Comparison of Graphite PIRT Results with DOE Research Plan

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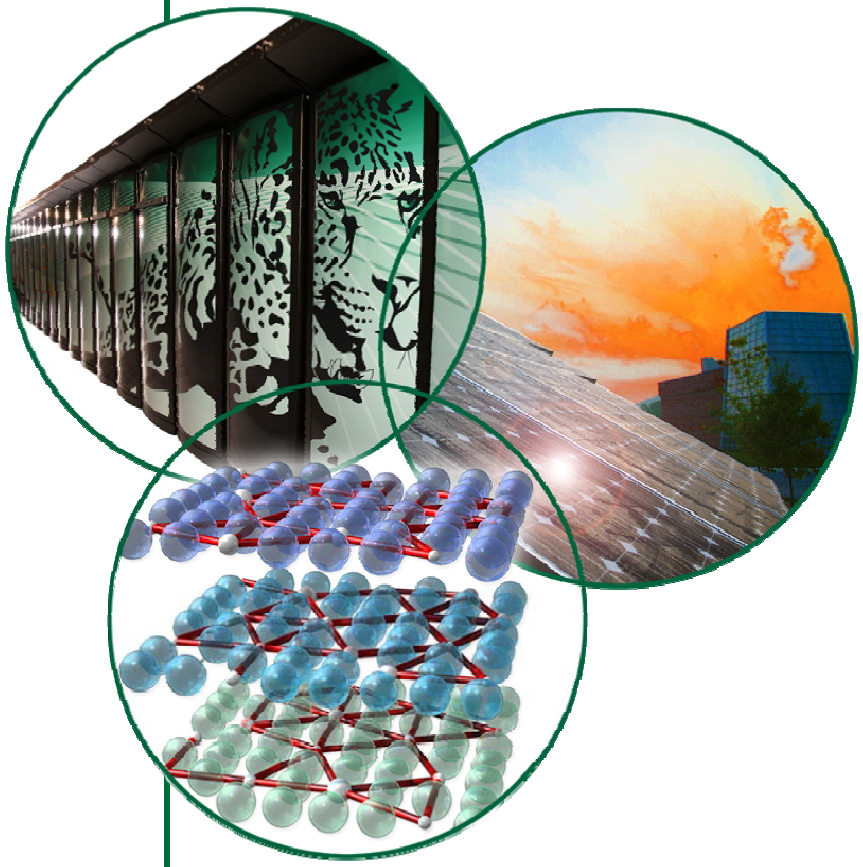

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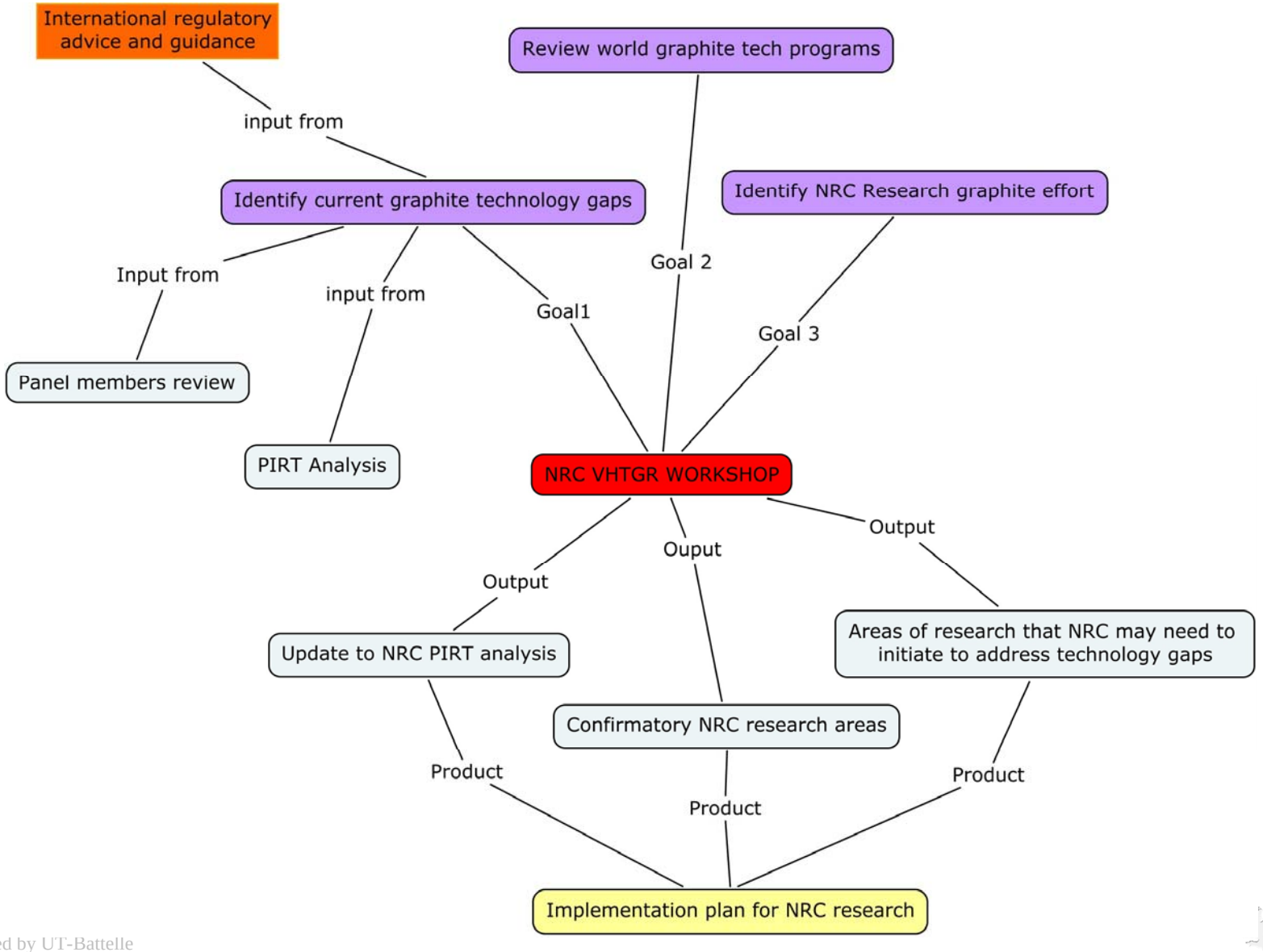
Overview of Presentation

- Background
- NRC Workshop & PIRT/R&D Comparison
- Phenomena Rankings Considered
- U.S. NGNP Graphite R&D Gap Analysis
- Recommended Research Areas

NRC GRAPHITE WORKSHOP LOGIC



Summary Of The Phenomena Importance and Knowledge Rankings

PIRT Rank	No. 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

Emphasis Was Placed On The Following Categories Of Phenomena

- I-H, K-L (5 Phenomena)
- I-H, K-M (9 Phenomena)
- I-M, K-L (2 Phenomena)
- I-M, K-M (14 Phenomena)

The phenomena were grouped into common areas were it was possible (within rankings)

The Following Documents Were Used for Source Materials Regarding US NGNP Program

- NUREG/CR-6944, “Next Generation Nuclear Plant Phenomena Identification and Ranking Tables (PIRT), Volume 5: Graphite PIRTs”.
- INL/EXT-07-13165, “Graphite Technology Development Plan”.
- ORNL/TM-2007/153, “NGNP Graphite Selection and Acquisition Strategy”.
- ORNL-GEN4/LTR-06-019, “Experimental Plan and final Design Report for HFIR High Temperature Graphite Irradiation Capsules HTV-1 and -2”.
- ORNL/TM-2008/129, “Generation IV Reactors Integrated Materials Technology Program Plan: Focus on Very High Temperature Reactor Materials”.

U.S. NGNP GRAPHITE R&D GAP ANALYSIS

Phenomena Ranked Importance-High, Knowledge-Low

(I-H, K-L)

Phenomena:
•Irradiation-induced creep (irradiation-induced dimensional change under stress)
•Irradiation-induced change in CTE, including the effects of creep strain
•Irradiation-induced changes in mechanical properties (strength, toughness), including the effect of creep strain (stress)

	GAPS / WEAKNESSES
Normal Operations*	•Experimental data fully bounds conditions for PMR design. •Need additional experimental data if PBR design is selected.
Anticipated operational occurrences	•Data will enable development of predictive models. •Weakness is in model development. Effort for model development needs to be augmented and accelerated
Design basis accidents	•Creep data will have to be combined with data from oxidation studies to account for effects due to accidents involving air and moisture ingress. •Weakness/gap is more related to the lack of knowledge in the area of graphite oxidation.

*Normal operations for a PMR design currently do not include recycling of graphite blocks.

Phenomena:
•Blockage of fuel element coolant channel due to graphite failure and/or graphite spalling
•Blockage of coolant channel in reactivity control block due to graphite failure and/or graphite spalling

	GAPS / WEAKNESSES
Normal Operations*	•Would the design code (ASME code) be available for core design? Need to accelerate code development. •Determining the adequacy of the design code (ASME code)
Anticipated operational occurrences	
Design basis accidents	•Understanding weakening of graphite surfaces due to long term oxidation.

*Normal operations for a PMR design currently do not include recycling of graphite blocks.

Phenomena Ranked Importance-High, Knowledge-Medium

(I-H, K-M)

Phenomena:
•*Statistical variation of non-irradiated properties*

	GAPS / WEAKNESSES
Normal Operations	•The current plan will provide sufficient experimental data to have a good characterization of the statistical variation of important non-irradiated properties for the selected graphite types. •There is a gap/weakness with respect to the characterization of additional graphites in order to expand the pool of qualified graphites for use in either type of reactor. However, if there are no additional graphites, presently a gap does not exist for this phenomenon.
Anticipated operational occurrences	
Design basis accidents	

Phenomena: *•Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)*	
	GAPS / WEAKNESSES
Normal Operations	•The major gap is with respect to identifying alternative coke sources to the two currently available (U.S. pet coke and Japanese pitch coke) for manufacturing HTGR graphite, and testing the validity of the ASTM standard specifications to new graphites. •Another gap is with respect to exploring the options for graphite recycling and reuse for nuclear applications.
Anticipated operational occurrences	
Design basis accidents	

Phenomena: *•Irradiation-induced dimensional change* *•Irradiation-induced thermal conductivity changes and degradation of thermal conductivity*	
	GAPS / WEAKNESSES
Normal Operations	•Experimental data bounds conditions for PMR design for up to the expected volume change turnaround behavior with probably not enough margin in dose or temperature. •Need additional experimental data if PBR design is selected •Data will enable the development of predictive models. •Weakness is in model development, i.e., effort for model development needs to be augmented and accelerated. •Weakness is also in the validation of models to include new graphites.
Anticipated operational occurrences	
Design basis accidents	•Dimensional and thermal conductivity changes are large sources of internal stresses. Experimental data from this task will be combined with data from oxidation studies to develop whole core models in order to model behavior under accidents relating to air and moisture ingress. •Weakness/gap is related to the lack of knowledge in the area of graphite oxidation, especially on irradiated graphite.

Phenomena: *•Irradiation-induced changes in elastic constants, including the effects of creep strain*	
	GAPS / WEAKNESSES
Normal Operations	•Experimental data bounds conditions for PMR design for up to the expected volume change turnaround behavior with probably not enough margin in dose or temperature. •Need additional experimental data if PBR design is selected •Data will enable the development of predictive models. •Weakness is in model development, i.e., model development effort needs to be augmented and accelerated.
Anticipated operational occurrences	
Design basis accidents	•These data will be combined with data from oxidation studies to develop/improve predictive models that account for accidents relating to air and moisture ingress. •There is gap/weakness in the understanding and predictive model development for irradiation-induced crystal strain in the graphite block. •Weakness/gap is related to the lack of knowledge in the area of graphite oxidation, particularly on irradiated graphite.

Phenomena: *•Tribology of graphite in (impure) helium environment*	
	GAPS / WEAKNESSES
Normal Operations	•The current DOE research plan considers wear and friction only a significant problem for the PBR design. However, wear and friction have the potential of being significant issues for PMR design as well due to the erosion of relatively soft surface of graphite by the high-velocity helium flow in the coolant channels. •Need to study tribological properties of graphites considered for PMR design. •Need to study the tribological properties of graphite in helium environment, and at high pressures and temperatures. •Need to study the tribological properties over the life of reactor, i.e., as function of temperature, dose, and oxidation weight loss. •Need to study tribological properties for graphites for PBR and PMR design as a function of oxidation and weight loss.
Anticipated operational occurrences	
Design basis accidents	•Graphite dust generation is a serious issue, and therefore significant research is needed focused on characterizing the dust formed and on understanding what happens to the dust generated, as well as to develop models for fission product transport.

Phenomena: *•Blockage of Reactivity Control Channel due to graphite failure, spalling*	
	GAPS / WEAKNESSES
Normal Operations	•Need emphasis on analytical model development capable of accounting for key factors such as: o Statistical variation of inherent properties o Microstructural differences between grades o Anisotropy due to forming and manufacture, and o Geometric factors, such as stressed volume and specimen/component dimensions o Strength changes due to oxidation, temperature, and neutron irradiation.
Anticipated operational occurrences	
Design basis accidents	•Whole Core model needs to account for changes in properties due to graphite oxidation and weight loss. However, there is a gap regarding oxidation behavior and diffusion of species within the graphite structure, both for non-irradiated and irradiated graphite.

Phenomena Ranked Importance-Medium, Knowledge-Low

(I-M, K-L)

Phenomena: *•Graphite dust generation*	
	GAPS / WEAKNESSES
Normal Operations	•Need to study tribological behavior of graphite in a helium environment, both under solid-solid abrasive contact conditions and under high velocity gas-solid contact conditions. •Need to study the effect of irradiation and temperature on tribological behavior. •Need to include graphites considered for PMR design and not only those considered for PBR design. •Need to study the oxidation behavior of graphite dust and whether graphite dust can be a vehicle for the transportation of fission products.
Anticipated operational occurrences	
Design basis accidents	•Need to develop models for fission product transport based on information about chemistry, quantity, size and shape distribution of graphite dust. •Need to understand the effect of surface oxidation of core graphite on the tribological behavior of graphite.

Phenomena Ranked
Importance-Medium, Knowledge-Medium

(I-M, K-M)

- ***Graphite contains inherent flaws:*** Graphite contains a distribution of inherent flaws that controls the strength. The characteristics of this flaw population must be established, and their effects on important mechanical properties understood in order to design NGNP graphite structures. The flaw structure is one of the components of the graphites texture. Characterization of these flaws by nondestructive methods also needs research and development.

- ***Cyclic fatigue (non-irradiated):*** The extent to which a given grade suffers from cyclic fatigue (S-N Curve) strength needs be determined for both non-irradiated and irradiated graphite. However, data from previous studies on non-NGNP graphites indicate that the cyclic fatigue has a small and negligible effect compared to other phenomena. Thus, limited tests could be performed to confirm this assumption.

- ***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. Performance of limited testing can clarify this issue.

- ***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. However, this is mostly a design issue, and can be addressed from material test reactor data.

- ***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. However, this is mostly a design issue, and can be addressed from material test reactor data.

- ***Effect of chronic chemical attack on properties*:** Oxidation by air of impurities in the helium coolant to chronic levels will reduce graphite's mechanical integrity and increase the rate of dust formation. Analytical models and predictive methods are needed to estimate the extent of weight loss of graphite, and its effects in reducing graphite strength.

- ***External (applied) loads*:** Such loads must be quantified and properly accounted for in the design process.

Recommended Research Areas

- **Oxidation modeling capability, which requires both oxidation kinetics and diffusion behavior of species within the graphite structure. Kinetics is being actively researched in the USA. However work on studying the diffusion behavior in graphite is necessary so that the desired modeling capability can be developed.**
- **Accelerated development of ASME code for graphite core components. Adequacy of ASME codes needs to be evaluated to enable core design. This effort needs to be augmented and accelerated.**
- **Graphite tribological behavior in helium. The current plan does not address this issue properly. An assessment of dust formation, possibility of pebbles sticking and of blocking of channels should be derived from detailed studies on the tribological behavior of graphite, as a function of environment, pressure, temperature and dose.**
- **Oxidative reactivity of graphite dust powder compared to graphite blocks. Graphite dust can potentially become a carrier for fission products. Models need to be developed on this area, and the appropriate experimental data to support the development of such models need to be generated.**

Recommended Research Areas (cont'd)

- **Enhanced analytical modeling and predictive capability for irradiation induced dimensional change and creep. These analytical predictive models, supported by phenomenological data and relationships, provide a key input to core behavioral models used to determine core structural degradation and end of core component life. The current effort for this model development should be augmented and accelerated.**
- **An accepted fracture criteria for nuclear graphite. More work is needed in the US to develop whole core models that integrate all the inputs and predict local stresses of graphite components. Whole core models are critical to enable an agreement on acceptable fracture criteria for graphite.**
- **An accepted in-service inspection method for graphite core component**
- **Overall graphite degradation (prediction) model (GDM).**
- **A graphite core stress analysis method. Although this depends largely on the design, a need exists to develop general guidelines and specific finite element behavioral codes to map the core stress as a function of reactor operation.**

Recommended Research Areas (cont'd)

- **The potential for stored energy release in irradiated graphite exposed to high temperatures during reactor accidents (i.e., high temperature energy release).**
- **Knowledge needs for graphite decommissioning: Considerable research is required to address handling and disposal issues of discharged graphite. PMR block reuse should be considered. In addition some of the reactor vendors are considering the option of recycling graphite for nuclear use, which may become a design requirement. However, significant research effort is required on this are before graphite could be recycled**