NGNP-CDWP TI-DDN
Revision 1

April 2009

NEXT GENERATION NUCLEAR PLANT
Conceptual Design Study

DESIGN DATA NEEDs (DDNs)
RECONCILIATION AGAINST PIRTs

APPROVALS

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BACKGROUND INTELLECTUAL PROPERTY CONTENT

Section	Title	Description
3. Accident and Thermal Fluid PIRTs	Ref. 3-1 “Lower Plenum CFD Report”, PBMR (Pty) Ltd. Report T001045	Privately funded study
4. Fission Product Transport PIRTs	Ref. 4-1 Wickham A.J., “PBMR Graphite Dust Explosibility Review” PBMR (Pty) Ltd. Report: AJW/REP/068/07, Issue 1, June 2007 and Issue 2, September 2007, PBMR (Pty) Ltd.	Privately funded study
4. Fission Product Transport PIRTs	Ref. 4-4. Johnson P.A.V., G.J. Roberts, P.N. Smith and M. A. Mignanelli (Nexia Solutions), “Preliminary Studies on Fission Product Chemistry in PBMR MPS,” PBMR (Pty) Ltd. Report: SERCO/TAS/000276/001 Issue 1, December 2007.	Privately funded study

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LIST OF TABLES

LIST OF FIGURES

ACRONYMS

Acronym	Definition
ACTF	Accident and Thermal Fluid
BDBE	Beyond Design Basis Event
BEA	Battelle Energy Alliance
CD	Conceptual Design
CFD	Computational Fluid Dynamics
CTE	Coefficient of Thermal Expansion
CR	Control Rods
DBA	Design Basis Accident
DBE	Design Basis Event
DDN	Design Data Need
DLOFC	Depressurised Loss of Forced Cooling
DPP	Demonstration Power Plant
FOM	Figure of Merit
FP	Fission Products
GRAPH	Graphite
HTMAT	High Temperature Materials
I	Importance
IHX	Intermediate Heat Exchanger
INL	Idaho National Laboratory
KL	Knowledge Level
NGNP	Next Generation Nuclear Plant
NRC	Nuclear Regulatory Commission
NUREG/CR	Nuclear Regulatory/Contractor Report
PBMR	Pebble Bed Modular Reactor
PCDR	Pre-Conceptual Design Report
PIRT	Phenomena Identification Ranking Tables
PHHP	Process Heat and Hydrogen Production
RPV	Reactor Pressure Vessel
RN	Radionuclide
SSC	Structure, System, and Component

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SUMMARY AND CONCLUSIONS

The Next Generation Nuclear Plant (NGNP) Project has entered the Conceptual Design Phase; however, there remains a significant level of technology down-selection and technical risk reduction areas to be addressed prior to commencing focused design in support of licensing applications. To prepare for the licensing application, the NRC has used the Phenomena Identification Ranking Table (PIRT) process to identify and rank the safety related issues for the NGNP in the following topical areas:

- Accident and Thermal Fluid
- Fission Product Transport
- High Temperature Materials
- Graphite
- Hydrogen Production and Process Heat
- Fuel

During the NGNP Pre-Conceptual Design phase, the WEC PBMR Team developed Design Data Needs (DDNs) for technology development incremental to that underway and planned for the PBMR Demonstration Power Plant (DPP) to be built at Koeberg, South Africa. The DPP is a direct cycle 400MWt PBMR with a core outlet of 900C that is in the basic or preliminary design phase. The DDNs were also further refined during Conceptual Design Studies in preparation for the Conceptual Design Phase. DDNs are the designer needs for R&D activities to validate assumptions made in the iterative, top-down design process depicted in Figure 1. This design process assures that the top level functional requirements from all stakeholders are explicitly addressed. Note the process is broader than meeting only the safety and licensing requirements that are the subject of the NRC PIRTs.

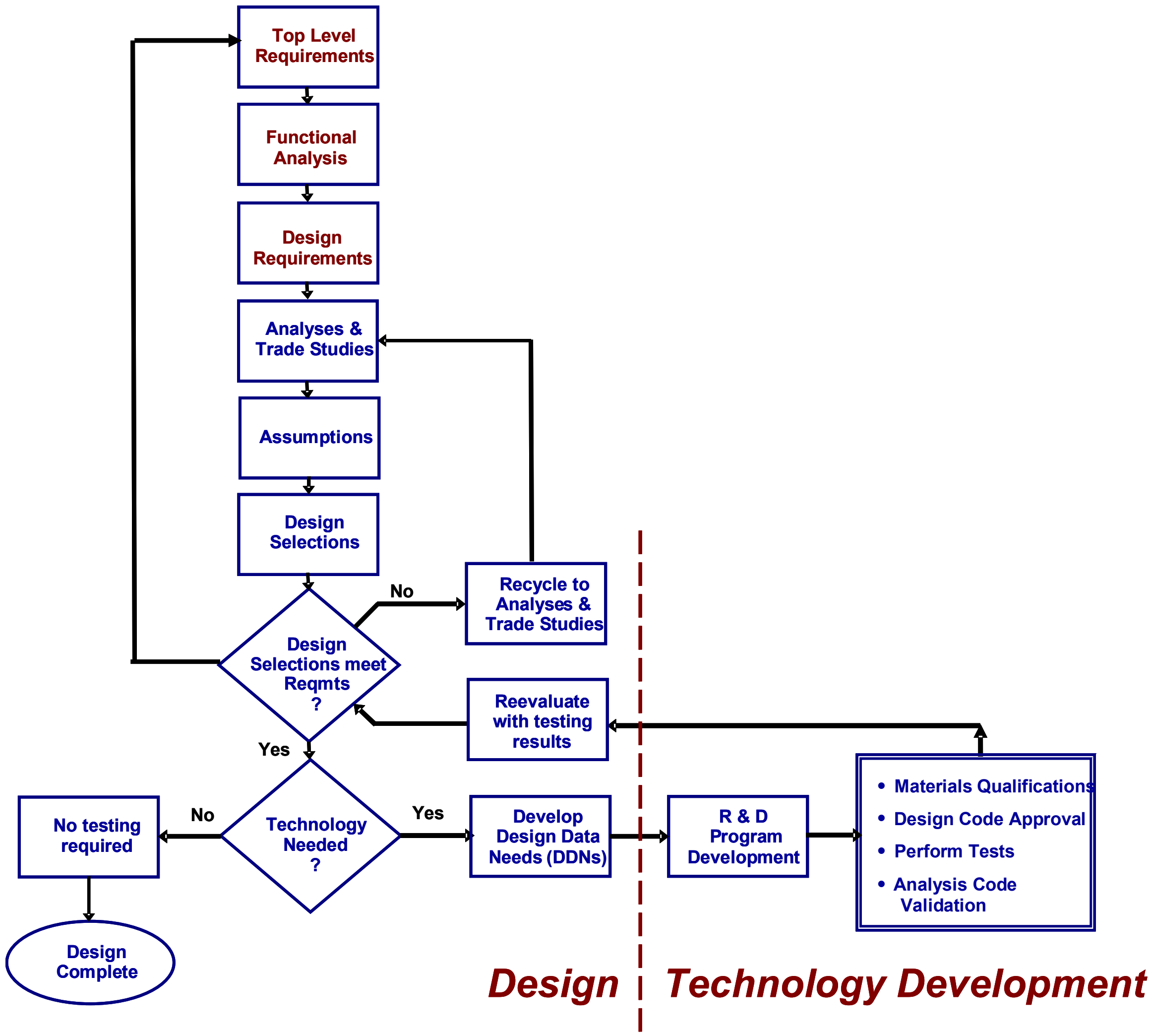

Figure 1 DDNs Place and Role in the NGNP Design and Development Process

A series of one-day workshops for each of the six PIRT topics, identified by the NRC, were held at PBMR Pty. Ltd to elicit from the PBMR DPP and NGNP designers input on the relevance of the NRC PIRT phenomena to the PBMR NGNP design. Only phenomena that were identified by the NRC as phenomena with "High" significance and "Low" or "Medium" knowledge level were used in the reconciliation. Appendix A provides the names and specialties of the participants in the workshops. The structured process utilized with each of the PIRT topic workshops had a number of sequential steps as shown in Figure 2.

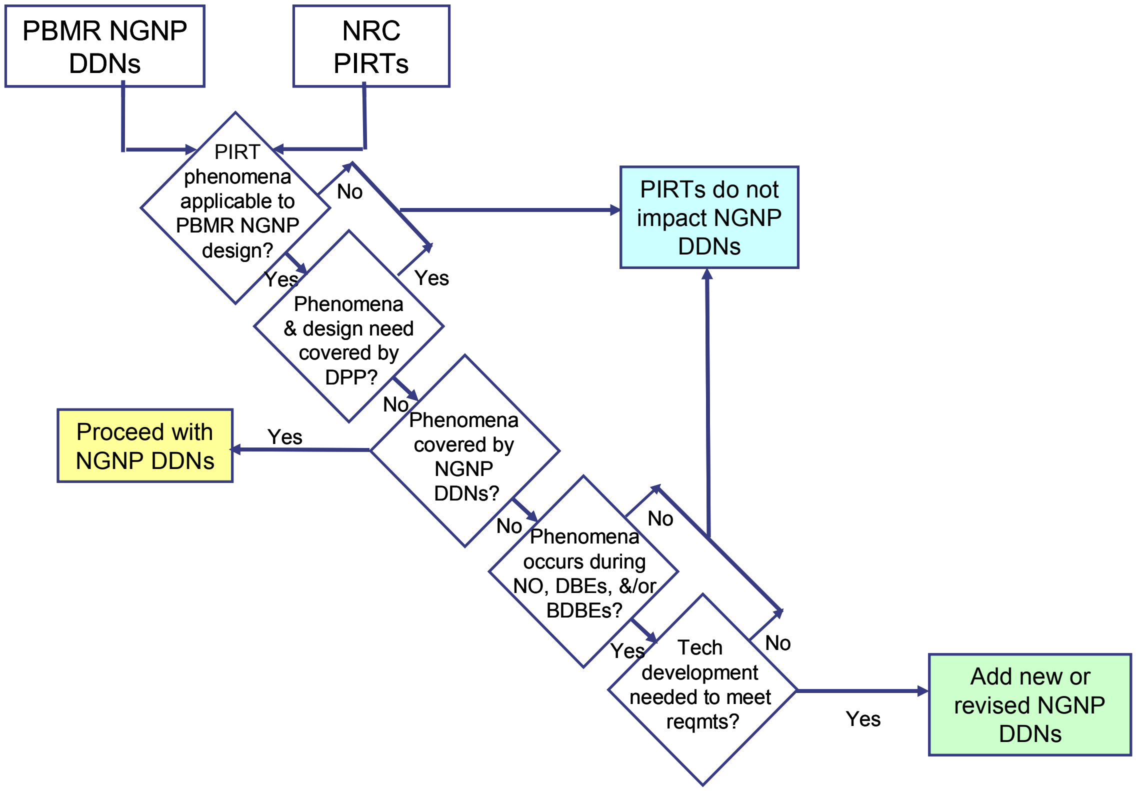

Figure 2 Structured Process for Reconciliation of NRC PIRTs and PBMR NGNP DDNs

The results of the PBMR NGNP DDN – NRC PIRT reconciliation process are summarized below. The results are highly dependent on the topic:

- For the accident and thermal fluid (ACTF) and the process heat and hydrogen production (PHHP) that are especially design- and application-dependent topics, the PIRTs were spread over the range of not applicable to not judged to be needed to meet requirements. However, it is recognized that further review is necessary at later design phases.
- For the fission product transport (FPT) and high temperature materials (HTMAT) topics, the reconciliation process found substantial agreement with the importance and knowledge level of the applicable NRC PIRT phenomena and concluded that they are being addressed by the PBMR DPP program as detailed in the tables.
- For the fuel topic, the reconciliation process found substantial agreement with the PIRT phenomena and concluded that they are being addressed by the PBMR NGNP DDNs that supplement the existing PBMR fuel development, qualification, and testing program.
- For graphite (GRAPH), there was general agreement with the importance and knowledge level of many of the applicable NRC PIRT phenomena and concluded that they are being addressed by the PBMR DPP program. Further the PIRT reconciliation identified two new DDNs that are required:
    - Irradiation-induced creep (irradiation-induced dimensional change under stress)

- o Irradiation-induced change in the coefficient of thermal expansion (CTE), including the effects of creep strain.

Table 1 Summary of PBMR NGNP DDN and PIRT Reconciliation

PIRT Reconciliation Summary								
PIRT Topic	Proceed with NGNP DDNs	PIRTs do not impact NGNP DDNs				TBD in later design phase	Add new or revised NGNP DDNs	Total Phenomena
		PIRT phenomena applicable to PBMR NGNP design? NO	Phenomena & design need covered by DPP? YES	Phenomena occurs during NO, DBEs, &/or BDBEs? NO	Tech development needed to meet reqmts? NO			
ACTF	1	2	6	0	5	6	0	20
FPT	0	3	23	0	0	3	0	29
HTMAT	3	5	8	0	0	1	0	17
GRAPH	5	2	5	0	3	0	2	17
PHHP	0	3	0	0	2	2	0	7
Fuel	9	0	0	0	2	0	0	11
Totals	**18**	**15**	**42**	**0**	**12**	**12**	**2**	**101**

INTRODUCTION

This report documents the results of the reconciliation of the PBMR NGNP Design Data Needs (DDNs) to the Phenomena Identification Ranking Tables (PIRTs) identified by the NRC. The objectives of the study and the organization of this report are summarized below.

Objectives and Scope

The overall objective of the study is for the WEC PBMR Team to reconcile the PBMR DDNs against the high-significance, low- and medium-knowledge level NRC PIRTs to ensure each phenomenon identified in the PIRTs is either addressed by one or more DDNs or the rationale for its exclusion is sound. The above objectives were achieved in the course of the task and the results are documented in this report.

Organization of Report

The report initially provides a background for the DDNs identified to date for the WEC Team's PBMR NGNP and for the NRC-identified NGNP PIRTs. The structured reconciliation process is delineated in Section 2. Sections 3 through 8 provide the results of the reconciliation for each of the PIRT topics. Section 9 provides an overall summary of the results.

1 BACKGROUND

The Next Generation Nuclear Plant (NGNP) Project has entered the Conceptual Design phase; however, there remains a significant level of technology down-selection and technical risk reduction areas to be addressed prior to commencing focused design in support of licensing applications. To prepare for the licensing application, the NRC has used the PIRT process for the NGNP.

The PIRT process was conducted for the NGNP design in order to meet the safety and licensing requirements of the NRC. Expert panels identified safety-relevant phenomena, ranked their importance, and assessed the knowledge levels in the areas of accidents and thermal fluids, fission-product transport and dose, high-temperature materials, graphite, and process heat and hydrogen production. The NGNP Phenomena Identification and Ranking Table (PIRT) Meetings/Reports, NUREG/CR-6944, summarizes and documents the process and scope of these reviews, noting the major activities and conclusions. The identified phenomena, analyses, rationales, and associated ratings of the phenomena, plus a summary of each panel's findings are contained in the report. The WEC Team had four of the eight industry representatives providing additional expert resources in these NGNP PIRT sessions as noted in Appendix A.

A PIRT process was also conducted for the TRISO coated particle fuel design, manufacture, and operation, as well as behavior during accidents. The objectives of the TRISO Coated Particle Fuel PIRT were to (1) identify key attributes of gas-cooled reactor fuel manufacture which may require regulatory oversight, (2) provide a valuable reference for the review of vendor fuel qualification plans, (3) provide insights for developing plans for fuel safety margin testing, (4) assist in defining test data needs for the development of fuel performance and fission product transport models, (5) inform decisions regarding the development of NRC's independent reactor performance fuel code and fission product transport models, (6) support the development of NRC's independent models for source term calculations, and (7) provide insights for the review of vendor fuel safety analyses. To support these objectives, the NRC commissioned a PIRT panel to identify and rank the factors, characteristics, and phenomena associated with TRISO coated particle fuel. PIRTs were developed for (1) manufacturing, (2) operations, (3) a depressurized heatup accident, (4) a reactivity accident, (5) a depressurization accident with water ingress, and (6) a depressurization accident with air ingress. The TRISO Coated Particle Fuel Phenomena Identification and Ranking Table (PIRT) Meetings/Reports, NUREG/CR-6844, summarizes and documents the process and scope of these reviews, noting the major activities and conclusions. The identified phenomena, analyses, rationales, and associated ratings of the phenomena, plus a summary of each panel's findings are contained in the report.

During the NGNP Pre-Conceptual Design phase (Ref. 1-1), the WEC PBMR Team developed Design Data Needs (DDNs) for technology development incremental to that underway and planned for the Demonstration Power Plant (DPP) to be built at Koeberg, South Africa. The DDNs were also further refined during the Conceptual Design Studies in preparation for the Conceptual Design phase (Ref. 1-2). DDNs are the designer needs for R&D activities to validate assumptions made in the iterative, top-down design process depicted in Figure 1-1 and will be used to establish the technology development plans required for the NGNP project. This design process assures that the top level functional requirements from all stakeholders are explicitly addressed. Note that the process is broader than meeting only the safety and licensing requirements that are the subject of the NRC PIRTs.

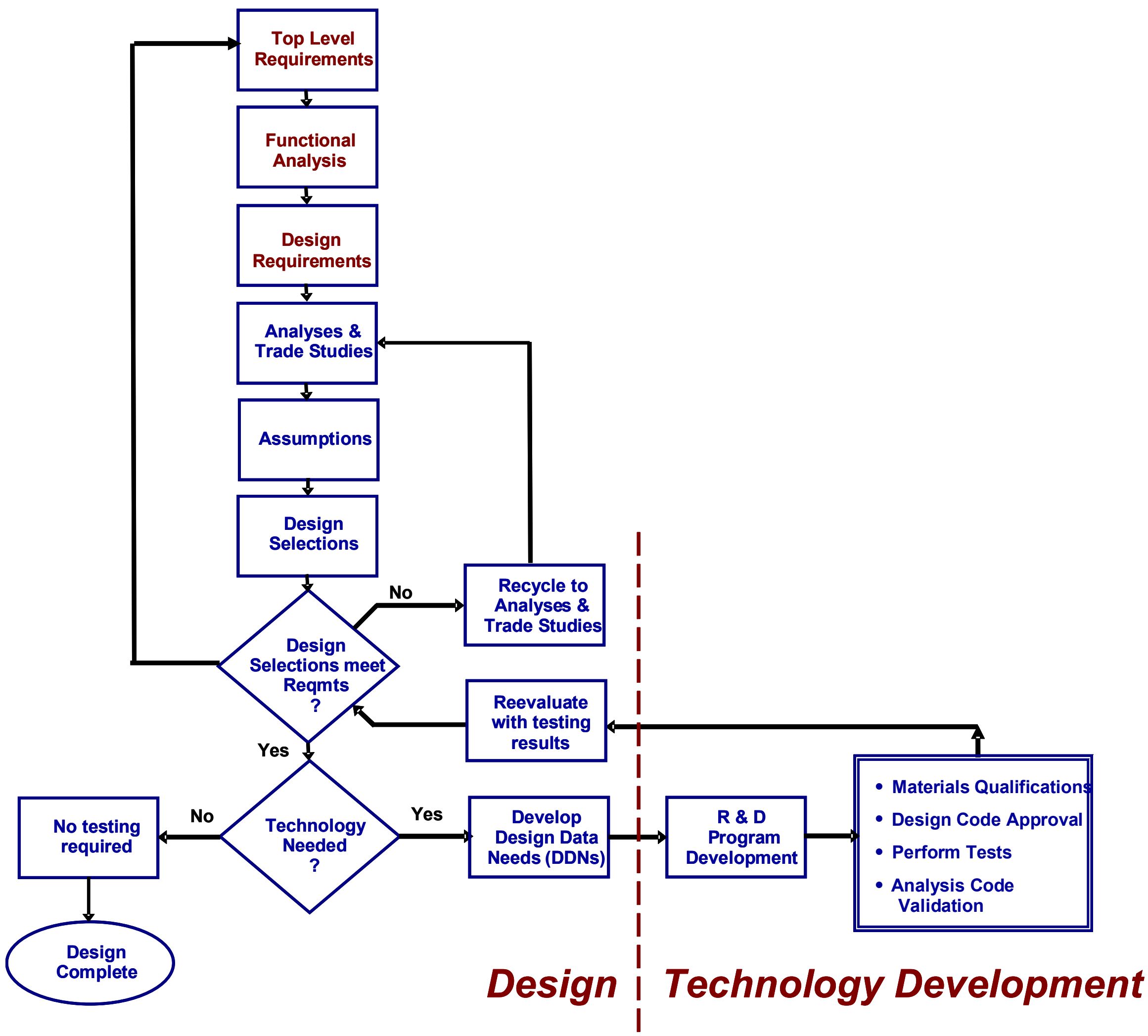

Figure 1-1 DDNs Place and Role in the NGNP Design and Development Process

2 RECONCILIATION PROCESS

A series of one-day workshops for each of the six NRC PIRT topics were held at PBMR Pty. Ltd to elicit from the PBMR DPP and NGNP designers input on the relevance of the PIRT phenomena to the PBMR NGNP design. Appendix B provides the names and specialties of the participants in the workshops.

The structured process utilized with each of the PIRT topic workshops had a number of sequential steps as shown in Figure 2-1. An explanation of each step is provided below:

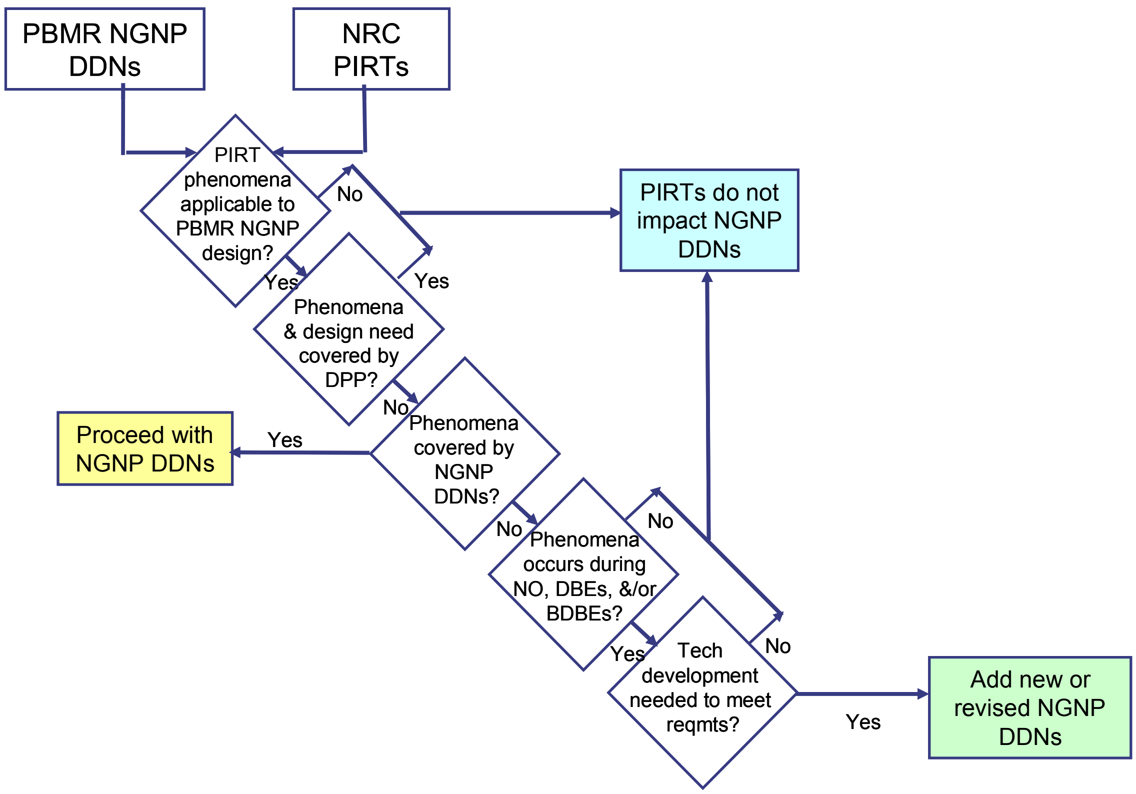

Figure 2-1 Structured Process for Reconciliation of NRC PIRTs and PBMR NGNP DDNs

PIRT Phenomena Applicability to PBMR NGNP Design

Since the PIRTs identified covered a range of designs in terms of fuel element, configuration, power cycle, and heat transfer fluids, the first step in the process is to determine if the phenomena is applicable to the PBMR NGNP concept. If not, the PIRT was not pursued further (as shown in the figure by the blue-shaded rectangle) and the basis for its inapplicability recorded.

PIRT Phenomena and Design Need Covered by DPP

For the PIRT phenomena applicable to the PBMR NGNP, the next screening question is whether the phenomena and need are addressed by the DPP design and development process. Since the NGNP is based on the DPP Reactor Unit, this screen was expected to filter more phenomena in that part of the NGNP design than in the Heat Transfer System, the Hydrogen Production System, and the Power Conversion System. If the phenomena and need are covered the PIRT was not pursued further (again leading to the blue-shaded rectangle) and the basis for this categorization stated.

PIRT Phenomena Covered by NGNP DDNs

For the PIRT phenomena not addressed by the DPP design and development process, those phenomena previously identified as an NGNP DDN are identified (as indicated in the figure by the yellow-shaded rectangle).

PIRT Phenomena Occurs during NGNP Normal Operation, Design Basis Events (DBEs), and/or Beyond Design Basis Events (BDBEs)

For the PIRT phenomena not previously identified by the WEC PBMR Team as an NGNP DDN, the next filter was on whether the phenomena occurs during the licensing basis. The licensing basis includes normal operation (and anticipated operational occurrences), DBEs (and the corresponding deterministic Design Basis Accidents that rely only on safety-related Structures, Systems, and Components (SSCs), and BDBEs). In the risk-informed performance-based licensing approach (Ref. 2-1), these events are defined with respect to their frequency per plant year and have specific evaluation rule sets. If the phenomenon is not in the licensing basis, the basis is recorded. However, since in the pre-conceptual design phase the design and these events are not sufficiently developed to be complete, this step in the process is expected to have more significance in later design phases.

Technology Development Needed for PIRT Phenomena to Meet Top Level Safety Requirements

The final step in the process is to determine if the PIRT phenomena requires additional technology development to show compliance with sufficient certainty and margin to the top level safety requirements. If so, a new or revised NGNP DDN is identified (as indicated in the green-shaded rectangle). If not, justification is provided.

This PIRT-DDN reconciliation process will be repeated at each design phase.

3 ACCIDENT AND THERMAL FLUID PIRTS

The high-importance and low- and medium-knowledge level NGNP PIRTs for the accident and thermal fluid PIRT phenomena are reproduced from NUREG/CR 6944 in Table 3-1. As shown of the total of 20 PIRT phenomena in this topic 7 PIRT phenomena are categorized as low-knowledge and 13 as medium-knowledge.

The workshop participants (identified in Appendix A) reviewed each phenomena one-at-a-time in terms of its Figure of Merit (FOM) and the rationale for its importance and knowledge level. The sequential reconciliation process of Section 2 was followed for each. The results are provided in Table 3-2. As shown in the table, for 6 of the PIRT phenomena there is not sufficient design detail at this stage to judge whether a new or modified DDN is required. These will be reviewed again towards the end of the conceptual design. Several of the phenomena and design needs were judged to "partially" be addressed by the DPP project. In this case, since they are not fully addressed, the next question in the logic diagram is addressed as if the answer to the DPP question was "No." One of the PIRT phenomena (yellow-shaded to correspond to the rectangle in the logic diagram) for this topic is presently included in the PBMR NGNP DDNs. This phenomenon has to do with fuel performance envelope during normal operation and off-normal events that due to the PBMR NGNP parameters (e.g., power level) are beyond the DPP's planned testing. It is noted in the next to last column that this DDN is expected to be applicable for NGNP applications requiring lower core outlet temperatures of less than 800C.

The workshop participants judged that at this time the remaining 13 PIRT phenomena do not lead to new or modified DDNs for the NGNP (green-shaded rectangle in the logic diagram). The basis for judging that the PIRT phenomena do not impact the DDNs (shaded blue to correspond to the logic diagram) varied as shown. Two PIRT phenomena were judged to be not applicable to the PBMR design: one involved a phenomenon involving a direct Brayton cycle design; the other considered an example with a molten salt intermediate loop. Six PIRT phenomena are included as part of the DPP design and technology development. The remaining PIRT phenomena are judged at this time to not need technology development to meet the top requirements.

It is recognized that this topic area is especially design-dependent and will need to be re-reviewed at later design phases.

Table 3-1 Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Cavity	Cavity filtering performance (air ingress LOFC) {Affects radioactive dust releases; dust can contribute to the source term for PBR}	dose to public	H	M	I: – affects release to public KL: – Good knowledge base for HEPA filters, design dependent – Dust filter options should be investigated and tested
Core Support; Fuel	Molecular diffusion (air ingress LOFC) {Air remaining in the reactor cavity enters into RV by molecular diffusion, prior to onset of natural circulation}	core support structure, fuel temperature, dose, fuel failure fraction	H	M	I: – Low rate of transport of oxygen not important in driving fuel temperatures; process can occur over a period of days; local circulation may occur before large circulation; will determine onset of natural circulation, number of other factors – operator actions, initial conditions, where break occurs – can override diffusion; don't know how much circulation will be induced by oxidation vs diffusion; slow process will lag other phenomena. Uncertainties in circulation start time can affect severity of event. KL: – Good agreement with calculations under idealized conditions. – Many other factors could influence processes leading to a significant ingress flow rate.
Core Support; Fuel	Core support structures oxidation (air ingress LOFC) {Low-temperature oxidation potentially damaging to structural strength}	core support structure, fuel temperature, dose, fuel failure fraction	H	M	I: —Core structure area first seen by incoming ingress air. KL: – Complex zone, mixing, heterogeneous, difficult to calculate boundary conditions. – Oxidation behavior of graphite well known.
Core Support Structures	Outlet plenum flow distribution (normal operation). {Affects mixing thermal stresses in plenum and down stream, outlet pressure distribution}	worker dose, core support structures	H	L	I: – Localized hot spots; excessive thermal gradients may lead to structural problems, and thermal streaking may lead to problems with downstream components such as a turbine or IHX. Problem led to failures in thorium high-temperature reactor (THTR). KL: – Very complex turbulent mixing with incoming jets over large temperature spans. – PMR geometry contributes to the uncertainties in the pressure distribution.
Fuel	Core coolant bypass flow (normal operation) {Determines active core cooling; affects Tmax.fuel}	fuel time at temperature, fuel failure fraction	H	L	I: – Bypass flow varies with shifts in block gaps, etc. – Results in uncertainties in fuel temperatures since there is no way to measure bypass flow. KL: – Medium knowledge of bypass fraction (inferred) with good instrumentation. – Instrumentation in PBRs not practical, poor ability to model phenomena. – Bypass flows vary axially; difficult to measure in-core temperatures. – Test during initial startup for bypass flow cold gas will not leak into core; as a result, less uncertainty in bypass flow. Depend upon code validation; graphite shrink/swell effect on bypass flow. – Knowledge adequate for bounding estimates.
Fuel	Pebble-bed core wall interface effects on bypass flow (normal operation) {Diversion of some core cooling flow. Number of pebbles across impacts interface effects}	fuel time at temperature, fuel failure fraction	H	L	I: – Combination of cooling anomalies and flux peaking leads to uncertainties. KL:– Pebble-bed pressure drop equations: large uncertainty band with larger uncertainty in wall friction correlations, need experimental data. – Different packing fraction at wall. – Void fraction has large uncertainty. – Calculation tools improved recently. – Heat transfer coupling between flow regime; local values of heat transfer vary significantly from average heat transfer; close to wall there is laminarization of flow. – PBMR doing experiments with high-pressure test unit (HPTU)/heat transfer test facility (HTTF). – Heat transfer calculations in high-temperature regions are difficult.
Fuel	Reactivity-temperature feedback coefficients (normal operation) {Affects core transient behavior}	dose to worker, fuel failure fraction, fuel time at temperature, core support	H	L	I: – Important for estimating control rod worth and power defect. KL: – Limited available experimental data for validation of reactivity temperature effects, particularly direct measurements of reactivity coefficients rather than using tests of overall transient response of the system. – Limited data for high-burnup fuels. High temperature of HTR systems magnifies errors in differential feedback coefficients over that of relatively well-known systems. Evidence of difficulty in prediction of power coefficients in recent startup experiments. Physical phenomenon that may be important in accurate calculation of neutron capture in resonances is not accurately modeled in spectral codes; this may have a significant impact of reactivity coefficients (resonance scattering). Lack of understanding of resonance capture phenomena at high temperatures; need for graphite reactor critical experiments with high burnup; evidence of miscalculation of power coefficients.
Fuel	Fuel performance modeling (normal operation and accidents) {Fuel type dependent. Crucial to design and siting; depends on performance envelope, quality assurance (QA)/quality control (QC), …}	fuel failure fraction	H	L	I: – Primary barrier. KL: – Many unknowns; kernel migration; silicon carbide morphology relation to release. For D-LOFC, affects defining transient for rated power level.

Table 3-1 Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena (cont)

Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Core effective thermal conductivity (D-LOFC) {Affects TFuel max for D-LOFC}	dose to public, peak fuel temperature	H	M	I: – Major parameter affecting peak fuel temperature in D-LOFC. KL: – Core thermal conductivity uncertainties due to inherent difficulty with comprehensive measurements (both pebble and prismatic cores) – Number of models for effective conductivity exist; lack of consensus on which model is best. – Not all data are available. – Not important in P-LOFC. – More variability in PBR than PMR data.
Power and flux profiles (initial conditions for accidents) (normal operation) {Affects fuel potential for failures in accident conditions due to long-term exposures}	dose to public, peak fuel temperature	H	M	I: – Major factor in fuel accident performance models. KL: – Need for code validation with newer designs—annular core, higher burnup, core reflector interface, fuel location.
Decay heat (temporal and spatial) (general LOFC) {Time dependence and spatial distribution major factors in TFuel maximum estimate}	fuel failure fraction	H	M	I: – Dependent on fuel type and burnup; major factor in peak temperatures in the D-LOFC accidents but not important for P-LOFC. KL: – Spatial dependence calculation is difficult for annular core, axial,and radial peaking factors, inner reflector, higher burnups; need for validation. – Standard correlations appear to be conservative (vs experiments).
Fuel performance with oxygen attack (air ingress LOFC) {Consideration for long-term air ingress involving core (fueled area) oxidation; fission product (FP) releases observed for high temperature exposures}	fuel temperature, dose, fuel failure fraction	H	M	I: – Low probability; fueled core area of exposure probably at temperatures less than critical for FP release. KL: – Uncertainties in accident calculations due to wide variety of possible conditions. – Fuel qualification. – Active R&D. – Much oxidation data based upon fresh fuel; need more data on irradiated fuel.
Phenomena (various accident conditions) that affect cavity gas composition and temperature with inflow (air ingress LOFC) {Provides gas ingress and coldleg conditions; needed to calculate ingress flow rate and properties. Possible entrainment through relief valve, etc.}	fuel temperature, dose, fuel failure fraction, core integrity	H	M	I: – In terms of overall damage to reactor core, it is a question of total oxygen available over course of accident, not specific composition; and impact on corrosion, conservative assumptions would result in less importance of phenomena. KL: – Very complicated; various phenomena; difficult to know composition and temperature at inlet. – Link transient to opening of vent valve; pulses can affect phenomena. – Bounding calculations can define limits within large uncertainties. – How much air is carried out with valve break (size dependent; large break with vent valve more important).

Table 3-1 Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena (cont)

Confinement-to-reactor cavity air ingress (air ingress LOFC) {Determines long-term oxidation rate if accident unchecked}	fuel temperature, dose, fuel failure fraction, core integrity	H	M	I: – Defines long-term damage. KL: – Lack of data on pressure differential between confinement and cavity. – Performance criteria provided by confinement vendor.
Reactivity temperature feedback coefficients (fuel, moderator, reflectors) [reactivity (ATWS)] {Affects passive safety shutdown characteristics}	fuel failure fraction, time at temperature	H	M	I: – Inherent defense against reactivity insertions; major argument for inherent safety design. KL:– Lack of understanding of resonance capture phenomena at high temperatures; need for graphite reactor critical experiments with high burnup; evidence of miscalculation of power coefficients. Calculations of absorber worths can have large differences based on fixes to diffusion theory approach. Control rod worths impacted by core axial power distribution, which may be difficult to predict because of temperature and burnup distributions. Measurement of control rod worths generally performed as part of reactor startup procedures.
Core oxidation (air ingress LOFC) {Determination of "where" in core the oxidation would take place, graphite oxidation kinetics affected by temp oxygen content of air, irradiation of graphite}	fuel temperature, dose, fuel failure fraction, core integrity	H	M	I: – Oxidation might occur at the top of the core, depending upon break location. KL: – Data needed on effects of radiation damage on graphite. – Existing data from experiments varies with geometries and manufacturers. – Need to reduce uncertainties in graphite oxidation data.
Fission product transport through IHX loop (part of confinement bypass [IHX failure (molten salt)] {Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out}	public and worker dose	H	M	I: – Determines activity released out of IHX relief valve, and residuals in IHX loop. KL: – Lack of scrubbing data applicable to countercurrent helium – MS flow, yet bounding models may be able to reduce uncertainties. [This postulated event was a "sample consideration" by the ACTH panel for possible accidents related to the process heat plant. A molten salt heat transport loop design was arbitrarily assumed.]
Vessel and RCCS Panel emissivity (general LOFC) {Radiant heat transfer from vessel to RCCS affects heat transfer process at accident temperatures}	vessel integrity	H	M	I: – maintain coolable geometry; limit vessel temperature—Change in inner surface vessel emissivity based on degraded environment; T4 (radiant) heat transfer dominates (85–90%) in LOFC transients; and scoping: calculations large temperature differences between vessel and RCCS reduce emissivity importance. KL: – In-service steel vessel emissivities are fairly well known. – Emissivities not well known during accidents as a function of time, dust on surface, optical transparency, etc., as a result of disturbances from a depressurization. – Knowledge of inner emissivity 0.5–>0.3, change nature of surface coating; e.g., from loss of oxide film. – Emissivities are fairly well known for steel, once oxidized (in air cavity). Complex geometries involved – difficult to calculate for transient cases, especially in upper head region with control rods (standpipes) in between vessel and RCCS.
Reactor vessel cavity air circulation and heat transfer {Affects upper cavity heating}	vessel and vessel support integrity	H	L	I: – Affects RCCS performance; skewed (toward top) heat distribution; generation of hot-spots.
Ag-110m release and plate-out	worker dose	H	L	I: – Large uncertainty level; a function of fuel type, burnup, and temperature. Could be a maintenance (dose) problem for gas turbine maintenance (if direct cycle). KL: FP release mechanism (from TRISO particle) not understood.

Table 3-2 Reconciliation of Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Cavity filtering performance (air ingress LOFC) {Affects radioactive dust releases; dust can contribute to the source term for PBR}	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Topic for CD and later NGNP design phases. DPP testing for dust with respect to performance versus particle size.
Molecular diffusion (air ingress LOFC) {Air remaining in the reactor cavity enters into RV by molecular diffusion, prior to onset of natural circulation}	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Diffusion is not of high importance compared to natural convection because the rates are lower. Extent of air ingress is design- and event scenario-specific both in terms of frequency and consequences. Studies are planned and underway in CD to determine extent of air ingress for DBEs and BDBEs for the NGNP.
Core support structures oxidation (air ingress LOFC) {Low-temperature oxidation potentially damaging to structural strength}	Yes	No	No	Yes	No	No	---	Phenomena relatively well understood. Existing design performance codes address limited oxidation. Structural margins acceptable.
Outlet plenum flow distribution (normal operation) {Affects mixing thermal stresses in plenum and down stream, outlet pressure distribution}	Yes	No	No	Yes	No	No	---	PBMR has more uniform outlet flow distribution that makes this phenomena less important to core structures (Ref. 3-1)
Core coolant bypass flow (normal operation) {Determines active core cooling; affects Tmax.fuel}	Yes	Yes	---	---	---	No	---	DPP use of bounding analyses with extensive sensitivity analyses coupled with separate effect tests (e.g., characterization of sleeve bypass flows) are to be confirmed by bulk flow measurement during startup testing and operation
Pebble-bed core wall interface effects on bypass flow (normal operation) {Diversion of some core cooling flow. Number of pebbles across impacts interface effects}	Yes	Partially	No	Yes	No	No	---	Two parts to this phenomenon: flow distributions and thermal heat transfer effects. Latter covered by DPP. Uncertainty around boundaries but importance on maximum fuel temps is judged as medium not high. The bulk bypass flow is the important parameter (Ref. 3-2)

Table 3-2 Reconciliation of Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Reactivity-temperature feedback coefficients (normal operation) {Affects core transient behavior}	Yes	No	No	Yes	No	No	---	Disagree with H/L rating for normal operation relative to FOMs identified. Prior HTR experience and ongoing HTR-10 experience confirms negative reactivity feedback. For predictions of point of criticality, the fuel and reflector temperature has a greater uncertainty than the reactivity coefficient.
Fuel performance modeling (normal operation and accidents) {Fuel type dependent. Crucial design and siting; depends on performance envelope, quality assurance (QA)/quality control (QC), …	Yes	Partially	Yes NHSS-01-01 NHSS-01-02	---	---	---	Yes	NGNP normal operation parameters and DLOFC time-at-temperatures led to identification of incremental DDN to German test experience and planned DPP testing.
Core effective thermal conductivity (D-LOFC) {Affects TFuel max for D-LOFC}	Yes	Yes	---	---	---	No	---	HTTU will partially confirm conductivity assumptions. Conservative assumptions and sensitivity analyses will supplement the testing.
Power and flux profiles (initial conditions for accidents (normal operation) {Affects fuel potential for failures in accident conditions due to long-term exposures}	Yes	Yes	---	---	---	No	---	The legacy codes VSOP and TINTE can calculate these with a high degree of confidence. The neutronics results are supported with MCNP
Decay heat (temporal and spatial) (general LOFC) Time dependence and spatial distribution major factors in TFuel maximum estimate}	Yes	Yes	---	---	---	No	---	German DIN standard used to calculate the decay heat in the TINTE code. The same rules are applied in FLOWNEX NUCLEAR calculations as well. Temporal and spatial decay heat is calculated with a high degree of confidence.
Fuel performance with oxygen attack (air ingress LOFC) {Consideration for long-term air ingress involving core (fueled area) oxidation; fission product (FP) releases observed for high temperature exposures	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Topic for later NGNP design phase. Fuel performance under oxidation conditions for various temperatures has been characterized by Kora experiments (FZJ, Germany).
Phenomena (various accident conditions) that affect cavity gas composition and temperature with inflow (air ingress LOFC) {Provides gas ingress and coldleg conditions; needed to calculate ingress flow rate and properties. Possible entrainment through relief valve, etc.}	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Extent of air ingress is design- and event scenario-specific both in terms of frequency and consequences. Studies are planned and underway in CD to determine extent of air ingress for DBEs and BDBEs for the NGNP. PBMR analysis tools include those that have been benchmakred to NACOK testing results (Ref 3-3).

Table 3-2 Reconciliation of Significant Accident and Thermal Fluids (ACTF) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Confinement-to-reactor cavity air ingress (air ingress LOFC) {Determines long-term oxidation rate if accident unchecked}	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Extent of air ingress is design- and event scenario-specific both in terms of frequency and consequences. Studies are planned and underway in CD to determine extent of air ingress for DBEs and BDBEs for the NGNP. PBMR analysis tools include those that have been benchmarked to NACOK testing results. (Ref. 3-3)
Reactivity temperature feedback coefficients (fuel, moderator, reflectors) reactivity (ATWS) {Affects passive safety shutdown characteristics}	Yes	Yes	---	---	---	No	---	PBMR utilizes diffusion theory and MCNP analyses; response to no trip transients has been demonstrated at AVR and HTR-10.
Core oxidation (air ingress LOFC) {Determination of "where" in core the oxidation would take place, graphite oxidation kinetics affected by temp oxygen content of air, irradiator of graphite}	TBD	TBD	TBD	TBD	TBD	TBD	TBD	Extent of air ingress is design- and event scenario-specific both in terms of frequency and consequences. Studies are planned and underway in CD to determine extent of air ingress for DBEs and BDBEs for the NGNP. PBMR analysis tools include those that have been benchmarked to NACOK testing results. (Ref. 3-2)
Fission product transport through IHX loop (part of confinement bypass) [IHX failure (molten salt)] {Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out}	No	---	---	---	---	No	---	PBMR NGNP does not have molten salt intermediate loop
Vessel and RCCS Panel emissivity (general LOFC) {Radiant heat transfer from vessel to RCCS affects heat transfer process at accident temperatures}	Yes	Yes	---	---	---	No	---	Bounding PBMR analyses and testing at Duisburg (Germany) is underway for ferritic/austenitic steels. RPV performance of more importance than RCCS which is exposed to air at lower temperatures RCCS forms and maingains oxide layer which ensures a high emissivity.
Reactor vessel cavity air circulation and heat transfer {Affects upper cavity heating}	Yes	No	No	Yes	No	No	---	Bounding analyses show that radiation transport to RCCS is sufficient to protect identified components with margin to their limits.
Ag-110m release and plate-out	No	---	---	---	---	No	---	NGNP does not have turbine in the primary loop; worker doses to other components during infrequent maintenance will be addressed with maintenance program.

4 FISSION PRODUCT TRANSPORT PIRTS

The high-importance and low- and medium-knowledge level NGNP PIRTs for the fission product transport PIRT phenomena are reproduced from NUREG/CR 6944 in Table 4-1. As shown of the total of 29 PIRT phenomena in this topic, 7 PIRT phenomena are categorized as low-knowledge, 21 as medium-knowledge, and one deferred to the ACTH group.

As for the other topics, the workshop participants reviewed each phenomena one-at-a-time in terms of its Figure of Merit (FOM) and the rationale for its importance and knowledge level. The sequential reconciliation process of Section 2 was again followed for each. The results are provided in Table 4-2. As shown in the table, for 3 of the PIRT phenomena there is not sufficient design detail at this stage to judge whether a new or modified DDN is required. These will be reviewed again towards the end of conceptual design. No PIRT phenomenon for this topic is presently included in the PBMR NGNP DDNs (yellow-shaded).

The workshop participants judged that at this time the remaining 26 PIRT phenomena do not lead to new or modified DDNs for the NGNP (green-shaded). The basis for judging that the PIRT phenomena do not impact the DDNs (shaded blue) varied as shown. Three PIRT phenomena were judged to be not applicable to the PBMR design: one involved a phenomenon of dust combustion in the reactor building; and two were for block fuel elements. The remaining 23 PIRT phenomena are included in the DPP design and technology development.

Thus, for this topic the reconciliation process found substantial agreement with the importance and knowledge level of the PIRT phenomena and concluded that the design needs are being addressed by the DPP program.

Table 1-1 Significant Fission Product Transport (FPT) PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Confinement	Radiolysis effects in confinement	dose to control room and off-site location	H	M	I: – FP (e.g., I, Ru, Te) chemistry, paint chemistry. Dose will be dependent on confinement radiation level (Trans.). KL: – LWR experience and data applicable to some extent.
Confinement	Combustion of dust in confinement	dose to control room and off-site location	H	M	I: – Source of heat and distribution of FPs with in confinement. KL: – Data from international Tokomak (magnetic confinement fusion) experiment (ITER) development may be applicable. Contingent on specific design knowledge.
Confinement	Confinement leakage path, release rate through penetrations	dose to control room and off-site location	H	M	I: – Cable/pipe penetrations, cracks, holes, heating ventilating air conditioning (HVAC) provide potential leakage paths (Trans.). KL: – Building leakage experience, design specific.
Confinement	Cable pyrolysis, fire	dose to control room and off-site location	H	M	I: – Soot generation and changes to iodine chemistry. KL: – LWR experience.
Core	Recriticality (slow)	release from graphite in fuel form release into primary system release to confinement dose to control room and off-site location	H	M	I: – Additional thermal load to fuel. Increases source but not expected to affect transport path. KL: – Heat load easily computed with existing tools; effect on fission products not completely known.
Fuel	Fuel-damaging Reactivity Insertion Accident	release from graphite in fuel form release into primary system release to confinement dose to control room and off-site location	H	M	I: – An intense pulse could damage fuel. Increases source but not expected to affect transport path. KL: – Some data exist, but outside of expected accident envelope.
Fuel and Primary Coolant System	Dust generation	release from graphite in fuel form release into primary system	H	M	I: – pathway for FP transport; possibility of high mobility. KL: – Limited experience; lack specific system information.
Graphite and Core Materials	Matrix permeability, tortuosity	release from graphite in fuel form	H	L	I: – Needed for first principle transport modeling provides initial and boundary conditions for transient and accident analysis (IC and Trans.). KL: – FP holdup as barrier, release as dust; expected from material PIRT.
Graphite and Core Materials	FP transport through matrix	release from graphite in fuel form	H	L	I: – Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans.). KL: – FP holdup as barrier, release as dust; expected from HTMAT PIRT.
Graphite and Core Materials	Fuel block permeability, tortuosity	release from graphite in fuel form	H	M	I: – Needed for first principle transport modeling (IC and Trans.). KL: – Depends on specific graphite; expected from HTMAT PIRT.

Table 4-1 Significant Fission Product Transport (FPT) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Graphite and Core Materials	FP transport through fuel block	release from graphite in fuel form	H	M	I: – Effective release rate coefficient (empirical constant) as an alternative to first principles (IC and Trans.). KL: – Depends on specific graphite; expected from HTMAT PIRT.
Graphite and Core Materials	Sorptivity of graphite	release from graphite in fuel form release into primary system	H	M	I: – Historical data, need specific information on graphite and radiation effects. KL: – Depends on specific graphite; expected from HTMAT PIRT.
Graphite and Core Materials	Fluence effects on transport in graphite	release from graphite in fuel form release into primary system	H	M	I: – Influences transport, chemical reactivity. KL: – Historical data; need specific information on graphite and radiation effects.
Graphite and Core Materials	Air attack on graphite	release from graphite in fuel form release into primary system release to confinement dose to control room and off-site location	H	M	I: – Graphite erosion/oxidation, Fe/Cs catalysis liberating FPs (Trans.). KL: – Historical data largely applicable.
Graphite and Fuel	FP speciation in carbonatious material	release from graphite in fuel form release into primary system	H	L	I: – Chemical form in graphite affects transport (IC and Trans.). KL: – Uncertain and/or incomplete.
Graphite and Fuel	Steam attack on graphite	release from graphite in fuel form release into primary system	H	M	I: – If credible source of water present; design dependent (Trans.). KL: – Historical data largely applicable.
Graphite in Primary System	(De)Absorption on dust	release from graphite in fuel form release into primary system	H	M	I: – Provides copious surface area for FP absorption. KL: – Limited experience; lack specific details. Historical data from Peach Bottom HTGR largely applicable.
Primary Coolant System	Material/structure properties (critical initial and/or boundary condition)	release into primary system	H	M	I: – Density, viscosity, conductivity, etc., important parameters in calculations (IC and Trans.). KL: – Properties are well-known for steel and concrete, but graphite type not yet selected; data expected from HTMAT PIRTs. Well known for IC.
Primary Coolant System	Thermal-fluid properties	release into primary system release to confinement	H	M	I: – temperature, pressure, velocity computations (IC and Trans.) KL: – Well known for helium; uncertainty in composition of gas mixtures makes gas property calculation more difficult; expected from ACTF PIRT.

Table 4-1 Significant Fission Product Transport (FPT) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
	Gas composition	release into primary system	H	M	I: – Oxygen potential and chemical activity. KL: Central issue for chemical reaction modeling, FP speciation, scenario dependent.
Primary Coolant System	Gas flow path prior, during and post accident	release into primary system release to confinement dose to control room and off-site location–	H		I: – Information needed to model accident (IC and Trans.). KL: – Need to coordinate with other groups; expected from ACTF PIRT.
Primary Coolant System	FP speciation during mass transfer	release from graphite in fuel form release into primary system	H	M	I: – Chemical change can alter volatility. KL: – Historical data; need specific information. Good for metals, oxides. Uncertain for carbides and carbonyls.
Primary Coolant System, Cavity, Confinement	Ag-110m generation, transport	release from graphite in fuel form release into primary system	H	L	I: – Radioisotope, significant as potential O&M dose on cool, metallic components. Not significant as a potential dose to public from releases. KL: – Limited data, unknown transport mechanism.
Primary Coolant System, Cavity, Confinement	Aerosol growth	release into primary system release to confinement dose to control room and off-site location	H	L	I: – Low concentration growth can lead to high-shape factors and unusual size distribution. KL: – Regime has not been studied previously.
Primary Coolant System, Cavity and Confinement	Resuspension	release into primary system release to confinement dose to control room and off-site location	H	L	I: – Flow/vibration induced, saltation; mechanical forces can release FPs from pipe surface layers films (Trans.). KL: – Lack of data and models for anticipated conditions.
Primary Coolant System, Cavity and Confinement	Aerosol/dust deposition	release from graphite in fuel form release into primary system release to confinement dose to control room and off-site location	H	M	I: – Gravitational, inertial, thermophoresis, electrostatic, diffusional, turbophoresis (Trans.). KL: – Reasonably well-developed theory of aerosol deposition by most mechanisms except inertial impact in complex geometries; applicability to NGNP unclear. Theory, data, and models lacking.
Primary Coolant System/Fuel	FP plate-out and dust distribution under normal operation	release from graphite in fuel form release into primary system	H	M	I: – Starting conditions. KL: – Theory and models lack specifics.
Reactor Coolant System and Confinement	FP diffusivity, sorbtivity in nongraphite surfaces.	release into primary system	H	L	I: – Determines FP location during operation; acts as a trap during transient (IC and Trans.). KL: – Little information on surface materials (and operating conditions) of interest.
Reactor Coolant System and Confinement	Coolant chemical interaction with surfaces	release into primary system release to confinement	H	M	I: – Changes oxygen and carbon potential which can affect nature and quantity of sorbed species (IC and Trans.). KL: – Surface properties are critical; need alloy data.

Table 4-2 Reconciliation of Significant Fission Product Transport (FPT) PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Radiolysis effects in confinement	TBD	No	No	TBD	TBD	TBD	TBD	Need additional dialogue and discussion of why this phenomena was identified. First reaction is that this may be an LWR issue.
Combustion of dust in confinement	No	---	---	---	---	No	---	Study of dust combustion in reactor building performed by UK consultant indicated no combustion (Ref. 4-1).
Confinement leakage path, release rate through penetrations	Yes	Yes	---	---	---	No	---	Bounding analyses of leakage from DPP reactor building are utilized, no tests are needed
Cable pyrolysis, fire	Yes	No	No	TBD	TBD	TBD	TBD	Topic for CD and later NGNP design phases. Iodine released from fuel to reactor building much lower than for LWR core melt accidents, impact of fires on iodine within building a secondary or tertiary effect. Organic iodine less filtered, but health effect less from organic than elemental since deposition is less.
Recriticality (slow)	Yes	Yes	---	---	---	No	---	Bounding analyses of recriticality performed, insertion of control for DBAs, tests at AVR, HTR-100 demonstrated acceptable core response, increase in graphite temp after recriticality is small to negligible increase over normal operation: not expected to lead to important increase in RN transport from fuel
Fuel-damaging Reactivity Insertion Accident	Yes	Yes	---	---	---	No	---	RIAs for PBMR: CR withdrawal, seismic compaction, overcooling, water ingress. Events do not lead to HPB leak/breaks. Bounding analyses for impact of seismic compaction acceptable. Common mode events such as seismic meet requirements.
Dust generation	Yes	Yes	---	---	---	No	---	Data available from AVR/THTR. DEACO characterizing AVR piping sections in terms of deposited dust particle size and RN inventory. Bounding analyses in dust generation evaluation utilized to cover uncertainties. Additional dust generation tests under evaluation for DPP
Matrix permeability, tortuosity	Yes	Yes	---	---	---	No	---	German experience (TECDOC 978). Fuel irradiation and qualification program to provide data for DPP

Table 4-2 Reconciliation of Significant Fission Product Transport (FPT) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
FP transport through matrix	Yes	Yes	---	---	---	No	---	German experience (TECDOC 978). Fuel irradiation and qualification program to provide data for DPP.
Fuel block permeability, tortuosity	No	---	---	---	---	No	---	Not applicable for pebble fuel element
FP transport through fuel block	No	---	---	---	---	No	---	Not applicable for pebble fuel element
Sorptivity of graphite	Yes	Yes	---	---	---	No	---	Based on German experience (TECDOC 978)
Fluence effects on transport in graphite	Yes	Yes	---	---	---	No	---	Covered by bounding analyses of integrated transport phenomena (Refs 4-2,4-3)
Air attack on graphite	Yes	Yes	---	---	---	No	---	TINTE calculates oxidation of fuel spheres as a function of temp. and air ingress. Graphite oxidation properties of fuel spheres based on German and other data for matrix material of outer unfueled layer of sphere. TINTE input from NACOK and VELUNA testing. When outer layer of fuel sphere oxidizes, RN within layer are released
FP speciation in carbonatious material	Yes	Yes	---	---	---	No	---	GETTER groups fission products into volatility groups with conservative transport properties assigned to each that bounds consideration of chemical forms and compounds of the range of nuclides within a group
Steam attack on graphite	Yes	Yes	---	---	---	No	---	Calculations show that exothermic attack by air more bounding than endothermic attack by limited water of CCS
(De)Absorption on dust	Yes	Yes	---	---	---	No	---	DAMD calculates based on AVR experience the transport of FPs to and from the dust on the fuel spheres. Analyses include the FPs on dust, on the spheres, and on the dust on the spheres, as well as on the metallic components within the HPB. Benchmarked with AVR/THTR experience as well as from VAMPYRE tests. Location of FPs whether on dust or on surfaces is important.
Material/structure properties (critical initial and/or boundary condition)	Yes	Yes	---	---	---	No	---	Graphite type known; properties relative to FP transport can be approximated and uncertainties assigned. Not expected to be a critical parameter for accident offsite analyses. FP release more temperature-dependent than graphite property-dependent
Thermal-fluid properties	Yes	Yes	---	---	---	No	---	For release from HPB to RB, FLOWNEX and other models provide input to the RB's gas thermo fluid analyses. For release within the RB, Accident Source Term Evaluation Code (ASTEC) is used with testing input from THAI experiments. ASTEC, under development by IRSN/GRS since 1996, is a multi-module code: 1) SOPHAREOS (Aerosol and FP behavior in primary circuit), 2) CESAR (Thermal-hydraulics in primary circuit), 3) DIVA (Core degradation), 4) ELSA (FP release from primary circuit into containment), 5) CPA (Thermal hydraulics, aerosol and FP behaviour in containment), 6) IODE (Iodine behaviour in containment), 7) ISODOP (Isotope treatment and activity in containment), and 8) SYSINT (Safety system management in containment, e.g., water)

Table 4-2 Reconciliation of Significant Fission Product Transport (FPT) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Gas composition	Yes	Yes	---	---	---	No	---	Oxidation covered by evaluation tools and analyses; review of FP chemistry in RB and possible need for testing underway
Gas flow path prior, during and post accident	Yes	Yes	---	---	---	No	---	For release from HPB to RB, ASTEC code available with testing input from THAI experiments. For release from RB offsite, PCCosyma and GENII are utilized with site input.
FP speciation during mass transfer	Yes	Yes	---	---	---	No	---	Evaluation of analytical models and possible testing for FP chemistry within HPB has been performed by SERCO in the UK (Ref. 4-4).
Ag-110m generation, transport	Yes	Yes	---	---	---	No	---	Modeled in GETTER with data input from German experience
Aerosol growth	Yes	Yes	---	---	---	No	---	Aerosol growth considered in RB with ASTEC. AVR particle size distribution initially assumed. Industry standards used for particulate behavior.
Resuspension	Yes	Yes	---	---	---	No	---	Modeled by shear force ratio based on conservative data base from TECDOC 978. NRG developing SPECTRA model to complement other PBMR codes. Further, an integrated code DAMD for PBMR under development. CIEMAT (Spain) performing literature review.
Aerosol/dust deposition	Yes	Yes	---	---	---	No	---	In HPB, modeled with AVR data in DAMD to cover all deposition mechanisms in an integrated manner by an empirical treatment. In RB, modeled with ASTEC using industry standard aerosol transport algorithms.
FP plate-out and dust distribution under normal operation	Yes	Yes	---	---	---	No	---	In HPB, modeled with AVR data in DAMD to cover all deposition mechanisms in an integrated manner by an empirical treatment
FP diffusivity, sorbtivity in nongraphite surfaces.	Yes	No	No	Yes	TBD	TBD	TBD	To be developed in later design phases when HPB materials selected.
Coolant chemical interaction with surfaces	Yes	Yes	---	---	---	No	---	Evaluation of analytical models and possible testing for FP chemistry within HPB has been performed by SERCO in the UK (Ref. 4-4).

5 HIGH TEMPERATURE MATERIALS PIRTS

The high-importance and low- and medium-knowledge level NGNP PIRTs for the high temperature materials PIRT phenomena are reproduced from NUREG/CR 6944 in Table 5-1. As shown of the total of 17 PIRT phenomena in this topic, all but one was categorized as low-knowledge.

As for the other topics, the workshop participants reviewed each phenomena one-at-a-time in terms of its Figure of Merit (FOM) and the rationale for its importance and knowledge level. The sequential reconciliation process of Section 2 was again followed for each. The results are provided in Table 5-2. As shown in the table, for one of the PIRT phenomena there is not sufficient design detail at this stage to judge whether a new or modified DDN is required. These will be reviewed again towards the end of conceptual design. Three PIRT phenomena (yellow-shaded) for this topic are presently included in the PBMR DDNs.

The workshop participants judged that at this time the remaining 13 PIRT phenomena do not lead to new or modified DDNs for the NGNP (green-shaded). The basis for judging that the PIRT phenomena do not impact the DDNs (shaded blue) varied as shown. Five PIRT phenomena were judged to be not applicable to the PBMR design: one on composites for piping, two on piping insulation; and two on an advanced vessel material. The remaining 8 PIRT phenomena are included in the DPP design and technology development.

Thus, for this topic the reconciliation process found substantial agreement with the importance and knowledge level of the applicable PIRT phenomena and concluded that they are being addressed by the DPP program.

Table 5-1 Significant High Temperature Materials (HTMAT) PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Control Rods (nonmetallic)	Composites structural design methodology limitations for new structures (lack of experience)	maintain insertion ability	H	L	I: – Carbon-Cabon (C-C) composites are prime candidates but need approved method of designing, proof testing, model testing, testing standards, design methods, and validation tests. KL: – Some code work is being developed by the American Society of Mechanical Engineers (ASME) and American Society of Testing Metals (ASTM). Extendsive aerospace industry design and usage can be assessed for applicability.
Intermediate Heat Exchanger (IHX)	Crack initiation and propagation [due to creep crack growth, creep, creep-fatigue, aging (with or without load), subcritical crack growth]	integrity of IHX	H	L	I: - secondary loop failure/breach- Environmental effects on subcritical crack growth, subject to impacts of design issues, particularly for thin section must be addressed. Stresses on IHX (both thin and thick sections) can lead to these failure phenomena; thermal transients can cause toughness concerns; carbide redistribution as a function of thermal stress can change through-thickness properties, loading direction. KL: - More is known about Alloy 617 from HTGR and industry usage than for Alloy 230. Both environment and creep play significant roles in initiation and cyclic crack growth rate of 671 and 230. Mechanistic models for predicting damage development and failure criteria for time-dependent phenomena have to be developed d to enable conservative extrapolation from short-term laboratory test data to ling-term design life.
Intermediate Heat Exchanger (IHX)	Primary boundary design methodology limitations for new structures (lack of experience)	integrity of IHX	H	L	I: – secondary loop failure/breach – Time-dependent design criteria for complex structures need to be developed and verified by structural testing. ASME Code-approved simplified methods have not been proven and are not permitted for compact IHX components. KL: – No experience for the complex shape IHX. No experience for designing and operating high-temperature components in the (safety) class 1 environment. Difficulties of design and analyses of compact IHX are discussed in Refs. 16–25 of Volume 4–High-Temperature Materials PIRT (Ref. 3).
Intermediate Heat Exchanger (IHX)	Manufacturing phenomena (such as joining)	integrity of IHX	H	L	I: – secondary loop failure/breach – Compact heat exchanger (CHE) cores (if used) will require advanced machining, forming, and joining (e.g., diffusion bonding, brazing, etc.) methods that may impact component integrity. Must assess CHE vs traditional tube and shell concepts. However, these phenomena are generic and extend beyond the compact HXs to all the very high-temperature HXs. KL: – Compact HXs have not been used in nuclear applications; the candidate alloys and their joining processes not adequately established in nonnuclear applications.

Table 5-1 Significant High Temperature Materials (HTMAT) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Intermediate Heat Exchanger (IHX)	Inspection/testing phenomena	integrity of IHX	H	L	I: – secondary loop failure/breach - Traditional nondestructive evaluation (NDE) methods will not work for CHEs because of geometrical constraints. Proof testing of some kind will be required (maybe leak testing with tracer). Preservice testing will be difficult, and in-service testing will be even harder. Condition monitoring may be useful. Preoperational testing, preservice inspection, fitness for service, issue with leak tests, KL: – have very little knowledge here. Uncertainties in the margins
Piping	Aging fatigue, environmental degradation of insulation	peak fuel temperature	H	L	I: – Concern is about insulation debris plugging core cooling channels, causing damage due to chunks of internal insulation falling off (ceramic sleeves or C–C composites would be most likely source of problems). KL: – Little system-relevant information about insulation failure mechanism is available.
RPV Internals (metallic)	Change in emissivity	maintain heat transfer capability	H	L	I: – To ensure passive safety, high emissivity is required to limit core temperatures – (affect coolant pathway, high emissivities on both surfaces of the core barrel, formation and control of surface layers, consider under helium environments). KL: – Limited studies on SS and on Alloy 508 show potential for maintaining high emissivity.
RPV Internals (metallic)	Radiation-creep	maintain structure geometry	H	L	I: – Irradiation creep and dimensional changes particularly for Alloy 800H at moderately low-dose should be assessed. KL: – Little information on irradiation creep is available for Alloy 800H.
RPV Internals (nonmetallic)	Composites structural design and fabrication methodology limitations for new structures (lack of experience)	maintain structure geometry	H	L	I: – C–C composites are prime candidates but need approved method of designing, proof testing, model testing, testing standards, design methods, validation tests, scalability issues, fabrication issues, probabilistic methods of design. Must address large-scale (meters in diameter) structures as well as smaller ones. KL: – Extensive experience within the aerospace industry; applicability must be assessed.
RPV Internals (nonmetallic)	Environmental and radiation degradation and thermal stability at temperature	Maintain insulation capability	H	L	I: – Relatively low dose and exposure is expected, but LOFC can result in temperatures high enough to challenge stability of fibrous insulation such as Kaowool. Need to assess effects on microstructural stability and thermophysical properties during irradiation and high-temperature exposure in impure helium. KL: – Limited commercial information available for conditions of interest.

Table 5-1 Significant High Temperature Materials (HTMAT) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Reactor Pressure Vessel	Crack initiation and subcritical crack growth	RPV integrity	H	L	I: – 9 Cr–1 Mo steel (grade 91) must be assessed for phenomena due to transients and operationally induced – thermal loading, pressure loading, residual stress, existing flaws (degradation of welds, cyclic loading, low-cycle fatigue). KL: – There is a limited database from fossil energy applications at these temperatures. Low-cycle fatigue data in air, vacuum, and sodium (ANL unpublished data) at >482°C show life is longest in sodium, followed by vacuum and air. Aging in helium (depending on impurities) will most likely be greater than in air. Aging in impure helium may perhaps depend on impurity type and content.
Reactor Pressure Vessel	Compromise of emissivity due to loss of desired surface layer properties	RPV integrity peak fuel temperature	H	L	I: – To ensure passive safety, high emissivity of the RPV is required to limit core temperatures – must maintain high emissivities on both inside and outside surfaces. Formation and control of surface layers must be considered under both helium and air environments. KL: – There are limited studies on SS and on Alloy 508 that show potential for maintaining high emissivity. Some studies currently being conducted on emissivity but NOT on materials of concern.
Reactor Pressure Vessel	Field fabrication process control	RPV integrity	H	L	I: – Fabrication issues must address field fabrication because of vessel size [including welding, postweld heat treatment (PWHT), section thickness (especially with 9 Cr–1 Mo steel) and preservice inspection]. KL: – Fossil energy experience indicates that caution needs to be taken. On-site nuclear vessel fabrication is unprecedented.
Reactor Pressure Vessel	Property control in heavy sections	RPV integrity	H	L	I: – Heavy-section properties are difficult to obtain because of hardenability issues. Adequate large ingot metallurgy technology does not exist for 9 Cr–1 Mo steel. Maintaining fracture toughness, microstructural control, and mechanical properties in through-thickness of heavy sections, 9 Cr materials must be maintained. (Concerns in utilities regarding P91, >3-in. piping heat treatment a challenge.) Excess deformation was listed because of the emphasis on minimizing changes in core geometry. KL: – Very limited data; not much over 3 to 4 in. thickness. Few data available for specimens from 300-mm-thick forgings show thick section properties lower than thin section.
Reactor Pressure Vessel	Thermal aging (long term)	RPV integrity	H	M	I: – Uncertainty in properties of 9 Cr–1 Mo steel (grade 91), especially degradation and aging of base metals and welds for a critical component like the RPV must be addressed for 60-year lifetimes. Although it was not discussed in our meeting, Type IV cracking has been observed in operating fossil plants at 545°C after 20,000 h. Although unlikely, is Type IV cracking at NGNP operating temperatures possible for very long time (60 years) exposure? It is assumed that grade 91 is the prime candidate for NGNP, and no back up material is considered in this report for designs without active cooling. KL: – This is beyond experience base for conditions of interest, extensive fossil energy experience and code usage, though significant aging data exist at high temperatures (>500°C). Need is for long-term aging data at NGNP relevant temperatures.
Valves	Isolation valve failure	primary system pressure boundary integrity	H	L	I: –Isolation valve failure (includes categories such as self-welding, galling, seizing) is possible. Concerns about isolation valves are similar to "breach to secondary" issues on IHX since they would provide barriers to secondary heat transport system. KL: – Information possibly available from previously constructed HTGRs, but relevance needs to be assessed. State of knowledge about helium-leak-tightness in large valves is unknown.
Valves	Valve failure (general)	primary system pressure boundary integrity	H	L	I: – Concerns about a variety of valve failure mechanisms that will be design-dependent (includes categories such as self-welding, galling, seizing) will need to be assessed once design-specific details are available. Helium-tribology issues must be considered. Allowable identified and unidentified coolant leakage must be established. KL: – Information available from previously constructed HTGRs, but relevance needs to be assessed.

Table 5-2 Reconciliation of High Temperature Materials (HTMAT) PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomen a covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP Applicable to <800C NGNP?	Basis
Composites structural design methodology limitations for new structures (lack of experience)	No	—	—	—	—	No	—	NGNP to use same CR design/materials (Alloy 800H) as DPP Normal operations conditions generally less challenging due to lower core inlet; DLOFC slightly higher in temperature but within margins. To be confirmed as design progresses.
Crack initiation and propagation [due to creep crack growth, creep, creep-fatigue, aging (with or without load), subcritical crack growth	Yes	No	Yes	—	—	—	Yes	Covered by incremental NGNP DDNs, e.g., HTS-01-04 for 617 material
Primary boundary design methodology limitations for new structures (lack of experience)	Yes	No	Yes	—	—	—	Yes	Covered by incremental PBMR NGNP DDNs, e.g., HTS-01-04 for 617 material
Manufacturing phenomena (such as joining)	Yes	No	Yes	—	—	—	Yes	Covered by incremental PBMR NGNP DDNs, e.g., HTS-01-04 for 617 material
Inspection/testing phenomena	Yes	No	No	Yes	TBD	TBD	TBD	In later design phase, approach to classification of IHX HPB will be developed. Dependent on that Reliability Integrity Management (RIM) measures will be selected. Certain traditional RIM measures such as ISI likely not possible for CHEs; other measures must be developed and shown to be adequate. In a broader sense, ISI can also include leak detection during operation.
Aging fatigue, environmental degradation of insulator	No	—	—	—	—	No	—	No insulation in CIP nor in counter flow of COP that would lead to core flow blockage impacting FOM of high fuel temps.
Change in emissivity	Yes	Yes	—	—	—	No	—	DPP has emissivity testing of the Type 316 SS (CBA) and SA-533 Type B (RPV) as a function of aging in facilities in SA and Germany.
Radiation-creep	Yes	Yes	—	—	—	No	—	Alloy 800H CRs have supplemental irradiation and creep testing planned to extend lifetime of the current design; consequently the CRs are also designed to be replaceable.

Table 5-2 Reconciliation of Significant High Temperature Materials (HTMAT) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP Applicable to <800C NGNP?	Basis
Composites structural design methodology limitations for new structures (lack of experience)	**Yes**	**Yes**	—	—	—	**No**	—	DPP uses non-metallic materials for reactor internals in selected components in low fluence levels (e.g., reflector restraints, tie rods), but not for high fluence control rods. Testing planned and underway (at SGL in Germany) for the selected material and component qualification for in-reactor use as non-code items.
Environmental and radiation degradation and thermal stability at temperature	**No**	—	—	—	—	**No**	—	Only insulation materials used are non-fibrous baked carbon and/or fused silica which are utilized in a low fast neuron fluence area (<0.5dpa)
Crack initiation and subcritical crack growth	**No**	—	—	—	—	**No**	—	NGNP does not utilize 9Cr 1Mo material for RPV. For the NGNP, SA-533 Type B material are used, this information is covered by the code for the DPP design conditions and has the extensive LWR experience base on irradiation effects and crack behaviour.
Compromise of emissivity due to loss of desired surface layer properties	**Yes**	**Yes**	—	—	—	**No**	—	DPP has emissivity testing of the Type 316 SS (CBA) and SA-533 Type B (RPV) as a function of aging in facilities in SA and Germany
Field fabrication process control	**Yes**	**Yes**	—	—	—	**No**	—	For DPP, SA-533 Type B material for the RpV, field fabrication of the closure weld of the top head and cylindrical part, at Koebert site, will be performed through qualified welding/inspection procedures in accordance with the ASME code.
Property control in heavy sections	**Yes**	**Yes**	—	—	—	**No**	—	DPP uses SA-508/SA-533 material for the RPV, for which there is far greater manufacturing experience than 9Cr-1Mo – in thick section property control. DPP manufacturing experience at ENSA to benefit NGNP.
Thermal aging (long term)	**No**	—	—	—	—	**No**	—	NGNP does not utilize 9-CR-1Mo material for RPV. For the NGNP SA-533 material, no thermal aging concerns anticipated at 350C operating temperature (core inlet temperature)
Isolation valve failure	**Yes**	**Yes**	—	—	—	**No**	—	DPP isolation valves incorporate appropriate coatings to prevent self-welding; performance confirmed in component testing at a range of facilities. HTF will have prototype valves and will be tested for range of DPP conditions.
Valve failure (general)	**Yes**	**Yes**	—	—	—	**No**	—	DPP valves incorporate appropriate coatings to prevent self-welding performance confirmed in component testing at a range of facilities. HTF will have prototype valves and will be tested for range of DPP conditions.

6 GRAPHITE PIRTS

The high-importance and low- and medium-knowledge level NGNP PIRTs for the graphite PIRT phenomena are reproduced from NUREG/CR 6944 in Table 6-1. As shown of the total of 17 PIRT phenomena in this topic, 7 rated as low-knowledge and 10 as medium.

As for the other topics, the workshop participants reviewed each phenomena one-at-a-time in terms of its Figure of Merit (FOM) and the rationale for its importance and knowledge level. The results of the reconciliation process are provided in Table 6-2. Five PIRT phenomena (yellow-shaded) for this topic are presently included in the PBMR DDNs.

The workshop participants judged that at this time the remaining 12 PIRT phenomena do not lead to new or modified DDNs for the NGNP (green-shaded). The PBMR workshop participants agreed with the PIRT reviewers that two phenomena should be added to the PBMR NGNP DDNs:

- Irradiation-induced creep (irradiation-induced dimensional change under stress)
- Irradiation-induced change in the coefficient of thermal expansion (CTE), including the effects of creep strain

The basis for judging that the remaining PIRT phenomena do not impact the DDNs (shaded blue) varied as shown. Two PIRT phenomena concerning coolant channels in the fuel element were not applicable to the PBMR design. Five PIRT phenomena are included in the DPP design and technology development. Finally 3 phenomena were judged to not need technology development for the NGNP to meet its top requirements.

Thus, for this topic the reconciliation process identified two new DDNs that are required for the PBMR NGNP and generally was in agreement with the importance and knowledge level of many of the applicable PIRT phenomena and concluded that they are being addressed by the DPP program.

Table 6-1 Significant Graphite (GRAPH) PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Graphite	Irradiation-included creep (irradiation-induced dimensional change under stress) {Could potentially reduce significantly internal stress}	Ability to maintain passive heat transfer; ability to control reactivity; thermal protection of adjacent components, maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activitiy in the coolant.	H	L	L: – Required for graphite finite-element method (FEM) stress analysis; acts to reduce stress. KL: – It is essential that irradiation creep is better understood; mechanistic understanding essential. There are interaction affects with the CTE and may be dimensional change and modulus. New modes are needed along with data on new graphites.
Graphite	Irradiation-induced change in CTE, including the effects of creep strair	Ability to control reactivity; thermal protection of adjacent components; prevent excessive mechanical load on the fuel ; minimize activities in the coolant.	H	L	I: – Essential input into irradiated graphite component stress analysis. KL: – Extensive database, some microstructural/mechanistic studies required.
Graphite	Irradiation-induced changes in mechanical properties (strength, toughness), including the effect of creep strain (stress) {Tensile, bend, compression, shear (multiaxial), stress-strain relationsihp, fractures, and fatigue strength}	Ability to control reactivity; thermal protection of adjacent components; prevent excessive mechanical load on the fuel ; minimize activities in the coolant.	H	M	I: – Essential input into irradiated graphite component stress analysis. KL: – Extensive database, some microstructural/mechanistic studies required. Better understanding of fracture process required.
Graphite	Statistical variation of nonirradiated properties {Variability in properties (textural and statistical); isotropic. Probabilistic approach use is prudent. Purity level; implications for chemical attack, degradation, decommissioning}	Ability to maintain passive heat transfer, ability to control reactivity, thermal protection of adjacent components; shielding of adjacent components; maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activity in the coolant.	H	M	I: – 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. KL: – Statistical methods need to be in agreement, improved upon, and validated. Standards need establishing.
Graphite	Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)	Ability to maintain passive heat transfer, ability to control reactivity, thermal protection of adjacent components; shielding of adjacent components; maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activity in the coolant.			I: – Raw materials and manufacturing techniques may change with resultant change in properties and irradiation behavior. KL: – 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 it out.
Graphite	Graphite contains inherent flaws {Need methods for flaw evaluation}	Ability to control reactivity; thermal protection of adjacent components; shielding of adjacent components; maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activity in the coolant.	M	M	I: – Available techniques need further development, demonstration, and confirmation. New improved component NDE techniques are desirable. KL: – New improved NDE methods require developing.

Table 6-1 Significant Graphite (GRAPH) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Graphite	Irradiation-induced dimensional change {Largest source of internal stress}	ability to maintain passive heat transfer; ability to control reactivity; thermal protection of adjacent components; shielding of adjacent components; maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activity in the coolant.	H	M	I: – Required for graphite FEM stress analysis, main driver for stresses. KL: – Data available or can be measured, but better mechanistic understanding desirable.
Graphite	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}	ability to maintain passive heat transfer; thermal protection of adjacent components; maintain coolant flow path; minimize activity in the coolant.	H	M	I: – Important input to loss of coolant accidents and used to define temperatures for FEM irradiated graphite component stress analysis. KL: – Low fluence data available and understanding adequate. High fluence data and understanding required. Methodology for temperature dependence requires validation.
Graphite	Irradiation-induced changes in elastic constants, including the effects of creep strain	ability to control reactivity; thermal protection of adjacent components; prevent excessive mechanical load on the fuel; minimize activity in the coolant.	H	M	I: – Essential for input into irradiated graphite FEM stress analysis. KL: – Data available or can be measured; better mechanistic understanding desirable. Concept of increase in modulus due to “pinning” needs further investigation.
Graphite	Tribology of graphite in (impure) helium environment	maintain coolant flow path	H	M	I: – Depends on design. Impacts seismic assessments. Whole-core modeling needs this data. KL: – Limited data available.
Graphite Component	Blockage of fuel element coolant channel—due to graphite failure, spalling {Debris generated from within the graphite core structures}	maintain coolant flow path.	H	L	I: – Two mechanisms: (a) component failure due to internal or external component stresses and (b) component failure due to very high irradiation and severe degradation of the graphite. KL: – 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.
Graphite Component	Blockage of coolant channel in reactivity control block due to graphite failure, spalling {Debris generated from nongraphite components within the RPV}	ability to control reactivity; thermal protection of adjacent components.	H	L	I: – Significant uncertainty exists as to the stress state of any graphite component in the core. Moreover, the strength of the component 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. KL: – 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 6-1 Significant Graphite (GRAPH) PIRT Phenomena (cont)

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Graphite Component	Blockage of reactivity control channel—due to graphite failure, spalling {Debris generated from within the graphite core structures}	ability to control reactivity.	H	L	I: – Two mechanisms: (a) component failure due to internal or external component stress and (b) component failure due to very high irradiation and sever degradation of the graphite. KL: – 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.
Graphite Component	Degradation of thermal conductivity {Has an implication for fuel temperature limit for loss-of-forced cooling accident}	ability to maintain passive heat transfer.	H	M	I: – Important input to loss-of-coolant accidents and used to define temperature for FEM irradiated graphite component stress analysis. KL: – Low-fluence data available and understanding adequate. High-fluence data and understanding required. Methodology for temperature dependence requires validation.
Graphite Component	Blockage of fuel element coolant channel—channel distortion {Deformation from individual graphite blocks and block assemblies. There is a link to the metallic core support structure}	maintain coolant flow path.	M	M	I: – 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 (i.e., in a column of graphite bricks). KL: – 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.
Graphite Component	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. However, in some cases, gas temperatures and heat transfer coefficients are supplied, and the graphite specialists calculate the graphite temperatures from these}	ability to maintain passive heat transfer; ability to control reactivity; thermal protection of adjacent components; shielding of adjacent components; maintain coolant flow path; prevent excessive mechanical load on the fuel; minimize activity in the coolant.	H	M	I: – 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 temperatures from these. KL: – Justification for the use (or not of EDT-equivalent DIDO temperatures) requires validation.
Graphite Component	Tribology of graphite in (impure) helium environment	ability to control reactivity; thermal protection of adjacent components.	H	M	I: – Depends on design. Impacts seismic assessments. Whole- core modeling needs these data. KL: – Limited data available.

Table 6-2 Reconciliation of Graphite (GRAPH) PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Irradiation-induced creep (irradiation-induced dimensional change under stress) {Could potentially reduce significantly internal stress}	Yes	No	No	Yes	Yes	Yes (new)	Yes	Existing data suggest that the mitigative effects of irradiation-induced creep are relatively materials independent in the fluence range prior to the turnaround point. On this basis, existing data, along with the large margins provided within the PBMR DPP CSC design, are evaluated to provide sufficient certainty to support initial operation (5-10 years). After that time, irradiation creep data or other means of assuring integrity (e.g., component inspection) would be required to confirm the remaining life of the more highly irradiated components of the CSC. Creep data at high fluence levels are also needed for the PBMR NGNP and it is recommended that a NGNP DDN be established to acquire the necessary data.
Irradiation-induced change in CTE, including the effects of creep strain	Yes	No	No	Yes	Yes	Yes (new)	Yes	Existing data suggest that the mitigative effects of irradiation-induced creep are relatively materials independent in the fluence range prior to the turnaround point. On this basis, existing data, along with the large margins provided within the PBMR DPP CSC design, are evaluated to provide sufficient certainty to support initial operation (5-10 years). After that time, irradiation creep data or other means of assuring integrity (e.g., component inspection) would be required to confirm the remaining life of the more highly irradiated components of the CSC. Creep data at high fluence levels are also needed for the PBMR NGNP and it is recommended that a NGNP DDN be established to acquire the necessary data.
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}	Yes	Partially	Yes NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	This phenomenon has two elements, properties and conditions. In the properties, there are strength and toughness. Strength is covered by DPP and both NGNP DDNs. Toughness is not used in PBMR design methods. PBMR (and others) utilize methods that show margins to the quantitative requirements for the FOMs without fracture toughness being considered through the use of bounding analyses. It is noted; however, that toughness could be used, in part, to justify continued operation of components in which cracks are detected or predicted to occur after extended operation. In the conditions, there are temperatures, fluence, and stress. PBMR methods include the first two and provide design margins to cover the third. Operational monitoring, inspection, replacement are used to manage the margins through the lifetime. The planned DPP testing and the testing for the incremental DDNs will adequately meet the PBMR NGNP design and operational needs.
Statistical variation of nonirradiated properties {Variability in properties (textural and statistical); isotropic. Probabilistic approach use is prudent. Purity level; implications for chemical attack, degradation, decommissioning}	Yes	Yes	---	---	---	No	---	Required characterization is complete for NBG18 for the DPP.
Consistency in graphite quality over the lifetime of the reactor fleet (for replacement, for example)	Yes	No	No	Yes	No	No	---	This is a supply chain issue for future plants. PBMR's strategy is to address this later if the supply chain is disrupted. It is understood that there is a risk that additional testing and qualification may be required for new graphite. It is recognized that supply and market changes may change PBMR's position.
Graphite contains inherent flaws {Need methods for flaw evaluation}	Yes	Yes	---	---	---	No	---	PBMR methods address this graphite characteristic. Required characterization is complete for NBG18 for the DPP

Table 6-2 Reconciliation of Graphite (GRAPH) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Irradiation-induced dimensional change {Largest source of internal stress}	Yes	Partially	Yes NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02)
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}	Yes	Partially	Yes NHSS-01-03 NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02)
Irradiation-induced changes in elastic constants, including the effects of creep strain	Yes	Partially	Yes NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02) Effects of creep strain are not included in PBMR PSMP.
Tribology of graphite in (impure) helium environment	Yes	Yes	---	---	---	No	---	DPP friction and wear testing and operation will characterize this phenomena.
Blockage of fuel element coolant channel—due to graphite failure, spalling {Debris generated from within the graphite core structures}	No	---	---	---	---	No	---	PBMR NGNP does not have fuel elements with coolant channels.
Blockage of coolant channel in reactivity control block due to graphite failure, spalling {Debris generated from nongraphite components within the RPV}	Yes	No	No	Yes	No	No	---	PBMR NGNP does not have fuel elements for reactivity insertion with coolant channels. However, PBMR has graphite reflector blocks for reactivity insertion that have bypass cooling. The likelihood of blockage of the bypass flow in one of these blocks is small and the consequences are predicted to have negligible impact, that is, thermal protection of adjacent components, such as control rods needed for controlling reactivity, is maintained with large margins. Operational measures include the testing of control rod insertion. Failure to insert a control rod can be detected and corrective actions will be taken.

Table 6-2 Reconciliation of Graphite (GRAPH) PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Irradiation-induced dimensional change {Largest source of internal stress}	Yes	Partially	Yes NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02)
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}	Yes	Partially	Yes NHSS-01-03 NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02)
Irradiation-induced changes in elastic constants, including the effects of creep strain	Yes	Partially	Yes NHSS-02-01 NHSS-02-02	---	---	---	NHSS-02-02 not applicable	DPP testing will characterize this phenomena and will be extended with the incremental NGNP DDNs (NHSS-02-01, NHSS-02-02) Effects of creep strain are not included in PBMR PSMP.
Tribology of graphite in (impure) helium environment	Yes	Yes	---	---	---	No	---	DPP friction and wear testing and operation will characterize this phenomena.
Blockage of fuel element coolant channel—due to graphite failure, spalling {Debris generated from within the graphite core structures}	No	---	---	---	---	No	---	PBMR NGNP does not have fuel elements with coolant channels.
Blockage of coolant channel in reactivity control block due to graphite failure, spalling {Debris generated from nongraphite components within the RPV}	Yes	No	No	Yes	No	No	---	PBMR NGNP does not have fuel elements for reactivity insertion with coolant channels. However, PBMR has graphite reflector blocks for reactivity insertion that have bypass cooling. The likelihood of blockage of the bypass flow in one of these blocks is small and the consequences are predicted to have negligible impact, that is, thermal protection of adjacent components, such as control rods needed for controlling reactivity, is maintained with large margins. Operational measures include the testing of control rod insertion. Failure to insert a control rod can be detected and corrective actions will be taken.

7 PROCESS HEAT AND HYDROGEN PRODUCTION PIRTS

The high-importance and low- and medium-knowledge level NGNP PIRTs for the process heat and hydrogen production PIRT phenomena are reproduced from NUREG/CR 6944 in Table 7-1. As shown all 7 of the PIRT phenomena in this topic were categorized as medium-knowledge.

As for the other topics, the workshop participants reviewed each phenomena one-at-a-time in terms of its Figure of Merit (FOM) and the rationale for its importance and knowledge level. The results of the reconciliation process are provided in Table 7-2. No PIRT phenomena for this topic are presently included in the PBMR DDNs. As shown in the table, for 2 of the PIRT phenomena there is not sufficient design detail at this stage to judge whether a new or modified DDN is required. The basis for judging that the remaining PIRT phenomena do not impact the DDNs (shaded blue) varied as shown. Three PIRT phenomena were judged not applicable to the PBMR design with its helium intermediate loop essentially pressure balanced across the Intermediate Heat Exchanger (IHX) with the primary side. Two phenomena were judged to not need technology development for the NGNP to meet its top requirements.

It is recognized that this topic area is especially design- and application-dependent and will need to be re-reviewed at later design phases.

Table 7-1 Significant Process Heat and Hydrogen Production (PHHP) PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale
Primary System Components; SSCs	Fuel and primary system corrosion [process heat exchanger (PHX) failure]	damage or impairment of SSCs	H	M	I: – PHX failure would precipitate problems in IHX; more critical. It is a unique threat to IHX; ultimate impact would be on IHX. KL: – Novel PHX designs at this point do not yet exist; no experience base.
Primary System Components, SSCs	Blow-down effects, large mass transfer; pressurization of either secondary or primary side (IHX failures) {Fluid hammer. Thermal and concentration gradients can work against the D/P such that chemicals can diffuse toward the IHX}	damage or wear of SSCs	H	M	I: – Failure modes are equally important in both IHX and PHX. IHX is important because it is a boundary between the core and the secondary loop; small helium purge of a hot core. Small leaks more worrisome. KL: – Consensus: If salt intermediate loop, then no massive pressurization. Have models available that can handle these problems.
Primary System Components, SSCs	Loss of main heat sink (hydrodynamic loading on IHX; cutting margins down by increasing D/P over IHX; decrease operating life of IHX) (loss of intermediate fluids) {Rapid pulse cooling of reactor during depressurization of intermediate loop and IHX. Very rapid event. Self-closing valves act faster than I&C system}	damage, wear, or impairment of SSCs	H	M	I: – Loss of heat sink with all the blow-down effects. Potential for high probability in plant lifetime. Perhaps could occur in reactor lifetime? Uncertainty about IHX design. KL: – Good tools to work with currently, but design uncertainty exists.
Primary System Components, SSCs, TRISO Fuel Coatings	Reactivity spike due to neutron thermalization (mass addition to reactor: hydrogenous materials) {Power spike in fuel grains, could lead to TRISO-failure with prolonged high temperature}	damage, wear, or impairment of SSCs (TRISO layers; fission product confinement)	H	M	I: – The importance of hydrogenous mass additions was considered high because of the reactivity potential with possible power increases leading to a more severe thermal scenario. The neutronic and thermal effects of hydrogenous material additions can be readily analyzed with available tools. KL: – The knowledge base was designated M because the configurations, flow paths, and pressure characteristics are not well defined at this point in time.
Primary System Components, SSCs, TRISO Fuel Coating	Chemical attack of TRISO layers and graphite (mass addition to reactor: hydrogenous materials) {Steam and graphite react; TRISO. More concerned with gases produced in core by the steam, rather than the chemical attack on fuel. Pressure relief valve would open in primary loop releasing hydrogen into confinement}	damage, wear, or impairment of SSCs (TRISO layers; fission product confinement)	H	M	I: – Accidentally dumped water into core in AVR; had to boil water off, no chemical attack. Graphite attack and reformer gas production. Hydrogenous mass additions could lead to thermal and pressure transients and corrosion issues if the introduction were severe. Fission product panel should be aware of this. KL: – The knowledge base was designated M because the configurations, flow paths, and pressure characteristics are not well defined at this point in time.
Safety System Components, SSCs	Allowable concentrations (oxygen releases) {What oxygen levels cause damage?}	structures, systems, and components (SSCs)	H	M	I: – High, partially over concerns of both accident and long-term elevated levels; is there a chance of locally high concentrations in NGNP that are higher than designed for? Are we changing chemical properties of equipment, I&C, and people if locally high O2 concentrations? Importance of plume issue; want to know where the O2 goes; worst case is low temperature, release. Small inventory but possibility of plume is important. – Question is really one of what flammable material is present and what are ignition sources? KL: – The tools and knowledge are available; models do not have any new physics or considerations. – Such extensive experience working with O2 in industry; understand effects on some equipment well.
SSCs	Spontaneous combustion (oxygen releases) {What levels cause spontaneous combustion?}	SSCs	H	M	I: – May not easily disperse if released in large quantities. Importance if plume issue; want to know where the O2 goes; worst case low-temperature release. Small inventory but possibility if plume important. – Question is really one of what flammable material is present and what are ignition sources? KL: – The tools and knowledge are available; models do not have any new physics or considerations.

Table 7-2 Reconciliation of Process Heat and Hydrogen Production (PHHP) PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800C NGNP?	Basis
Fuel and primary system corrosion [process heat exchanger (PHX) failure]	Yes	No	No	TBD	TBD	TBD	TBD	The likelihood and safety consequences for a spectrum of process hazards (including those that propagate through the PHX to the IHX and into the primary system) will be assessed in a later design phase.
Blow-down effects, large mass transfer; pressurization of either secondary or primary side (IHX failures) {Fluid hammer. Thermal and concentration gradients can work against the D/P such that chemicals can diffuse toward the IHX}	No	---	---	---	---	No	---	PBMR NGNP has pressure balanced IHX which is designed for full pressure difference in off normal event of depressurization of either primary or secondary loop.
Loss of main heat sink (hydrodynamic loading on IHX; cutting margins down by increasing D/P over IHX; decrease operating life of IHX) (loss of intermediate fluids) {Rapid pulse cooling of reactor during depressurization of intermediate loop and IHX. Very rapid event. Self-closing valves act faster than I&C system}	Yes	No	No	Yes	TBD	TBD	TBD	The IHX will be designed in order to meet the expected thermal and pressure transients within the licensing basis. If the existing 617 and 800H materials are found to be insufficient, new DDNs will be considered.
Reactivity spike due to neutron thermalization (mass addition to reactor: hydrogenous materials) {Power spike in fuel grains, could lead to TRISO-failure with prolonged high temperature}	No	---	---	---	---	No	---	The PBMR design has a helium intermediate loop which buffers the process and steam from the primary loop.
Chemical attack of TRISO layers and graphite (mass addition to reactor: hydrogenous materials) {Steam and graphite react; TRISO. More concerned with gases produced in core by the steam, rather than the chemical attack on fuel. Pressure relief valve would open in primary loop releasing hydrogen into confinement}	No	---	---	---	---	No	---	The PBMR design has a helium intermediate loop which buffers the process and steam from the primary loop.
Allowable concentrations (oxygen releases) {What oxygen levels cause damage?}	Yes	No	No	TBD	No	No	---	The likelihood and safety consequences for a spectrum of process hazards (including the generation of oxygen) will be assessed in a later design phase. This phenomenon will be addressed exclusively by design and will not include any testing.
Spontaneous combustion (oxygen releases) {What levels cause spontaneous combustion?}	Yes	No	No	TBD	No	No		The likelihood and safety consequences for a spectrum of process hazards (including the generation of oxygen) will be assessed in a later design phase. This phenomenon will be addressed exclusively by design and will not include any testing. The knowledge level in the process industry should be adequate.

8 FUEL PIRTS

The NGNP PIRTs for the fuel PIRT phenomena taken from NUREG/CR 6844 in Table 8-1. The fuel PIRT was a forerunner of the NGNP PIRTs discussed in the previous sections. Many of the lessons learned from the fuel PIRT were incorporated in the NGNP PIRT process, e.g., the merit in having a large number of participants from a spectrum of related backgrounds. Thus, the level of the fuel review and the format of the results in the summary volume are not consistent with the later NGNP topics. For this reason, Table 8-1 differs from the other topics. For instance, a single knowledge-level assignment is usually not stated in the report and not all of the rationales for the importance and knowledge level are provided.

Also two screening criteria were utilized in the fuel PIRT. The first screening criterion was a consensus importance ranking of High in three or more of the six conditions: manufacturing, operations, a depressurized heatup accident, a reactivity accident, a depressurization accident with water ingress, and a depressurization accident with air ingress. The second screening criterion was the appearance of a phenomenon three or more times when considering all conditions and all components of the TRISO-coated particle fuel. Table 8-1 lists the phenomena results of both screening criteria with those phenomena from the second screening criteria footnoted that the phenomena appeared more than three times in NUREG/CR 6844 Table 5-1.

The results of the fuel reconciliation process are provided in Table 8-2. Of the 11 PIRT phenomena from both screening criteria, nine were found to be covered by PBMR NGNP DDNs. Two phenomena were judged to not need technology development for the NGNP to meet its top requirements.

Thus, for this topic the reconciliation process found substantial agreement with the PIRT phenomena and concluded that they are being addressed by the NGNP DDNs that supplement the fuel development and testing for the DPP.

Table 2 Significant Fuel PIRT Phenomena

SSC	Phenomena	Figure of Merit (FOM)	Importance (I)	Knowledge Level (KL)	Rationale (from Section 5.1 of NUREG/CR 6844)
Fuel	thermodynamic state of the fission products in the kernel (Item 2 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	H	M-M-H	I: – important during water and air ingress events KL: –
Fuel	cracking of the inner PyC layer (Item 3 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	H	L/M	I: – KL: –
Fuel	pressure loading of the inner PyC layer by carbon monoxide (Item 5 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	H	H-H-L	I: – KL: –
Fuel	fission product release through SiC layer failures (Item 6 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	H	M/H	I: – KL: –
Fuel	gas phase diffusion through the SiC layer (Item 7 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	H	M/H	I: – KL: –
Fuel	gas phase diffusion through the fuel element (Item 8 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel element	H	L/H	I: – KL: –
Fuel	chemical form of the metallic fission products transported through the fuel element (Item 9 of 9 Items in 5.1 of NUREG/CR 6844)	fp release from fuel element	H	M	I: – KL: –
Fuel	Condensed-phase diffusion (Item 1 of 4 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	4 times*	M/H	I: – important for normal operation KL: –
Fuel	Gas-phase diffusion (Item 2 of 4 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	15 times*	M/H/L	I: – KL: –
Fuel	Particle layer cracking especially of inner PyC ad Si C layers (Item 3 of 4 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	10 times*	L/M	I: – KL: –
Fuel	pressure or pressure-loading on particle layers primarily of inner PyC (Item 4 of 4 Items in 5.1 of NUREG/CR 6844)	fp release from fuel particles	5 times*	M/H/L	I: – important for pressure retention KL: –

*appeared >3 times in Table 5-1 when considering all conditions and all components of the TRISO-coated particle fuel.

Table 8-2 Reconciliation of Fuel PIRT Phenomena with PBMR NGNP DDNs

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800 NGNP?	Basis
Thermodynamic state of the fission products in the kernel (Item 2 of 9 Items in 5.1 of NUREG/CR 6844)	Yes	No	No	TBD	No	No	—	LD 1096 discusses PBMR fuel qualification from manufacturing through fuel handling through operations to storage. No specific tests on this phenomena. Based on existing German program. Critical issues identified for PBMR conditions. Resulting program is on the integral particles on a statistical basis relative to the German data envelope. Phenomena of interest occurs during rare events involving water and/or air ingress to such an extent and duration that the kernels of initially failed particles are attacked by the oxidants. PBMR NGNP design will develop the LBEs during later design phases. The thermodynamic stability of the oxide kernel is not strongly influenced by the presence of additional oxidation. For that reason the importance of this phenomena is low relative to the other important phenomena in such an event.
Cracking of the inner PyC layer (Item 3 of 9 Items in 5.1 of NUREG/CR 6844)	Yes	Partial	Yes NHSS-01-01 NHSS-01-02	—	—	—		DPP intends to manufacture and test to show performance within this envelope. Any particle failures observed during the DPP and during the incremental NGNP DDN NHSS-01-01 and DDN NHSS-01-02 irradiation and heating tests will be examined and information on this Phenomena judged as to importance.
Pressure loading of the inner Pyc layer by carbon monoxide (Item 5 of 9 Items in 5.1 of NUREG/CR 6844)	Yes		Yes NHSS-01-02		—	—	No	DPP intends to manufacture and test to show performance within the German envelope. Any particle failures observed during the DPP and during the incremental NGNP DDN NHSS-01-01 and DDN NHSS-01-02 irradiation and heating tests will be examined and information on this phenomena judged as to importance.
Fission product release through SC layer failures (Item 6 of 9 Items in 5.1 of NUREG/CR 6844)	Yes	Partial	Yes NHSS-01-01 NHSS-01-02	—	—			Any particle failures observed during the DPP and during the incremental NGNP DDN NHSS01-02 irradiation and heating tests will be examined and information on this phenomena judged as to importance.
Gas phase diffusion through the SiC layer (Item 7 of 9 Items in 5.1 of NUREG/CR 6844)	Yes	Partial	Yes NHSS-01-01 NHSS-01-02		—	—	No	Release of fission product (e.g., Cs) diffusion at high temperatures observed during the DPP and during the incremental NGNP (DDN NHSS-01-02 and irradiation and heating tests will be examined and information on this phenomena judged as to importance. The PBMR DPP reactivity and water/air ingress, are not in the test conditions. Whether these events are within the licensing basis as either DBEs or BDBEs will be determined in CD and later designed phases. If within the licensing basis the importance of this phenomena in meeting the requirements will be judged as to the need for testing.
Gas phase diffusion through the fuel element (Item 8 of 9 Items in 5.1 of NUREG/CR 6844)		Partial	Yes NHSS-01-01 NHSS-01-02		—	—	No	The PBMR DPP and NGNP testing is fro DLOFC conditions; the other LEEs identified by the panel, such as reactivity and water/air ingress, are not in the test conditions. Whether these events are within the licensing basis as either DBEs or BDBEs will be determined in later design phases. If within the licensing basis the importance of this phenomena in meeting the requirements will be judged as to the need for testing.

Table 8-2 Reconciliation of Fuel PIRT Phenomena with PBMR NGNP DDNs (cont)

Phenomena	Phenomena applicable to PBMR NGNP?	Phenomena and design need covered by DPP?	Phenomena covered by NGNP DDN?	Phenomena occurs during NO/AOOs, DBEs, and/or BDBEs?	Technology development needed to meet requirements? (Agree with I/KL?)	New or Modified NGNP DDN needed?	NGNP DDN Applicable to <800 NGNP?	Basis
Chemical form of the metallic fission products transported through the fuel element (Item 9 of 9 Items in 5.1 of NUREG/CR 6844)	Yes	No	No	Yes	No	No	—	The matrix material is not a major retention barrier for most metallics nor for long-lived radionuclides. For Sr, the matrix material will provide some retention, however the Sr source term from the kernel is relatively small (e.g., relative to Kr) and there are many other retention factors in the HPB and RB for Sr. For these reasons this phenomena is not judged to be of high importance.
Condensed-phase diffusion (Item 1 of 4 Items in 5.1 of NUREG/CR 6844)	Yes	Partial	Yes NHSS-01-01 NHSS-01-02 NHSS-01-03	—	—	—	No	Release of fission product (e.g., Cs) diffusion at high temperatures observed during the DPP And during the incremental NGNP DDN NHSS-01-01, DDN NHSS-01-02 and DDN NHSS-01-03 Irradiation and heating tests will be examined and information on this phenomena judged as to Importance. The PBMR DDP and NGNP testing is for DLOFC conditions; the other LBEs identified by the panel, such as reactivity and water/air ingress, are not in the test conditions. Whether these events are within the licensing basis as either DBEs or BDBEs will be determined in CD and later Design phases. If within the licensing basis the importance of this phenomena in meeting the Requirements will be judged as to the need for testing.
Gas-phase diffusion (Item 2 of 4 Items in 5.1 of NUREG/CR 6844)	Yes	Partial	Yes NHSS-01-01 NHSS-01-02 NHSS-01-03	—	—	—	No	Release of fission product (e.g. Cs) diffusion at high temperatures observed during the DPP And during the incremental NGNP DDN NHSS-01-01, DDN NHSS-01-02 and DDN NHSS-01-03 Irradiation and heating tests will be examined and information on this phenomena judged as to Importance. The PBMR DDP and NGNP testing is for DLOFC conditions; the other LBEs identified by the panel, such as reactivity and water/air ingress, are not in the test conditions. Whether these events are within the licensing basis as either DBEs or BDBEs will be determined in CD and later Design phases. If within the licensing basis the importance of this phenomena in meeting the Requirements will be judged as to the need for testing.
Particle layer cracking especially of inner PyC ad Si C layers (Item 3 of 4 Items in 5.1 of NUREG/CR 6844).	Yes	Partial	Yes NHSS-01-01 NHSS-01-02	—	—	—	No	This phenomena was not observed in the German data base for quality fuel within their spec. DPP intends to manufacture and test to show performance within this envelope. Any particle failures observed during the DPP and during the incremental NGNP DDN NHSS-01-01 and DDN NHSS-01-02 irradiation and heating tests will be examined and information on this phenomena judged as to importance
Pressure or pressure-loading on particle layers primarily of inner PvC (Item 4 of 4 Items in 5.1 of NUREG/CR 6844).	Yes	Partial	Yes NHSS-01-01 NHSS-01-02	—	—	—	No	DPP intends to manufacture and test to show performance within the German envelope. Any particle failures observed during the DPP and during the incremental NGNP DDNs NHSS-01-01 and DDN NHSS-01-02 irradiation and heating tests will be examined and information on this phenomena judged as to importance

9 SUMMARY OF DDN-PIRT RECONCILIATON PROCESS

The results of the PBMR NGNP DDN - PIRT reconciliation process are summarized below.

Table 9-1 Summary of PBMR NGNP DDN and PIRT Reconciliation

PIRT Reconciliation Summary								
PIRT Topic	Proceed with NGNP DDNs	PIRTs do not impact NGNP DDNs				TBD in later design phase	Add new or revised NGNP DDNs	Total Phenomena
		PIRT phenomena applicable to PBMR NGNP design? NO	Phenomena & design need covered by DPP? YES	Phenomena occurs during NO, DBEs, &/or BDBEs? NO	Tech development needed to meet reqmts? NO			
ACTF	1	2	6	0	5	6	0	20
FPT	0	3	23	0	0	3	0	29
HTMAT	3	5	8	0	0	1	0	17
GRAPH	5	2	5	0	3	0	2	17
PHHP	0	3	0	0	2	2	0	7
Fuel	9	0	0	0	2	0	0	11
Totals	**18**	**15**	**42**	**0**	**12**	**12**	**2**	**101**

As discussed in each of the sections and summarized in the table, the results are highly dependent on the topic:

- For the accident and thermal fluid (ACTF) and the process heat and hydrogen production (PHHP) that are especially design- and application-dependent topics, the PIRTs were spread over the range of not applicable to not judged to be needed to meet requirements. However, it is recognized that further review is necessary at later design phases.
- For the fission product transport (FPT) and high temperature materials (HTMAT) topics, the reconciliation process found substantial agreement with the importance and knowledge level of the applicable NRC PIRT phenomena and concluded that they are being addressed by the DPP program.
- For the fuel topic, the reconciliation process found substantial agreement with the PIRT phenomena and concluded that they are being addressed by the PBMR NGNP DDNs that supplement the existing PBMR fuel development, qualification, and testing program.
- For graphite (GRAPH) there was general agreement with the importance and knowledge level of many of the applicable NRC PIRT phenomena and concluded that they are being addressed by the DPP program. Further the PIRT reconciliation identified two new DDNs that are required for the PBMR NGNP:
    - Irradiation-induced creep (irradiation-induced dimensional change under stress)
    - Irradiation-induced change in the coefficient of thermal expansion (CTE), including the effects of creep strain

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Appendix A: Westinghouse TEAM PARTICIPANTS in the NRC PIRT Reviews

Peter Robinson	PBMR PIRT and V&V Manager	ACTF/FPT
Mark Mitchell	PBMR Reactor and Graphite Senior Specialist	GRAPH/HTMAT
Chuck Kling	Westinghouse Accident Consequence Specialist	ACTF
Scott Penfield	TI Systems Engg and Heat Exchanger Specialist	GRAPH/HTMAT/PHHP

APPENDIX B: DDN-PIRT WORKSHOP PARTICIPANTS

Accident and Thermal Fluid PIRTs

Michael Correia	PBMR (Pty) Ltd.	Process Heat Delivery Manager
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Walter Schmitz	PBMR (Pty) Ltd.	Graphite Oxidation Analyst
Gerhard Strydom	PBMR (Pty) Ltd.	Neutronic/Thermal Fluid Chief Analyst

Process Heat and Hydrogen Production PIRTs

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Fuel PIRTs

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