed FP.	Irradiated graphite will have degraded structure, potentially having enhanced oxidation; it will release FP and a link to FP transport.	M	H	L	M	After irradiation, does the chemical reactivity of graphite change? The graphite panel needs more information on the need and relevance of this phenomenon from FP panel.	H	H	H	H	A significant amount of data available from UK, Germany, United States, Russia, etc. System-specific data may be required. Some very high-temperature tests may be required.

Table 6. PIRT for graphite components
(Bu = Burchell, M = Marsden, Br = Bratton, P = Panel)

Graphite Component														
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
21	3-1	Degradation of thermal conductivity	Has implications for fuel temperature limit for loss-of-forced cooling accident.	H	H	H	H	Important input to loss-of-coolant accidents and used to define temperatures for FEM irradiated graphite component stress analysis.	M	M	H	M	Low fluence data available and understanding adequate. High fluence data and understanding required. Methodology for temperature dependence requires validation; see Kelly (1967).
21(a)	3-3	Degradation of thermal conductivity	Has implications for maintaining temperature limits for adjacent (metal) components.	H	M	M	M	Presumably metal parts are well away from maximum flux.	M	M	M	M	Low fluence data available and understanding adequate. Methodology for temperature dependence requires validation; see Kelly (1967).
22	3-1	Annealing of thermal conductivity	During accident improves heat conduction, has implications for maintaining fuel temperature limit.	M	M	M	M	This can be categorized as "nice to have" data and understanding, will help with safety margins.	M	L	H	M	Physics well-understood. Data lacking for relevant grades. Experimental data required, probably generic to all graphite, except at high fluence.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
22(a)	3-3	Annealing of thermal conductivity	During accident improves heat conduction—detrimental to adjacent metallic component temperature.	M	M	L	M	Not required?	M	L	H	M	Physics well-understood. Data lacking for relevant grades. Experimental data required, probably generic to all graphite, except at high fluence.
23	3-1	Stored energy release	Above 350°C, this is not an issue. Low-temperature release of stored energy is not an issue. The reported minimal high-temperature reduction (due to irradiation) of specific heat needs to be confirmed by additional experiments and analyses.	M	L	L	L	Not an issue as temperatures in HTR too high to be a problem. But, high-temperature long-term behavior needs to be confirmed by further experiments.	M	M	M	M	At low temperatures, enough information is available. However, for high temperatures, experimental data and model would be needed. May need limited validation experiments, (DSC up to 1600°C); however, data probably available.
24	3-5	Blockage of fuel element coolant channel	Results in increased fuel temperature in localized areas.										
25(a)	3-5	Foreign object (debris)	Broken pieces of nongraphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials [carbon fiber composite (CFC)]	M	M	H	M	Since this is failure of nongraphite, the materials panel should consider this issue.	M	M	L	M	Nonvalidated codes are available. Codes are likely to be reactor specific.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
25(b)	3-5	Due to graphite failure, spalling	Debris generated from within the graphite core structures.	H	M	H	H	Two mechanisms: (a) component failure due to internal or external component stresses, (b) component failure due to very high irradiation and severe degradation of the graphite.	L	M	L	L	Generic graphite codes available for the prediction of internal stresses in irradiated graphite components, however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these codes will also require validation.
25(c)	3-5	Channel distortion	Deformation from individual graphite blocks and block assemblies. There is a link to the metallic core support structure.	H	M	H	M	Individual graphite component dimensional changes are normally significant but relatively small. However, in damaged components dimensional changes can become quite large. The accumulation of dimensional changes in an assembly of components can result in significant overall dimensional changes and kinking, that is, in a column of graphite bricks.	M	M	L	M	Generic graphite codes available for the prediction of deformations in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these will also require validation.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
26	3-1	Blockage of reflector block coolant channel	Results in reduced thermal capacity of the core during accident conditions										
26(a)	3-1	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Collapse of upper insulation and deposition onto channel (PCR). Tied to high-temperature materials (hanger rods).	M	M	M	M	Since this is failure of non-graphite, the materials panel should consider this issue.	M	M	L	M	
26(b)	3-1	Due to graphite failure, spalling	Debris generated from within the graphite core structures.	H	M	M	M		L	M	L	L	Generic graphite codes available for the prediction of internal stresses in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these codes will also require validation.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
26(c)	3-1	Channel distortion	Deformation from individual graphite blocks and block assemblies. There is a link to the metallic core support structure.	M	M	M	M		M	M	L	M	Generic graphite codes available for the prediction of deformations in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these will also require validation.
27	3-2 3-3	Blockage of coolant channel in reactivity control block	Results in damage to the reactivity control components; physical misalignment of channel interfaces.	M	M	H	M						
27(a)	3-2 3-3	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials [carbon fiber composite (CFC)].	M	M	H	M	Since this is failure of non-graphite, the materials panel should consider this issue.	M	M	L	M	
27(b)	3-2 3-3	Due to graphite failure, spalling	Debris generated from within the graphite core structures.	H	M	H	H		L	M	L	L	Generic graphite codes available for the prediction of internal stresses in irradiated graphite components; however, they require validation.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
													There are also whole-core models for component interaction; however, these are reactor specific; these codes will also require validation.
27(c)	3-2 3-3	Channel distortion	Deformation from individual graphite blocks and block assemblies. There is a link to the metallic core support structure.	M	M	H	M		M	M	L	M	Generic graphite codes available for the prediction of deformations in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these will also require validation.
28	3-2	Blockage of reactivity control channel	Results in inability to freely insert absorber materials.										
28(a)	3-2	Foreign object (debris)	Broken pieces of non-graphite core components, such as ceramic tie-rods, etc. Tied to high-temperature materials [carbon fiber composite (CFC)].	M	M	H	M	Since this is failure of non-graphite, the materials panel should consider this issue.	M	M	L	M	

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
28(b)	3-2	Due to graphite failure, spalling	Debris generated from within the graphite core structures.	H	M	H	H	Two mechanisms: (a) component failure due to internal or external component stresses, (b) component failure due to very high irradiation and severe degradation of the graphite.	L	M	L	M	Generic graphite codes available for the prediction of internal stresses in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these codes will also require validation.
28(c)	3-2	Channel distortion	Deformation from individual graphite blocks and block assemblies.	M	M	H	M	Individual graphite component dimensional changes are normally significant but relatively small. However, in damaged components dimensional changes can become quite large. The accumulation of dimensional changes in an assembly of components can result in significant overall dimensional changes and kinking; that is, in a column of graphite bricks.	M	M	L	M	Generic graphite codes available for the prediction of deformations in irradiated graphite components; however, they require validation. There are also whole-core models for component interaction; however, these are reactor specific; these will also require validation.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
29	3-5 3-7	Increased bypass coolant flow channels by break, distortion, etc.	Due to channel distortion, cracking in graphite bricks, etc. Reduced coolant flow through fuel requires higher fuel temperature to maintain the same core outlet temperature.	M	M	H	M	Component cracking due to either internal generated or external component stresses. Individual graphite component dimensional changes are normally significant but relatively small. However, in damaged components dimensional changes can become quite large leading to development of by-pass flow paths. The accumulation of dimensional changes in an assembly of components can result in significant overall dimensional changes and kinking that is, in a column of graphite bricks. Once significant bypass flow is established this can change temperature gradients and hence, dimensional change rates. This can feed back to greater gaps and greater by-pass flow.	M	M	L	M	Graphite codes available for the prediction of irradiated component displacements; however, they require validation. There are also whole-core models for component interaction and gap formation; however, these are reactor specific; these will also require validation.

Table 6 (continued)

Graphite Component													
ID No.	**FOM**	**Phenomena**	**Comment**	**Importance rank**				**Rationale**	**Knowledge rank**				**Rationale**
				Bu	**M**	**Br**	**P**		**Bu**	**M**	**Br**	**P**	
30	3-3	Increased bypass coolant flow channels by break, distortion, etc.	If the bypass is near to the adjacent metallic structures, this phenomenon may challenge the temperature limit of metallic structures.	M	M	M	M		M	M	L	M	
31		Outlet plenum collapse	Gross collapse of structures that define the core outlet plenum.										
31(a)	3-1	Outlet plenum collapse	Disrupts heat conduction path.	H	H	H	H	Low irradiation area. Serious if occurs but unlikely, good design important.	H	H	M	H	Effect can be limited by good design, statistical data required for within block, block to block within batch and batch to batch.
31(b)	3-2	Outlet plenum collapse	Potentially distortion/displacement of reactivity control channels.	H	H	H	H	Low irradiation area. Serious if occurs but unlikely, good design important.	H	H	M	H	Effect can be limited by good design, statistical data required for within block, block to block within batch and batch to batch.
31(c)	3-5	Outlet plenum collapse	Disrupts coolant flow path	H	H	H	H	Low irradiation area. Serious if occurs but unlikely, good design important.	H	H	M	H	Effect can be limited by good design, statistical data required for within block, block to block within batch and batch to batch.

Table 6 (continued)

ID No.	FOM	Phenomena	Comment	Importance rank				Rationale	Knowledge rank				Rationale
Graphite Component													
				Bu	M	Br	P		Bu	M	Br	P	
31(d)	3-6	Outlet plenum collapse	Could potentially result in excessive mechanical load in the fuel.	H	H	H	H	Low irradiation area. Serious if occurs but unlikely, good design important.	H	H	M	H	Effect can be limited by good design, statistical data required for within block, block to block within batch and batch to batch.
32	3-7	Chemical attack	During air/moisture ingress accident, chemical impurities in graphite have effect on the rate of chemical attack.					Data needed for fault studies.					Data required for specific graphite, effect of irradiation and impurities from existing work. There is a significant amount of work available from UK, Germany, and United States. Higher temperature data understanding may be required.
32(a)	3-1 3-2 3-7	Catastrophic chemical attack.	Excessive change in component geometry, such as reduction in cross section, due to large and sustained chemical attack.	H	H	H	H	Could lead to considerable damage.	H	H	M	H	Data required for specific graphite, effect of irradiation and impurities from existing work. There is a significant amount of work available from UK, Germany, and United States. Higher temperature data understanding may be required.

Table 6 (continued)

Graphite Component													
ID No.	FOM	Phenomena	Comment	Importance rank				Rationale	Knowledge rank				Rationale
				Bu	M	Br	P		Bu	M	Br	P	
32(b)	All Level 3	Effect of chronic chemical attack on properties.	Change in graphite pore structure due to (slow) chemical attack over long period of time. Degradation of strength, thermal conductivity, Young's modulus. CTE not relevant as per existing data (University of Bath). The consequences have been dealt with for phenomena 12, 13, 14, 15, 16, and 17.	M	H	L	M	Could lead to problems if remained undetected, on-line monitoring important.	L	H	M	M	Data required for specific graphite, effect of irradiation and impurities from existing work. There is a significant amount of work available from UK, Germany, and United States. Higher temperature data understanding may be required.
33	3-2 3-3 3-4 3-5 3-6 3-7	External (applied) loads	Can become significant if not properly addressed in design. For example, heat up (thermal expansion of core barrel, deformation of the integrated, whole-core graphite structure, dimensional change). Consequences of this phenomena have been addressed in other (e.g., 12 through 17)	M	M	M	M	Should be mitigated by good design.	M	H	M	M	FEM codes for individual and whole core models available, or could be easily developed.
34	3-1 3-2 3-3 3-4 3-5 3-6 3-7	Fast neutron fluence	All graphite component life (structural integrity) predictions rely on an accurate time and spatial calculation of fast neutron fluence (data supplied to graphite specialists by reactor physicists).	H	H	H	H	All graphite component life (structural integrity) predictions rely on an accurate time and spatial calculation of fast neutron fluence (data supplied to graphite specialists by reactor physicists).	H	H	H	H	Although the knowledge rank is high, the accuracy depends on the quality of the codes and nuclear data used.

Table 6 (continued)

ID No.	FOM	Phenomena	Comment	Importance rank				Rationale	Knowledge rank				Rationale
				Bu	M	Br	P		Bu	M	Br	P	
Graphite Component													
35	3-1 3-2 3-3 3-4 3-5 3-6 3-7	Gamma and neutron heating	About 5% of the heat in the reactor is generated in the graphite due to gamma and neutron heating. Predictions of the graphite temperatures for use in structural integrity calculations rely on this quantity. Accurate calculation of the spatial distribution of gamma and neutron heating is required to be supplied to the graphite specialist by reactor physicist.	H	H	H	H	About 5% of the heat in the reactor is generated in the graphite due to gamma and neutron heating. Predictions of the graphite temperatures for use in structural integrity calculations rely on this quantity. Accurate calculation of the spatial distribution of gamma and neutron heating is required to be supplied to the graphite specialist by reactor physicist.	H	H	H	H	Although the knowledge rank is high, the accuracy depends on the quality of the codes and nuclear data used.
36	3-1 3-2 3-3 3-4 3-5 3-6 3-7	Graphite temperatures	All graphite component life and transient calculations (structural integrity) require time dependent and spatial predictions of graphite temperatures. Graphite temperatures for normal operation and transients are usually supplied to graphite specialists by thermal-hydraulics specialist. Although in some cases gas temperatures and heat transfer coefficients are supplied, and the graphite specialist calculates the graphite temperatures from these.	H	H	H	H	All graphite component life and transient calculations (structural integrity) require time-dependent and spatial predictions of graphite temperatures. Graphite temperatures for normal operation and transients are usually supplied to graphite specialists by thermal-hydraulics specialist. Although in some cases gas temperatures and heat transfer coefficients are supplied, and the graphite specialist calculates the graphite temperatures from these.	M	M	M	M	Justification for the use (or not of EDT equivalent DIDO temperatures) requires validation.

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5. SUMMARY AND CONCLUSIONS

Much has been learned about the behavior of graphite in reactor environments in the 60 plus years since the first graphite rectors went into service. The extensive list of references in the next section is plainly testament to this fact. Our current knowledge base is well developed. Although data are lacking for the specific grades being considered for Generation IV concepts, such as the NGNP, it is fully expected that the behavior of these graphites will conform to the recognized trends for near isotropic nuclear graphite. Thus, much of the data needed is confirmatory in nature. Theories that can explain graphite behavior have been postulated and, in many cases, shown to represent experimental data well. However, these theories need to be tested against data for the new graphites and extended to higher neutron doses and temperatures pertinent to the new Generation IV reactor concepts. It is anticipated that current and planned future graphite irradiation experiments will provide the data needed to validate many of the currently accepted models, as well as providing the needed data for design confirmation.

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