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

Volume 2: Accident and Thermal Fluids Analysis PIRTs

OAK RIDGE NATIONAL LABORATORY

U.S. Nuclear Regulatory Commission
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Volume 2: Accident and Thermal Fluids Analysis PIRTs

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ABSTRACT

An accident, thermal fluids, and reactor physics phenomena identification and ranking process was conducted by a panel of experts on the next generation nuclear plant (NGNP) design (consideration given to both pebble-bed and prismatic gas-cooled reactor configurations). Safety-relevant phenomena, importance, and knowledge base were assessed for the following event classes:

1. normal operation (including some reactor physics aspects),
2. general loss of forced circulation (G-LOFC),
3. pressurized loss-of-forced circulation (P-LOFC),
4. depressurized loss-of-forced circulation (D-LOFC),
5. air ingress (following D-LOFC),
6. reactivity transients—including anticipated transients without scram (ATWS),
7. processes coupled via intermediate heat exchanger (IHX) (IHX failure with molten salt), and
8. steam/water ingress.

The panel's judgment of the importance ranking of a given phenomenon (or process) was based on the effect it had on one or more figures of merit or evaluation criteria. These included public and worker dose, fuel failure, and primary (and other safety) system integrity. The major phenomena of concern that were identified and categorized as high importance combined with medium to low knowledge follow:

- core coolant bypass flows (normal operation),
- power/flux profiles (normal operation),
- outlet plenum flows (normal operation),
- reactivity-temperature feedback coefficients for high-plutonium-content cores (normal operation and accidents),
- fission product release related to the transport of silver (normal operation),
- emissivity aspects for the vessel and reactor cavity cooling system (G-LOFC),
- reactor vessel cavity air circulation and heat transfer (G-LOFC), and
- convection/radiation heating of upper vessel area (P-LOFC).

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FOREWORD

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

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

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

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

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

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

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

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

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ACRONYMS

ANL	Argonne National Laboratory
AOO	anticipated operational occurrence
ATWS	anticipated transient without scram
AVR	Atomgeneinschaft Versuchs Reaktor
B_2O_3	boron oxide
B_4C	boron carbide
BDBA	beyond design basis accident
BOP	balance of plant
D-LOFC	depressurized loss-of-forced circulation
DBA	design basis accident
DNB	departure from nucleate boiling
DOE	Department of Energy
FOM	figure of merit
FSV	Fort St. Vrain reactor
G-LOFC	general loss-of-forced circulation
GT-MHR	gas-turbine modular helium reactor
HTGR	high-temperature gas-cooled reactor
HTR-PM	high-temperature reactor–power module
IAEA	International Atomic Energy Agency
IHX	intermediate heat exchanger
INL	Idaho National Laboratory
KL	knowledge level
LCO	limiting condition for operation
LEU	low-enriched uranium
LOFC	loss-of-forced circulation
LWR	light-water reactor
MHTGR	modular high-temperature gas-cooled reactor
MS	molten salt
NGNP	next generation nuclear plant
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
P-LOFC	pressurized loss-of-forced circulation
PBR	pebble bed reactor
PIRT	phenomena identification and ranking table
PMR	prismatic-core modular reactor
PSA	probabilistic safety assessment
QA	quality assurance
QC	quality control
RCCS	reactor cavity cooling system

RPV	reactor pressure vessel
SC-MHTGR	steam-cycle MHTGR
SCS	shutdown cooling system
SG	steam generator
SNL	Sandia National Laboratory
SSC	structures, systems, and components
T/F	thermal fluid
THTR	thorium high-temperature reactor
UCO	uranium oxycarbide
UO_2	uranium dioxide
VHTR	very high temperature gas-cooled reactor

1. INTRODUCTION

This section of the Next Generation Nuclear Plant (NGNP) Phenomena Identification and Ranking Table (PIRT) discusses the application of the Nuclear Regulatory Commission (NRC) PIRT process to the issue of Accident and Thermal Fluid Analysis (with neutronics), considering both routine (normal operation) and postulated accident conditions for the NGNP. The NGNP is assumed to be a modular high-temperature gas-cooled reactor (HTGR), either a gas-turbine modular helium reactor (GT-MHR) version (a prismatic-core modular reactor–PMR) or a pebble bed modular reactor (PBMR) version (a pebble bed reactor–PBR) design, with either a direct- or indirect-cycle gas turbine (Brayton cycle) system for electric power production, and an indirect-cycle component for hydrogen production. This process heat application will consume a small (~10%) part of the total thermal power output. The linkage to the chemical process utilizes an intermediate heat exchanger (IHX) and a long high-temperature (high-pressure) heat transport loop. The heat transfer medium for this loop has not yet been selected. The safety implications of coupling to process heat systems have not received much attention; the chemical process, however, will eventually become a factor in accident scenario development and fission product transport evaluations. NGNP design options with a high-pressure steam generator (Rankine cycle) in the primary loop are not considered in this PIRT.

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

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

The NGNP will use either a pebble-type fuel element or a fuel element of prismatic geometry. United States designs have historically favored the prismatic core, while the pebble-bed modular reactor (PBMR) of South Africa and the high-temperature reactor–power module (HTR-PM) of China have adopted the German pebble fuel element. The materials are somewhat different in these two fuel element types. The PBMR uses fuel particles with uranium dioxide (UO_2) kernels; however, a uranium oxycarbide (UCO) fuel form is being considered for the prismatic fuel element design because of the potential for improved burn-up capability.[1] Also, the prismatic-core modular reactor (PMR) utilizes nuclear-grade graphite block fuel elements, whereas the graphitized coatings on the pebble bed reactor (PBR) fuel pebbles cannot be processed at the high temperatures needed to produce nuclear-grade graphite, so they would have a tendency to have higher oxidation rates in air ingress accidents than would prismatic fuel elements.[2]

Implicit in the accident PIRT panel's discussions was the role played by high-temperature materials, including graphite, fission product release and transport, and the dual role that the NGNP reactor would play in incorporating a high-temperature hydrogen process heat application, in addition to electrical power production. Hence the accident PIRT panel maintained a high level of coordination with the other

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[1] D. Petti, R. Hobbins, J. Kendall, and J. Saurwein, *Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program*, INEL/EXT-05-00465, Rev. 12, Idaho National Laboratory, August 2005.

[2] R. Mooremann, H. K. Hinssen, and K. Kuhn, "Oxidation Behaviour of an HTR Fuel Element Matrix Graphite in Oxygen Compared to a Standard Nuclear Graphite," *Nuclear Engineering and Design*, **227**, 281–284 (2004).

PIRT groups. Although the thermal-fluids aspects of the accident scenarios were of primary concern, the neutronic behavior also played a part in some events and was considered as needed.

The role for the accident PIRT is seen as a two-part task. First, normal operation is the starting point for the accident analyses. During normal operation, some fission products will be released by the fuel due either to imperfections in particle coatings or to the presence of tramp uranium outside the particle coatings. Released fission products are then distributed throughout the reactor primary circuit. The major concern from normal operation is the contamination and dose associated with maintenance and operational issues. With an accident transient, there could be a possible redistribution of fission products within the reactor primary circuit in addition to a possible breach of the primary system that leads to releases. It is ultimately the dose to humans that then becomes of primary interest and is the primary figure of merit (FOM) for the PIRT.

This report segment first briefly reviews HTGR accident scenarios and then proceeds with the description of the step-by-step NRC PIRT process adopted for accidents and thermal fluid analysis.

2. MODULAR HTGR ACCIDENT SCENARIO BACKGROUND

Typically the grouping of HTGR accident scenarios is based on either the nature of the challenge to fundamental safety functions or on dominant phenomena occurring during the course of the event.

A typical grouping based on challenges to fundamental safety functions results in the following:

- challenge to heat removal,
- challenge to reactivity control,
- challenge to confinement of radioactivity, and
- challenge to control of chemical attacks.

The PIRT panel's initial listing of phenomena of interest was organized according to these safety function categories.

The initiating event and ensuing event sequence for a postulated accident often challenges more than one safety function, as noted in the following two examples:

1. Primary system pressure boundary breaks (challenge to confinement of radioactivity). The common feature of these events is that they result in a release of radioactivity from the primary system that may result in a dose to workers and/or the public. These include all leaks greater than normal operational leakage rates. Breaks with an accompanying loss of forced core cooling result in challenges to heat removal as well. Pressure boundary breaks may also lead to air ingress, which in turn challenges the control of chemical attack.
2. Primary system breaks in the interface with cooling water systems (e.g., heat exchanger tube breaks may result in water ingress). Depending on the design and primary-to-water system pressure differences, there may be radioactivity releases resulting in worker and/or public dose. Such events therefore challenge reactivity control if steam in the core introduces positive reactivity, and control of chemical attack, as well as confinement of radioactivity.

There is a wide variety of event sequences that may be postulated and accident states that could be encountered. The main objective here is to ensure that the appropriate event phenomena are covered, as well as to avoid duplication if possible. Events are therefore grouped according to dominant phenomena in the event sequence. Examples are

- primary system breaks;
- loss of primary system heat sink;
- air ingress events;
- steam/water ingress events;
- reactivity transients, including anticipated transients without scram (ATWS);
- long-term pressurized loss-of-forced circulation (P-LOFC) events;
- long-term depressurized loss-of-forced circulation (D-LOFC) events; and
- turbine trip and station blackout.

Both the normal operation and accident characteristics of modular HTGRs are very different from those of most standard power reactor designs, and because of the differences, their passive safety features and the response of the plant systems and operators need to be considered appropriately. Because of the constraints put on the modular HTGR design (by the designers), and its passive safety features, traditional design-basis accident (DBA) events such as loss of flow and coolant do not result in fission product releases, so the applicability of probabilistic safety assessment (PSA) and risk-informed decision making differs from those for light-water reactors (LWRs). As a result, ultimate safety is more likely to be determined by low-probability initiating events. Safety margins are enhanced due to the passive features that accomplish some of the safety functions. Furthermore, the plant response to "serious" events can typically be modeled with greater assurance [e.g., no departures from nucleate boiling (DNB), no core melting, no need for core catchers, etc.].

The NRC preapplication review of the modular high-temperature gas-cooled reactor (MHTGR) in the 1980s (NUREG-1338) and the extensive supporting documentation provided by DOE in the *Preliminary Safety Information Document* (*PSID) for the Standard MHTGR (HTGR-86-024)* give very thorough documentation of a multiyear regulatory review of a 350-MW(t) PMR plant similar to those currently under consideration for the NGNP. A major design difference is the former's use of a steam generator balance-of-plant (BOP), where by far the dominant risk was from steam/water ingress via steam generator tube breaks. The NGNP PMR designs also have higher power ratings, ~600 MW(t). Candidate NGNP PBR reactor designs, with power ratings in the order of ~400 MW(t), are similar to the German Module design of ~200 MW(t), but with an annular (and taller) active core utilizing a solid central reflector. All NGNP candidate designs utilizing steam generators would probably be decoupled from the primary system via an intermediate heat exchanger (IHX). Another major difference is the inclusion of the high-temperature process heat (hydrogen production) system in all proposed NGNP designs.

The current series of PIRT reports does not cover TRISO fuel. That was covered earlier in a previous NRC PIRT report dealing exclusively with TRISO-coated fuel particles (NUREG/CR-6844). In that PIRT, the assumptions were made that the fuel kernels would be uranium dioxide (UO_2) and that the reactor was a PBR; however, the report authors maintained that the approach was more general and less plant-specific since "The information needed to develop more detailed specifications was not available to the panel." In that case, detailed PIRTs were prepared for fuel manufacturing, normal operation in a general sense, and four accident scenarios. The four accidents selected for the fuel PIRT emphasized those scenarios that the panel thought to present the greatest challenge to fuel integrity and included

- reactivity insertion based on the effect of rod ejection in the PMR, given excess reactivity representative of that in a PMR, but applied to conditions in the PBR;
- power pulse of several seconds duration;
- depressurized core heat-up followed by water ingress; and
- depressurized core heat-up followed by air ingress.

By contrast, the scenarios covered in this PIRT include variations of loss-of-forced circulation (LOFC) accidents, air and steam/water ingress, reactivity events, and considerations dealing with a coupled hydrogen (process heat) production plant. Normal operation is also considered.

Major design and technology areas that either influence safety or have relevance to safety in the context of satisfying regulatory requirements would normally cover the following:

- Design, including design standards and the selection and qualification of materials, especially those materials used or relied upon in applications for safety-related structures, systems and components (SSCs).
- Fabrication, installation, preservice inspection and testing, maintenance, and in-service inspection and testing of materials and components, especially for "a structure, system, or component that is part of the primary success path and which functions or actuates to mitigate a design basis accident or transient that either assumes the failure of or presents a challenge to the integrity of a fission product barrier."
- Operation, including the safety functions of the operator, the maintenance of the plant within technical specification limits based on reliable and adequately calibrated instrumentation, and the potential risk from insider threat in an otherwise "inherently safe" reactor. Particular attention should be paid to instrumentation that is "used to detect, and indicate in the control

room, a significant abnormal degradation of the reactor coolant pressure boundary," or that is "used to detect and quantify a process variable, design feature, or operating restriction that is an initial condition of a design basis accident, or a transient analysis that either assumes the failure of or presents a challenge to the integrity of a fission product barrier," or that is "used for post-accident monitoring."

- Accident conditions, as affected by design selections, testing, and inspections of key materials and components to assure continued functionality and operability, operator or maintenance errors, and potential insider threat.

This PIRT does not cover all of the above functions, however, since it is focused more on phenomena related to the operations and accident sequence areas. During the PIRT process, panel members consulted historical data from operational experiences at Fort St. Vrain (NUREG/CR-6839) and the MHTGR Preliminary Safety Evaluation Report (NUREG-1338), which were useful in the selection, evaluation and ranking of phenomena for NGNP design, operations, and maintenance aspects of importance to safety. Two examples are as follows:

- ***Design and maintenance considerations:*** At Fort St. Vrain, an incident involving failure of control rods to scram was caused by a design deficiency in the helium purification system purge flow to the control rod drive mechanisms, which used carbon steel for the purge lines. Rust formation (resulting from persistent water ingress from helium circulator bearing water system upsets) and the resulting movement of moisture and rust particles to the control rod drive winches and cables caused the problems. Also at Fort St. Vrain, failures were experienced in the actuation of the reserve shutdown system where a high boron oxide (B_2O_3) content in the boron carbide (B_4C) balls allowed for leaching of boric acid during water ingress events, where the acid formed crystals that stuck the balls together, preventing some of them from falling into the reserve shutdown system holes in the core blocks when the reserve shutdown system was activated (in a test). At Fort St. Vrain, the effects of water ingress events (especially during startups following extended outages) were made more severe by the lack of adequate moisture monitors and inadequate means for removing large quantities of water. These resulted in a major control rod drive refurbishment program.

  In the design of the earlier PMR concept for the steam cycle-MHTGR (SC-MHTGR), the inner reflector control/shutdown rods were not required to be scrammed automatically to achieve hot shutdown, which could be achieved by scram of only the outer reflector control rods. An additional reason for SC-MHTGR's no scram of the inner control/shutdown rods was due to concern about a possible follow-on core heat-up event causing damage to the inner reflector rods that were being designed to be clad in Alloy 800, which could warp and become stuck in the reflector during a high-temperature transient. Thus, in the SC-MHTGR, the operator would have the safety function of subsequently activating the reserve shutdown system in the inner reflector to achieve cold shutdown. An alternative high-temperature clad material was later proposed for control rods based on qualifying carbon-carbon composites to be used in place of Alloy 800.

- ***Depressurized core heatup****: Design, inspection, and testing considerations*—during a depressurized core heat-up, two major parameters affect the peak temperature of the fuel: (1) the decay heat load in the core and (2) the effective core thermal conductivity, which depends on the graphite's temperature and neutron irradiation. Other factors involved to a lesser degree are the emissivity of the metallic surfaces of the core barrel, reactor vessel and the passive reactor cavity cooling system (RCCS), and the efficiency of the RCCS in removing heat from the reactor cavity. The effective core thermal conductivity for the PMR varies somewhat as a function of graphite selection, and its demonstrated thermal-conductivity characteristics are based on experimental data because no predictive tool exists to predict the variation based solely on unirradiated properties and calculated neutron exposure. Whether it is necessary to have removable graphite coupons in the radial reflector to verify actual irradiation-dependent thermal-conductivity variations may depend on design choices, available margin, and whether worst case or best-estimate assumptions are made in the safety analyses.

In addition to the four accident scenarios addressed in the TRISO-coated particle fuel PIRT (NUREG/CR-6844), several other scenarios were considered based on past plant operating experience.

- Restart and operation of the reactor following an undetected major water-ingress during shutdown.
- Restart and operation of the PMR following refueling with an incorrect positioning of fresh fuel such as reverse loading, which should be observable in the expected critical position of control rods, and impact on peak fuel temperature during operation.
- Conduction cooldown in a D-LOFC accident with degraded emissivity on the core barrel and inner and outer sides of the reactor vessel, assuming no in-service inspection or testing regimen.
- Impact of control rod misalignment on power peaking and initiation of azimuthal or axial xenon oscillations with subsequent power peaking, and the subsequent impacts on peak fuel temperatures during operation.

The development and ranking of phenomena are dependent somewhat on the plant design and operational requirements. Example requirements and design features that could affect rankings include:

1. classification (such as safety grade) and reliability of systems and components (both passive and otherwise) as well as operator actions;
2. quality specifications (and testing) of the reliability of the billion-or-so TRISO fuel particles' protective coating barriers; and
3. characteristics (performance specifications) of the "non-leak-tight" confinement building that could allow a release of the primary system coolant directly to the environment during a depressurization accident.

Historically, some of these modular HTGR design features were also key issues for the U.S. DOE MHTGR, Peach Bottom Unit 1, and Fort St. Vrain reactors.

In view of some of the considerable differences in design philosophy and passive safety features of the modular HTGRs compared to those of the more conventional reactors, a study identifying and characterizing the phenomena involved in the important postulated accident sequences is appropriate. The event selection process was based on the PIRT panel's study of these features. Some members had been involved in various aspects of HTGR programs, with direct involvement in these studies. For others, it involved a familiarization with the historical events in previous HTGR operation and licensing exercises. All contributed to the selection process defining the important event sequences.

3. ACCIDENT AND THERMAL FLUIDS ANALYSIS PIRT PROCESS

The NRC has adopted a nine-step process for implementing a standard PIRT.

3.1 Step 1—Issues

In anticipation of future licensing applications for modular HTGRs as the NGNP, the NRC seeks to identify and recommend needed work on major design and technology areas for NGNP candidates that either influence safety or have relevance to analyses satisfying applicable regulatory requirements. This is a multi-step process, one of which is to identify phenomena that are characteristic of the NGNP designs. Certain phenomena come into play in influencing the response of the plant to initiating events and the postulated event sequences that follow. The issue addressed by this PIRT is the importance of these phenomena in the prediction of the eventual outcome of the sequence, and how well these phenomena can be characterized by existing data and analytical techniques.

3.2 Step 2—PIRT Objectives

For the case of this PIRT, the objectives are to

1. identify safety-relevant NGNP phenomena;
2. establish evaluation criteria;
3. rank phenomena applicable to plant operation and postulated accident scenarios, accounting for interaction with the other four topical PIRTs;
4. identify and rank the knowledge base associated with safety-relevant phenomena; and
5. provide a reference database for subsequent NRC reviews and evaluations.

3.3 Step 3—Hardware and Scenario

3.3.1 Hardware

The NGNP is currently in the conceptual design stage, and the Department of Energy's (DOE's) selection of the design of the reactor and process heat sectors is in progress. Reactor candidates include the direct-cycle prismatic-block gas turbine HTGR [such as the GT-MHR design by DOE/NNSA and Rosatom (Russia)], and an indirect-cycle prismatic core version by AREVA, and a pebble bed reactor version similar to the South African PBMR.

Prismatic fuel elements consist of fuel compacts inserted into holes drilled in graphite hexagonal prism blocks ~300 mm across the flats and 800-mm long (very similar to the Fort St. Vrain reactor fuel elements). Pebble fuel elements, developed in Germany in the 1960s, are 6-cm-diam spheres containing a central region of TRISO fuel particles in a graphitized matrix material, surrounded by a 5-mm protective outer coating of graphitic material (only). The pebble bed employs continuous refueling, with pebbles recycled approximately six to ten times, and depending on measured burnup.

Several confinement and containment options have been investigated in the past, with the vented confinement option generally selected as a baseline (with or without filters). Any early fission product release is usually assumed to be very small, requiring no holdup, while any later releases are assumed to be modest with little or no pressure differential driving force.

3.3.2 Accident scenarios

While classification of plant events is not within the scope of this PIRT, some judgments of the importance of phenomena were affected by risks posed by the accidents being considered, and the potential frequency of occurrence of those events. A typical set of event classifications are given below.

- ***Anticipated Operational Occurrence (AOO):*** An AOO is an expected event that may occur one or more times during the life of a plant. AOOs typically have a mean frequency of occurrence of 10^{-2} per plant year or higher.
- ***Design Basis Accident (DBA):*** A DBA is an infrequent event not expected within the lifetime of one plant, but perhaps occurring once during the collective lifetimes of a large number of plants. Plants are designed to mitigate the effects of a DBA using only equipment classified as safety grade. DBAs typically have a mean frequency between 10^{-2} and 10^{-4} per plant year.
- ***Beyond Design Basis Accident (BDBA):*** A BDBA is a rare event that is not expected to occur even within the collective lifetimes of a very large number of similar plants. However, the plant is designed to mitigate their consequences, taking credit for available safety-related equipment, operator actions, any existing or ad hoc non-safety-related equipment, and accounting for long time periods potentially available for corrective actions. BDBAs are usually associated with events having a mean frequency between 10^{-4} and 5×10^{-7} per plant year. Typically, the lower frequency limit is considered a cut-off frequency below which consideration and analyses are not required.

The accident scenarios selected for consideration in this PIRT were

1. the P-LOFC accident;
2. the D-LOFC accidents;
3. the D-LOFC followed by air ingress;
4. reactivity-induced transients, including ATWS events;
5. steam-water ingress events; and
6. events related to coupling the reactor to the process heat plant.

"Normal Operation" was also considered because it can affect the plant's vulnerability in subsequent postulated events.

3.3.2.1 The P-LOFC accident

The reference case P-LOFC assumes a flow coast-down and scram with the passive RCCS operational for the duration of the event. The natural circulation of the pressurized helium coolant within the core tends to make core temperatures more uniform, lowering the peak temperatures, than would otherwise be the case for a depressurized core where the buoyancy forces would not establish significant recirculation flows. The chimney effect in P-LOFC events makes the core (and vessel) temperatures higher near the top. Maximum vessel head temperatures are typically limited by judiciously placed insulation. The use of Alloy 800H (or equivalent high-temperature steel) for the core barrel allows for extra margin in that area. In P-LOFCs, the peak fuel temperature is not a concern because it falls well within nominal limits for TRISO fuel; the major concern is more likely to be the maximum vessel temperature and the shift in peak heat load to locations near the top of the reactor cavity.

3.3.2.2 The D-LOFC accident

The D-LOFC reference case assumes a rapid depressurization of the primary system helium along with a flow coast-down and scram, with the passive RCCS operational. It also assumes that the depressurized coolant is helium (no air ingress). This event is known as a “conduction heat-up” (or “cool-down”) accident because the core effective conductivity is the dominant mechanism for the transfer of afterheat from the fuel to the reactor vessel. Typically the maximum expected fuel temperature would peak slightly below the limiting value for the fuel (by design), and the peak would typically occur ~2 days into the accident. For these cases, the peak fuel (and vessel) temperatures occur near the core center (beltline) rather than near the top as in the P-LOFC case because the convection effects for atmospheric pressure helium are minimal.

There are several parameter variations of interest for this accident, which is generally considered to be the defining accident for determining accident peak fuel temperatures. These variations are: effective core graphite conductivity (which is a function of irradiation history, temperature, orientation, and annealing); afterheat power vs time after shutdown; and, to a much lesser extent, the power peaking factor distribution in the core after shutdown.

3.3.2.3 Air ingress following a D-LOFC accident

The more extreme case of the D-LOFC accident involves a significant and continued inflow of air to the core, which is only possible with a major reactor building and reactor system fault that establishes a convective air path between the reactor vessel and the environment. The significant areas of concern for such events are

1. graphite structure oxidation to the extent that the integrity of the core and its support is compromised;
2. oxidation of the graphite fuel elements that leads to exposure of the TRISO particles to oxygen, with possible subsequent fission product release; and
3. release of fission products previously absorbed in the graphite structures.

The most significant features of the event are configurations and conditions that would support sustained (and large) flows of ingress gas and the long-term availability of oxygen in the gas. The characterization of air ingress accidents is made particularly difficult by the extremely large set of possible scenarios.

3.3.2.4 Reactivity events, including ATWS accidents

The most common postulated reactivity events assume a LOFC (either P- or D-) accompanied by a long term failure to scram. These are extremely low-probability events because for the modular HTGRs, the core heatup transients are unaffected by a scram (or not) until recriticality finally occurs upon the decay of the xenon poisoning, which is typically nearly 2 days from the initiation of the accident. One must assume long-term failure of operation of two independent (safety-grade) scram systems, plus a failure of the nonsafety control rods.

Other potential reactivity events include the compaction of the pebble bed core during a prolonged earthquake (which can cause a significant reactivity increase), and the potential for a positive reactivity insertion from a steam-water ingress event or a “cold-slug” induced by a sudden decrease in core inlet coolant temperature.

3.3.2.5 Other events: process heat plant-related accidents

The consideration of other events was influenced by difficulties in postulating any accidents relating to pertinent plant design features because those features are not yet defined for NGNP. As an example consideration for coupling to a process heat (hydrogen) plant, a scenario was arbitrarily devised for a postulated IHX failure involving a molten-salt heat transport loop coupling the reactor and the hydrogen plant.

Note that spent fuel storage is also a potential area for accidents that could result in fission product releases. As the NGNP design matures, this area should be considered if it has vulnerable subsystems for controlling contamination and releases.

3.4 Step 4—Evaluation Criteria

Each factor, characteristic, process, or phenomenon is assessed relative to its importance to fission product release from the fuel, or in a more licensing-specific term, its impact on source term. Specific evaluation criteria established by the panel at the initial PIRT meeting were

1. top level: dose at the site boundary or radioactive release from the confinement structure;
2. second level: worker dose;
3. third level: fuel failure fraction during events (accidents); and
4. lower level criteria:
    - Fraction of fuel above a critical fuel temperature for a critical time period (as designated by an applicable fuel performance model). This criterion is considered as a precursor to the level 3 fuel failure.
    - Reactor pressure vessel (RPV) and vessel supports, core barrel, and other crucial in-vessel metal components service conditions (time-at-temperature, pressure, etc.).
    - Reactor cavity concrete time-at-temperature.
    - Circulating (primary system) coolant activity (including dust).

3.5 Step 5—Knowledge Base

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

- recent design information available for both reactor types;
- relevant operational experience from Fort St. Vrain, the Thorium High-Temperature Reactor (THTR-300) in North Rhine Westphalia, Germany, and the Atomgeneinschaft Versuchs Reaktor (AVR) in Jülich, Germany;
- the findings from the NRC preliminary safety evaluation of the steam-cycle MHTGR (NUREG-1338); and
- a database of extensive and comprehensive international reports available for downloading from the International Atomic Energy Agency (IAEA) website (www.iaea.org).

An extensive set of references may also be found in the “Bibliography” section.

3.6 Step 6—Identify Phenomena

As in the TRISO-coated particle fuel PIRT effort, the panel members first identified and then refined the phenomena lists. The term “phenomena” was expanded to include the terminologies “factor, process, and characteristics” as well.

Accident phenomena are typically classified by their challenges to the safety functions noted previously. The challenges to the designer-operator and the regulator are to ensure and confirm that the defense-in-depth provided will reduce the probability and risks of serious accidents to acceptable levels. The PIRT activity is part of a larger effort that will lead to a comparison of the requirements with the existing (or developing) capabilities determining the analytical tools and data needed for confirmatory analyses. The applicability of confirmation activities, such as “proving code capability” via benchmarking (both code-to-code and code-to-experiment), is subject to varied interpretations because severe accidents cannot be simulated experimentally in their entirety.

Noting the major licensing issues listed previously, it is clear that both technological and regulatory perspectives will be needed to provide essential "importance rankings" to the elements involved.

Phenomena identification involves the listing of potentially significant situations and sequences, characterizing them with respect to their effect on core cooling, reactivity control, and radionuclide confinement, for the three classifications of events noted previously. The following are examples:

1. normal operation—peak fuel temperatures, fission product plateout (e.g., Ag-110*m* maintenance dose), loss of shutdown cooling system (SCS);
2. design basis accidents (DBAs)—long-term P- and D-LOFC accidents. control rod withdrawal accident, water and air ingress,… where single-failure criterion applies;
3. beyond DBA—multiple failures of safety-grade and/or passive systems, failure to maintain subcriticality, inadequate defense for a major earthquake, inability to limit air ingress, loss of all core heat sinks, …

In addition to equipment successes and failures, operator actions (both positive and negative) are considered, accounting for the typical very long accident response times. Examples (negative) are maintaining flow on loss of heat sink or restarting flow during either ATWS or enhanced air ingress situations. A complete listing of the phenomena identified by the panel is compiled in Table 1.

Table 1. Accident and T/F PIRT chart

- **Rearrangement into phenomena categories roughly according to their basic safety functions:**
  - core heat removal,
  - reactivity control, and
  - radioactivity confinement and control of chemical attack.

Note:

1. Items that were discussed at the PIRT-1 meeting but NOT recorded in the original chart are denoted by “**@**”
2. Items that were added for consideration by the panel at the PIRT-2 meeting are denoted by “**&**”

	P-LOFC	D-LOFC	Air In	ATWS	H_2O In	H_2 Upset	NormOp
Factors affecting core cooling and coolant distribution:							
* Core geometry and effects							
– core coolant (channel) bypass flows	x						x
– flow distribution (and changes due to):	x						x
& – temperature gradients							x
& – graphite irradiation							x
& – core barrel geometry							x
+ prismatic core:							
– fuel block warping							x
@ *– fuel block stability*							*x*
+ pebble core:							
– compaction (packing fraction)				x			x
@ *– bridging*							*x*
@ *– wall interface effects*							*x*
* Core coolant flow and properties:							
– friction/viscosity effects	x		x		x		x
– heat transfer correlations	x		x		x		x
– coolant properties							
– helium	x			x			x
– mixed gases			x		x	x	
– mixed convection							
– control system							x
– circulator stall/surge							x
* Inlet plenum							
– inlet flow distribution							x
– thermal fluid mixing from separate loops							x
@ *– stratification and plumes*	*x*						
& – radiant heat to vessel head	x						
* Outlet plenum							
– flow distribution							x

Table 1 (continued)

	P-LOFC	D-LOFC	Air In	ATWS	H_2O In	H_2 Upset	NormOp
– mixing of core outlet (channel) flows							x
– steady-state and fluctuations							x
& – support/component thermal stresses							x
& * Pebble flow channeling: viscosity vs temperature							x
* Core properties:							
– effective core thermal conductivity	x	x	x	x	x		x
@ – *fuel element annealing (prismatic)*		*x*	*x*	*x*	*x*		
– reflector conductivity	x	x	x	x	x		x
@ – *reflector annealing*		*x*	*x*	*x*	*x*		
– fuel and reflector specific heat	x	x	x	x	x		x
– stored (Wigner) energy releases							
* Side reflector—core barrel—vessel heat transfer							
– core barrel emissivity		x	x				x
– heat transfer to inlet coolant							x
& – vessel conductivity	x	x	x	x	x		x
– vessel emissivity (inside and outside)	x	x	x	x	x		x
* Reactor vessel cavity							
– RCCS panel emissivity	x	x	x	x	x		x
– cavity air recirculation flow, heat transfer	x	x	x	x	x		x
– vessel—RCCS effective view factors	x	x	x	x	x		x
– participating media (“gray gas”)	x	x	x	x	x		
** RCCS Performance:							
& – fouling (coolant side)							x
@ – *axial/azimuthal heat load redistribution*	*x*	*x*	*x*				
– failure of 1 of 2 channels	x	x	x				
– failure of both channels—transfer to ground	x	x	x				
– blowdown loads on structures in/out vessel							
– panel damage from missile(s); leakage		x	x				
– misplaced insulation							
– forced—natural circulation transitions	x	x	x				
– single-phase—boiling transitions	x	x	x				
– subcooled boiling							
– liquid/steam phase separation							
– parallel channel interactions	x	x	x				x
& – horizontal panel natural circ flow distribution	x	x	x				x
@ * *Shutdown Cooling System (SCS)*							
@ – *startup flow/temperature transients*	*x*	*x*					*x*
& – maintaining water coolant inventory	x	x					
@ – *water/steam ingress into primary*					*x*		
@ – *thermal shocks*							
& * Intermediate Heat Exchanger (IHX)							

Table 1 (continued)

	P-LOFC	D-LOFC	Air In	ATWS	H_2O In	H_2 Upset	NormOp
@ _– over/under cooling transients_	_x_	_x_				_x_	
@ _– transients involving pri/sec ΔP transients_	_x_	_x_				_x_	
@ _– ruptures leading to coolants—ingress_					_x_	_x_	
@ * _Brayton cycle coolers—ruptures as w/IHX_					_x_		
Factors affecting reactivity, power transients, and power distribution							
* Power/flux profiles, peaks at boundaries	x	x	x	x	x		x
* Excess reactivity				x			x
@ _– burnable poisons_				_x_			_x_
& – FP/actinide buildups				x			x
* delayed neutrons							
* decay heat:							
– vs time	x	x	x	x	x		x
– spatial distribution	x	x	x	x	x		
* Reactivity-temperature coefficient							
– fuel (Doppler), moderator				x			x
– outer/inner reflectors				x			x
* Control rod, scram, reserve shutdown worths				x			x
*Xenon and samarium buildup				x			x
@ *_xenon oscillation and control_							_x_
* Scram and reserve shutdown failures				x			
@ * _Rod ejection prevention (design)_				_x_			
@ * _Coolant flow restarts during ATWS_				_x_			
* water/steam ingress reactivity effects					x		
* water/steam ingress pressure transients					x		
* reactivity: (pebble) core compaction—quake				x			
Control of chemical attack and confinement of radioactivity							
* Dust accumulation in primary (pebble bed) and associated radioactivity							x
* Dust distribution, liftoff, dispersion		x					
* Molecular diffusion following depressurization			x				
* Critical flow at break		x					
* High-temperature steam-graphite reactions					x		
* Radioactivity washoff					x		
& * Ag-110*m* (and other) release and plateout (maint)							x
@ * _Fuel performance modeling:_							_x_
– heatup accidents (time at temperature)	x	x	x	x	x	x	
– with oxidation (air ingress)			x				
– with steam (water ingress)					x		
* Graphite oxidation modeling							
– core support structures			.x		.x		
– fueled core: prismatic blocks, pebbles			.x		x		

Table 1 (continued)

	P-LOFC	D-LOFC	Air In	ATWS	H_2O In	H_2 Upset	NormOp
– reflectors			x		x		
* Confinement building (cavity)							
– cavity leakage rates (performance)			x		x		
– cavity gas composition and temperature			x		x		
– cavity gas stratification/mixing							
– cavity air in-leakage							
– cavity combustible gases							
– cavity structural performance							
– cavity filtering performance							

3.7 Step 7—Importance Ranking

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

Importance ranks and definitions

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

Plant designs include various lines of defense to mitigate the consequences of postulated accident sequences. The panel evaluated the importance of the phenomenon or process to these sequences. Characterizations vary depending on plant design features (such as pebble or prism core, process heat plant type, IHX, and loop design, …), as well as on the sequence assumptions. Coordination of these issue identification and importance rankings with the other PIRT panels was helped in certain cases. A compilation of the rankings for all the scenarios covered is found in Tables 2.1 through 2.7.

3.8. Step 8—Knowledge Level Ranking

Panel members assessed and ranked the current knowledge level for applicable phenomenon in each PIRT table. Compiled (averaged) values for each of the knowledge level assessments are also shown in Tables 2.1 through 2.7. High, medium, and low designations were assigned to reflect knowledge levels and adequacy of data and analytical tools used to characterize the phenomena, using the NRC-supplied definitions shown below.

Knowledge levels and definitions

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

3.9 Step 9—Documentation of the PIRT—Summary

The lists and tables generated at the PIRT panel meetings document the discussions of phenomena identification plus the importance and knowledge level rankings, with accompanying rationales. The resulting charts document both the collective and individual member assessments. In cases where the "collective assessment" or averaged result differed significantly from that of an individual panel member, the "minority view" could be noted in the "rationale" column of the table. Further descriptions of the individual assessments and rationales are in the panel members' individual charts (see Appendix), which were typically generated prior to the discussion by the panel. In some cases the discussions resulted in some members' changing their rankings.

4. PIRT TABLES

4.1 Organization of Tables for the Accident and Thermal Fluids (T/F) PIRT

For the accident evaluations, it was recognized that many of the phenomena involved were important, to varying degrees, in a variety of different postulated accident or event scenarios. To avoid duplication of considerations and importance/knowledge rankings for phenomena applicable to each accident, an accident and T/F PIRT matrix was developed that listed all phenomena of interest, with check marks in columns pertaining to accident cases where each phenomenon was judged to be particularly applicable (see Table 1). This table was used as a guide to create PIRT tables for each individual scenario or accident type considered.

Furthermore, most modular HTGR accidents of primary interest are based on the assumption of a long-term LOFC, so therefore a generalized PIRT table was created that included common LOFC phenomena. This table is meant to be the basic building block for variations of the LOFC accident, such as for the pressurized (P-LOFC) and depressurized (D-LOFC) cases. For example, to evaluate D-LOFC events, one should consider entries in both the general and D-LOFC tables. A possible follow-on for the D-LOFC case would be air ingress after the depressurization; therefore a third table, for air ingress accidents, is added for consideration along with the first two. Other PIRT tables were developed for reactivity events, steam/water ingress accidents, and accidents involving the coupling of the reactor system with high-temperature process heat (hydrogen production) systems. Because plant “normal operation,” including transients and anticipated operational occurrences (AOOs) is crucial, in some cases, for providing initial conditions for postulated accident scenarios, a special PIRT table was developed for normal operations as well. AOOs can be considered as possible precursors for next-level (DBA) events, and a means of characterizing vulnerabilities that could affect the outcomes of DBA events.

A prevailing challenge in the PIRT deliberations was that many major design features of the NGNP system being evaluated were not yet established. For example, the modular HTGR may have either a prismatic or pebble-bed core; the primary system may or may not include a direct-cycle gas turbine with a small IHX for coupling to the process heat plant, or it may have a large IHX for coupling to all BOP systems; and the heat transport loop that couples the IHX to the process heat plant—potentially a half-mile or more long—may use, for example, pressurized molten salt or high-pressure helium. Pressurization on the secondary side will probably be required to assure the design integrity of the IHX structure, given the high-pressure helium on the primary side.

Considering resource limits for this PIRT, some of the many possible options and design variations were not covered here and should be revisited as appropriate in subsequent PIRT activities.

Other process problems related to the limited availability of some panel members for the three PIRT meetings. Some were not available for one or more of the meetings, and in the third meeting, two additional panel members joined to provide additional expertise in the neutronics area.

Tables resulting from the PIRT panel deliberations are attached in the following order:

- normal operation,
- general LOFC,
- P-LOFC,
- D-LOFC,
- air ingress,
- reactivity transients—including anticipated transients without scram (ATWS),

- processes coupled via IHX (IHX failure with molten salt), and
- steam/water ingress.

The first set of tables represents conglomerates of the rankings and rationales for the accident categories listed above. The importance and knowledge level rankings were averaged, often representing a consensus of the responses of the participating panel members. Summary ranking tables follow (denoted Table 3–Accident T/F PIRT Rankings after PIRT Meeting 3), where the H-M-L entries of individual participants are shown for each phenomenon in the table. In cases where there were disparities between member rankings for a given phenomenon, explanations were typically given in the rationale sections of the conglomerate tables, with elaborations noted in individual members' tables. The conglomerate tables also identified the primary figure of merit (FOM) for safety/licensing concerns most affected by each phenomenon listed. The FOMs were derived from the list assembled at the first PIRT meeting (see Sect. 3.4. "Step 4: Evaluation Criteria"). Member tables for each of the accident categories follow in groupings by member, for panel "voting" members, as a set of tables numbered 4.1 through 14.8 (in the Appendix).

4.2 Accident and Thermal-Fluid PIRT Chart (Table 1)

This chart was created at the first PIRT meeting, where the panel decided to list the phenomena pertaining to any and all accidents or events and then check off their major applicability to each of the selected accident types. The phenomena in this table are grouped roughly according to function (heat removal, reactivity control,… etc.). In most cases, this grouping method, plus use of the building block charts for variations on the LOFC accidents, helped to avoid unnecessary duplications.

In certain cases, such as those where a phenomenon was important in one accident type but unimportant in another, multiple evaluations were given. Although some of the phenomena listed were not considered in any of the subsequent ranking tables, the full listing in this table may be useful in future more comprehensive studies, after more details of the NGNP design have been established.

4.3 PIRT Tables: Combined Evaluations for Accident Sequence Categories (Tables 2.1 through 2.7)

Tables 2.1 through 2.7 show the combined evaluations for each of the phenomena considered in seven of the eight accident categories, noting "averaged" H, M, and L values for the importance and knowledge levels. (See "water–steam ingress" section below for an explanation of why Table 2.8 is omitted). In most cases, these evaluations represent a consensus of the panel members, while in some others there were rather wide spreads due to variations in panel members' interpretations, understanding, or opinions about the potential effects on accident outcomes. Further elaborations on individual opinions may be found in the collections of individual ranking and rationale tables (Tables 4.1 through 14.8) in the Appendix. Some highlights of the discussions are noted in these rationale columns. Rating letters in the combined evaluation tables (2.1–2.7) that have asterisks (*) indicate "close races" in the arrival at an average evaluation.

4.4 Normal Operation (Table 2.1)

Normal Operation refers here to steady-state, routine load changes, startup and shutdown, and other conditions and transients not involving failures of safety-grade systems or components. Some event sequences nominally classified as AOOs were arbitrarily considered by the panel to fall into this category. Event classification was not meant to be one of the panel's tasks; the objective here was simply to try not to exclude any significant phenomena, processes, or events.

One of the major safety-related concerns in the normal operation category is the possibility of maximum operating fuel temperatures being significantly higher than expected. Factors considered included, for example, such phenomena as "core coolant bypass flow," which refers to the fraction of the total primary coolant flow that does not directly cool the fuel elements. In the PMR, direct cooling is done by the flow through the fuel element cooling holes, and in the PBR, it is the flow through the main annulus containing the fuel pebbles. The bypass flow is typically a factor very difficult or impossible to measure or even infer in HTGRs because most bypass is typically through the spaces between fuel and reflector blocks, which vary with temperature, temperature gradient, and block shrink/swell effects due to irradiation. While important in normal operation, the bypass flow fraction would be an insignificant factor in D-LOFC accidents, thus providing a good example of how one phenomenon can be of high importance in one case and low in another. Core coolant bypass flow was ranked by the panel as high importance (H) and the knowledge level low (L*), or overall an (H, L*) ranking, indicating suggested further study.

Another form of bypass flow in PBRs is the flow at the pebble-wall interfaces. In annular core designs, this applies both to the side and central reflector interfaces. This was also ranked (H, L) by the panel, although a number of studies have been able to successfully characterize the effective gap (flow area) as a function of distance from the wall. Other mechanisms related to core coolant flow distributions and its variations were considered and ranked (M, L) or (H, M), indicating the interest in refining predictions in these areas.

Power/flux profiles in PBRs (H, L) were of concern to the panel due to the history of pebble operating temperature prediction problems (in the AVR), and the lack of operating experience with tall annular cores. Furthermore, the flux tends to peak sharply in the areas of pebble-wall interface. The panel concern (H, L) about the reactivity-temperature feedback coefficients is also due to the relative lack of experimental data for this core configuration and the eventual large plutonium content due to the use of low-enriched uranium (LEU) (and no thorium). These coefficients (for fuel, moderator, and reflector) are important for establishing inherent reactivity control safety, and vary with temperature and burnup. On-line tests can be used to infer these parameters. Such tests run to date on current experimental reactors (HTTR and HTR-10) with cylindrical cores have shown good agreement with predictions so far, at least, at low burnups.

Other phenomena characterized as (H, L) by the panel included the outlet plenum flow distribution. This was significant because the temperature differences in the coolant discharges from the bottom of the core can be large due to variations in both axial flows and radial peaking factors, and can lead to both steady-state and fluctuating jets in the lower plenum. While not normally considered a direct safety concern, this phenomenon presents stress concerns for the plenum and outlet duct and the downstream gas turbine, where applicable.

Fuel performance modeling (a cross-cutting issue) was also ranked as very important (H, L) by the panel because such performance is a crucial factor in the overall safety case, particularly for designs utilizing confinement buildings (with controlled leakage) rather than containments.

Another (H, L)-ranked phenomenon relates to fission product release and transport of silver (Ag-110*m*), where, for example, the potential for deposition on turbine blades for direct-cycle gas-turbine BOPs is a maintenance or worker dose concern. Silver is released from in-tact SiC TRISO particles by a yet-to-be-understood mechanism, primarily at very high operating temperatures and high burnups. The problem is likely to be greater for plutonium-bearing fuel, since the silver generation from plutonium fissions is ~50 times greater than for uranium fissions.

The radioactive dust component in the primary circulating gas (for the PBR) that could be released to the confinement, along with other dust shaken loose, originates during normal operation. Its potential release in a rapid-depressurization accident is addressed in the D-LOFC table, and in more detail in the fission product transport PIRT.

Events that included failure to start or a delayed start of the SCS, which is typically a nonsafety grade system, is considered here to be in the AOO category. This concern received a (H*, M) ranking. While delayed starts were a significant concern for the large HTGRs, analyses have shown it to be of a much lesser concern for the modular designs. This is because LOFC peak core temperatures in the modular HTGRs are much lower than those in the large HTGRs, so the core exit (SCS inlet) temperatures upon restart are lower. However, SCS performance and reliability are likely to be subjects of technical specification limiting conditions for operation (LCOs), because the SCS is in the primary success path for responding to LOFC events.

Other features of normal operation that could lead to persistent (unexpected) high temperatures in other areas (such as the reactor cavity concrete), or high thermal gradients and/or temperature fluctuations, were noted as a general concern for RCCS performance (ranked H, M). These included concerns for potential RCCS panel differential expansion/contraction problems and cooling water flow distribution disparities, especially in horizontal regions such as at the top of the reactor vessel cavity.

Table 2.1. Normal operation (20–100% power) PIRT chart

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	FOM—fuel time at temperature, fuel failure fraction. >Varies with shifts in block gaps, etc. No way to measure it.	L*	>Medium knowledge with good instrumentation. >Instrumentation in PBRs not practical, poor ability to model phenomena. >Bypass flows vary axially, difficult to measure temperatures. >Test during initial startup for bypass flow cold gas won't leak into core; as a result less uncertainty in bypass flow. Depend upon code validation; graphite shrink/swell effect on bypass flow. >Knowledge adequate.
2	Core flow distribution, flow in active core.	Determines fuel operating temperatures. Assumes known bypass flows.	H	FOM—fuel time at temperature, fuel failure fraction. >Redistribution within very tall core can be counterproductive.	M	>Difficulty in predicting local hot spots. >Considering active core only, uncertainties due to packing fraction. >Local flow in PBR, hot spots.
3*	Core flow distribution changes due to temperature gradients.	Some effect on fuel operating temperatures. Active core flow. Large delta T from inlet to outlet. Gradients different from LWRs.	M	FOM—fuel time at temperature, fuel failure fraction. >During normal operation axially driven, local velocity variations affect temperature gradients. >Wide range of flow from 20–100% power, temperature gradients in core required inlet orifices to control gradients.	M	>Haven't built a 10 block high core; don't have information on long skinny annular cores. >Good understanding of phenomena, understand viscosity influence, problem with localized prediction. >Have CFD capability but need to couple energy, momentum equations.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
4*	Core flow distribution changes due to graphite irradiation.	Some effect on fuel operating temperatures.	M	FOM—fuel time at temperature, fuel failure fraction. >Affects core bypass flow due to change in graphite geometry. >Small contributing factor to bypass flow. >Graphite changes in conductivity will affect heat transfer and affect flow pattern.	L*	>Don't know which graphite will be used. >Active research area lack of quantification. >Hard to predict effect. >Confidence that new graphite will behave in a similar manner to previous reactor graphite.
5*	Core flow distribution changes due to core barrel geometry changes.	Some effect on fuel operating temperatures. Wouldn't apply to case where inlet flow enters through reflectors.	M*	FOM—fuel time at temperature, fuel failure fraction. >Design isn't finalized, warping can be serious problem if not taken into account, irregularities may result in local hot spots; very design dependent. >Tall structure dimensions need to be constant for extended period of time, driven more by temperature gradients than radiation. >Alloy 800H has lateral and axial supports, no stress corrosion cracking, no swinging support problems; problem can be designed out. >Changes friction, velocity.	M*	>Hard to predict and measure the change in geometry. >Conservative design practice won't be a problem. >Can calculate flow in simple geometry very easily.
6*	Core flow distribution due to core block stability (prismatic).	Problem at Fort St. Vrain.	M	FOM—fuel time at temperature, fuel failure fraction. >Fluid induced vibration.	M*	>Experience from Fort St. Vrain, high knowledge base, however design dependent. >Tied to bypass leakage flow.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				>Enough variations may not be able to design out, 100 degree oscillation due to core block instability, can be avoided by design. >No orifices; longer skinny core.		>Hard to predict onset of oscillations, longer core different from Fort St. Vrain.
7*	Pebble bed core bridging.	Problem at AVR. Happened at bottom of core at beginning of life.	M*	FOM—fuel time at temperature, fuel failure fraction. >Not going to have large bridging effect. >Not important for beginning of life bridging effect. >How long will bridge (void) persist and contribute to local hot spots. >Connected holdup to bridging pebbles staying in core too long, if you have bridging then the design is not optimized.	M	>Solutions established for AVR; however, design-dependent applicability yet to be established for newer designs.
8*	Pebble bed core wall interface effects on bypass flow.	Diversion of some core cooling flow. Number of pebbles across impacts interface effects.	H*	FOM—fuel time at temperature, fuel failure fraction. >Combination of cooling anomalies and flux peaking = uncertainties.	L*	>Pebble bed pressure drop equations large uncertainty band larger uncertainty in wall friction correlations, need experimental data PBMR doing experiments in HPTU/HTTF. >Different packing fraction at wall. >Void fraction has large uncertainty. >Calculation tools improved recently.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	H	FOM—fuel time at temperature, fuel failure fraction. >Determines core temperatures. >Coolant flow square root of pressure drop factors. >Pressure drop (in PBR) important parameter.	H	>Helium properties well known, flow friction correlations are standard for PMR designs. >Friction correlations for PBR have a wide spread.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	FOM—fuel time at temperature, fuel failure fraction. >Determines fuel temperature, significant film temperature drop contributes to peak fuel temperature, will contribute to stresses in PMR.	H for PMR M for PBR	>Heat transfer coupling between flow regime, local values of heat transfer vary significantly from average heat transfer, close to wall laminarization of flow. >PBMR doing experiments with HPTU/HTTF. >Heat transfer calculations in high temperature regions are difficult.
11*	Core Inlet flow distribution.	Important for core cooling calculations.	M*	FOM—fuel time at temperature, fuel failure fraction. >Flow square root of pressure drop, flow in PBR would tend to equalize before reaching hot portion of the core. >Flow may be skewed with warped inlet paths.	M*	>Inlet pressure distribution function of complicated geometry of inlet plenum. >Uncertainty in data and correlations.
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations. Very design dependent.	M	FOM—fuel time at temperature, fuel failure fraction. >Lead to nonuniform inlet temperature distribution, thermal stress problems.	M	>Inlet temperature distribution function of complicated geometry of inlet plenum. >Uncertainty in data and correlations.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream, outlet pressure distribution.	H	FOM—worker dose, core support structures. >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 THTR.	L*	>Very complex turbulent mixing with incoming jets over large temperature spans. >PMR geometry contributes to the uncertainties in the pressure distribution.
14*	Pebble flow.	Affects core maximum temperatures, pebble burnup; problem at THTR (pebbles with higher peaking factors flowed faster in the middle).	H	FOM—fuel failure fraction, time at temperature. >Potential for pebbles to be entrained, recirculation zones, held-up unexpectedly. >Determines the void fraction for core flow calculation, less of an effect on annular cores.	M	>Lack of validated models, lack of applicable data. >Models are statistic, lack of mechanistic modeling for wall-effects (unlocking) >effect of dust on changes in local friction factors around pebbles.
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.	L	FOM—time at temperature. >Convection heat transfer dominates at rated flow.	M	>See item #1 in G-LOFC chart.
16	Effective fuel element thermal conductivity.	Affects core maximum temperatures during operation.	H	FOM—fuel time at temperature. >Fuel element temperature drop is 50% of total temperature drop to coolant.	M	>Need to know effects of irradiation on thermal conductivity. >Sensitivity analyses show little effect of change in core thermal conductivity to time at temperature.
17	Core specific heat.	Affects transients.	M*	FOM—time at temperature. >Large thermal inertial means slower response to load/reactivity changes. >Defines core capacitance	H	>No significant variation in Cp for different types of graphite. >Fair amount of data exists.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				(i.e., stored energy). >For steady-state or load changes, thermal inertia does not matter.		
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures. (radiation, convection, conduction).	M	FOM—time at temperature, vessel and vessel supports temperature, RCCS cavity temperature. >Integral part of total heat balance.	M	>Have good data for heat transfer material properties during steady-state normal operation; view factors easily calculated for in-vessel. >Need emissivities over the lifetime of the plant, but this data can be easily collected during normal operation, >Calculating conjugate heat transfer can be difficult. >IAEA report shows temperatures at higher and lower portion of vessel during normal operation (most likely due to convection effects). >Need good data on heat transfer calculation in long skinny cores.
19	RCCS heat removal.	Affects residual heat losses, vessel temperatures.	H	FOM—RCCS cavity temperatures, vessel supports, vessel temperatures. >Integral part of total heat balance. >Calculation of parasitic heat loss. >Verifies RCCS during normal operation as it could impact RCCS reliability during accident conditions, which can impact fuel failure fraction and dose to	M	Can calculate, but need validation data, historically there have been difficult design challenges for water-cooled designs, for air-cooled systems (completely passive) natural circulation issues are the same as item #7 in the G-LOFC chart. >Need for integral data and/or tech specs for validation

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				worker and public. >Potential to exceed cavity concrete temperature limits.		
20*	Shutdown cooling system startup transients during core heatup.	Can affect component thermal stresses; dependent on design and operational details.	H*	FOM—primary system boundary integrity. >Potential for hot streaks during startups leading to IHX failure. >Previous concern with large HTGRs; modular HTGRs have lower inlet gas temperatures.	M	>Models are adequate, however model validation is required, refer to upper plenum mixing in G-LOFC.
2	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	H	FOM—dose to worker, fuel failure fraction, fuel time at temperature, core support. >Important for estimating control rod worth and power defect.	L*	>Limited available experimental data for validation of reactivity temperature effects, particularly direct measurements of reactivity coefficients rather than overall transient response of the system and 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 may

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						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.
23	Xenon buildup and oscillation.	Affects core transient behavior.	M	FOM—fuel failure fraction. >Fuel doesn't see extended periods of high temperatures on average. >Xenon oscillations are more likely in large/tall cores and result in large local power densities that over time can result in fuel damage. >With proper instrumentation and controls, xenon oscillations are likely to be detected and suppressed, or otherwise overcome. >Overall, steady-state xenon concentration is expected to be well predicted and understood.	M	>Applicability of past analyses on current designs, large portion of knowledge is proprietary. >Reactivity defect resulting from xenon buildup at startup can be calculated and directly compared to operation. >Understanding of xenon oscillations well-known and with proper calculation tools and methods, stability can be assured.
24*	Fuel performance modeling.	Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC, …	H	FOM—fuel failure fraction. >Primary barrier.	L*	>Many unknowns, kernel migration, silicon carbide morphology relation to release.

Table 2.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
25*	Ag-110*m* release and plateout.	Affects maintenance dose. May be dependent upon fuel design, columnar grains vs pearl grains. Will be dependent upon fuel temperature.	H*	FOM—worker dose. >Coupled with fuel performance modeling and fission product transport.	L*	>Large uncertainty band.
26-D	Power and flux profiles(initial conditions for accidents).	Affects fuel potential for failures in accident conditions due to long-term exposures. For affecting conditions, see item #19.	H	FOM—dose to public, fuel failure fraction >Major factor in fuel accident performance models.	M*	>Need for code validation with newer designs—annular core, higher burnup, core reflector interface, fuel location.

*(On ID) Issue not written down in the first PIRT meeting, but was discussed.
*(On ranking) Average or consensus ranking involved diverse opinions.
-D suffix denotes additions or alterations proposed by D. E. Carlson (NRC).
[1] H, M, or L (high, medium, or low).

4.5 General LOFC (Table 2.2)

The building block approach to this PIRT documentation led to the creation of a general LOFC table (G-LOFC) that included common elements for the variations on the LOFC theme, encompassing both the pressurized (P-LOFC) and depressurized (D-LOFC) cases. It also has the flexibility of adding air ingress phenomena to the D-LOFC PIRT or an ATWS (or reactivity event) to either. RCCS behavior is generally very important in LOFC events because the RCCS becomes the only effective means of removing afterheat from the core and vessel. The processes are generally the same for variations in the LOFC, but some differences exist, such as the heat redistribution in the core and vessel for the P-LOFC (hotter at the top), potential for "gray gas" (particulates) in the air cavity between the vessel and RCCS that reduces the effective emissivity, and potential mode changes (e.g., to and from boiling) in a water-cooled RCCS.

In initial discussions of the G-LOFC, two interpretation problems came to light for phenomenon knowledge level (KL) rankings. In the first case, some panelists' rankings of KL as high (H), or sufficient, was influenced by the fact that the phenomenon had little effect on the outcome (e.g., core effective thermal conductivity in a P-LOFC), while ranking KL lower (M or L), possibly insufficient, for the same phenomenon where it has a major effect (e.g., in a D-LOFC). In a second case, some panelists tended to give lower KL rankings due to the uncertainties in the current NGNP design—the details of which are yet to be established. Other panelists tended to disregard this as a KL consideration, assuming design features, once established, would not necessarily affect R&D needs.

One phenomenon in this category ranked by the panel as (H, L) was the emissivity estimate for the vessel and RCCS panel, particularly due to uncertainties from aging effects. Emissivities are key factors in the ultimate heat sink performance in LOFCs because at high temperatures most of the heat removal (~80–90%) is by thermal radiation to the RCCS, the rest being by convection. Steels have been shown to have high emissivities (~0.8) at high temperatures given that an oxide layer (typically formed in most service conditions) is in tact; however, there was concern that this layer, particularly for surfaces inside the vessel in a relatively pure helium atmosphere, might be compromised, resulting in significantly lower emissivities.

The other phenomenon given (H, L) ratings was the reactor vessel cavity air circulation and heat transfer. While this typically provides only a small fraction (~10–20%) of the total heat removal in an LOFC, it is a crucial factor in the temperature distributions within the reactor cavity, where the chimney effect tends to make the upper cavity regions much hotter.

Conductivities and other heat transfer mechanisms in the side reflector and core barrel areas were also of concern to the panel, some receiving (H, M) and (M, L) rankings, indicating the advisability for some further study.

Table 2.2. General LOFC PIRT chart

This chart is for general cases of loss-of-forced circulation (G-LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	FOM—fuel failure fraction. >Major factor in peak temperatures in the D-LOFC accidents but not important for P-LOFC.	M	>Fairly good data available for prism and pebble cores; most differences probably due to difficult measurement.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	M*	FOM—fuel failure fraction. >~75–100ºC difference in peak fuel temp based on realistic sensitivities in fuel element annealing (D-LOFC). >Hard to take credit for it in a safety analysis. >Uncertainty in data too large to separate out annealing effects.	M*	>Difficulties tracking and predicting core conductivity via irradiation and annealing histories.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	FOM—fuel failure fraction. >Slow response for large MCp; time for remedies and FP decay.	H	Cp values close to (well-known) graphite Cp vs temperature.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	FOM—vessel integrity—maintain coolable geometry; limit vessel temperature. >Change in inner surface vessel emissivity based on degraded environment. >T^4 heat transfer dominates (85–90%) in LOFC transients. >Scoping calculations:	M*	>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, aging. >Knowledge of inner emissivity 0.5—0.3, change nature of

Table 2.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				large temperature differences between vessel and RCCS reduce emissivity importance.		surface coating.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	Same as #4	Same as #4.		>Emissivities are fairly well-known for steel, once oxidized (in air cavity).
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	H*	FOM—vessel and vessel support integrity. >Determination of spatial temperature distribution, especially in upper reactor pressure vessel (RPV) cavity.	M*	>Complex geometries involved.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating, assume controls inserted either through automatic or manual action relatively quickly.	H	FOM—vessel and vessel support integrity >RCCS performance, heat distribution, location of hot spots.	L	>Lack of applicable prototypic data. >Difficult to predict local hot spots with CFD and other codes. >Lack of codes for modeling conjugate heat transfer.
8	Reactor vessel cavity “gray gas” (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	FOM—vessel and vessel support integrity. >Modest effect on peak vessel temperature, negligible effect on T-max-fuel.	M*	>Size of particulates, level of knowledge aerosol codes, aerosol distribution, optical transparency. >Introduction of aerosols will affect natural convection and radiation heat transfer; difficult to predict how. >Effect of gas medium in cavity on radiation heat transfer not that important; bounding

Table 2.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						calculations.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	FOM—fuel failure fraction; vessel and vessel support integrity. >Sensitivity study: reflector conductivity uncertainties = small impact on peak fuel temperature and peak vessel temperature.	M*	>Knowledge of graphite reflectors, phenomenon well understood.
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H*	FOM—fuel failure fraction; vessel and vessel support integrity. >Deposition in small stagnant regions, low flow. >Significant amount of dust generated in AVR. >Sensitivity studies: little difference to vessel, fuel temperature.	M*	Dust issues.
11	Stored (Wigner) energy releases.	Effects apply to low-temperature operation graphite reactors.	L	FOM—fuel failure fraction. >Not expected for high-temp irradiation of graphite.	H	>Effects well known; not a factor in modular HTGRs.
12*	RCCS fouling on coolant side.	Affects heat sink effectiveness; deterioration can be measured on-line in some designs.	H	FOM—vessel and vessel support integrity. >Affects pressure drops, ultimate heat sink. >Avoid condition, tech specs.	M*	>Difficult to estimate fouling, conservative estimates. >Need for experimental tests to validate RCCS. >Phenomena understood.
13*	RCCS spatial heat loadings.	Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.	H*	FOM—vessel support temperatures, concrete temperature. >Affects maximum vessel temperature in some accident scenarios.	M*	>Lack of experimental data; aspect ratio, stand pipes, parallel channel effects, plumes, coupling upper head stratification circulation

Table 2.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						paths.
14	RCCS performance including failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved, differential expansion leads to support structure concerns.	H	FOM—vessel support temperatures, concrete temperature >Affects maximum vessel temperature in some accident scenarios.	M	>Difficult modeling to determine deformation.
15	RCCS failure of both channels; heat transfer from RCCS to concrete cavity wall. – Concrete thermal response. – Concrete degradation.	Involves complex heat transfer to cavity walls.	H	FOM—vessel and support temperatures, concrete temperature. >Important when considering integrity of RCCS, concrete. >Also important for calculating vessel and vessel support temperature distribution.	M*	>Difficult modeling; bounding calculations.
16*	RCCS panel damage from missiles.	Complex phenomena involved.	Skip		Skip	
17	RCCS forced-to-natural circulation transitions (part of ID#14).	Complex phenomena (more so with water coolant); crucial to function.	H	FOM—vessel and support temperatures, concrete temperature (applies to ID 18–20). >Important transition in accident sequence.	M	>Detailed calculations and tests needed (major need).
18	RCCS single phase boiling transitions (part of ID#14).	Complex phenomena; crucial to function.	H	>Important transitions (both ways) in accident sequence.	M	>Detailed calculations needed (major need).
19*	RCCS parallel channel interactions (part of ID#14).	Complex phenomena; crucial to function.	H	>Difficulties more likely with water (vs air) and horizontal panels.	M	>Detailed calculations needed (major need).
20	RCCS natural circulation in horizontal panel(s) (part of ID#14).	Complex phenomena (more so with water coolant); crucial to function.	H	>Most cavity heating problems occur in top panel.	M	>Detailed calculations needed (major need).

Table 2.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21	Decay heat (temporal and spatial).	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	FOM—fuel failure fraction. >Dependent on fuel type and burnup >Major factor in peak temperatures in the D-LOFC accidents, but not important for P-LOFC.	M	>Spatial dependence difficult, annular core, axial and radial peaking factors, inner reflector, higher burnups; need for validation. >Standard correlations appear to be conservative (vs experiments).

*(On ID No.) Issue not written down in the first PIRT meeting, but was discussed.

*(On ranking) Average or consensus ranking involved diverse opinions.

[1] H, M, or L (high, medium, or low).

4.6 Pressurized P-LOFC (Table 2.3)

Characterizations of P-LOFC events (for a given design) are relatively straightforward compared with other LOFC accident sequences, which can have a myriad of variations to consider. The P-LOFC is characterized simply by “helium forced circulation stops.” The subsequent natural circulation of pressurized helium that takes place within the core tends to equalize core temperatures, thus reducing the tendency to form very hot regions, as would happen in D-LOFC cases, where the heat transfer mechanism is primarily conduction (PMR) or thermal radiation (PBR). In the P-LOFC case, the main concern shifts to the tops of the core and vessel, which become the hottest, rather than the coolest, areas. While no phenomena were given (H, L) rankings, several concerns rated (H, M) related to the convection and radiation heating of the upper vessel area, which is the basis for the design of the special insulation inside the top head. High-temperature insulation development is typically an important issue in HTGR designs, due to considerations such as behavior during rapid depressurization events (which tend to dislodge it), and dry-out following water ingress events (which might not be a factor in NGNP designs).

4.7 Depressurized D-LOFC (Table 2.4)

The D-LOFC, unlike the P-LOFC, has many variations, including the size of the “break” and its location(s) within the primary system. A large break/rapid blowdown of very hot helium could cause structural damage of critical items in the path of the discharge that may need to be factored into consequence estimates and postulated mitigation schemes. Its location can affect the atmospheric conditions impacting the potential for subsequent air ingress and the ingress gas’ effective oxygen content. A very slow depressurization can put the reactor into a “limbo” state (between P- and D-) for long periods, possibly making effective emergency response planning perplexing. Following depressurization, the effective core conductivity, along with afterheat (vs time), become the two major influences on peak fuel temperatures. The D-LOFC accident is typically the design determinant for reactor maximum operating power level (for a given vessel size).

No phenomena received (H, L) rankings by the panel, although there was considerable attention given to the major factors affecting peak fuel and vessel temperatures. The consensus (with H, M rankings) was that although there are uncertainties in these factors (core effective conductivity and afterheat for fuel temperature, plus RCCS performance for vessel temperature), the importance factors were mitigated somewhat considering the large safety margins typically included in the designs.

Fuel performance modeling, as it applies to heat-up accidents, was also ranked (H, M), noting its importance and the need for accommodation to fuel design, quality assurance (QA)/quality control (QC) in fuel manufacture, and operating conditions, in addition to heatup trajectories.

Dust suspension in the reactor vessel cavity (considering dust possibly dislodged by the helium discharge) could impede the radiant heat transfer from the vessel to the RCCS. This phenomenon was rated (H, M) by the panel, considering the difficulty of predicting geometry and deposition effects.

Table 2.3. Pressurized LOFC PIRT chart

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	FOM—upper vessel support, vessel. >Important to control rod drive (CRD) motor and other upper internal structures, thermal stresses.	M*	>Plumes driven by configuration of core, flow function of time; cannot calculate distributions as function of time, need experimental data. >Coupled problem between core and top plenum. >Turbulence modeling.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	FOM—upper vessel temperature, CRD, in-vessel equipment, instrumentation. >Reserve shutdown system, pressure boundary integrity.	M	>Uncertainties in model inputs (core top surface temperatures, standpipe interference, etc.).
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	FOM—vessel support temperatures, concrete temperature. >More important for the P-LOFC.	M*	>Shifts in T^4 and convective heating distributions.

Table 2.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	FOM—fuel temperature, upper vessel support, vessel. >Important to CRD and other upper internal structures, thermal stresses. >Fuel temperature stays below temperature of concern for P-LOFC. >Hot spots can cause structural failure.	M*	>Huge uncertainty in bypass flow, limited ability to model. >Need experimental data, flow reversal, natural circulation pathways, uncertainties in core geometry. >Laminarization of heat transfer close to wall difficult to predict, but phenomena well understood.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	H	FOM—fuel temperature, upper vessel support, vessel. Important to CRD and other upper internal structures, thermal stresses. >By-pass flow can have large effect on total reversal flow rates.	M*	>Huge uncertainty in bypass flow, limited ability to model. >Need experimental data, flow reversal, natural circulation pathways, uncertainties in core geometry. >Laminarization of heat transfer close to wall difficult to predict, but phenomena well understood.

Table 2.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	H	FOM—fuel temperature, upper vessel support, vessel. Important to CRD and other upper internal structures, thermal stresses. >Affects changes in core temperature profiles, but maximum temperatures are well below limits.	M	>Uncertainties due to low-flow correlations and flow reversal transitions.
7*	Impacts (thermal shock) in SCS due to startup flow transient.	Thermal transients for P-LOFCs more pronounced.	M	FOM—damage to SCS HX, pressure boundary failure. >Pressure boundary concerns. >Heatup of core not big enough to cause large thermal shock.	M	>Models required are well-known (enough).

*(On ID No.) Issue not written down in the first PIRT meeting, but was discussed.
*(On ranking) Average or consensus ranking involved diverse opinions.
[1] H, M, or L (high, medium, or low).

Table 2.4. Depressurized LOFC PIRT chart

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	FOM—dose, peak fuel temperature. >Major parameter affecting peak fuel temperature in D-LOFC.	M	>Core thermal conductivity uncertainties in gaps; however not that sensitive to gaps. >Number of models for effective conductivity; lack of consensus which model is best. >Not all data is available. >More variability in PBR than PMR data.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	FOM—dose, peak fuel temperature. >Major parameter affecting peak fuel temperature.	M	>Don't know how well established neutronics, spectrums, cross sections. >Pebble bed random packing; sensitivity study: peaking factors do not affect fuel temperatures that much, neutronic codes are adequate. >Standard decay heat curves are generally conservative.
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved; reference: #13 from general LOFC table,	M*	FOM—structural integrity of RCCS. >Not as hot in upper structure where supports are located.	M*	>Uncertainties probably not significant.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	FOM—dose. >Determines fuel time-at-temperature limits; defining transient for rated power level.	M	>TRISO fuel particle quality assurance >Tests on specific fuels are needed.

Table 2.4 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Hydrodynamic conditions for dust suspension (Fluid Structure Interactions).	From discussion with fission product panel.	H	FOM—dose. >Moving dust out of pressure boundary.	M	>Complex geometries. >Boundary conditions on dust deposition difficult to predict.
6	Dust effect on coolant properties and flow in vessel.	Affects circulation.	L	FOM—dose. >Affects natural circulation paths, Grashof number. >Concentration of dust near wall heat transfer different.	M	>Complex physical phenomena close to wall with gas and micron-sized particle.
7	Cavity over-pressurization	Possible damage to cavity components.	H	FOM—RCCS structural integrity.	H	>Complex geometry. >Good models.
8	Pressure pulse in confinement.	Possible damage to cavity components.	H	FOM—failure of additional pipes.	M	>Complex phenomena involved.

*(On ID No.) Issue not written down in the first PIRT meeting, but was discussed.
*(On ranking) Average or consensus ranking involved diverse opinions.
[1] H, M, or L (high, medium, or low).

4.8 Air Ingress Following Depressurization (Table 2.5)

Events involving significant air ingress are generally considered to be of very low probability; however, they add considerably more possible complications and degrees of severity to an already potentially complex D-LOFC event. The two primary crucial factors here are the propensity to ingest "air" into the core and the oxygen content of the ingested gas.

For some single-break scenarios, there could be a long (~days) delay before a significant air ingress flow would occur—depending on the break size and orientation and other factors. This delay would allow major shifts in the core temperature profiles to occur before the onset of oxidation (as well as several days to take corrective action). For large postulated breaks, as the pressurized blowdown is in its last stage, a phenomenon known as "exchange flow" is likely to occur. This phenomenon, best characterized by the densimetric Froude number, results in the confinement gas (air) moving into the vessel to replace the helium that is discharged from the vessel. The net result is a filling of the lower reaches of the reactor vessel only a short time (minutes) after the break occurs, and sets the stage for air to move into the core as the oxygen begins to react with the hot graphite structures in the lower plenum. The process of air encroaching into the space originally occupied by helium, known as molecular diffusion, is typically a very slow process, and as long as the helium "bubble" in the top region of the vessel is intact, the substantial ingress flow is inhibited.

The first impact of air ingress (from natural circulation) in the lower plenum area where the graphite core support structure resides might, in some scenarios, affect core structural integrity.

Not specifically considered here is the scenario in which forced convection augments the air ingress process, with the potential net graphite oxidation rates increasing considerably (clearly a more bounding event). There are also wide variations in the possible composition of the ingress gas. In the panel's initial deliberations on air ingress, the various means of defining the cavity that surrounds the RPV (a potential location of the break) were not clearly established. The question was does the gas consist of an average atmosphere in the confinement building or rather the gas in a compartment or cavity within the confinement building. The answers are clearly design-dependent.

A crucial factor in determining the extent of long-term graphite damage if no mitigating action is taken is the ingress of fresh air into the confinement and its eventual access to the area of the break. Factors such as gas density, stratification, and confinement out-leakage significantly affect these predictions. Because the availability of the air (oxygen) to the break location, along with the in-leakage of air to the confinement, can vary widely depending on the scenario assumptions, bounding calculations with very large boundaries would be applicable, especially until more design details are available.

The possibility for a double break that exposes both the reactor upper and lower plenum to the confinement cavity was also considered, even though any double vessel break would be of extremely low probability. A chimney effect would result in a larger ingress flow rate (with minimal delay in starting); however, total long-term graphite oxidation damage would be more dependent on total oxygen availability in the confinement building. An earlier start of the oxidation would reduce the time for corrective actions to be taken.

The panel's judgment was that no phenomena considered have (H, L) rankings, in part due to the fact that for the bounding condition calculations, there are wide variations in the unknowns (as noted above), so that the imprecise, but available, data would likely be sufficient.

Another mitigating factor in the importance rankings was that considering the possibilities for fuel oxidation damage, tests have shown that fission product releases (for SiC TRISO) are not likely in the projected accident temperature ranges in the lower part of the core, where the oxidation would take place.[3] The very low probability of occurrence of these scenarios also tended to enter into this ranking process.

The integrity of the graphite core support system would depend on its design details as well as the conditions for oxidation, where oxidation at lower temperatures tends to result in more structural damage. This phenomenon was ranked as (H, M) by the panel.

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[3] Section 5.4 of *Fuel Performance and Fission Product Behavior in Gas Cooled Reactors*, IAEA-TECDOC-978, International Atomic Energy Agency, Vienna, Austria, November 1997.

Table 2.5. Air ingress LOFC PIRT chart

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D- LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow and thermal properties for mixed gases in vessel.	Determines friction and heat transfer characteristics in core. Viscosity and thermal conductivity.	H*	FOM—fuel temperature, fuel and structural damage. >Simulation of accident: properties of coolant→small impact on outcome of accident. >Different densities between helium and air mixing need diffusion properties for both gases in plenum. >Viscosity increases with temperature; hotter= less flow through, steady state circulation paths. >Onset of natural circulation affected by mixed gas properties >Important for air flow rate.	H*	>Affect friction and flow velocities; difficulty in determining local flow characteristics, affects fluid temperature. >Knowledge of properties; lack of knowledge of mixing. >Need CFD code, limited capacity, better knowledge of delta Ps. >Lack of knowledge of gas mixture with respect to time. >Properties well-known, but some composition uncertainties.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	M	FOM—fuel temperatures, fuel and structural damage. >Heat capacity of gas small compared to core. >Low flow, oxygen used up quickly assuming hot core; small effect on accident outcome. >Heat removed by gas. >Gas will come to temperature of fuel >Time scale for heat transfer.	M*	>Properties of mixed gases during combustion more difficult to determine. >Mixture of known gases, known heat transfer. >Not clear what gas composition is, not straightforward to determine properties. >Lack of knowledge of correlations for this phenomena, high temperature sections low

Table 2.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						temperature sections complicated effects. >Large gradient between wall and gas heat transfer not well known, temporal evolution of mixture.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved. As seen in G-LOFC #8.	M	FOM—concrete integrity, and reactor vessel support. >Concrete temperatures lower with lower RCCS emissivity, increase in temperature goes to vessel support.	L*	>Models adequate for bounding calculation.
4*	Fuel performance with oxygen attack.	Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	FOM—fuel temperature, dose, fuel failure fraction. >Low probability; fueled core area of exposure probably at temperatures less than critical for FP release.	M*	>Fuel qualification. >Active R&D. >Adding oxidation knowledge based upon fresh fuel; need more data on irradiated fuel.
5*	Core support structures oxidation.	Low-temperature oxidation potentially damaging to structural strength.	H	FOM—core support structure, fuel temperature, dose, fuel failure fraction. >Core structure area first seen by incoming ingress air.	M	>Complex zone, mixing, heterogeneous, difficult to calculate boundary conditions. >Oxidation behavior of graphite well known.
6	Core oxidation.	Determination of “where” in core the oxidation would take place, graphite oxidation kinetics affected by temp oxygen content of air, irradiation of graphite.	H	FOM—fuel temperature, dose, fuel failure fraction, core integrity. >Oxidation can occur at the top of the core depending upon break location.	M	>Data on effects of radiation damage on graphite. >Existing data from experiments varies with geometries and manufacturers. >Need to reduce uncertainties in graphite

Table 2.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						oxidation data. >Uncertainty in graphite manufacturers.
7	Rx cavity-to-reactor vessel air ingress [see #14 and 15].	Air from cavity to vessel after D-LOFC.	H	See # 14 and 15.	M	
8	Phenomena that affect Cavity gas composition and temperature with inflow.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties. Entrainment through relief valve, etc. Dependent variable.	H*	FOM—fuel temperature, dose, fuel failure fraction, core integrity. >In terms of overall damage to reactor core it is a question of total oxygen available over course of accident, not specific composition. >Impact on corrosion, conservative assumptions would result in less importance of phenomena.	M	>Very complicated, various phenomena, difficult to know composition and temperature at inlet. >Link transient to opening of vent valve, pulses will affect phenomena. >Bounding calculations. >How much air carried out with valve, break size dependent, large break = vent valve more important.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	M*	FOM—fuel temperature, dose, fuel failure fraction, core integrity. >More mixing than stratification, well mixed environment. >Break location, stratification dependent upon conditions, complex geometry, helium bubble.	M*	Same as #8.
10	Confinement-to-reactor cavity air ingress.	Determines long-term oxidation rate if accident unchecked.	H	FOM–fuel temperature, dose, fuel failure fraction, core integrity. >Defines long-term damage.	M	>Lack of data on pressure differential between confinement and cavity. >Performance criteria provided by vendor.

Table 2.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
11	Cavity combustion gases.	Some CO formed as oxidation product.	L	FOM—Cavity temperature and pressure. >Little danger from CO combustion; shouldn’t affect cooldown.	M	>Models available for bounding calculations. >Concentration difficult to determine.
12	Cavity structural integrity during blowdown.	Influence on air ingress analysis modeling.	M	FOM—cavity temperature, vessel support, vessel temperature, RCCS integrity. >Considers damage to confinement structure from fast depressurization, could affect heat transfer.	M	>Existing models available; need some validation.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBR.	H	FOM—dose to public. >Affects release to public.	M*	>Good knowledge base for HEPA filters, design dependent. >Dust filter options should be investigated and tested.
14	Duct exchange flow.	Stratified flow phenomena leading to helium flow exit and air ingress into lower plenum.	H	FOM—core support structure, fuel temperature, dose, fuel failure fraction. >One factor in the determination of onset of natural circulation and significant air ingress flow.	M	>Difficult to calculate counter current natural circulation. >Need experimental data. >There is some light/heavy gas experimental data available from containment experiments. >Complex phenomena enough knowledge to model flow for most cases.
15	Molecular diffusion.	Air remaining in the reactor cavity enters into RV by molecular diffusion, prior to	H*	FOM—core support structure, fuel temperature, dose, fuel failure fraction.	M	>Good agreement with calculations under idealized conditions.

Table 2.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
		onset of natural circulation.		>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 oxidation vs diffusion. >Slow process will lag other phenomena. >Ensure on-set of bulk natural circulation and the reaction rate of bulk CO and graphite oxidation. >Diffusion process very slow → graphite chemical reaction with oxygen is very slow.		>Many other factors could influence processes leading to a significant ingress flow rate.
16	Chimney effects.	In case of double break exposing both the upper and lower plenum to confinement air.	M	FOM—cavity temperature, vessel support, vessel temperature. >Increase air flow through the core.	M	>Uncertainty of level of oxidation in upper and lower level of core, models available for bounding calculation. >Models probably sufficient for bounding calculations.

Table 2.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
17	Thermal stratification/ mixing in the lower plenum.	[See #14].		Needed to well predict the molecular diffusion of air into plenum into plenum → significant effect on the natural convection phase.		
	Environment-to-confinement air leakage.	[See #10].				
	Core flow distribution following onset of natural circulation.	[See #1].				

*(On ID No.) Issue not written down in the first PIRT meeting, but was discussed.

*(On ranking) Average or consensus ranking involved diverse opinions.

[1] H, M, or L (high, medium, or low).

4.9 Reactivity (ATWS) Events (Table 2.6)

These were initially referred to as ATWS events, but several other events were considered that involved reactivity insertions, not necessarily “without scram.”

A classic ATWS case (for PBRs) is a reactivity insertion due to pebble bed core compaction in a severe, prolonged earthquake event. Bounding calculations of the potential positive reactivity insertion have shown that significant positive reactivity could theoretically result; however, realistically the reactivity increase would occur over a relatively long time period (minutes). Even without a scram or other corrective action, the natural negative temperature-reactivity feedback mechanisms would prevent damaging power excursions.

The possibility of positive reactivity insertions from steam/water ingress was also considered. Depending on design and operating conditions, the ingress may or may not cause a significant positive reactivity insertion. It was assumed, however, that credible mechanisms for significant ingresses (during reactor power operation) did not exist in this case because the potential water sources would remain at pressures lower than those in the primary system, and water inventories in the secondary systems were assumed to be limited to small values by design. The conclusion was predicated on the assumption that the design does not include a steam generator in the primary circuit.

There were no (H, L) panel rankings in this category. However, the reactivity-temperature feedback coefficients for the fuel, moderator, and reflectors were ranked as (H, M*). This negative feedback is crucial to the inherent defenses against reactivity insertions, and due to the complex and untested (to date) design features such as the very tall annular core, there were some predictability concerns, particularly for high burnup conditions.

Table 2.6. Reactivity (ATWS) PIRT chart

Includes anticipated transients without scram (ATWS), and other reactivity insertion events.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1-D	Reactivity insertion due to pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction	M*	FOM—fuel failure fraction. >Large reactivity insertion can occur. Negative temperature-reactivity feedback prevents excessive fuel temperature excursion.	M	>Given the compaction porosity, reactivity can be easily calculated. >Specific pebble bed compaction dependent on seismic event and subject to wide variations.
~~2*~~	~~[Prismatic] Excess reactivity due to burnable poison loading error—BP).~~	~~Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.~~		~~FOM—fuel failure fraction.~~		
3	Reactivity insertion due to steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H*	FOM—fuel failure fraction, corrosion of core supports, dose to public. >Design dependent and based on amount of steam-water inserted into primary system. >Past experience (FSV) indicates difficulty in ensuring sufficient separation of primary gas system and secondary water sources. >High reactor temperatures would result initially in steam ingress for which reactivity impacts will be less than for liquid.	M	>If distribution is known, reactivity can be calculated; however, significant variations in calculations (maybe due to design differences or assumptions on amount and distribution of steam-water). >Scoping calculations are sufficient.

Table 2.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
4a	Phenomena for water or steam ingress from SCS, or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity.	L	FOM—fuel failure. >Very low probability accident; even unlikely scenarios introduce very little water (for steam generator in primary loop, this is a high risk event).	M	>Scoping calculations are sufficient,
4b	Mechanisms for water or steam ingress from steam generator.	Some water ingress scenarios are postulated; effects on reactivity.		FOM—fuel failure fraction, core support. **Not considered.**		>Effect of supercritical water used in secondary side processes.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).	Affects passive safety shutdown characteristics.	H	FOM—fuel failure fraction, time at temperature. >Inherent defense against reactivity insertions. >Major argument for inherent safety design.	M*	>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.
6	Control and scram rods, and reserve shutdown worths.	Needed for cold or hot shutdown validation.	H*	FOM—fuel failure fraction. >Needed for safety case. >Control rods and reserve shutdown methods are required to control reactor and to ensure sufficient shutdown margin exists.	M	>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.

Table 2.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Xenon and samarium buildup.	Determination of poison distribution; xenon decay determines recriticality time.	M	FOM—fuel failure >Needed to check shutdown margin .>Transient behavior of xenon will impact recriticality, shutdown margin, and core power distribution. >Xenon transients occur over relatively long time scales (~10 h).	M	>Can predict power and flux profiles. >If power distribution and burnup distribution are well known. >Xenon and samarium distributions can be predicted, as well as the time-dependent behavior.
~~8~~	~~Scram and reserve shutdown system fails.~~	~~Needed for cold shutdown validation.~~		~~omit.~~		
~~9*~~	~~Rod ejection.~~	~~Design features.~~		~~omit.~~		
10*	Coolant flow restarts during loss of forced circulation ATWS.	Can lead to selective undercooling of hot regions. Coupled thermal-fluids and neutronics.	M*	FOM—fuel failure fraction. >Recovery operation can lead to fuel failure.	L	>Distribution of flows, reactivity feedback, power distribution uncertainty. >Generally difficult to predict local power peaking because of a combination of the coupled thermal-fluids/neutronics behavior and uncertainties in reactivity coefficients. >Complex flow distribution in pebble bed results in difficulty to predict undercooled regions.
11-D	Decay heat during loss of forced circulation ATWS (vs time and distribution).	See entry in G-LOFC chart (item #21).		FOM—fuel failure fraction.		

Table 2.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance^1	Rationale	Knowledge level^1	Rationale
12-D	Reactivity insertion from overcooling transients with ATWS.	Positive reactivity from decreases in core inlet temperature.	L	FOM—fuel failure fraction. >Negative feedback coefficients control transients, high heat capacity. >Long-term power stable because of negative reactivity coefficients and overall temperature increases.	H	>Readily bounded by current analyses. >Feedback coefficients known sufficiently well for bounding analysis.
13-D	Reactivity insertion from core support failure due to air ingress corrosion.	Core drop pulling away from control rods would insert reactivity.	L	FOM—fuel failure fraction. >Maximum withdrawal of control rods probably won't lead to recriticality (not far to fall).	M	>Lack of knowledge about scenario. >Maximum reactivity insertion can be bounded by system geometry and assumptions regarding the location of control rods.

*(On ID No.) Issue not written down in the first PIRT meeting, but was discussed.
*(On ranking) Average or consensus ranking involved diverse opinions.
-D suffix—added or amended per D. E. Carlson (NRC) suggestion.
[1] H, M, or L (high, medium, or low).

4.10 IHX Failure, Assuming Molten Salt (MS) as the Transport Medium (Table 2.7)

Initially this PIRT table was developed as a more general coverage of phenomena associated with the coupling of the modular HTGR to a high-temperature process heat hydrogen plant. In extensive discussions with the process heat PIRT panel chair (C. W. Forsberg) at PIRT meeting 3, the panel concluded that because there were still very large uncertainties in the selection of an eventual NGNP process heat component design, the focus instead should be on an example event for one of the "likely" designs. The panel also decided to consider internal events instead of external hazards from upsets in the chemical plant. The focus would be specifically on the interfacing component (IHX) and pipeline between the two plants. If MS were chosen to be the intermediate heat-transport coolant, its selection would lead to a significantly different (and interesting) set of phenomena from those addressed to date in this PIRT exercise.

With the MS pipeline coolant selected, the event was developed using a transport loop that was pressurized to help balance the pressure difference between the IHX primary and secondary sides. The loop is coupled to a nonspecific high-temperature hydrogen production plant. The event scenario is described in the table's preamble and summarized as follows:

The heat transport pipelines are assumed to be quite long (~0.5 miles or more), so the molten salt inventory is large. An initial break in the IHX tubing allows the higher pressure primary helium coolant to penetrate ("blowdown") into the pipeline, with some of the primary system helium escaping to the outside via a secondary relief valve in the pipeline, bypassing the reactor confinement building. From the inertia of the flowing MS in the pipeline, and other factors, MS flows into the reactor primary system and partially fills some of the reactor vessel. The MS is assumed to contain no nitrates.

While the IHX failure as assumed would initially lead to primary system helium penetration into the MS-filled heat transport loop (and possible release of part of the helium's circulating activity to the environs), the more interesting part involves the possible back-flow of salt into the reactor primary system, and eventually into the reactor core.

Some current NGNP exploratory designs employ MS as the coolant fluid of an "HTGR," so such a back-flow is not likely to have any major adverse impact, except for potential thermal shocks from hot salt impacts on the vessel and in-vessel metals being a possible source of high transient stresses. As the SCS will not be started up under a pool of MS, the longer-term decay heat removal mode through the vessel wall will end up with higher vessel wall temperature changes due to the higher conductivity of salt compared to the radiation heat transfer through helium.

There were no (H, L) panel rankings in this category. Some concerns (H, M) were raised about possible doses to the public from the initial release of activity in the primary circuit; however, this was tempered by the likely scrubbing action during the countercurrent MS-helium flow. All other concerns in the (H, M) category were due to possible thermal shocks from hot MS entering primary system areas that had normally cooler operating temperatures.

One design variation was also discussed (but not evaluated)—that of using high-pressure helium (instead of MS) in the heat transfer loop. An IHX break scenario that causes eventual leakage of the heat transfer loop's huge (hot) helium inventory into the reactor confinement building would have a major impact on the building and any filter design employed.

Several panel members had addressed the more general process heat scenarios prior to the meeting and completed draft ranking tables for these event/design phenomena. In those cases, their individual PIRT tables appear (in the appendix) as Tables X.7a. More general accident scenario descriptions and evaluations are covered more thoroughly in the process heat (hydrogen) PIRT report, including a much wider variety of design options and accident scenarios.

Table 2.7. IHX failure (molten salt) PIRT chart

Design assumptions: Molten salt (~800°C), inventory = 130,000 kg (3000 ft^3), 15,000 ft^3 in reactor, isolation valves?
Scenario: Break of IHX internal tubes, blowdown of primary to secondary, then possible ingress of molten salt (no nitrates).
Conditions: Secondary side press lower than primary (no nitrate salts), lower plenum filled with molten salt by ~X hrs with Partial P/D-LOFC. He escapes by secondary relief valve out molten salt lines (confinement bypass), countercurrent flow, lots of inertia as 0.5 miles of molten salt slows down and pump coasts down.
Single failure: isolation valve fails to close.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Ingress of He into IHX loop (part of confinement bypass).	Blowdown of primary system into secondary system, gas jet into liquid, initial circulating activity is the prime source of the public and worker dose.	M	FOM—public and worker dose. >Helium flow rate determines how much activity is transported into IHX loop.	H*	>Most likely bounding assumptions/calculations are sufficient. >Uncertainties in secondary system side conditions (operating pressure, relief valve settings) make accurate calculation of total He into IHX loop difficult.
2	Fission product transport through IHX loop (part of confinement bypass).	Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out.	H	FOM—public and worker dose. >Determines activity released out of IHX relief valve, and residuals in IHX loop.	M	Lack of scrubbing data applicable to counter-current He–MS flow, yet bounding models may be able to reduce uncertainties.
3	He transport in IHX loop (part of confinement bypass).	Possible He/molten salt countercurrent flow, blocking bubble in IHX loop.	M	FOM—public and worker dose. >Affects fission product transport through IHX to relief valve.	M	>Lots of air/steam-water data on countercurrent flow that may be applicable; however, does this scale well to He–MS data?
4	Ingress of molten salt (MS) into primary system and RPV.	After partial blowdown, relies on items #1, 2, 3 as initial/boundary conditions.	H	FOM—vessel, vessel support, and core support temperatures. >Determines amount/mass of MS in vessel, core MS level.	M	>Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.

Table 2.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				>Hot MS bypass into primary possible source of high transient stresses.		
5	Riser fill with molten salt.	Through cold duct.	H	FOM—vessel, vessel support, and core support temperatures. >Affects vessel temperatures, heat transfer to RCCS.	M*	>Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.
6	Lower plenum fill with molten salt.	Through hot duct.	H	FOM—vessel, vessel support, and core support temperatures. >Temperatures not much different from normal operating temperatures. >Structural integrity effects.	M*	>Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.
7	Molten salt (in cold duct)-to-core support/vessel heat transfer.		H	FOM—vessel, vessel support, and core support temperatures. >Impact on cross duct and vessel temperatures.	M	>Knowledge sufficient for bounding calculations. >Heat transfer calculations are more complex due to nonwetting nature of MS and trapping of helium in cavities, two-phase flow.
8	Molten salt (in hot duct)-to-core support/vessel heat transfer.		M	FOM—vessel, vessel support, and core support temperatures. >Temperatures not much different from normal operating temperature.	M	>Models sufficient for bounding calculations, heat transfer problem well understood. >Heat transfer calculations are more complex due to nonwetting nature of MS and trapping of helium in cavities, two-phase flow.

Table 2.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	RCCS heat removal.	Heat transfer from vessel wall to RCCS and cavity.	H	FOM—vessel, vessel support, and core support temperatures. >Ultimate heat sink, abnormal temperature distribution on RCCS and vessel.	M*	>Models sufficient for bounding calculations. >Skewed vessel heat loading below RCCS design.

*Average or consensus ranking involved diverse opinions.

[1] H, M, or L (high, medium, or low).

4.11 Water-Steam Ingress

As noted in the discussion of the reactivity PIRT (Table 2.6), originally the intent was to cover events including potential design options for a steam generator (SG) in the primary loop, as well as for direct-cycle gas turbines and IHXs only in the primary BOP. In the former case, steam in-leakage from a high-pressure SG would be a dominant risk factor; in the latter cases, where the primary water-cooled heat exchanger secondary sides in the Brayton cycle design run at lower operating pressures, they present minimal risks of any substantial steam-water ingress during power operation. Hence, after much discussion, the panel decided to eliminate this accident type from the current ranking process. The table used in the discussion (originally Table 2.8) listed the initial concerns (but without summary rankings). Since no rankings were assigned by the panel, the table was eliminated. For further discussions of the originally posed phenomena, refer to Tables X.8 in some individual member evaluations (X = 4 to 14) in the Appendix. The reader should note that for just about every HTGR that was ever operated, significant water ingress events occurred. However, no significant reactivity insertion events of this type were recorded in the experience base.

4.12 Summaries of Rankings for All PIRT Tables (Table 3)

These tables summarize the rankings by individual PIRT panel voting members for each phenomenon associated with the various accident tables. Voter identification (by initials) is shown in the first set of columns for importance (IMP) and in the second set of columns for knowledge level (KL). Panel member individual ranking tables, with rationales for importance and knowledge level evaluations, are in the Appendix.

Table 3. Accident T/F PIRT rankings

Normal Operation

	IMP								KL								
P#	**DM**	**GG**	**JR**	**JG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**JR**	**JG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	H	H			H	H	H	H	H	M	M			L	M	L	L	M
2	H	H			H	M	M	H	H	M	H			L	H	M	L	M
3	M	H			H	M	M		M	M	H			H	M	M		M
4	L	H			H	M	M	M	M	L	M			L	L	M	L	M
5	L	H			H	M	M	M	M	H	M			H	L	M	L	M
6	H	H			M	M	M	M	H	M	L			H	L	M	L	M
7	H				H	L	M	M	H	M				M	M	M	L	M
8	M	H			H	M	M	HM	H	M	L			L	M	M	L	L
9	H	H			H	H	H	M	M	H	H			H	M	H	H	H
10	H	H			H	H	H	H	H	H	M			L	M	H	H	M
11	H	H			H	M	M	M	M	M	M			L	L	M	L	M
12	L	H			M	M	M	L	M	M	M			M	M	L	L	M
13	H	H			H	M	H	M	H	L	L			L	M	M	L	M
14	M				H	M	H	H	H	M				M	M	M	M	L
15	L	H			L	L	L	L	L	M	M			M	H	H	M	M
16	H				H	H	H	H	H	L				M	M	H	M	M
17	M	H			H	M	M	L	M	M	H			H	H	H	M	M
18	H				H	H	M	H	H	L				M	M	M	M	M
19	H	H			H	H	H	H	H	L	M			H	M	M	M	M
20	H				M	L	H	M	H	M				L	M	M	M	M
21-D	H		H	H	H	H	H	H	H	L		LM	M	L	M	M	M	L
22	H	H	H	H	H	M	H	M	H	L	M	L	L	–	M	M	M	L
23	H	H	H	M	H	M	M	M	M	M	M	M	M	M	H	H	M	M
24(Fuel)	H				H	H	H	H	H	L				L	M	M		L
25(Silver)	H					M	H	H	M	L					L	M		M
26-D	H		H	H	H	H	M	H	H	L		M	M	L	M	M	M	M

Table 3 (continued)

Reactivity (ATWS)

	IMP									KL								
P#	**DM**	**GG**	**JR**	**JG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**JR**	**JG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	L		M	M	H	M	L	H	H	H		M	M	M	H	H	M	M
~~2~~	~~L~~					~~M~~		~~M~~	~~M~~	~~H~~					~~M~~		~~M~~	~~M~~
3	M		M	H	H	M	M	H	H	H		M	M	L	M	H	M	M
4a	L				L	L	–	L	M	L				M	M	–	M	M
4b																		
5	H		H	H	M	H	H	H	M	L		L	L	–	M	M	M	M
6	M		M	H	H	H	H	L	M	L		L	M	M	M	M	M	M
7	M		M	M	M	M	M	M	M	L		M	M	M	M	M	M	M
8	H					M			H	L					M			H
9	L					L			H	H					M			M
10	M		M	M	H	M	H	–	H	L		L	L	L	M	M	–	L
11																		
12	L		L	L	M	L	M	–	L	H		H	H	H	H	H	–	H
13	L		L	L	L	L	L	M	M	M		M	M	M	M	M	M	M

Table 3 (continued)

General LOFC

	IMP									KL								
P#	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	H	H		H	H	H	H	H	H	M	M		M	M	M	H	M	M
2*	L	H		M	L	H	H	H	M	H	M		L	M	M	H	L	M
3	H	H		M	H	H	H	H	H	H	H		H	M	H	H	M	M
4*	H	H	H	H	H	H	H	M	H	L	M	ML	M	L	H	H	M	M
5*	H	H	H	H	H	H	H	M	H	L	M	ML	H	L	H	H	M	M
6	M	H	H	H	H	H	M	M	M	M	H	M	H	H	M	M	H	M
7*	M	M		M	H	H	H	H	H	H	M		H	L	M	M	L	L
8*	M	M	H	M	H	M	M	H	M	M	L	M	M	M	M	M	L	L
9	H	H		H	H	M	H	M	H	M	M		H	M	H	H	M	M
10	H	H	H	H	H	M	M	M	H	L	M	M	M	M	H	H	M	H
11	L	L		L		L	L	L	L	H	H		H		H	H	M	H
12*	M	M	H		H	M	M	H	H	H	L	M		M	M	H	M	M
13*	M	H	H		H	M	H	M	M	H	L			M	M	M	L	M
14	H	H	H	H	H	M	H	H	H	H	M	L	M	M	M	M	L	M
15	H	H	H	H	H	M	H	H	H	H	M	L	M	M	L	M	M	L
16	M					M	H		H	M			L		L	M		H
17	M	H	H	M		H	H	H	H	M	L	H	M		M	M	L	M
18*	M		H	M		H		H	M	M		H	H		M		L	M
19	M		H			H		H	M	M		H			M		L	M
20	M		H	H/M		H			M	M		H	L		M			M
21	M	H		H		H	H	H	H	M	H		H		H	M	M	H

Table 3 (continued)

Pressurized LOFC

	IMP									KL								
P#	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	H	H	H	H	H	M	M	H	H	M	M	M	M	L	M	M	L	M
2	H	M	H	H	H	M	H	M	H	M	M	M	M	M	M	M	H	M
3	H		H			M		H		M		L			M		L	
4	H	H	M	H	H	M	M	H	H	L	M	M	M	L	M	M	L	M
5	H			H		M		M		L			M		M		L	
6	H	H	H	H	H	M	M	M	H	L	M	M	M	M	M	H	M	M
7	H					M				L					M			

Depressurized LOFC

	IMP									KL								
P	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	H	H	H	H	H	H	M	H	H	M	M	M	M	M	M	L	M	M
2	M	H	H	H	H	H	M	H	H	H	H	M	M	M	M	M	M	M
3	M	H	H	M	H	M	M	M	H	H	M	L	M	L	M	M	L	M
4	H				H	H	H	H		L				M	M	M		
5		H	H	H	H	M	H	H	H		M	H	H	M	M	L	M	M
6		L	L	L	L	L	L	M	M		M	M	L	M	M	L	L	M
7		H	H	H	H	H	H	H	H		H	H	H	H	M	H	M	H
8		H	H	H	H	H	H	H	H		M	M	M	M	M	M	M	M

Table 3 (continued)

Air Ingress

	IMP									KL								
P#	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	L	H	M	H	H	L	M	H	H	H	M	H	H	H	M	H	M	M
2	L	H	M	M	H	L	M	H	H	M	M	H	M	M	M	H	M	M
3	M	M	H	L	H	M	M	H	M	M	L	M	M	L	M	M	L	L
4	L	H	H	H	H	M	H	H	H	M	M	L	L	M	M	M	–	M
5	L	H		H	H	H	H	H	M	M	L		M	M	M	H	M	M
6	L	H	H	H	H	M	M	H	H	H	M	L	M	M	M	H	M	M
7		H	H	H	H	M	H	H	H		M	H	L	M	M	M	M	M
8	L	M		H	H	M	H	H	M	H	L		M	M	M	M	L	M
9	L	M		M	H	M	M	H	H	H	L		M	L	M	M	L	M
10		H		H	H	H	H	H	H		M		H	M	M	M	M	M
11	L			L		L	L	L	L	M			L		M	M	M	M
12	M			M	H	M	H	M	M	M			L	M	M	M	M	M
13	H		H	M	H	M	H	H	H	M		L	L	M	M	H	L	M
14GG		M/L									H							
14RS		H	H	H	H	M	H	H	H		M	M	L	L	M	M	L	M
15GG		H	H	M	H	M	M	H	H		M	H	M	M	M	M	H	M
16GG	L	H				M	M	–	M	M	M				M	M	–	M

Table 3 (continued)

Water Ingress (small amount)

	IMP									KL								
P#	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	L		H			L		H	M	M		H			M		H	M
2	L		H			L		H	M	M		H			M		H	M
3	M		H			L		H	M	M		M			M		L	M
4a																		
4b																		
4old	H		H		M	L	M	H	H	M		L		M	M	M	H	M
5	L				L	L	L	L	M	L				M	M	M	–	L
6	H					M		H	H	M					M		M	M
7	L		H	H		M		H	H	M		L	M/L		M		M	M
8	L					L		M	M	M					M		L	M
9	L					L		M	M	M					M		L	M
10	L		H			L		M	M	M		M			M		L	M
11	L					L		M	M	M					M		M	M
12	L					L		H	M						M		L	M
13	H		H			L		L	H	L		L			M		M	M
14	L		H			L			M	M		M			M			

IHX Failure

	IMP									KL								
P	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**	**DM**	**GG**	**MC**	**RG**	**RS**	**SB**	**SF**	**TW**	**YH**
1	H				M	M	M	H	M	H				H	H	H	M	M
2	H				H	M	H	H	H	M				M	M	M	M	M
3	M				M	L	M	M	M	M				M	M	M	M	L
4	H				H	H	H	H	H	L				M	M	M	M	M
5	H				H	H	H	H	H	L				M	M	M	M	L
6	H				M	M	M	M	H	L				M	M	M	M	L
7	H				H	H	H	H	H	M				M	M	M	M	L
8	M				M	M	M	M	M	M				M	M	M	M	M
9	H				H	H	H	H	H	M				M	M	M	L	L

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5. SUMMARY AND CONCLUSIONS

In the Accident and T/F PIRT conducted for the DOE NGNP design, the panel evaluated phenomena and processes deemed pertinent to the plant's safety characteristics. The objective was to assist NRC in determining areas where additional information may be needed to substantiate licensing-related cases. In some instances, important specifics of the NGNP design had not yet been established, so evaluations were either made of the general features (e.g., common to the likely design alternatives), or else specific assumptions were made about the design selection. For example, certain phenomena common to PBR designs-only were evaluated and likewise for the PMR. It was assumed that more specific evaluations would be made again after the major NGNP design selections are completed.

As one of five PIRT exercises conducted simultaneously, the Accident—T/F PIRT panel benefited greatly from interactions with the other panels.

The PIRT panel evaluated both normal operation and postulated accident scenarios, concentrating on the T/F aspects of the events, but considering the neutronic behavior as well where appropriate. Four types of challenges were evaluated: challenges to heat removal, reactivity control, and confinement of radioactivity, and challenges to the control of chemical attacks.

The panel's evaluation of the importance ranking of a given phenomenon (or process) was based on the effect it had on one or more FOMs or evaluation criteria. Such rankings were sometimes subject to different interpretations—and discussions, however. For example, the effective core conductivity would not be important to peak fuel temperature concerns for the P-LOFC accident scenarios, but would be a major factor in the D-LOFC. Also, RCCS performance is crucial to reactor vessel and reactor cavity overheating concerns in LOFC scenarios but has little effect on peak fuel temperatures. In cases where rankings were not straightforward, explanations were given in the rationale comments. Importance evaluations are functions of the reactor design, and because of some of the inherent safety features of modular HTGRs, the importance of some phenomena typically of concern in reactor accident sequences were reduced significantly.

The panel was not uniformly in agreement on some KL assessments. One view was that the KL should be based on a judgment of how much is known about the phenomenon independent of its importance. In the other view, the KL was judged as a relative, rather than absolute, factor because it relates to a judgment of whether or not more work is needed. This difference in views, which affected some individual KL rankings, should be noted in interpreting the results.

The PIRT evaluations were done using a matrix—building block format that allowed consideration of all the important phenomena or processes without having to resort to unwelcome repetition. The nine-step PIRT process developed by the NRC was employed. Consideration of a wide range of postulated accidents was based in part on extensive review of operating experience as well as on detailed and extensive accident analysis and licensing exercises for designs similar to NGNP (but without the process heat component).

Phenomena with average or consensus rankings of high importance (H) with a corresponding low knowledge level (L) were flagged (H, L) as the major candidates for further consideration. In some other cases, phenomena ranked (H, M) or (M, L) were given consideration as well, especially in view of the concern about possible differences between the panel's "assumed" plant design and the eventual NGNP design feature selections.

The phenomena highlighted in the consensus ranking tables (Tables 2.1–2.7) included those having to do with fuel potentially running at or reaching higher-than-expected temperatures, the concern about RCCS performance, particularly during accident scenarios, and the uncertainties in scenarios of postulated air ingress accidents that, however unlikely, could lead to major core and core support damage. The panel discussed the potential accidents involving the high-temperature process heat (hydrogen plant) design, but since that design was essentially undefined, opted instead to select and evaluate one example event for a specific (MS heat transport loop) design. Followup studies of these and other areas of uncertainty are recommended.

In Table 3 and the summary rankings tables (Tables 4 through 14), PIRT members are identified by initials. An initials key listing, along with notes on which of the three PIRT meetings they participated in (and individual table numbers), is as follows:

DM = David Moses (ORNL)—Meetings 1 and 3 (Table 4)
GG = Genevieve Geffraye (CEA, France)—Meetings 1 and 2 (Table 5)
JG = Jess Gehin (ORNL)—Neutronics discussions in meeting 3 (Table 6/7)
JR = John-Paul Renier (ORNL)—Neutronics discussions in meeting 3 (Table 6/7)
MC = Michael Corradini (Univ. Wisconsin)—Meetings 1 and 2 (Table 8)
RG = Randall Gauntt (SNL)—Meetings 1 and 2 (Table 9)
RS = Richard Schultz (INL)—Meetings 2 and 3 (Table 10)
SB = Syd Ball (ORNL)—All meetings (Table 11)
SF = Steve Fisher (ORNL)—Meetings 2 and 3 (Table 12)
TW = Tom Wei (ANL)—All meetings (Table 13)
YH = Yassim Hassan (Texas A&M)—All meetings (Table 14)

The wide variety in the attendance record helps explain, in part, why some evaluations in some PIRT processes are not covered by all participants. Clifford Davis (INL) substituted for Richard Schultz in Meeting 1, participating in the phenomenon selection process, but not in the rankings, which were done in Meetings 2 and 3. Rankings for all LOFC cases and air ingress events were evaluated in PIRT Meeting 2, and all other areas in Meeting 3.

Panel deliberations were aided by non-voting participants that provided technical support in various areas; these included members of the other four PIRT panels, and industrial representatives Charles Kling (Westinghouse), Larry Parme (General Atomics), and Farshid Sharokhi (AREVA). Special assistance in the reactivity-related discussions was from Ian Gauld (ORNL) on decay heat R&D, and by Don Carlson (NRC). Administrative support was provided by Kent Welter, Peter Cochran, and Samina Sheikh (NRC). Overall PIRT direction and support was provided by Sud Basu (NRC).

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APPENDIX A

INDIVIDUAL PANELISTS’ RANKING TABLES

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Table 4.1. Normal operation PIRT chart—DM

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	As illustrated by the PBMR decision to go with a prismatic inner reflector instead of using pebbles.	M	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.
2	Core flow distribution.	Determines fuel operating temperatures.	H	Bounded by experience at and data from FSV, AVR and THTR.	M	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	M		M	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	L		L	Need data for new graphites to assure that observed effects in previous cores are bounded.
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	L		H	
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	H	Columnar realignments as occurred at FSV and need to know the effectiveness of upper restraints in the PMR.	M	

Table 4.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7*	*Pebble bed core bridging.*	*Problem at AVR.*	H		M	
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	M		M	
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	H		H	
10	Coolant heat transfer correlations.	Determines core temperatures.	H		H	
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	H	Important for PMR since no inlet orificing is proposed.	M	
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	L	Is this only applicable to the PBR?	M	
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	H	Must assure no hot streaks to turbine or SCS HX.	L	
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	M	PBR should be more like AVR than THTR.	M	
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.	?	You need to know the local thermal conductivity not the global value. This depends on graphite thermal conductivity that varies with the graphite crystalline structure, neutron-irradiation, and temperature as a function of the location in the core. Subject to change with change in graphite.	M	The effect of neutron-irradiation on the temperature-dependent thermal conductivity of the new graphites must be established. Substantial data should exist on previous graphites that may be used to interpret and interpolate/extrapolate a sparser data collection for the new graphites.
16	Effective fuel element thermal conductivity.	Affects fuel maximum temperatures during operation.	H		L	

Table 4.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
17	Core specific heat.	Affects transients.	M		M	
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	M	Cooler helium will pass by the surface of the RV; the RV temperature should remain relatively constant.	M	
19	RCCS behavior.	Affects residual heat losses, vessel temperatures.	H	Will the RCCS be instrumented sufficiently along with the RV wall so that a heat balance can be performed to check RCCS performance as meeting FSAR and technical specifications requirements incidental to normal operation?	L	It's all based on analysis unless there are full-sized tests and adequate in-service instrumentation on the RC and in the RCCS to check/verify RCCS performance during normal operation. See Criteria 2, 3, and 4 at 10 CFR 50.36(c)(2)(ii).
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*	H	Depends on time after LOFC initiates that SCS can started up without concern about primary system integrity.	M	Will the SCS be subject to operability LCOs under Criterion 4 of 10 CFR 50.36(c)(2)(ii)? Will that LCO include a time for assured start-up after LOFC similar to the 90 min for the PCRV cooling system start-up at FSV except that damage limits to the SCS and primary system integrity will be the basis here not fuel damage as it was at FSV?

Table 4.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21-D	Power and flux profiles.	Affects core maximum temperatures.	M	For different reasons, both the prismatic and pebble bed cores will have a top-peaked power distribution which is required for a down-flow core. This will result naturally in the pebble bed but has to be designed and loaded into the prismatic.	L	How will loading of the prismatic core be controlled to assure that the fuel columns are not reversed loaded leading to power peaking in the bottom of the core?
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	H	Lack of relevant test data at the conditions of interest.	L	Limited applicable critical experiments and poor or lacking QAed data from reactor testing.
23	Xenon buildup and oscillation.	Affects core transient behavior.	H	GA claims this is not a problem due their analyses but no evidence this has ever been put into a topical report and reviewed by NRC; same applies to other vendors.	M	There's quite a bit in the literature about xenon stability, but there are no universally accepted methods. PWR vendors who worry about this for axial offset keep their methods proprietary.
24*	*Fuel performance modeling.*	*Fuel type dependent. Crucial to design and siting; depends on performance envelope, QA/QC,…*	H	Need test data and full QA/QC in fabrication facility to assure reproducibility.	L	German fabrication QA/QC has yet to be demonstrated in new facility.
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*	H		L	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.2. General LOFC PIRT chart—DM

This chart is for general cases of loss-of-forced circulation (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Depends on graphite thermal conductivity that varies with the graphite crystalline structure, neutron-irradiation and temperature. Subject to change with change in graphite. In pebble bed, usually the result of a fitted correlation from experimental data.	M	The effect of neutron-irradiation on the temperature-dependent thermal conductivity of the new graphites must be established. Substantial data should exist on previous graphites that may be used to interpret and interpolate/extrapolate a sparser data collection for the new graphites.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	L	This effect should be an integral part of the data collection on graphite neutron-irradiation effects on properties.	H	This effect should be an integral part of the data collection on graphite neutron-irradiation effects on properties.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Varies primarily with graphite density changes under irradiation.	H	Varies primarily with graphite density changes under irradiation
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	No data exist on the effects of aging on this. Surface roughening is not likely to change but surface chemistry preparations may scale off under aging due to irradiation, thermal cycling, and inner surface coolant flow conditions.	L	No data exist on the effects of aging on this property. An effective ISI and test program is required to assure that these properties don't change.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	See 4.	L	See 4.

Table 4.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	M	Edge effects should be able to be calculated.	M	Edge effects should be able to be calculated.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	M	Should be bounded by analysis.	H	There should be ample examples from industrial HVAC, or lack thereof, applications.
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	Heated particulates will vibrate and heat the surrounding air leading to thermal convection to the top of the cavity.	M	There should be examples from industrial application against which to benchmark.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	Depends on graphite thermal conductivity that varies with the graphite crystalline structure, neutron-irradiation, and temperature. Subject to change with change in graphite. The annealing effect should be an integral part of the data collection on graphite neutron-irradiation effects on properties.	M	The effect of neutron-irradiation on the temperature-dependent thermal conductivity of the new graphites must be established. Substantial data should exist on previous graphites that may be used to interpret and interpolate/extrapolate a sparser data collection for the new graphites.
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H	No data exist on the effects of aging on this property especially on the core barrel. Surface roughening is not likely to change but surface chemistry preparations may scale off under aging due to irradiation, thermal cycling, and coolant flow conditions.	L	No data exist on the effects of aging on this property especially on the core barrel. An effective ISI and test program is required to assure that these properties don't change.
11	Stored (Wigner) energy releases.		L	The graphites operate at temperatures that self-anneal.	H	No issue.

Table 4.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	M	Surely the designer, operator, and regulator are smart enough from FSV experience to require demineralized and polished water for use in the RCCS equivalent to LWR service water systems and to avoid the use of carbon steel piping.	H	Water chemistry and materials selections lessons-learned should be applied. This means use of low-carbon stainless steel piping to resist fouling and SCC and provide for continuous monitoring of the demineralizer for possible caustic release from the polishing resins.
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	M	With the tall core and the core-deposited heat passing through layers of graphite and metal with relatively high thermal conductivities axially, the temperatures on the surface of the RV are going to be flattened, meaning the heat deposition on the RCCS will also tend to be flattened.	H	Available 3D or RZ heat transport calculation tools can be used to look at the effects of uncertainties in RV internal axial and radial heat transfer properties on the distribution of the RV surface temperature and its effect on RCCS surface temperatures.
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	H	Should be the single failure design basis for RCCS performance.	H	It’s in the Introduction to the GDC.
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.	H	Should be the subject of margin assessment for Beyond-DBE.	H	Should be subject to standard engineering analyses.
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	M	Design issue to identify potential sources of missiles and mitigating engineering solutions.	M	Should be addressed in Chapter 3 of the FSAR and analyzed for impacts in Chapter 15.
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	M	Design issue to be addressed by analysis and testing if needed.	M	

Table 4.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	M	Design issue to be addressed by analysis and testing if needed.	M	
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	M	Design issue to be addressed by analysis and testing if needed.	M	
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	M	Design issue to be addressed by analysis and testing if needed.	M	
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	**M**	Due to the absence in HTGRs of significant in-core metal structures present in LWRs, the decay heat deposition will be flattened by decay gammas passing though the graphite and preferentially depositing in the dispersed high-Z fuel material. However, graphite has a high heat capacity and thermal conductivity so that the effect of ignoring flattening in decay heat deposition on peak fuel temperature is likely small (a few tens of degrees Celsius).	**M**	3D maps of alpha, beta, and gamma heat deposition are doable with the latter based on using 3D radiation transport codes. Due to the high thermal conductivity and heat capacity of graphite, assuming an even more peaked decay heat distribution not accounting for radiation transport of the gammas may not make much difference in the peak fuel temperature during a LOFC accident.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.3. Pressurized LOFC PIRT chart—DM

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	Can adversely impact the integrity of CRDMs and RSS and their RV head penetrations.	M	Needs detailed engineering analyses and possibly testing of flow paths around or through insulation.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	Can adversely impact the integrity of CRDMs and RSS and their RV head penetrations.	M	Needs detailed engineering analyses and possibly testing.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	Can adversely impact RCCS performance by overheating the upper portion of the system.	M	Needs detailed engineering analyses.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	Impacts 1, 2, and 3.	L	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutble, detailed, and independently reviewed documentation.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	H	Impacts 1, 2, and 3.	L	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	H	Impacts 1, 2, and 3.	L	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.

Table 4.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*	H	Need to define time in transient that restart should be precluded due to danger to integrity of SCS components and the primary system boundary.	L	Depends on quality of data used to benchmark GRSAC and other codes; may only lack scrutable, detailed, and independently reviewed documentation.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.4. Depressurized LOFC PIRT Chart—DM

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Depends on graphite thermal conductivity that varies with the graphite crystalline structure, neutron-irradiation and temperature. Subject to change with change in graphite. In pebble bed, usually the result of a fitted correlation from experimental data.	M	The effect of neutron irradiation on the temperature-dependent thermal conductivity of the new graphites must be established. Substantial data should exist on previous graphites that may be used to interpret and interpolate/extrapolate a sparser data collection for the new graphites.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	M	Due to the absence in HTGRs of significant in-core metal structures present in LWRs, the decay heat deposition will be flattened by decay gammas passing though the graphite and preferentially depositing in the dispersed high-Z fuel material. However, graphite has a high heat capacity and thermal conductivity so that the effect of ignoring flattening in decay heat deposition on peak fuel temperature is likely small (a few tens of degrees Celsius).	H	3D maps of alpha, beta, and gamma heat deposition are doable with the latter based on using 3D radiation transport codes. Due to the high thermal conductivity and heat capacity of graphite, assuming an even more peaked decay heat distribution not accounting for radiation transport of the gammas may not make much difference in the peak fuel temperature during a LOFC accident.

Table 4.4 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	M	With the tall core and the core-deposited heat passing through layers of graphite and metal with relatively high thermal conductivities axially, the temperatures on the surface of the RV are going to be flattened meaning the heat deposition on the RCCS will also tend to be flattened.	H	Available 3D or RZ heat transport calculation tools can be used to look at the effects of uncertainties in RV internal axial and radial heat transfer properties on the distribution of the RV surface temperature and its effect on RCCS surface temperatures.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	This is complex because it's tied to the QA/QC of fuel fabrication and the test data on fuel performance for the "standard" product that the QA/QC program is trying to produce.	L	Fuel fabrication QA/QC equivalent to that achieved by the Germans in the 1970s and 1980s has not been demonstrated to be reproducible. The model is only as good as the assurance of the reproducibility of the product it's modeling.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.5. Air ingress LOFC PIRT chart—DM

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	L	Heat transport by thermal radiation and conduction will dominate during D-LOFC. Natural circulation during a depressurized event will be a secondary or tertiary effect. Unless the SCS is to be operated, this can be ignored and even then the impact is likely small due to the very low density of the mixed gases.	H	Air flow by natural convection in heated beds should be well understood.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	L	See above.	M	Likely unimportant.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	M	Heated particulates will vibrate and heat the surrounding air leading to thermal convection to the top of the cavity.	M	There should be examples from industrial application against which to benchmark.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	L	Air will react first with surrounding graphitic material and the small amount of air that gets through will slowly erode the OPyC but the SiC will resist attack.	M	
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*	L	The transient, even if it lasts for days, will likely not last long enough to significantly degrade the support structure.	M	Previous testing for time- and temperature-oxidation kinetics for graphites should be revisited.
6	Core oxidation modeling.	Determination of “where” in core the oxidation would take place.	L	Where the air first hits the warmest graphite.	H	Depends on break locations.

Table 4.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	L	Helium will diffuse out of cavity and be replaced by air faster than you can think about it.	H	Assume it's all air in the cavity at the break location or wet air.
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	L	Air is air; it contains O_2 and water vapor. Get a leak in the RCCS and there'll be more water vapor and even droplets.	H	Air is air; it contains O_2 and water vapor. Get a leak in the RCCS and there'll be more water vapor and even droplets.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	L	Not important.	H	Hot gas rises; cool gas sinks.
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.	L	Depends on where the breaks are.	H	One break is not enough to get air good flow past the core.
11	Cavity combustion gases.		L	Graphite isn't coal or charcoal.	H	CO_2 is formed if graphite reacts with air; CO_2 doesn't burn.
12	Cavity structural performance.	Influence on air ingress analysis modeling.	M		M	
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H		L	We don't even know the source term from lift-off inside the RV.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.6. Reactivity (ATWS) PIRT chart—DM

This chart reactivity phenomena including LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	L	You push in the sides of a bag of marbles and they go up; in a cylinder or annulus of pebbles rising will increase neutron leakage. You're not going to significantly influence reactivity unless you apply pressures sufficient to crush the pebbles into powder and that is beyond the capability of an earthquake.	H	
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*	L	The BPs are used for power shaping not reactivity control. You'd have more problems if the core were loaded upside down by a refueling error.	H	
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	L	In the pressurized operating condition, this is not going to happen since the helium is at higher pressure than any water or steam source. As in FSV, the likelihood of abnormal criticality due to water ingress occurs on restart from shutdown.	H	
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; affects reactivity.	L	Only a start-up problem from a depressurized shutdown and that is one for dry-out not reactivity transients.	H	
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).		H	Lack of relevant test data at the conditions of interest.	L	Limited applicable critical experiments and poor or lacking QAed data from reactor testing.

Table 4.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	M	Need careful start-up testing and detailed, documented comparisons to analytical predictions unlike the sloppy and poorly documented results from Peach Bottom and FSV.	L	Limited test data to validate codes.
7	Xenon and samarium buildup.	Determination of poison distribution.	L	Directly related to the ability to calculate flux and power distributions.	L	FSV has good zero-power maps but lacks defensible analysis and applies to HEU/Th not LEU. Need either to provide convincing evidence from poorly-documented Zenith and HITREX LEU criticals or need new critical experiments to demonstrate capability of analytical tools to predict power distributions in LEU-fueled HTGR-type fuel environments. Not sure if KAHTER experiments apply to pebble bed design. The xenon stability analysis by GA has never been documented in a topical report and reviewed by NRC.
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.	H	Will the prismatic design adopt a C–C control rod clad replacing Alloy 800 and allowing scram under all transients? Will the pebble bed design keep requiring RSS insertion for cold shutdown with no inner reflector control	L	Insufficient testing for material acceptance specifications.

Table 4.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				rods? Will the C–C clad resist water ingress? Will the RSS not stick together following water ingress during cold shutdown as experienced at FSV due to high B_2O_3 contaminant levels in B_4C?		
9*	*Rod ejection prevention.*		L	Limited place for the CRDM to go if pressure boundary fails.	H	Design issue for upper head and cavity ceiling.
10*	*Coolant flow restarts during ATWS.*		M	Depressurized—minimum effect. Pressurized—cooling will increase core reactivity and raise power but the core is being cooled. Requires bounding analyses on reactivity coefficient assumptions.	L	Needs analysis and documentation of assumptions.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 4.7a. Process heat PIRT chart—DM

This chart is for phenomena specific to process heat plant interactions; see other applicable charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Oxygen plume encroachment.	Cloud release can be a problem if cold, ground-hugging plume (from upwind). Disable reactor plant operators, equipment; possible combustion.	L	FOM—plant integrity. This can be designed away by siting location (distance between reactor and chemical plant) and channeling by use of a berm or ditches to carry O_2 plume away from reactor.	H	The solution is from civil engineering at Linde plants.
2	Corrosive and/or toxic gas plume encroachment.	Cloud release can be a problem if cold, ground-hugging plume (from upwind). Burns and suffocation possible.	L	FOM—plant integrity. See 1 above.	H	The solution is from civil engineering at chemical plants.
3	Gas ingress to reactor via IHX failure.	Loss of reactor heat sink (partial?); possible effect on reactivity (e.g., steam); core inlet temperature perturbation.	M	FOM—vessel and RCCS integrity. If second is higher pressure, this is a blow-down of secondary side gas through the relief valve located in the primary IHX vessel leading to lift-off possible of plate-out in the IHX vessel—no effect on core.	H	Design should have relief valve on primary IHX vessel.
4	Gas ingress to reactor and reactor cavity via IHX failure.	For high-pressure (helium) heat transfer loop, possible severe overpressure of reactor cavity and confinement building.	M	FOM—RCCS integrity. RCCS structural design must accommodate this event; since blow-down should be designed to occur in IHX cavity, cavity separation should be used to mitigate effect on RCCS cavity.	H	Engineering solution exists.
5	Hydrogen gas plume encroachment.	Only a problem if inside or otherwise contained. Burning possible.	L	FOM—plant integrity See 1 above; the key here is distance in case there's a fire at chemical plant.	H	Hydrogen disperses rapidly unless there's a fire then it burns at the site of fire.

Table 4.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Loss of heat transfer fluid in pipe to process heat plant.	Loss of reactor heat sink (partial?).	L	FOM—fuel temperature Bounded by LOFC.	H	Already addressed by LOFC.

[1] H, M, or L (high, medium, or low).

Table 4.8. Water–steam ingress PIRT chart—DM

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	L	The likelihood of significant water/steam ingress occurs only during depressurized shutdown such as during refueling so this is only important if the operators start up blind on their moisture monitors as they did at FSV on occasion. The reactor should be designed with drains at all low points within the primary system. Restart procedures should require (1) draining any liquid water from low points within the primary system and (2) careful monitoring of moisture detectors during restart heat-up on nuclear heat wherein hide-out moisture in graphite and in-vessel insulation will vaporize and be removed through the helium purification system as at FSV and AVR. Water ingress accompanying a rapid depressurization accident may occur due to the specific break location and the possible mechanical interactions resulting from the break dynamics. In this case, procedures should require cooling the	M	Coolant flow is not the issue. Based on FSV and AVR experience, the issues are engineering (1) to recognize that liquid water will gather or drain to primary system low points so that drains must be provided to those low points with appropriate procedural controls to facilitate dry-out during restart from a depressurized shutdown, (2) to recognize that moisture will hide out in the graphite and in-vessel insulation and that heat-up is needed to drive out such moisture that can only be removed from the coolant over time by the water-cooled chiller-dryer in the helium purification system (with the drained water being tritiated requiring collection for proper disposal), and (3) to recognize that water breakthrough of the molecular sieve downstream of the chiller-dryer will lead to icing and loss of function in the LN_2-

Table 4.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				core down on the RCCS while isolating the SCS and PCU, then testing each to see where the leak is occurring to ensure permanent isolation of the affected unit so that active cooldown can be resumed using the unaffected systems as long as there's no danger from delayed start-up of causing more damage from hot streaks. Care must be exercised during a pressurized LOFC to avoid a delayed start of the SCS after core temperatures have reached the point that hot streaks could damage the SCS heat exchanger and initiate a depressurization followed by water ingress. The FSAR. Technical specifications and procedural controls should recognize and minimize the vulnerabilities to primary system integrity resulting from the core heat up during an LOFC.		cooled krypton trap in the helium purification system leading to radioactive krypton release to the purified helium stream which may still contain water if the krypton trap is iced over.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	L	See above; typically, except for restart following a long shutdown, the core will be sufficiently hot that any water will be vaporized and so gas heat transfer would predominate.	M	The mission is dry-out on nuclear heat so the vaporization of the water in the core graphite will be a major component of heat removal until water is only present in the ppm levels.

Table 4.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	M	Heated particulates will vibrate and heat the surrounding air leading to thermal convection to the top of the cavity.	M	There should be examples from industrial application against which to benchmark.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H	These sources would only affect depressurized cases as discussed above. A substantial water-ingress during shutdown will have a positive reactivity effect impacting the expected critical control rod configuration. Based on FSV experience, the real phenomena of concern are the reliability of moisture detectors to identify and quantify the extent of the ingress, tritium content of the water condensed by the chiller-dryer in the helium purification system, and the potential for icing in the LN_2-cooled krypton trap in the helium purification system. Dry-out should be conducted at the lowest temperatures practical to minimize degradation of graphitic components but there is a time and temperature balance that must be studied. Another FSV-based consideration is the avoidance of the use of carbon steel on the surfaces of components in contact	H L M	We know that ingress can happen. But we also know that better moisture detectors are needed. The temperature-dependent graphite oxidation kinetics studies performed at ORNL for the NPR-MHTGR need to be revisited and possibly updated to quantify the time-at-temperature reaction rates needed to base the optimum dry-out conditions for restart procedural controls. An optimum method for de-icing the LN_2-cooled krypton trap is needed along with consideration of parallel redundant traps to minimize the effect of icing on the potential for moisture carry-over into the components supplied with purified helium such as the CRDMs.

Table 4.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				with primary system helium to eliminate production of rust particles.		
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	There are test data from irradiations at Petten showing the effects of hydrolysis on PyC and SiC during irradiation but, as I recall, these data are from unjacketed fuel and core graphite (or graphitic materials as in the pebbles) will significantly reduce the ingress of moisture to fuel particles.	M	
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	H	Impacts materials selections (high-strength but likely more porous extruded graphite vs slightly lower-strength but denser molded graphite), preservice and in-service inspection requirements (oxidation coupons?).	M	New graphites are required due to loss of petroleum pitch sources used previously. As noted previously, graphite oxidation kinetics parameters need to be verified.
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	L	The probability of steam ingress is much lower in the gas-turbine plants than in FSV or AVR; the considerations discussed above are relevant here.	M	The issue is more of timing of the dry-out on nuclear heat (as discussed above) rather than "where."
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	L	Bounded by water from SCS or PCU.	M	

Table 4.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	L	Bounded by water from SCS or PCU.	M	
10	Cavity combustion gases.		L	Look at the test data; this is graphite not coal or charcoal used for making water-gas.	M	
12	Cavity structural performance.	Influence on ingress analysis modeling.	L	Bounded by water from SCS or PCU.		
13	Cavity filtering performance.	Affects radioactive releases.	H		L	
14	Pressure transients from steam formation.	Potential damage to primary system structures.	L	The likelihood of water ingress is highest during depressurized shutdown conditions; secondary system pressures on water side are too low to cause ingress during pressurized operation of the primary system.	M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 5.1. Normal operation PIRT chart—GG

ID No.	Issue (phenomena process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel.}$	H	Q bypass from zero to 20% → decrease of T_{max} fuel ~70°C.	M	
2	Core flow distribution.	Determines fuel operating temperatures.	H	Change the location of the core hot spots.	H	
Simulation of flow resistance through a PB core important for obtaining T distribution in the fuel						
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	H	Large variation of transport properties with T → reduction in gas density → possible acceleration of the flow in specific region.	H	
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	H		M	
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	H		M	
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	H		L	
7*	*Pebble bed core bridging.*	*Problem at AVR.*				
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	H		L	
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	H	Viscosity increases with T, so friction factor increases with temperature.	H	Existing experimental data.

Table 5.1 (continued)

ID No.	Issue (phenomena process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10	Coolant heat transfer correlations.	Determines core temperatures.	H		M	Heat transfer coefficient decreases with temperature → possible instabilities.
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	H		M	
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	H	If not good mixing → impinge lower pl. structural components and internal components within the cross-vessel.	M	
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	H	Hot streaking + impact on the cycle efficiency.	L	Difficult to evaluate the impact on TM behavior.
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*				
15	Effective core thermal conductivity.	Affects core maximum temperatures.	H		M	
16	Fuel element conductivity.	Affects fuel maximum temperatures.		[not evaluated]		
17	Core specific heat.	Affects transients.	H		H	
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	H		H	
19	RCCS behavior ①.	Affects residual heat losses, vessel temperatures.	M	Parasitic heat loss desirable to be minimized. However, in passive systems, not advisable.	M	
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*				

Table 5.1 (continued)

ID No.	Issue (phenomena process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21-D	Power and flux profiles.	Affects core maximum temperatures.	H		H	
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	H		M	
23	Xenon buildup and oscillation.	Affects core transient behavior.	H		M	
24*	*Fuel performance modeling.*	*Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC.*				
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*				
Additionally						
GG	PCU behavior.	Ensure the forced convection.	H		M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium or low).

① Another concern with some RCCS designs is the potential for severely overcooling the vessel and cavity if the reactor is shutdown during very cold weather shutdown. There is also a concern regarding freezing of the coolant fluid in liquid-cooled RCCS designs.

Table 5.2. General LOFC PIRT chart—GG

This chart is for general cases of loss-of-forced circulation (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases (see other tables).

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Dominant mechanism for the transfer of afterheat from fuel to vessel.	M	Existing correlations function of geometries, graphite temp and radiation terms. Difficulties to measure the inlet parameters.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	H	Partly impact the value of the effective core graphite conductivity. Decrease of 20% → increase of 120°C on T_{max} fuel.	M	Conductivity function of irradiation history, temperature, orientation and annealing effects.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Impact the temperatures evolution function of time.	H	fuel property close to that of graphite which are well-known.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	A emissivity decrease of 25% → Peak vessel T°+37°C. Peak fuel T°+7°C.	M	To be measured function of inlet parameters (surface state, material, T°…).
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H		M	
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	H	Impact the total heat flux.	H	Design depending. Existing tools.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	M	Upper cavity T° dependent of the efficiency of the air convection.	M	Complex geometry→ limiting capacity of CFD.
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M		L	Complex processes involved, in complex geometries: – particulates sizes, concentration localization…

Table 5.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	Item points 1and 2.	M	
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H	For the D-LOFC: allows to reduce peak vessel temperature, could lead to higher peak fuel temperature.	M	
11	Stored (Wigner) energy releases.					
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	*M*	*An over-design capacity of the system could lead to excessive parasitic heat loss during normal op.*	*L*	RCCS is necessarily large, distributed structure in the reactor cavity → not easily amenable to inspection and cleaning → inevitable fouling and degradation occurring over the reactor life.
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	*H*	In a P-LOFC, natural circulation within the vessel causes the peak vessel temperatures to occur near the top. For D-LOFC accident, the peak temperature appears near the vessel belt line.	*H*	Two types of analytical tools: – Very detailed finite-element or finite-difference model (>10000 nodes) for SS analysis. – A simpler dynamic model (>100 nodes) in the overall accident analysis.
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.		Redundancies in coolant flow paths to offset effects of blockages or breaks may be needed.		
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.				

Table 5.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*				
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	H	Accurate prediction of buoyancy flow in chimney is to ensure RCCS heat removal rate.	L	
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.				
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*				
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.				
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H		H	Need of a 3D kinetics coupling.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

The objectives of the most RCCS designs is to serve as an ultimate heat sink, ensuring the TH integrity of the fuel, core, vessel, and critical equipment within the reactor cavity for the entire spectrum of postulated acc. sequences.

A common solution to the problem of ensuring adequate heat removal is to over-design the capacity of the system (during normal operation, excessive parasitic heat losses are undesirable).

RCCS is necessarily large, distributed structure in the reactor cavity → not easily amenable to inspection and cleaning → inevitable fouling and degradation occurring over the reactor life.

Another challenging aspect of RCCS design is the fact that the heat load distribution during long-term LOFC accident can vary considerably with the accident characteristics. In a P-LOFC, natural circulation within the vessel causes the peak vessel temperatures to occur near the top.

For D-LOFC accident, the peak temperature appears near the vessel belt line.

For rapid depressurization accidents, the RCCS may be required to withstand simultaneous hot jet of coolant gas impinging on the structure and an over-pressurization of the cavity.

Analysis methods and codes for predicting detailed RCCS and vessel temperature/profiles must be used in conjunction with whole system accident simulators to determine the adequacy of the design → 2 types of analytical tools:

- Very detailed finite-element or finite-difference model (>10000 nodes) for steady state analysis.
- A simpler dynamic model (>100 nodes) in the overall accident analysis.

Table 5.3. Pressurized LOFC PIRT chart—GG

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	Challenge to vessel integrity.	M	CFD in complex geometries → capacity limitation.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	M	Axial distribution of max. fuel T peaking towards the inlet. Heat capacity and thermal resistance of the thermal shroud are important factors in the T seen by vessel at the upper head.	M	Complex geometries.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	The peak heat load to near the top of reactor cavity → reduces natural circulation enhancement in the RCCS.	M	Need a whole-system calculation.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	Affects TH conditions in the hot channel.	M	PMR: detailed spatial PBR: porous body modeling. Need to have a proper radial heating profile, important for the flow distribution by natural convection. High uncertainties in heat transport at low Re and in natural circulation calculations.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	H	Important for fuel T.	L	Fraction related to core configuration and is dependent on fuel blocks dimensional changes over life for PMR possible flow diversion for PBR porosity at the

Table 5.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						vessel >Bulk → bypass overcooling.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	H	Ph. Important in the hottest channel.	H	
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Natural circulation within the core → core T more uniform → lowering the peak T.

Chimney effect → core and vessel T higher near the top.

Table 5.4. Depressurized LOFC PIRT chart—GG

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Dominant mechanism for the transfer of afterheat from fuel to vessel –20% → +124°C for T_{max} fuel.	M	Effective core graphite conductivity function of irradiation history, temperature, orientation and annealing effects.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	Afterheat P + of 15% → T_{max} fuel + 120°C.	H	3D kinetics coupling needed.
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved. *No natural conv. effect → peak of temperature at the vessel mid plane.*	H	→ possible decrease in the efficiency of the RCCS to remove afterheat by natural circulation.	M	Need a whole-system accident simulation.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*				
GG	Power peaking factor distribution.		M	+ 20% max. radial peaking factor → +30°C.	M	For pebble bed: variable packing density and variability of the reactivity. Random variations in power factor due to random loading of new fuel balls.
GG	Emissivity effects.		L/M	• L for max fuel temperature (–25% for emissivity → +14°C). • M for the max vessel temperature (→ +54°C).	M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, med, or low).

For rapid depressurization acc., the RCCS may required to withstand simultaneous hot jet of coolant gas impinging on the structure and an over pressurization of the cavity.

Table 5.5. Air ingress LOFC PIRT chart—GG

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	H	Net air flow rate into the reactor vessel and core, strongly dependent on the buoyancy forces due to differential temperature and the flow resistances in the core and at the breaks.	M	CFD calculations: capacity limitations. System calculations allow to well represent DP all along the flow.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	H		M	
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	M	Generated heat = afterheat + power generated from oxidation transferred from the core to the RCCS, and a part by convective air flow.	L	Complex processes involved, in complex geometries: – particulates sizes, concentration localization…
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	Source terms for FP.	H/M	Experimental data base. Concept dependent.
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*	H	Mechanical support. Depending on break assumptions and other factors, up to 2% of the core graphite/day may be consumed if fresh air available.	L/M	Nonhomogeneous zone (mixing zone). L: in accident conditions. M: in nominal conditions.
6	Core oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	When a net air ingress flow is established, oxidation begins in the lower part of the core, in the bottom support and reflector areas. Oxidation may occur in the lower part of active core if the lower reflector has	M	Strong coupling TH/mechanics/chemical processes. Air flow and oxidation rate would eventually decrease due to limitations in available oxygen and the

Table 5.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				cooled sufficiently and no longer oxidizes.		decreased buoyancy forces as the core cool, but could either increase or decrease due to core geometry changes.
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	M		L	
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Gas mixing would reduce the draught and also reduce the corrosion. Assuming air at the inlet is conservative. When T° increases → Qair increases.	L	For precise knowledge → conservative assumptions acceptable.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.				
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.	H	Availability of fresh air over the course of the acc. is a key parameter.	H	
11	Cavity combustion gases.					
12	Cavity structural performance.	Influence on air ingress analysis modeling.				
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.				
		Additionally				
GG	*Molecular diffusion.*	*Air remaining in the reactor cavity enters into RV by molecular diffusion.*	*M* *L*	*Ensure on-set of bulk natural circulation and the reaction rate of bulk CO and graphite oxidation.* *Diffusion process very slow → graphite chemical reaction with oxygen is very slow.*	*H*	
	Chimney effects.	*In case of double break.*				

Table 5.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
GG	*Thermal stratification/ mixing in the inlet plenum.*		*H*	*Needed to well predict the molecular diffusion of air into plenum → significant effect on the neural conv. phase.*	*M*	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

The potential threat lies in the chemical reaction of oxygen with hot graphite at a temperature above 500°C leading to reaction heat and graphite corrosion.

Air ingress does not lead to an increase in the peak fuel temperature in comparison to the case of depressurization without air ingress (possible core cooling due to air convection).

The limiting time till the graphite layer is completely burnt-off and the fuel pellets are exposed depends on the air flow rate and the time when air ingresses. Taking into account of the non-uniformity of the flow distribution in various coolant channels of the fuel block, the limiting time is estimated at 20 hours.

Within the limiting time of 20 h, about 15% of the graphite in the bottom reflector has been burnt-off (total graphite oxidized quasi proportional to the air flow exposure time).

Key factors:

- net air flow rate into the reactor vessel and core, strongly dependent on the buoyancy forces due to differential temperature and the flow resistances in the core and at the breaks, and
- availability of fresh air over the course of the accident.

Sensitive parameters:

- kinetic data of graphite,
- estimation of air flow rate, and
- thermal/geometrical data of the core…

For a single break, it may take many hours or days before a sustained, significant net air inflow is established (air diffusion into a helium bubble). In case of a double-break, a chimney-like configuration could promote a higher net air flow more quickly.

When a net air ingress flow is established, oxidation begins in the lower part of the core, in the bottom support and reflector areas. Oxidation may occur in the lower part of active core if the lower reflector has cooled sufficiently and no longer oxidizes.

Table 5.5 (continued)

Air flow and oxidation rate would eventually decrease due to limitations in available oxygen and the decreased buoyancy forces as the core cool, but could either increase or decrease due to core geometry changes.

If oxidation rate multiplied by 2: negligible differences in the accident outcomesc affect the location in the core.

Possible mitigation: to limit fresh air availability.

Table 5.6. Reactivity (ATWS) PIRT chart—GG

This chart is for phenomena specific to LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	Affect reactivity feedback.	L	Difficult to evaluate.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*				
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	Neutronic event.	M	Coupling CFD/3D neutronics. Simulation depends on core neutronics but also on T° and water vapor distribution in the core.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects reactivity.	H		H	
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).		H		M	
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.				
7	Xenon and samarium buildup.	Determination of poison distribution.	H	Recriticality occurs after xenon decay.	M	
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.				
9*	*Rod ejection prevention.*					

Table 5.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10*	*Coolant flow restarts during ATWS.*		H	If after recriticality the SCS is started → peak fuel temperature would exceed limits due to the selective undercooling effect.	H	3D TH with good knowledge of fluid properties: T increases → viscosity increases → friction increases → Q decreases.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Early part of the transient similar to P-LOFC w/o SCRAM:

- Negative temperature reactivity feedback coefficient quite strong (P decreases when T-nuclear increases and xenon poison builds up).
- Recriticality occurs around 32 h.
- Max T-fuel >1600°C after 2 days.

Variations in the accident consequences sensitive to:

- assumed values of fuel and moderator T reactivity feedback coefficients = f(T, burnup), and
- temperature reactivity feedback effects of the central and side reflectors.

Recriticality after xenon decay.

Table 5.8. Water-steam ingress PIRT chart—GG

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	H		H	
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	H		H	
3	RCCS performance with "gray gas" in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H		M	
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H		L/M	Vaporization with NC not well known → need of experiments. Steam condensation with NC better known.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H		H	
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	H		L	
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	H		M	Strong coupling TH/mechanics/chemical processes.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M		L	
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	M		L	
10	Cavity combustion gases.					
12	Cavity structural performance.	Influence on ingress analysis modeling.				

Table 5.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13	Cavity filtering performance.	Affects radioactive releases.	H		H	
14	Pressure transients from steam formation.	Potential damage to primary system structures.	M	Rapid depressurization → peak of pressure.	L	Boiling curve not well known in these geom. conditions.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 6/7.1. Normal operation 20–100% power PIRT chart—JG/JR

Table entries are the combined responses of Jess Gehin and John-Paul Renier (JG/JR). Responded only on neutronic issues.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21-D	Power and flux profiles (normal operation),	Affects core maximum temperatures; changes due to fuel burnup; control rod position; fuel, moderator, and reflector temperature-reactivity feedback; moderator/reflector fluence damage; pebble flow pattern (PBR); fuel loading (PMR).	H/H	FOM—Dose to worker, fuel failure fraction, fuel time at temp, core support. >Power and flux profiles determine burnup distribution, control rod effectiveness, key input into temperature distribution, and fluence to structural components.	M/M (prismatic) AND M/L (pebble)	> Currently there is a limited amount of available experimental data (both prismatic and pebble bed) for validation with new core designs (annual core) and lower fuel enrichments. > In terms of mean-free-path of neutrons, the core is compact such that the reflector has a significant influence well-within the core. This leads to difficulty in determining few-group neutron cross sections for core analysis. > There is potential for high power peaking near the reflector interface. Suppression with burnable absorbers may be effective for prismatic designs, but may be difficult to accurately calculate. >The stochastic nature of the pebble arrangement and burnup distributions leads to an inherent uncertainty in the local power density in a pebble bed reactor. >Lack of in-core instrumentation results in difficulty in measuring detailed core power and flux distributions. > Need for code validation with

Table 6/7.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						newer designs—annular core , higher burnup, core reflector interface, fuel location.
22	Reactivity–temperature feedback coefficients.	Affects core transient behavior.	H/H	FOM—Dose to worker, fuel failure fraction, fuel time at temp, core support. >Reactivity coefficients are important for determining core power distribution.	L/L	>Limited available experimental data for validation of reactivity temperature effects, particularly direct measurements of reactivity coefficients rather than overall transient response of the system and for high burnup fuels. >High temperatures of HTR systems magnifies errors in differential feedback coefficients over than of relatively well-known system. >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 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.

Table 6/7.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
23	Xenon buildup and oscillation.	Affects core transient behavior.	M/H	FOM—fuel failure fraction, fuel time at temperature >Fuel doesn't see extended periods of high temperatures on average >Xenon oscillations are more likely in large/tall cores and result in large local power densities that over time can result in fuel damage. >With proper instrumentation and controls, xenon oscillations are likely to be detected and suppressed or otherwise overcome. >Overall, steady-state xenon concentration is expected to be well predicted and understood.	M/M	>Reactivity defect resulting from xenon buildup at startup can be calculated and directly compared to operation. >Understanding of xenon oscillations well-known and with proper calculational tools and methods, stability can be assured.
26-D	Power and flux profiles(initial conditions for accidents).	Affects fuel potential for failures in accident conditions due to long-term exposures. For affecting conditions, see item #19.	H/H	FOM—dose to public, fuel failure fraction. >Major factor in fuel accident performance models.	M/M	>Need for code validation with newer designs—annular core, higher burnup, core reflector interface, fuel location.

*Issue not written down in the first PIRT meeting, but was discussed.
-D suffix denotes additions or alterations proposed by D. E. Carlson.
[1] H, M, or L (high, medium, or low).

Table 6/7.6. Reactivity (ATWS) PIRT chart—JG/JR

Includes ATWS, reactivity insertion events, etc.
Table entries are the combined responses of Jess Gehin and John-Paul Renier (JG/JR). Responded only on neutronic issues.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1-D	Reactivity insertion due to pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction.	M/M	FOM—fuel failure fraction, > Reactivity transients in HTRs relatively slow (in comparison with LWR) and negative feedback effects will limit power excursions.	M/M	>Given the compaction porosity, reactivity insertion can be bounded by conservative calculations with the maximum packing fraction. >Specific pebble bed compaction dependent upon seismic event and subject to wide variations.
3	Reactivity insertion due to steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H/H	FOM—fuel failure fraction, corrosion of core supports, dose to public >Design dependent and based on amount of steam-water inserted into primary system. >Past experience (FSV) indicates difficulty in ensuring that there is full separation of primary gas system and secondary water sources. >High reactor temperatures will result initially in steam ingress for which reactivity impacts will be less than for liquid.	M/M	If distribution is known, reactivity can be calculated. However, significant variations in calculations (maybe due to design differences or assumptions on amount and distribution of steam-water).

Table 6/7.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).	Affects passive safety shutdown characteristics.	H/H	FOM—fuel failure fraction, time at temperature Inherent defense against reactivity insertions.	L/L	>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.
6	Control and scram rods, and reserve shutdown worths.	Needed for cold or hot shutdown validation.	H/M	FOM—fuel failure fraction. >Needed for safety case. >Control rods and reserve shutdown methods are required to control reactor and to ensure sufficient shutdown margin exists to ensure that the core is maintained in a safe shutdown configuration.	M/L	Calculations of absorber worths can have large differences based on fixes to diffusion theory approach. >Control systems located in reflectors may result in greater difficulty in prediction of control rod/shutdown reactivity worths. >Control rod worths impacted by core axial power distribution, which may be difficult to predict because of temperature and burnup distributions. >Measurements of control rod worths generally performed as part of reactor startup procedures.

Table 6/7.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Xenon and samarium buildup.	Determination of poison distribution; xenon decay determines recriticality time.	M/M	FOM—fuel failure >Needed to check shutdown margin. >Transient behavior of xenon will impact recriticality, shutdown margin, and core power distribution. >Xenon transients occur over relatively long time scales (~10 h).	M/L	>Can predict power and flux profiles. >If power distribution and burnup distribution are well known, the xenon and samarium distribution can be predicted as well as the time-dependent behavior.
10*	*Coolant flow restarts during loss of forced circulation ATWS.*	*Can lead to selective undercooling of hot regions. Coupled thermal-fluids and neutronics.*	M/M	FOM—fuel failure fraction. >Recovery operation can lead to fuel failure.	L/L	>Distribution of flows, reactivity feedback, power distribution uncertainty. >Generally difficult to predict the local power peaking because of a combination of the coupled thermal-fluids/neutronics behavior and uncertainties in reactivity coefficients. >Complex flow distribution in pebble bed results in difficulty to predict undercooled regions.
12-D	Reactivity insertion from overcooling transients with ATWS.	Positive reactivity from decreases in core inlet temperature.	L/L	FOM—fuel failure fraction. >Negative feedback coefficients control transients, high heat capacity. >Long-term power stable because of negative reactivity coefficients and overall temperature increases will be slow.	H/H	>Readily bounded by current analyses, feedback coefficients known sufficiently well for bounding analysis.

Table 6/7.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13-D	Reactivity insertion from core support failure due to air ingress corrosion.	Core drop pulling away from control rods would insert reactivity.	L/L	FOM—fuel failure fraction. >Maximum withdrawal of control rods probably won't lead to recriticality (not far to fall).	M/M	>Lack of knowledge about scenario. >Maximum reactivity insertion can be bounded by system geometry and assumptions regarding the location of control rods.

*Issue not written down in the first PIRT meeting, but was discussed.

-D suffix—added or amended per D. E. Carlson suggestion.

[1] H, M, or L (high, medium, or low).

Table 8.1. Normal operation PIRT chart—MC

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.				
2	Core flow distribution.	Determines fuel operating temperatures.				
3*	*Core flow distribution changes due to T gradients.*	*Some effect on fuel operating temperatures.*				
4*	*Core flow distribution changes due to G irradiation.*	*Some effect on fuel operating temperatures.*				
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*				
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*				
7*	*Pebble bed core bridging.*	*Problem at AVR.*				
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*				
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.				
10	Coolant heat transfer correlations.	Determines core temperatures.				
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*				
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.				
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.				

Table 8.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	H	Path of flow is important to burnup.	L	Not clear how this is done and may be “High.”
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.				
16	Effective fuel element thermal conductivity.	Affects core maximum temperatures during operation.		[evaluation not recorded].		
17	Core specific heat.	Affects transients.				
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.				
19	RCCS behavior.	Affects residual heat losses, vessel temperatures.	H	Last level of safety for ultimate heat sink.	L	Design has not been scale tested and may be “High.”
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*				
21-D	Power and flux profiles.	Affects core maximum temperatures.				
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.				
23	Xenon buildup and oscillation.	Affects core transient behavior.				
24*	*Fuel performance modeling.*	*Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC,…*				
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 8.2. General LOFC PIRT chart—MC

This chart is for general cases of loss-of-forced circulation (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.				
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.				
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.				
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	This is an important heat transfer resistance for RCCS.	M-L	This is an area where R&D can optimize the emissivity value.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	Same as above.	M-L	Same as above.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	H	Same as above.	M-L	This is a design parameter that can be optimized by R&D.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.				
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	H	This will affect heat loss from the vessel (noted before).	M	This should be bounded and research will improve. estimates
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.				
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.				

Table 8.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
11	Stored (Wigner) energy releases.					
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	*H*	*Fouling is a common issue for heat exchangers.*	*M*	*This can be bounded if one is planning to over design the RCCS but can be part of 14–15.*
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	*H*	*Spatial effects will affect the heat removal capabilities.*		*Bound if planning to over design the RCCS but can be part of 14.*
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	H	This is a key ultimate heat sink system that needs more study.	L	The design of RCCS is a complete system that needs more study.
15	RCCS failure of both channels	Involves complex heat transfer to cavity walls.	H	Same as above.	L	Same as above.
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*				
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	H	Same as above.	H	Same as above.
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	H	Same as above.	H	Same as above.
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	*H*	Same as above.	*H*	Same as above.
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	H	Same as above.	H	Same as above.
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 8.3. Pressurized LOFC PIRT chart—MC

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.				
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperature				
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	If one loses flow then RCCS is sole heat sink even at high pressure.	L	This is not likely as an unknown of a topic area as low pressure but still low.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversal.				
5	Core coolant channel bypass flow.	Involves low-flow correlations, flow reversal.				
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.				
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 8.4. Depressurized LOFC PIRT chart—MC

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.				
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.				
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	H	If one loses flow then RCCS is sole heat sink especially at lo pressure.	L	This is likely an area of complicated heat transport from RPV to RCCS.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history .*				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 8.5. Air ingress LOFC PIRT chart—MC

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.				
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.				
3	RCCS performance with "gray gas" in cavity.	Particulates, etc. in cavity reduces radiant heat transfer; complex processes involved.	H	Particulates would reduce the heat loss.	M	This should be bounded and research will improve estimates.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	This is a source term issue—but needed.	L	This is a source term issue—but needed since the behavior of metallic fission products are not well known?? See the source term group work.
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*				
6	Core oxidation modeling.	Determination of "where" in core the oxidation would take place.	H	Oxidation with air or water ingress is key item to consider.	L	Oxidation is known but the geometrical effects need to be verified.
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	H	Controls the depressurization rate.	H	This should be known given the breaksize—research will not help?
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.				
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.				
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.				
11	Cavity combustion gases.					

Table 8.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
12	Cavity structural performance.	Influence on air ingress analysis modeling.				
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	Dusty gas can have dose effects that need to be quantified.	L	This effect can be bounded?? If not, then it is not well-known.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 8.6. Reactivity (ATWS) PIRT chart—MC

This chart is for phenomena specific to LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	FOM—dose; worker dose; fuel failure fraction; I am unsure of the mechanism other than pebble rubblization—but think its an issue.	L	I am unaware of any studies that look at pebble fracture, chipping or rubblization.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*		**WHAT THE ISSUE IS IN REGARD TO T/H PHENOMENA?**		
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	Covered elsewhere.	L	Covered elsewhere.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects reactivity.	H	Covered elsewhere.	L	Covered else where.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).			No opinion w/o more discussion—expertise is limited and do not see this as crucial.		
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.		No opinion w/o more discussion—expertise is limited and do not see this as crucial.		
7	Xenon and samarium buildup.	Determination of poison distribution.		No opinion w/o more discussion—expertise is limited and do not see this as crucial.		
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.		No opinion w/o more discussion—expertise is limited and do not see this as crucial.		

Table 8.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9*	*Rod ejection prevention.*	*Reactivity insertion.*	M	FOM—fuel failure fraction. Needs to be considered.	M	There would be uncertainty as to the CRD design for conceptual VHTR designs.
10*	*Coolant flow restarts during ATWS.*	*Reactivity insertion.*	M	FOM—fuel failure fraction. Needs to be considered.	M	There would be uncertainty as to flow scenario for concept design.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

FOM—Dose; worker dose; fuel failure fraction; time @ temperature; vessel and supports; reactor cavity.

Table 8.8. Water-steam ingress PIRT chart—MC

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	H	**FOM—dose; fuel failure fraction; time @ temperature.** Variation in flow properties of mixed gases would affect the computed temperature	H	Given that one knows the hydrodynamic transport of the gas constituents (not this phenomenon) then the flow properties can be determined with minimal uncertainty.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	H	**FOM—dose; fuel failure fraction; time @ temperature.** Variation in flow correlations of mixed gases would affect the computed temperature	H	The single phase gas correlations for heat transfer under turbulent flow (forced or mixed convection) are well known and the benefit/cost to reduce uncertainty is small.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H	**FOM—fuel failure fraction; time @ temperature; vessel and reactor cavity.** Particles will affect the heat loss thru the space.	M	This can be bounded with some assumptions but additional studies can assist in reducing the uncertainty in the parameters.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H	**FOM—dose and fuel failure fraction; time @ temperature.** Is design dependent, but NGNP concepts do consider He/H_2O heat exchanger.	L	This is rated “low” because design specifics need to be considered in NGNP concept as the specific design evolves.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.		**THIS IS THE SAME AS #4 for AIR INGRESS PHENOMENA.**		

Table 8.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Core support structures oxidation modeling.	Core support structure area potential weakening.		**THIS IS THE SAME AS #5 for AIR INGRESS PHENOMENA—should not different.**		
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	H	**FOM—dose and fuel failure fraction; time @ temperature.** Oxidation with air or water ingress is key item to consider.	L	This is again geometry dependent and thus needs to be examined.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.		**NO PHENOMENON GIVEN HYDRO TRANSPORT—WE KNOW GAS COMP and TEMPERATURE.**		
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.		**THIS HAS BEEN ANSWERED IN AIR INGRESS W.**		
10	Cavity combustion gases.	Hydrogen generation would be produced by C-oxidation.	H	**FOM—dose and fuel failure fraction; time @ temperature.** Makes a combustible gas in containment.	M	Could calculate H_2 dispersal—particularly with complex geometries though.
12	Cavity structural performance.	Influence on ingress analysis modeling.		**D-LOFC and AIR INGRESS HAS ALREADY BEEN ANSWERED.**		
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	**HAS ALREADY BEEN ANSWERED IN AIR INGRESS** dusty gas can have dose effects that need to be quantified.	L	This effect can be bounded?? If not, then it is not well-known.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	H	Pressure rise due to tube rupture events.	M	This could be bounded but may need more detailed analyses.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

FOM: Dose; worker dose; fuel failure fraction; time @ temperature; vessel and supports; reactor cavity.

Table 9.2. General LOFC PIRT chart—RG

This chart is for general cases of loss-of-forced circulation (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Principal property in predicting heat loss and peak fuel temperature.	M	Many models exist and graphite properties span wide range.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	M	Rather hard to take credit for.	L	Low relevant operational experience.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	M	Determines heatup rate given energy input.	H	Easy to measure
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	Key rate limit determining peak fuel and vessel temperatures.	M	Design specific.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	Same as 4.	M	Same as 4.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	H	Key factor in heat transfer.	H	Simple cavity geometry.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	M	Radiation dominates vessel response—probably well mixed.	H	CFD modeling well in hand.
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	Same as before.	M	Difficult radiation problem needing good data.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	Affects peak temperatures.	H	For nongraphite material well known—not sure of the material.

Table 9.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H	Key element in radiation heat transfer.	M	Variable properties depending on surface condition, oxide layers, etc.
11	Stored (Wigner) energy releases.	Initiator in windscale accident.	M	Most graphite likely annealed—need to account for if some graphite unannealed.	H	Assume well studied but probably variable degrees of energy accumulated.
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*		***The next several points are not phenomena and are a bit imponderable.***		
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*		***Not a phenomenon.***		
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.		***Not a phenomenon***.		
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.		***Not a phenomenon***.		
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	*??*	*This needs to be better specified.*	*L*	
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	M	Probably important with respect to development of peak temperatures and timing.	L	Probably will require design specific testing to provide confidence in modeling.
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	M	??	H	Boiling water??
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	*???*	*Phenomenon??*	*??*	*Probably needs design specific experiments like done in AP1000 and ESBWR.*
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	M	Affects steady heat removal??	L	Design specific—probably needs specific experiments.

Table 9.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	Major factor in heating term.	H	Neutronics and burnup well studied.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 9.3. Pressurized LOFC PIRT chart—RG

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well,

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	Affects hot spot peak temperatures?	M	CFD and experiment needed.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	Affects head heating and strength?	M	Difficult radiation problem.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	??			
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	Affects heat distribution.	M	CFD can help, but experiments likely needed to verify modeling.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	H	Important heat distribution effect.	M	Low flow correlations often in error.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	H	Important heat distribution effect.	M	Properties may be well known but friction not necessarily well modeled.
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*	??			

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 9.4. Depressurized LOFC PIRT chart—RG

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Conduction more important in depressurized accident as convection not strongly operative.	M	Models exist, but verification for particular designs and for fuel graphite irradiation effects needed.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	Will affect temperature distribution.	M	Should be calculable to adequate accuracy.
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	M	Not a phenomenon—should not be considering this as a phenomenon.	M	Not a phenomena.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	Very important to have this capability.	M/L	This is not a phenomena in and of itself and we should not elicit on this.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 9.5. Air ingress LOFC PIRT chart—RG

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	H	Viscosity affects flow distribution and corresponding thermal response.	H	For gases of interest viscosity and deviations from ideal gas behavior well characterized—possible that high temperature regime not as well characterized.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	L	Low gas heat capacity and large core thermal mass suggests uncertainty in heat transfer correlation not likely to produce large uncertainty in fuel temperature.	M	Experiments for varied geometry and conditions are limited.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	L	Assuming normal air transparency heat transfer likely dominated by radiation component—degraded concrete could raise importance.	M	Difficult radiation problem and not likely studies that thoroughly.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	Not clear what is meant by “performance” but oxidation could change surface properties like emissivity and conductivity.	L	Likely lack of experimental data.
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*	H	Likely a first structure to be attacked and for a long duration—structural change affects coolability and recoverability.	M	Likely that experiments relating oxidation damage to strength is lacking aside from simple loss of mass.
6	Core oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	First order importance on fission product release.	M	Data on kinetics span a wide range depending on grade and radiation damage.

Table 9.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	H	Cavity cooling determines peak fuel temperature.	L	Strong function of specific building design—not known before design and characterization of as-built facility.
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	Important boundary condition for vessel analysis.	L	Same as 7.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	Affects boundary conditions, but likely well mixed due to thermal driving forces.	L	Same as 7.
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.	H	Affects duration of oxidation damage.	L	Same as 7.
11	Cavity combustion gases.	Generation of CO under oxygen starved conditions.	L	Likely low levels of CO but could affect confinement building performance if burned.	L	Lack of data under variety of conditions.
12	Cavity structural performance.	Influence on air ingress analysis modeling.	M	Structural degradation is likely an effect more so than a cause.	L	Same as 7.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	M	Radioactive dust is a concern for PBMR, but more of a chronic issue in comparison to fuel releases.	L	Degree of problem not know owing to lack of real experience.
14a	Effective thermal conductivity.	Same as other tables.				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 9.6. Reactivity (ATWS) PIRT chart—RG

This chart is for phenomena specific to LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	FOM—dose; worker dose; fuel failure fraction. Issue is densification of random variations in ball packing fraction.	M	I think this has been studied in other fields with respect to range of variation in random packing of regular spheres. The neutronic impact of these variations needs to be analyzed.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP)*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*	H	Fuel failure from transient overpower.	L	Design dependent (L), ability to analyze neutronics (H).
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	Fuel damage by oxidation aggravated by neutronic excursion from water moderation?	L	Neutronics and design dependent issue?
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects reactivity.	H	Impact of fuel temperatures, oxidation and potential for affecting ATWS.	L	Not clear that this is a phenomenon that one can express a quantitative knowledge, however, knowledge is assumedly low owing to design dependent nature.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).	Important to quantify potential for reactivity initiated transients and natural shutdown mechanisms.	H	No opinion w/o more discussion—expertise is limited and do not see this as crucial.	L	Can be assessed with neutronics codes, but ultimately may require actual measurements on actual reactors to understand how good our analyses are.
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	H	Design detail—not fundamental physics phenomena.	H	Should be calculable using neutronics codes, but also design dependent.

Table 9.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Xenon and samarium buildup.	Determination of poison distribution.	L	Seems a second order effect at best with respect to safety issues.	M	Should be calculable using neutronics codes, but also design dependent.
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.	M	Design detail—not fundamental physics phenomena.	M	Design dependent—not a phenomena.
9*	*Rod ejection prevention.*	*Reactivity insertion.*	M	**FOM—fuel failure fraction.** Needs to be considered NOT a phenomenon to be evaluated for knowledge level.	M	NOT a phenomena to be evaluated for knowledge level.
10*	*Coolant flow restarts during ATWS.*	*Reactivity insertion.*	M	**FOM—fuel failure fraction.** Needs to be considered.	M	Probably not actionable via any phenomenological research—does point to the need for integral codes to evaluate transient performance.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 9.8. Water-steam ingress PIRT chart—RG

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	H	**FOM—dose; fuel failure fraction; time @ temperature.** Variation in flow properties of mixed gases would affect the computed temperature	H	Adding water further complicates mixture property analysis—transport properties considerably more important than thermodynamic properties since mass circulation of fluid is much more important that specific heat content.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	M	**FOM—dose; fuel failure fraction; time @ temperature.** Heat transfer probably not as important as one might think since the mass flow rate dictates energy transfer way more than heat content or how long the gas thermally equilibrates with fuel.	H	No strong motivation to increase knowledge here—again mass transport properties (flow resistance) have more effect on heat transport spatially.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H	**FOM—fuel failure fraction; time @ temperature; vessel and reactor cavity.** Particles will affect the heat loss through the space.	M	Adding water vapor again affect and complicates radiative properties of a participating gas by adding heat capacity and possible specific wavelength absorption bands. What energy doesn't pass through the gas is absorbed and transported elsewhere—natural circulation can

Table 9.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						be influenced by enhanced gas heating.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H	FOM—dose and fuel failure fraction; time @ temperature. This is design specific and not really a physics phenomena.	L	Design specific performance and fault behavior cannot be characterized by research into fundamental phenomena effectively until design is determined. When determined design specific fault and performance analyses such as PANDA for ESBER PCCS are often required.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	**SAME AS #4 for AIR INGRESS PHENOMENA.**	L	Oxidation in moist air could be different than what has been characterized. In general, I feel that oxidation phenomena are deserving of additional research in order to ensure we understand potentially very important differences due to $O_2/N_2/H_2O$ mixtures AND graphite morphological/ crystalline changes resulting from radiation damage. In general, I think any property that has been well characterized for unirradiated unaged

Table 9.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						materials needs to be investigated from the standpoint of radiation effects. There is a powerful lesson-learned from LWR fuel/clad performance relating to very significant differences from behavior of fresh vs irradiated materials.
6	Core support structures oxidation modeling.	Core support structure area potential weakening		SAME AS #5 for AIR INGRESS PHENOMENA—should not be different.	L	I would reiterate we need to be sure that oxidation of air and steam simultaneously, including effects of radiation damage needs to be well understood.
7	Core (steam) oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	FOM—dose and fuel failure fraction; time @ temperature. Oxidation with air or water ingress is key item to consider.	L	This is again geometry dependent and thus needs to be examined.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	**Composition and temperature are not phenomena—rather they are properties determined by heat and mass transfer.**	M	These properties will be determined as well as our models of heat and mass transfer can perform, but are not phenomena in and of themselves. Having said this, some design specific testing could be needed to validate codes used to predict this heat and mass transfer.

Table 9.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.		**See Air Ingress table.**		
10	Cavity combustion gases.	Hydrogen generation would be produced by C-oxidation.	H	**FOM—dose and fuel failure fraction; time @ temperature.** As stated “cavity combustion gases” is not a phenomena.	M	Gas compositions depend on graphite oxidation models and heat and mass transfer models, so this category is not a phenomena itself, rather it is an extrinsic property of other more fundamental processes including graphite oxidation, and heat and mass transfer.
12	Cavity structural performance.	Influence on ingress analysis modeling.		**See D-LOFC and AIR INGRESS.**		
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	Not appropriate topic for phenomena assessment—this is design specific and probably a safety grade performance issue.	L	Need to know design details to quantify.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	H	Pressure rise due to tube rupture events.	M	This could be bounded but may need more detailed analyses—not possible to estimate uncertainty in what is ultimately a code validation question.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.1. Normal operation PIRT chart—RS

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	Huge uncertainties exist on the bypass flow and how it changes during the life of the reactor. This factor greatly influences the operational temperature distribution. This is true of both pebble-beds and prismatic core configurations.	L	Although there exists a general understanding of this phenomena the specifics are lacking. No model exists that models the overall bypass flow behavior.
2	Core flow distribution.	Determines fuel operating temperatures.	H	Influenced by power distribution, bypass, and geometry. The biggest influence is the bypass—which is, in part, defined by geometry although the geometry is very complex.	L	See item 1. Experiments will be required to build acceptable models.
3*	Core flow distribution changes due to temperature gradients.	Some effect on fuel operating temperatures.	H	Changes in geometry due to temperature gradients are important together with the effect of increasing gas viscosity with increasing temperature.	H	Effects are well known and there appears to be good quantity of information that describes this effect. Enough information should be available to build models.
4*	Core flow distribution changes due to graphite irradiation.	Some effect on fuel operating temperatures.	H	Important influence on bypass fraction as a function of system life.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
5*	Core flow distribution changes due to core barrel geometry.	Some effect on fuel operating temperatures.	H	Important factor that is a basic design problem. Once the geometry is defined the influence of the core barrel on the core flow should be well defined.	H	Fundamental design boundary condition.

Table 10.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6*	Core flow distribution due to core block stability (prismatic).	Problem at Fort St. Vrain.	M	Changes in the core block configuration will exert major influence on core flow distribution. However, these problems were examined in detail at Fort St. Vrain.	H	Major activity at Fort St. Vrain. Hopefully lessons learned are being used in present designs. Importance is M because knowledge level is H.
7*	Pebble bed core bridging.	Problem at AVR.	H	Potentially a basic problem for pebble-bed reactors. This is a design problem that hopefully has been solved.	M	Experience at AVR showed that this may be an important factor and it is related to design. There are some factors that influence this behavior that are not as well known as they should be. Hence, importance is H since knowledge level is M.
8*	Pebble bed core wall interface effects on bypass flow.	Diversion of some core cooling flow.	H	Very important factor that influences the bypass flow in pebble-bed.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	H	Important for determining flow distribution.	H	Well known properties.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	Important for determining core operational temperatures.	L	Although global heat transfer correlations are well known there are specific situations, e.g., laminarization, behavior of flow in zones where there is high heating on one wall while another wall is adiabatic, mixed convection, etc., that are important.

Table 10.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
11*	Core inlet flow distribution.	Important for core cooling calculations.	H	Important for determining temperature distribution in core and throughout vessel.	L	Experiments will be required to better define. Problem is complex geometries in inlet plenum and the temperature distribution.
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	?			
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	H	Complex geometry and complex flow patterns translate to difficulty in predicting the presence of localized hot spots and the potential for thermal streaking at various locations in the plenum and also in hot duct leading to IHX or direct-cycle power conversion system.	L	Experiments required to validate the models required to predict the mixing behavior and the presence of localized hot spots.
14*	Pebble flow.	Affects core maximum temperatures, pebble burnup; problem at THTR.	H	Important for determining power distribution. Also may lead to overexposure of some pebbles that may lead to failure.	M	Experiments have been done—however, there may be some particulars that are known and that will only be determined by experiment.
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.	H	Important for determining temperature distribution.	H	This will be a measured value during plant operation.
16	Effective fuel element thermal conductivity.	Affects core maximum temperatures during operation.				
17	Core specific heat.	Affects transients.	H	Important for determining temperature distribution.	H	This will be a measured value during plant operation.
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	H	Affects the system temperature distribution.	H	Should be quantified by continuous measurements.

Table 10.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
19	RCCS heat removal performance.	Affects residual heat losses, vessel temperatures.	H	The parasitic heat loss to the environment is one of the boundary conditions for defining the system temperature distribution.	H	This condition will be fully described during the startup sequence. It will also be measured continuously during operation.
20*	Shutdown cooling system (SCS) startup transients.	Can affect component thermal stresses; dependent on design and operational details.	M	Influence of shutdown cooling system during startup is a standard operational scenario and is defined by design.	H	Should be well known based on earlier operational data from AVR, THTR, and Fort St. Vrain systems.
21-D	Power and flux profiles.	Affects core maximum temperatures.	H	Fundamental boundary condition.	M	Work is ongoing to better calculate.
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	H	Important ingredient in calculating neutronic feedback.	M	Work is ongoing to better calculate.
23	Xenon buildup and oscillation.	Affects core transient behavior.	H	Crucial to determining transient scenario progression.	H	Given known fuel characteristics this piece of information is well known.
24*	Fuel performance modeling.	Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC,…	H	Crucial ingredient in calculating power distribution and potential fission product release.	L	Active experimental activity.
25*	Ag-110*m* release and plateout.	Affects maintenance dose.				

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.2. General LOFC PIRT chart—RS

This chart is for general cases of loss-of-forced circulation (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Crucial information required to analyze energy transfer from core to environment.	M	General knowledge of mechanism is well known. Specific knowledge is lacking.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	H	Has capability to influence final fuel temperature by ~100°C.	M	General knowledge of mechanism is well known. Specific knowledge may be lacking.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Important information that influences heat transfer characteristics of energy transfer to environment.	M	General knowledge of mechanism is well known. Specific knowledge is lacking.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	Important factor in the reactor vessel wall temperature since this variable influences energy transfer to RCCS wall.	L	Although emissivities are well known for particular materials, the change in emissivity as a function of time is not known since it is affected both by aging and the influence of releases of particulate matter and other substances to cavity during various scenarios.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	Same as 4.	L	Same as 4.

Table 10.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	H	Important factor that influences temperature distribution on reactor vessel and RCCS concrete.	H	View factors are obtained by performing analytical evaluations using well known relationships. The calculations may be complex, however.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	H	Although this contribution isn't as significant as radiation heat transfer, this factor does have significant contribution and affects temperature distribution. Also, air circulation affects the movement of particulate matter in the cavity and its distribution.	L	The air circulation behavior will have to be quantified on the basis of experiment.
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	The air circulation caused by natural circulation will dominate (item 7) and affect heat transfer	L	We have a limited understanding of the various factors that will contribute to "gray gas."
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	Crucial factor that affects the temperature distribution in core and system.	M	General knowledge of mechanism is well known. Specific knowledge is lacking.
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H	Same as item 4.	L	Same as item 4.
11	Stored (Wigner) energy releases.		NO	Unaware of potential effect on system.	M	Aware of large knowledge base—likely applicable to VHTR.
12*	RCCS fouling on coolant side.	Affects heat sink effectiveness; deterioration can be measured on-line in some designs.	H	This factor will influence the coolant flow and temperature distribution.	M	General knowledge of mechanism is well known. Specific knowledge is lacking.

Table 10.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13*	RCCS spatial heat loadings.	Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.	H	Will influence the temperature distribution in system.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	H	Will influence the temperature distribution in RCCS.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.	H	Crucial influence. May result in overtemperature of both reactor vessel and concrete.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
16*	RCCS panel damage from missiles.	Complex phenomena involved.	H	Will require special techniques to evaluate. Many potential scenarios are possible.	L	Will require special techniques to evaluate and many scenarios are possible. Experiments are probably required.
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	H	Large influence on temperature distribution on vessel and concrete.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	H	Large influence on temperature distribution on vessel and concrete.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.

Table 10.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
19*	RCCS parallel channel interactions.	Complex phenomena; crucial to function.	H	Large influence on temperature distribution on vessel and concrete.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	H	Large influence on vessel and concrete temperatures.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	Crucial boundary condition.	H	ANS standard.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.3. Pressurized LOFC PIRT chart—RS

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	The stratification and plumes will determine the location of localized hot spots in inlet plenum.	L	Although the general mechanisms that will define the temperature distributions are well known, the location of hot spots and the change in the location of hot spots as a function of decay power and bypass must be defined by experiment.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	Important mechanism that will define the temperature distribution.	M	General knowledge of mechanism is well known. Specific knowledge is lacking.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	Important influence on temperature distribution. Will influence of localized hot spots.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	Influence of bypass and the change in power distribution due to decay heat will influence the core distribution and thus the upflow–downflow behavior including location of localized hot spots.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required. The influence of the bypass is a particularly vexing problem.

Table 10.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	H	See item 4.	L	General factors that influence the bypass are well known, but a model for predicting the general behavior is not available. Experiments will be required.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	H	Important influence on the behavior of the plumes and general core flow distribution.	M	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required particularly to quantify effect of bypass.
7*	SCS startup flows—transients.	Thermal transients for P-LOFCs more pronounced.	H	Will influence the behavior of the flow in the reactor vessel.	L	General knowledge of mechanism is well known. Specific knowledge is lacking. Experiments may be required.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.4. Depressurized LOFC PIRT chart—RS

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Crucial in determining temperature distribution in core.	M	General knowledge of mechanism is well known, but specific knowledge is lacking.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	Boundary condition.	M	Decay heat characteristics are well known. Distribution of fuel in some cases is well known (prismatic) but not in all cases (pebble-bed).
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	H	Influential in determining the possibility for localized hot spots on vessel wall.	L	General knowledge of mechanism is well known, but specific knowledge is lacking. Experiments required.
4*	Heatup accident fuel performance modeling.	Crucial factor in reactor design limits; dependent on fuel type, operational history.	H	Important for power and temperature distribution. Also as source term for fission product release.	M	Ongoing experiments.
5	Exchange flows.	Stratified flow into the vessel at end of depressurization: determines the quantity of air that is available for molecular diffusion.	H	Determines the initial boundary condition for air quantity and distribution in the vessel.	L	General knowledge of mechanism is well known, but specific knowledge is lacking. Experiments required.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.5. Air ingress LOFC PIRT chart—RS

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	H	Important to determine diffusion and flow characteristics.	H	Well known behavior and fluid properties.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	H	Important: determines oxidation characteristics and temperature distributions.	M	Much work is ongoing to determine these effects. Experiments are necessary.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H	Important: determines heat transfer via radiation and also contributions to natural circulation behavior.	L	Contributors to “gray gas” are not well defined, and their contributions as a function of time also need to be modeled.
4*	Fuel performance with oxygen attack.	Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	Influential in determining potential fuel failure scenarios.	M	Work is ongoing.
5*	Core support structures oxidation modeling.	Low-temperature oxidation potentially damaging to structural strength.	H	Important since oxidation of support structures weakens the structures but also “uses-up” oxygen that might otherwise be available for damaging the core.	M	Work is ongoing.
6	Core oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	Important in determining sites for potential core failure and fission product release.	M	Work is ongoing.
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	H	Fission product release and may affect natural circulation and/or “gray gas” content.	L	General behavior characteristics are known but specifics are missing.

Table 10.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	Boundary condition.	H	Measurable.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	H	Stratification and mixing will determine zones of limited natural circulation and also zones where some particulates may congregate and influence local heat transfer.	L	General behavioral characteristics are well known but specifics must be modeled and quantified. Experiments will be required.
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.	H	Influences the quantity of available air for oxidation.	L	Configuration specific.
11	Cavity combustion gases.		?			
12	Cavity structural performance.	Influence on air ingress analysis modeling.	H	Important for fission product release and also defining the available oxygen for air ingress.	M	Should be design specific.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	Same as item 12.	M	General behavior characteristics are well known however this is design specific.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.6. Reactivity (ATWS) PIRT chart—RS

This chart is for phenomena specific to LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	Compaction density is crucial in determining core power levels.	M	Some work is ongoing and there is an ongoing theory to define compaction.
2*	[Prismatic] Excess reactivity (with burnable poison—BP).	Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.	H	Boundary condition for determining power level during reactor transients.	M	Some work is ongoing in R&D community to fully define implications of various initial enrichments in fuels.
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	Given a source of water is available the presence of water will change the neutronic behavior.	L	For low quantities of water that become available the knowledge base is not so large.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; affects reactivity.	H	Same as item 3.	L	Same as item 3.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).		H	Crucial for modeling neutronic behavior.	M	Some work is ongoing.
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	H	Fundamental boundary condition.	H	
7	Xenon and samarium buildup.	Determination of poison distribution.	H	Fundamental boundary condition.	L	Availability of validation data is low.
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.	H	Boundary condition.	M	Configuration dependent.
9*	*Rod ejection prevention.*		H	Boundary condition.	M	Configuration dependent.
10*	*Coolant flow restarts during ATWS.*		H	Boundary condition.	M	Configuration dependent.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 10.8. Water-steam ingress PIRT chart—RS

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	H	Boundary condition.	L	Must be some information available that can be used. Part of problem is defining appropriate mixed flow properties at specific location as a function of time.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	H	Same as 1.	L	Same as 1.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc. in cavity reduces radiant heat transfer; complex processes involved.	M	See General PIRT table.		
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H	Given water or steam ingress occurs—then the effect of the water/steam are important given significant quantities of water/steam are present.	M	Some information are available from Ft. St. Vrain and earlier experiments.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	Given water or steam ingress occur—then the effect of the water/steam are important given significant quantities of water/steam are present.	M	Contribution due to water/steam may need further investigation.
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	H	Given water or steam ingress occur—then the effect of the water/steam are important given significant quantities of water/steam are present.	M	Contribution due to water/steam may need further investigation.

Table 10.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Core (steam) oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	Given water or steam ingress occur—then the effect of the water/steam are important given significant quantities of water/steam are present.	M	Contribution due to water/steam may need further investigation.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	Boundary condition.	M	
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	H	Becomes boundary condition.	M	Standard for validation of tools will likely be required.
10	Cavity combustion gases.		?	Uncertain about formation of hydrogen and other potential combustion gases and their contributions.		
12	Cavity structural performance.	Influence on ingress analysis modeling.	?			
13	Cavity filtering performance.	Affects radioactive releases.	?			
14	Pressure transients from steam formation.	Potential damage to primary system structures.	M	If liquid quantities are large enough then there may be concerns for condensation-induced water hammer and also pressure-transients.		

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 11.1. Normal operation PIRT chart—SB

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	Varies with shifts in block gaps, etc. No way to measure it.	M	Not much to do about it except provide margin; design dependencies.
2	Core flow distribution.	Determines fuel operating temperatures.	M	Distribution within very tall core can tend to be counterproductive.	H	Correlations well known at high flows.
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	M	Probably secondary effect at high flows.	M	Correlations well known.
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	M	Could be secondary effect.	L	Hard to predict; random in nature; no means to measure.
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	M	Could be secondary effect; warping could affect inlet plenum jets.	L	Hard to predict and measure; design dependent (only applies to cases where inlet flow impacted).
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	M	Can be avoided or mitigated by design. Taller core makes problems more likely.	L	Hard to predict. Measurements of occurrence very clear.
7*	*Pebble bed core bridging.*	*Problem at AVR (early).*	L	Can be avoided by good pebble discharge design.	M	Solutions established.
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	M	Combination of cooling anomalies and flux peaking = uncertainties.	M	Calculation tools improved recently.
9	Coolant properties—viscosity and friction effects.	Determines core temperatures and pressure drop.	H	Pressure drop (in PBR) important parameter.	M	Good correlations available.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	Questions arise due to surprise results in AVR.	M	Good correlations for normal flow.
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	M	Flow may be skewed with warped inlet paths.	L	Difficult to predict and measure.

Table 11.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	M	Possible mismatched temperatures (parallel loops); stress problems.	M	Problems could be avoided (or reduced) by design.
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	M	Depends on fuel loading strategy (prism); effect on turbomachine; Probable cause of damage at THTR.	M	Difficult to predict and measure.
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	M	Less of a problem with higher multipass pebbles; flow viscosity reduced at higher temperatures.	M	Effects can be estimated.
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.	L	Convection heat transfer dominates at rated flows.	H	Models well known.
16	Effective fuel element thermal conductivity.	Affects core maximum temperatures during operation.	H	Large temperature rise in element at full power.	M	Variations due to gaps and decreases in graphite conductivity from irradiation.
17	Core specific heat.	Affects transients.	M	Slower response → more manageable transients.	H	Well-known
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	M	Can have significant effect on vessel operating temperature (design dependent).	H	Well-known
19	RCCS heat removal performance.	Affects residual heat losses, vessel temperatures.	H	Parasitic heat loss; vessel temperature and gradients are crucial; potential cavity concrete temperature problems.	M	Difficult design problems—historically. Needs experimental verification for specific design(s).
20*	*Shutdown cooling system (SCS) startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*	L	Previous concern with large HTGRs. SCS inlet gas in reasonable temperature range.	M	Modeling adequate. [Also noted in P-LOFC chart (#7), but considered "normal op" here.]

Table 11.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21-D	Power and flux profiles.	Affects core maximum temperatures.	H	Determines operating fuel temperatures.	M	Modeling usually adequate for normal operation, but some uncertainties for PBR.
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	M	Helps provide inherent control and safety.	H	Modeling adequate; can be inferred experimentally (on line).
23	Xenon buildup and oscillation.	Affects core transient behavior.	M	Possible problems (axial) for tall cores.	M	Modeling probably adequate; V&V needed.
24*	*Fuel performance modeling.*	*Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC.*	H	Key to licensing without containment.	M	Models improving; dependent on fuel type and QA/QC for final results.
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*	M	Possible concern for high temperature, after plutonium buildup.	L	Phenomena for Ag-110*m* release and transport not well understood.
26-D	Power and flux profiles (initial conditions for accidents).	Affects potential for subsequent fuel failure.		*Panel: "NOT required."*		

*Issue not written down in the first PIRT meeting, but was discussed.

-D suffix suggested by D. E. Carlson (NRC).

[1] H, M, or L (high, medium, or low).

Table 11.2. General LOFC PIRT chart—SB

This chart is for general cases of loss-of-forced cooling (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Major factor in peak temperatures in D-LOFC accidents, not important for P-LOFC.	M	Fairly good data available for prism and pebble cores; most differences probably due to difficult measurement.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	H	Can make ~100°C difference in peak fuel temperature (D-LOFC).	M	Difficulties tracking and predicting core conductivity via irradiation and annealing histories.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Slow response for large MCp; time for remedies and FP decay.	H	Cp values close to (well-known) graphite Cp vs temperature.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	T^4 heat transfer dominates (85–90%) in LOFC transients; may be important for vessel temperatures, but not for T-max-fuel.	H	In-service steel vessel emissivities are well-known.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	T^4 heat transfer dominates (85–90%) in LOFC transients.	H	Emissivities are fairly well-known for steel, once oxidized.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex.	H	Determination of spatial temperature distribution, especially in upper reactor pressure vessel (RPV) cavity.	M	Complex geometries involved.

Table 11.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	H	>L–minor contributor to total heat transfer. >H–major contributor to upper cavity heating.	M	Correlations not accurate for complex geometries; CFD models need some work.
8	Reactor vessel cavity "gray gas" (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	Modest effect on peak vessel temperature, negligible effect on T-max-fuel; unlikely event.	M	Influence on effective emissivities are known well enough for bounding calculations.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures in D-LOFC.	M	Modest effect on peak fuel and vessel temperatures.	H	Conductivities known well enough.
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures in D-LOFC.	M	Modest effect on peak fuel and vessel temperatures.	H	Emissivities are well known.
11	Stored (Wigner) energy releases.	Effects apply to low-temperature operation graphite reactors.	L	Not expected for high-temp irradiation of graphite.	H	Effects well known; not a factor in modular HTGRs.
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	M	Affects maximum vessel temperature in some accident scenarios.	M	Effect and extent of problem depends on RCCS design (air or water), etc.
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	M	Affects maximum vessel temperature in some accident scenarios.	M	Effect and extent of problem depends on RCCS design (air or water), etc.
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	M	Affects maximum vessel temperature in some accident scenarios; could cause panel strain (deformation) problems.	M	Difficult modeling to determine deformation.
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.	M	Affects maximum vessel temperature; unlikely accident.	L	Difficult modeling.
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	M	Unlikely accident.	L	Difficult modeling; design dependent.

Table 11.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	H	Important transition in accident sequence.	M	Detailed calculations and tests needed (major need).
18	RCCS single phase—boiling transitions.	Complex phenomena; crucial to function.	H	Important transitions (both ways) in accident sequence.	M	Detailed calculations needed (major need).
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	H	Difficulties more likely with water (vs air) and horizontal panels.	M	Detailed calculations needed (major need).
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	H	Most cavity heating problems occur in top panel.	M	Detailed calculations needed (major need).
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	Dependent on fuel type and burnup; major factor in peak temperatures in D-LOFC accidents, not important for P-LOFC.	H	Some refinements recommended (major impact); standard correlations appear to be conservative (vs experiments).

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 11.3. Pressurized LOFC PIRT chart—SB

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	M	Impact of hot plumes in P-LOFC minimized by insulation design.	M	Modeling of plumes and their effects are difficult.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	M	T^4 effects are significant contributors to reactor pressure vessel (RPV) top head heat load.	M	Uncertainties in model inputs (core top surface temperatures, standpipe interference, etc.).
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	M	Vessel and cavity heating problems more likely near top; RCCS load redistributions may be cause for panel strain and deformation.	M	Shifts in T^4 and convective heating distributions.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	M	Major changes in core temperature profiles, but maximum temperatures stay well below limits.	M	Uncertainties due to low-flow correlations and flow reversal transitions; correlation uncertainties greater in PBR.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	M	By-pass flow can have large effect on total reversal flow rates.	M	Uncertainties due to low-flow correlations (especially in PBR) and flow reversal transitions.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	M	Affects changes in core temperature profiles, but maximum temperatures are well below limits.	M	Uncertainties due to low-flow correlations and flow reversal transitions.
7*	*Impacts of SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*	M	This was a major concern for large HTGR designs, but less (or none) for modular HTGRs with much lower maximum core temperatures.	M	Models required are well-known (enough).

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 11.4. Depressurized LOFC PIRT chart—SB

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Major parameter affecting peak fuel temperature in D-LOFC.	M	Variation uncertainties remain, but large margins allow for them; more variability in PBR than PMR data.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	Major parameter affecting peak fuel temperature.	M	Uncertainty margins not as large as for core conductivity, but need to be accounted for. Standard decay heat curves generally conservative.
3	RCCS spatial heat loadings.	Major shifts in heat load to middle (beltline) of RCCS; complex geometries involved.	M	Could affect RCCS performance and T-vessel-max; little effect on T_{Fuel} max.	M	Uncertainties probably not significant.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	Determines fuel time-at-temperature limits; defining transient for rated power level.	M	Tests on specific fuels are needed.
5	Hydrodynamics conditions for dust suspension (Fluid Structure Interactions).	From discussion with fission product panel.	M	Possible dose concerns.	M	Complex process.
6	Dust effect on coolant properties and flow in vessel.	Affects circulation.	L	Minor impact.	M	Complex calculation.
7	Cavity over-pressurization.	Possible damage to cavity components.	H	Challenge RCCS structural integrity.	M	Complex geometry.
8	Pressure pulse in confinement.	Possible damage to cavity components.	H	Possible failures of confinement systems.	M	Complex phenomena involved.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 11.5. Air Ingress LOFC PIRT chart—SB

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	L	Little effect on accident outcome.	M	Properties well-known, but some composition uncertainties.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	L	Small effect on accident outcome.	M	Properties well-known, but some composition uncertainties.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc., in cavity reduce radiant heat transfer; complex processes involved.	M	Minor effect on accident outcome; very unlikely.	M	Models adequate for bounding calculation.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	M	Low probability; fueled core area of exposure probably at temperatures less than critical for FP release.	M	Models and data probably sufficient for SiC coatings (not ZrC).
5*	*Core support structures oxidation.*	*Low-temperature oxidation potentially damaging to structural strength.*	H	Core structure area first seen by incoming ingress air; low probability accident.	M	Crucial to maintaining coolable core geometry.
6	Core oxidation.	Determination of "where" in core the oxidation would take place.	M	Need for details of fuel area oxidation damage; low probability.	M	May be needed for core damage assessment.
7	Reactor cavity to reactor vessel air ingress (see 14 and 15).	Cavity to vessel flow after D-LOFCs.		[Covered elsewhere.]		
8	Phenomena affecting cavity gas composition and temperature with in-flow.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Mixing and stratification characteristics needed for detailed analysis; low probability event.	M	Needed to estimate long-term oxidation damage to structures and core.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	Mixing and stratification characteristics needed for detailed analysis; low probability.	M	Needed to estimate long-term oxidation damage; data needed; some may be available from LWR studies.

Table 11.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10	Confinement to reactor cavity air ingress.	Determines long-term oxidation rate if accident unchecked.	M	This assumes separate (effective) compartments for the confinement building and the cavity surrounding the reactor vessel; low probability.	M	More design data needed; assumptions made for bounding calculations.
11	Cavity combustion gases.	Some CO formed as oxidation product.	L	Low probability of danger (if not inhaled).	M	Models available.
12	Cavity structural integrity during blowdown.	Influence on air ingress analysis modeling.	M	Affects cavity holdup volume; account for damage due to large, fast depressurization.	M	Rough approximation modeling probably sufficient for bounding calculations.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBR.	M	May be significant release for PBR if not sufficiently filtered; filter assumed to be between confinement and environment; may also be a problem even without air ingress.	M	Dust filter options should be investigated and tested.
14-RS	Duct exchange flow.	Stratified flow phenomena leading to helium flow exit and air ingress into lower plenum.	M	One factor in the determination of onset of natural circulation and significant air ingress flow.	M	Model for molecular diffusion effects (one contributing phenomenon) is good for idealized cases.
15-GG	Molecular diffusion.	Air remaining in the reactor cavity enters into RPV by molecular diffusion prior to onset of natural circulation.	M	(See #14)—contributor to duct exchange flow phenomenon.	M	Contributes to determination of air ingress onset time.
16-GG	Chimney effects.	In case of double break.	M	Two breaks must be such that both core inlet and outlet exposed to cavity air; very low probability.	M	Models probably sufficient for bounding calculations.
17	Thermal stratification mixing in the lower plenum (see #14).	Affects support structural damage estimates.	M	Well-mixed conditions likely once ingress flow begins; low probability event.	M	Models probably sufficient for bounding calculations.

Table 11.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
18	Environment to confinement air in-leakage.	Long term air in-leakage to confinement building (see #10).	H	Total graphite oxidation determined by (fresh) air availability.	M	Tests on confinement structures needed for bounding calculations.
19	Core flow distribution following onset of natural circulation.	Affects spatial damage profiles in lower support, reflector, and core areas.	M	Useful in estimating maximum damage areas (see #1).	M	Models probably sufficient for bounding calculations.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 11.6. Reactivity events (including ATWS) PIRT chart—SB

This chart includes LOFC phenomena cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction.	M	One of the few reactivity accidents of interest; usual analyses are ultra-conservative by assuming instantaneous change in packing fraction.	H	Scoping calculations are sufficient; calculation of reactivity change with compaction is routine.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*		*Eliminated by panel.*		
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	M	Very low probability accident (nonsteam cycle plant); some calculations show no increase in reactivity with ingress for annular modular HTGR cores.	M	Scoping calculations are sufficient; effects are design dependent.
4a BC	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; affects reactivity.	L	Very low probability accident; even unlikely scenarios introduce very little water; (for steam generator in primary loop, this is a high risk event).	M	Scoping calculations are sufficient.
4b SG	Mechanisms for water or steam ingress from steam generator.	Some water ingress scenarios are postulated; effects on reactivity.		**Not considered by panel.**		
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).	Inherent defense against reactivity surges. Vary with temperature, burnup.	H	Major argument for inherent safety design.	M	Thorough investigations, experiments needed; dependent on fuel type. Some aspects can be deduced from on-line tests.

Table 11.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	H	Needed for safety case.	M	Calculations and experiments needed for operational modes.
7	Xenon and samarium buildup.	Determination of poisoning and its distribution.	M	Needed to check shutdown margins.	M	Models well known.
8**	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.	M	Rapid response not required. Modest negative insertion would probably suffice to avoid fuel failure.	M	Design review probably sufficient.
9**	*Rod ejection prevention.*	*Ejection can be avoided by design.*	L	Ejection very unlikely.	M	Need to assure avoidance by design fix.
10*	*Coolant flow restarts during ATWS.*	*Accident can be avoided by design.*	M	Very low probability, but bad outcome. Natural tendency for operator to restart flow.	M	Need to assure avoidance.

*Issue not written down in the first PIRT meeting, but was discussed.

**Item eliminated by panel vote (with SB dissent).

[1] H, M, or L (high, medium, or low).

Table 11.7. IHX failure (molten salt-MS) PIRT chart—SB

Design assumptions: Molten salt (~800°C), inventory = 130,000 kg (3000 ft^3), 15,000 ft^3 in reactor, isolation valves?
Scenario: Break of IHX internal tubes, blowdown of primary to secondary, then possible ingress of molten salt (no nitrates).
Conditions: Secondary side press lower than primary (no nitrate salts), lower plenum filled with molten salt by ~X hrs with partial P/D-LOFC. He escapes by secondary relief valve out molten salt lines (confinement bypass), countercurrent flow, lots of inertia as 0.5 miles of molten salt slows down and pump coasts down.
Single failure: Isolation valve fails to close.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Ingress of helium into IHX loop (part of confinement bypass).	Blowdown of primary system into secondary system, gas jet into liquid, initial circulating activity is the prime source of the public and worker dose.	M	FOM—public and worker dose. >Low probability. Primary circulating activity would be low, and what little of it that would make it to the MS loop would probably be totally adsorbed.	H	Processes well known.
2	*Fission product* transport through IHX loop (part of confinement bypass).	Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out.	M	FOM—public and worker dose. >See #1.	M	See #1.
3	*He* transport in IHX loop (part of confinement bypass).	Possible He/molten salt countercurrent flow, blocking bubble in IHX loop.	L	FOM—public and worker dose. >Helium by-passes confinement filters, but circulating activity low, adsorbed by MS.	M	Processes well known, but scenario is complex.
4	Ingress of molten salt into primary system and RPV.	After partial blowdown, relies on items #1, 2, 3 as initial/boundary conditions.	H	FOM—vessel temps, vessel support temps, core support temps. >Hot MS bypass into primary possible source of high transient stresses.	M	Complex scenario, model uncertainties, but OK for bounding calculations.
5	Riser fill with molten salt.	Through cold duct.	H	FOM—vessel temps, vessel support temps, core support temps. >See #4.	M	Complex scenario, model uncertainties, but OK for bounding calculations.

Table 11.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Lower plenum fill with molten salt.	Through hot duct.	M	FOM—vessel temps, vessel support temps, core support temps. >See #4; less of a problem with lower plenum, which is designed for higher temperatures.	M	Complex scenario, model uncertainties, but OK for bounding calculations.
7	Molten salt (in cold duct)-to-core support/vessel heat transfer.		H	FOM—vessel temps, vessel support temps, core support temps. >See #4.	M	Complex scenario, model uncertainties, but OK for bounding calculations.
8	Molten salt (in hot duct)-to-core support/vessel heat transfer.		M	FOM—vessel temps, vessel support temps, core support temps. >See #6.	M	Complex scenario, model uncertainties, but OK for bounding calculations.
9	RCCS heat removal.	Heat transfer from vessel wall to RCCS and cavity.	H	FOM—vessel temps, vessel support temps, cavity temps. >Possible need for higher heat removal rate.	M	Complex scenario, model uncertainties, but OK for bounding calculations.

[1] H, M, or L (high, medium, or low).

Table 11.7a. Process heat PIRT chart—SB

This chart is for phenomena specific to process heat plant interactions; see other applicable charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Oxygen plume encroachment.	Cloud release can be a problem if cold, ground-hugging plume (from upwind). Disable reactor plant operators, equipment; possible combustion.	H	Oxygen plumes can be disastrous.	M	Some models available.
2	Corrosive and/or toxic gas plume encroachment.	Cloud release can be a problem if cold, ground-hugging plume (from upwind). Burns and suffocation possible.	H	Burns, disable reactor personnel; can be disastrous.	M	Some models available.
3	Gas ingress to reactor via IHX failure.	Loss of reactor heat sink (partial?); possible effect on reactivity (e.g., steam); core inlet temperature perturbation.	M	Could initiate LOFC event; core inlet transients not likely to be a major problem.	H	LOFCs well understood.
4	Gas ingress to reactor and reactor cavity via IHX failure.	For high-pressure (helium) heat transfer loop, possible severe overpressure of reactor cavity and confinement building.	H	Release of large inventory in transfer loop might destroy confinement; unlikely event.	M	Bounding analysis modeling available.
5	Hydrogen gas plume encroachment.	Only a problem if inside or otherwise contained. Burning possible.	M	Can probably be "designed out."	M	Some models available.
6	Loss of heat transfer fluid in pipe to process heat plant.	Loss of reactor heat sink (partial?).	M	Reactor could handle transient.	M	Some models available.

[1] H, M, or L (high, medium, or low).

Table 11.8. Water-steam ingress PIRT chart—SB

This chart is for phenomena specific to LOFC cases (no steam generator in primary circuit); see also general LOFC chart.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	L	Small effect on accident outcome; very low probability accident.	M	Models sufficient.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	L	Small effect on accident outcome; very low probability accident.	M	Models sufficient.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	L	Small effect on accident outcome; very low probability accident.	M	Models sufficient.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	L	Very low probability accident.	M	Some scoping models would be needed.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	L	Effects of moisture on fuel should be checked; Very low probability accident.	M	Some scoping models and experiments may be needed; dependent on fuel type.
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	L	Effects of moisture on structures should be checked; very low probability accident.	M	Some scoping models and experiments may be needed.
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	L	Effects of moisture on fuel should be checked (combine with #5).	M	Some scoping models and experiments may be needed.
	***** Items 8–14	Were omitted by panel.***				
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	L	Very low probability accident.	M	Models probably sufficient.

Table 11.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	L	Very low probability accident.	M	Models probably sufficient.
10	Cavity combustion gases.	CO collection.	L	Very low probability accident.	M	Models sufficient for task.
12	Cavity structural performance.	Influence on ingress analysis modeling.	L	Very low probability accident.	M	Models sufficient for task.
13	Cavity filtering performance.	Affects radioactive releases.	L	Very low probability accident.	M	Models sufficient for task.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	L	Very low probability accident.	M	Models sufficient for task.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 12.1. Normal operation PIRT chart—SF

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	Affects core follow predictions/accident analysis because affects T_{fuel}. May not be as much of a factor as FSV due to lack of orifices—so may be considered to be an M; however with no orificing—P/F in each region is important.	L	In past, we lived with uncertainties related to this aspect (over time)—nice to define this better for range of conditions—testing/instrumentation required—wished FSV had more instrumentation—*need parameter for thermal power measurement.*
2	Core flow distribution.	Determines fuel operating temperatures.	M (applies to below)	Affects core follow predictions—effect is limited-indirect neutronics effects; FSV: orifices—but this does not-less challenging if bypass flow is well known.	M	Crossflow from reflectors causes uncertainty—will change over time with irradiation and fuel block bowing and other Rx specific reactors recommend series of calculations on this. *Need parameter for thermal power measurement.*
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	M	Not significant, because of forced circulator flow.	M	Properties generally understood.
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	M	Some effect, but essentially core flow distribution should not change in a major way due to changes in gaps.	M	Depends on graphite qualification data-but should be known reasonably well.
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	M	Not significant, compared to coolant hole surface area.	M	It is age related phenomena.
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	M	More significant: even with RCDs core moves causing changes in core flow—however, with no orifices	M	The phenomena is known to occur—there is some uncertainty due to taller core.

Table 12.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				and heavier columns—probably not as large a problem—design dependent.		
7*	*Pebble bed core bridging.*	*Problem at AVR.*	M		M	
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	M		M	
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	H	Important, yes, but known adequately.	H	I see no need to research coolant properties—they are well known.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	Affects code validation.	H	H-prism—well known and adequate M-pebble—known to be hot spot local effects in bed more difficult to model.
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	M	I assume this is mixing in upper plenum.	M	This phenomena closely tied with above phenomena—can be modeled to see effect. *Need parameter for thermal power measurement.*
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	M	Presumably separate loop temps should be similar anyway.	L	Instrumentation/testing needed to validate.
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	H	Combination of above effects—depends on power distribution and mixing—cooling at hottest part of fuel.	M	Core instrumentation should be used to measure—compare with physics predictions in normal operation. *Need parameter to feed thermal calc for fuel temperatures and (related to thermal power measurement).*
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	H	Pebble flow important to burnup and it changes, depending on bed.	M	Effect is known—but predicting flow is tricky.

Table 12.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
15	Effective core thermal conductivity.	Effects core maximum temperatures during operation.	M	Some uncertainties across inner/and outer reflect blocks: forced cooling not as important.	H	Properties of materials are well known.
16	Effective fuel element thermal conductivity.	Effects core maximum temperatures during operation.		[Evaluation not recorded.]		
17	Core specific heat.	Affects transients.	M	A large player in passive safety and operational response.	H	Properties of irradiated graphite are well known—passive behavior of graphite cores is well established—although may be differences in various graphites.
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	M	Normal ops—a factor in performing overall heat balance and measuring core power output—but secondary effect on fuel temperature.	M	Amenable to calculation—however *need good information to do heat balance on core power—long core—may be considerable loss on side*—instrumentation suggested.
19	RCCS behavior.	Affects residual heat losses, vessel temperatures.	M	Not much impact on normal ops—factor in expected transients—but transients are slow—runs during normal ops.	M	Amenable to calculation, not tested, but could be in prototype.
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*	H	Need better definition here on this class of transients.	M	Can be bounded.
21-D	Power and flux profiles.	Affects core maximum temperatures; Changes due to fuel burnup; control rod position; fuel, moderator, and reflector temperature—reactivity feedback; moderator/reflector fluence damage; pebble flow pattern (PBR); fuel loading (PMR).	H	Important to know axial power and radial profile over cycles. Biggest concern—must prevent power from flipping to bottom resulting in exceeding fuel temperature.	M	Physics methods are established, however, validation data for annular core not plentiful—a lot of reflector/fuel interface—spectral changes here—more plutonium in the core due to LEU—need to examine its effect and its cross-section aspects.

Table 12.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	H	Critical safety parameter, but also governs reactor behavior-must be well known.	M	Fuel driven parameter—feedback properties of U/Th fuels well established—UO_2 fuels not as established, but tools are pretty good—graphite cores have not been a problem here—more plutonium in this core however.
23	Xenon buildup and oscillation.	Affects core transient behavior.	M	Long axial core—however core is neutronically coupled more than LWRs.	H	Physics is well established—but dependent on power distribution. Current analysis methods can be used to examine susceptibility of core.
24*	*Fuel performance modeling.*	*Fuel type dependent. Crucial to design and siting; depends on performance envelope, QA/QC,…*	H	Credit for passive safety—dependent on FP containment of many coated particles.	M	A large safety burden for ***HTGRs should be based on fuel qualification and fuel QC and its performance so that accident doses are low***—previous experience shows SiC coating is robust—source terms come mainly from failed SiC coatings resulting from manufacture defects.
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*	M	Starting aspect for worker dose (FOM-workers—source term-for D-LOFC.	M	Assigned a M based on fact that some of this data for SiC fuels exists.
26-D	Power and flux profiles.	Affects fuel potential for failures in accident conditions due to long-term exposures. For affecting conditions, see item #19.	M	Over long term may effect some possible source terms, but within reason—uncertainty in power and flux will likely not have too much of an effect.	M	To get source term effects, this can be parametrically analyzed.

*Issue not written down in the first PIRT meeting, but was discussed.
-D suffix denotes additions or alterations proposed by D. E. Carlson.
[1] H, M, or L (high, medium, or low).

Table 12.1 (continued)

**Added by this reviewer, was not discussed by the group.

27**	Dynamic impact on core support structure.	Affects core support floor, in long core, CR is heavy (rod drop accidents-floor).	H	Must be evaluated-rods are heavy for long skinny core. Structural evaluation needed.	H	Probably can be shown that margin exists to handle a cable break accident—design dependent.

Table 12.2. General LOFC PIRT chart—SF

This chart is for general cases of loss-of-forced cooling (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Intrinsic feature that prevents rapid fuel heatup (except in reactivity insertion).	H	Proven by world experience with graphite reactors—some uncertainty in this particular configuration.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	H	Conductivity generally important.	H	Properties are known.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Intrinsic feature that prevents rapid fuel heatup (except in reactivity insertion).	H	Proven by world experience with graphite reactors.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	While important, robust design probably accommodates variability.	H	Should be easy to control and monitor over time—measurements could be taken.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	While important, robust design probably accommodates variability.	H	Should be easy to control and monitor over time.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	M	Assure vessel cools down and env. qual. of all top head equipment is acceptable.	M	Examine range of environmental conditions in cavity may shed light—view factor doesn't change.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	H	Must assure vessel cools down and env. qual. of all top head equipment is acceptable.	M	Amenable to modeling-need some validation data—actual configuration.

Table 12.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
8	Reactor vessel cavity “gray gas” (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	Assume vessel cools down and env. qual. of all top head equipment is acceptable.	M	Examine range of environmental conditions in cavity.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	Important factor in accident cool downs in general.	H	Properties are known
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	M	0.8 → 0.6–55/62°C increase vessel temperature	H	Should not radically change over time.
11	Stored (Wigner) energy releases.		L	Annealed at higher temperatures—was shown not to be a problem at FSV.	H	Can be calculated.
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	*M*	*Affects transmission to ultimate heat sink.*	*H*	*Aspects are known and this can be monitored in operation.*
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	*H*	*Need to find the bounds of this.*	*M*	*Needs analysis—can shed light on importance.*
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	H	*Needs analysis shed light on importance.*	M	*Needs analysis shed light on importance.*
15	RCCS failure of both channels. *Heat transfer from RCCS to concrete cavity wall* – *Concrete thermal response* – *Concrete degradation*	Involves complex heat transfer to cavity walls.	H	*Needs analysis shed light on importance.*	M	*Needs analysis shed light on importance.*
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	*H*	*If bad, could affect final outcome.*	*M*	*Requires systems analysis.*

Table 12.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
17	RCCS forced-to-natural circulation transitions (part of P#14).	Complex phenomena (more so with water coolant); crucial to function.	H	Natural circ (I think was shown to be adequate)—this must be proven to claim the passivity.	M	Models should show sensitivity on this.
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.				
*19**	*RCCS parallel channel interactions* (part of P#14).	*Complex phenomena; crucial to function.*				
20	RCCS natural circulation in horizontal panel(s) (part of P#14).	Complex phenomena (more so with water coolant); crucial to function.				
21	Decay heat (temporal and spatial).	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	Shown to be important.	M	Biggest uncertainty on this is ability to predict peaking factors in fuel.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 12.3. Pressurized LOFC PIRT chart—SF

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	M	Area contains shutdown systems—its operability must be assured—sees high temperatures.	M	Some modeling challenges. Existing codes good for a basis, but need some validation data—for final configuration.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	Area contains shutdown systems—integrity must be assured for this accident—sees high temperatures.	M	Amenable to modeling, but need validation data—exact configuration (same as above).
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	Passive HT aspects govern accident cooldown.	M	Amenable to modeling, not much impact on accident, but need validation data for exact complicated geometry.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low—flow correlations, flow reversals.	M	Depends on power peaking distribution/dec ht—natural circ compensates for higher temps—need to know peak temperature	M	Amenable to modeling, models are good but no direct validation data—exact geometry.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	L	Low impact on final outcome of event.	L	Can be modeled, no real need for "validation data."
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	M	Has an effect, but conduction also plays a role.	H	Properties and models are known.
7*	*Thermal shock in SCS due to startup flupow transient.*	*Thermal transients for P-LOFCs more pronounced.*	H	Startup could result in faster thermal transients than otherwise experienced.	M	Amenable to modeling, however validation data needed.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 12.4. Depressurized LOFC PIRT chart—SF

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	M	Graphite conductivity—important conduction now dominant—however, some runs show gaps do not matter—this is a slow event 25% dec → ~100–200°C increase—see IAEA 1163 TECDOC.	L	Conduction is amenable to modeling (but uncertainties due to radial gap conductances across core-reflector…).
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	M	Power distribution drives delta T in conduction model ~10% increase in decay H → ~100°C increase (see IAEA1163).	M	No natural circulation help—prediction relies on good calculated Rx physics peaking factors in core (neutronics).
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	M	See SBs accident analysis—but sensitive to vessel/barrel core leakage IAEA 1163.	M	Can be readily modeled—need validation data with actual configuration.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	Need good model—significant variable is temperature above—sensitivity studies need to be performed here.	M	Data exists, however, statistical data depends on QA for the fuel and fuel qualification data—model needs to be good-given that it will be used in many accidents—drives source terms.
5	Hydrodynamics conditions for dust suspension (Fluid Structure Interactions).	From discussion with fission product panel.	H	FOM—dose-potentially high for pebble; but do not think it is very significant for prismatic block.	L	Rated L; however, collection of information from various sources will shed light on this.

Table 12.4 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Dust effect on coolant properties and flow in vessel.		L	FOM—dose >Effect should be low—accident more dependent on conduction, not convection.	L	Complicated phenomena.
7	Cavity over pressurization.		H	FOM—RCCS structural integrity.	H	Pressurization models should easily be able to handle this.
8	Pressure pulse in confinement.		H	FOM—failure of additional pipe.	M	Uncertainty is due to what the mechanism is for this exactly—the models should be able to handle this.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 12.5. Air ingress LOFC PIRT chart—SF

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow and thermal properties for mixed gases in vessel.	Determines friction and heat transfer characteristics in core, viscosity and thermal conductivity.	M	Conduction dominates fuel temperature	H	Properties are known.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	M	Conduction dominates fuel temperature.	H	Properties are known.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved—as seen in G-LOFC #8.	M	Assume vessel cools down and env. qual. of all top head equip is acceptable.	M	Need to examine range of environmental conditions in cavity.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	However, doubtful this low probability accident would ever get to this stage.	M	Fuel qualification governs—hard to know if the models are good enough—they probably are comparable to LWR fuel.
5*	*Core support structures oxidation.*	*Low-temperature oxidation potentially damaging to structural strength.*	H	Must maintain coolable geometry.	H	Oxidation behavior of graphite well known—models should be adequate, but design margin needs to be large—this is a design materials selection issue.
6	Core oxidation.	Determination of “where” in core the oxidation would take place, graphite oxidation kinetics affected by temp oxygen content of air, irradiation of graphite.	M	Need to analyze worse place in core—it’s thermally driven—to get bounding answer.	H	Depends on what graphite is used (impurity level).
7	Rx cavity-to-reactor vessel air ingress—see 14 and 15.	Air from cavity to vessel after D-LOFC.	H	Need to use large range of assumed rates.	H	Set by accident scenarios—once you know them.
8	Phenomena that affect cavity gas composition and temperature with inflow.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	Accident scenario driven.	M	Calculations can bound this.

Table 12.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
		Entrainment through relief valve, etc. RG—dependent variable.				
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	Depending on the scenario—thermal currents should enable pretty good mixing—should have very minimal effect on fuel temperature	M	Calculational tools exist, may need actual validation data for cavity model.
10	Confinement-to-Rx cavity air ingress.	Determines long-term oxidation rate if accident unchecked.	H	Accident scenario driven—this summarizes the total air supply ultimately available to core.	M	Accident scenario driven—models exist for this type of thing.
11	Cavity combustion gases.	Some CO formed as oxidation product.	L	Some CO formed as oxidation product—impact should be very small.	M	Should be pretty easy to model—it is temp dependent—depends on inlet feed.
12	Cavity structural integrity during blowdown.	Influence on air ingress analysis modeling.	H	Must maintain structure.	M	Requires good look at design to make sure structure is intact, but tools exist for this.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBR.	H	Flow path for source term—affects source term.	H	Requires good examination of design to make sure conservative.
14 RS	Duct exchange flow.	Stratified flow phenomena leading to helium flow exit and air ingress into lower plenum.	H	FOM—same as 5.	M	Complex phenomena, existing models can give an analytical estimate.
15 GG	Molecular diffusion.	*Air remaining in the reactor cavity enters into RV by molecular diffusion, prior to onset of natural circulation.*	M	Slow process will lag other phenomena molecular diffusion phenomena should not be a make or break phenomena with respect to whether oxidation results in bad release.	M	Complex phenomena, enough models to get an analytical estimate and should be able to bound it.

Table 12.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				Chimney effect below is much better driver of air into vessel.		
16 GG	Chimney effects.	In case of double break exposing both the upper and lower plenum to confinement air.	M	This should be a bounding air ingress accident for sure.	M	This type of BDBA has been looked at for gas reactors—no need for experiments—equations and models can be used.
17 GG	Thermal stratification/ mixing in the lower plenum—see 14.					
	Environment-to-confinement air leakage.					
	Core flow distribution following onset of natural circulation.					

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 12.6. Reactivity (ATWS) PIRT chart—SF

Includes ATWS, reactivity insertion events, etc.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1-D	Reactivity insertion due to pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction.	L	Should not add a large Rx effect.	H	Should be able to bound this with normal physics models by simply increasing the moderator and fuel densities.
~~2*~~	~~[Prismatic] Excess reactivity due to burnable poison loading error—BP).~~	~~Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.~~				
3	Reactivity insertion due to steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	M	Entirely depends on conditions-steam not a large problem. – Solid water droplets neutronically can cause separation of CR with fuel-problem (H).	H	Existing models probably adequate to quantify or bound the accident.
4a-BC	Phenomena for water or steam ingress from SCS, or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity.	M	HTGRs are under moderated—entirely depends on conditions—steam not big problem—solid water droplets-problem.	M	Requires a systems review. Existing models probably adequate to quantify the accident.
4b-SG	Mechanisms for water or steam ingress from steam generator.	Some water ingress scenarios are postulated; effects on reactivity.				
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).	Affects passive safety shutdown characteristics.	H	No significant problems noted in experience base.	M	World experience has not shown any problems with this—however, more Pu in this core—however, U.S. experience is with Th/U systems with little Pu.

Table 12.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance^1	Rationale	Knowledge level^1	Rationale
6	Control and scram rods, and reserve shutdown worths.	Needed for cold or hot shutdown validation.	H	Reactor control worths must be known with some confidence to validate analyses.	M	Can be calculated with existing tools and measured—some uncertainty about rods so close to outer reflector—needs to be analyzed.
7	Xenon and samarium buildup.	Determination of poison distribution; Xe decay determines recriticality time.	M	Phenomena is well known.	M	Phenomena is well known—however, this depends on knowing power distributions/flux profiles.
~~8~~	~~Scram and reserve shutdown system failure modes.~~	~~Needed for cold shutdown validation.~~				
~~9*~~	~~*Rod ejection prevention.*~~	~~*Design features.*~~				
10*	*Coolant flow restarts during loss of forced circulation ATWS.*	*Can lead to selective undercooling of hot regions.* *Coupled thermal-fluids and neutronics.*	H	Liftoff/movement of source term—depending on accident could be very important—is scenario after ATWS termination? or before??	M	Needs to be analyzed to find out significance to source term and core structures.
11-D	Decay heat during loss of forced circulation ATWS (vs time and distribution).	See entry in G-LOFC chart (item #21).	M	Power distribution drives delta T in conduction model ~10% increase in decay heat → ~100°C increase (see IAEA 1163).	M	No natural circulation help-prediction relies on good calculated Rx physics peaking factors in core (neutronics)—this is most important thing—not the total decay heat—it's the distribution.
12-D	Reactivity insertion from overcooling transients with ATWS.	Positive reactivity from decreases in core inlet temperature.	M	Once graphite is heated up, these accidents will be very slow.	H	Slow transient so should be easy to bound.

Table 12.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13-D	Reactivity insertion from core support failure due to air ingress corrosion.	Core drop pulling away from control rods would insert reactivity.	L	Needs to be looked at to quantify amount and resilience—now structure is compromised.	M	Have good graphite models. Reactivity insertion can be modeled-uncertainty is in describing the resultant core geometry.

*Issue not written down in the first PIRT meeting, but was discussed.

-D suffix—added or amended per D. E. Carlson suggestion.

[1] H, M, or L (high, medium, or low).

Table 12.7. IHX failure (molten salt) PIRT chart—SF

Design assumptions: Molten salt (~800°C), inventory = 130,000 kg (3000 ft^3), 15,000 ft^3 in reactor, isolation valves?
Scenario: Break of IHX internal tubes, blowdown of primary to secondary, then possible ingress of molten salt (no nitrates).
Conditions: Secondary side press lower than primary (no nitrate salts), lower plenum filled with molten salt by ~X hrs with partial P/D-LOFC. He escapes by secondary relief valve out molten salt lines (confinement bypass), countercurrent flow, lots of inertia as 0.5 miles of molten salt slows down and pump coasts down.
Single failure: isolation valve fails to close.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Ingress of helium into IHX loop (part of confinement bypass).	Blowdown of primary system into secondary system, gas jet into liquid, initial circulating activity is the prime source of the public and worker dose.	M	FOM—public and worker dose. Helium flow rate determines how much activity is transported into IHX loop.	H	Most likely bounding assumptions/calculations are sufficient.
2	*Fission product* transport through IHX loop (part of confinement bypass).	Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out.	H	FOM—public and worker dose. Determines activity released out of IHX relief valve, and residuals in IHX loop.	M	Lack of scrubbing data applicable to counter-current He–MS flow, yet bounding models may be able to reduce uncertainties.
3	*Helium* transport in IHX loop (part of confinement bypass).	Possible helium/molten salt countercurrent flow, blocking bubble in IHX loop.	M	FOM—public and worker dose. Affects fission product transport through IHX to relief valve.	M	Lot of air/steam-water data on countercurrent flow that may be applicable, however, does this scale well to helium–molten salt data.
4	Ingress of molten salt into primary system and RPV.	After partial blowdown, relies on items #1, 2, 3 as initial/boundary conditions.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Determines amount/mass of MS in vessel, core MS level.	M	Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.

Table 12.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Riser fill with molten salt.	Through cold duct.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. >Affects vessel temperatures, heat transfer to RCCS.	M	Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.
6	Lower plenum fill with molten salt.	Through hot duct.	M	FOM–vessel temperatures, vessel support temperatures, core support temperatures. M > temperatures not much different from normal operating temperature. H > structural integrity effects.	M	M > models sufficient for bounding calculations, heat transfer problem well understood. L > uncertainty in calculating MS level and mass.
7	Molten salt (in cold duct)-to-core support/vessel heat transfer.		H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. >Impact on cross duct and vessel temperatures.	M	Knowledge sufficient for bounding calculations.
8	Molten salt (in hot duct)-to-core support/vessel heat transfer.		M	FOM—vessel temperatures, vessel support temperatures, core support temperatures. >Temperatures not much different from normal operating temperature.	M	Models sufficient for bounding calculations, heat transfer problem well understood.

Table 12.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	RCCS heat removal.	Heat transfer from vessel wall to RCCS and cavity.	H	FOM—vessel temperatures, vessel support temperatures, cavity temperatures. >Ultimate heat sink, abnormal temperature distribution on RCCS and vessel.	M	Models sufficient for bounding calculations.

[1] H, M, or L (high, medium, or low).

Table 12.8. Water-steam ingress PIRT chart—SF

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well (ASSUME DLOFC?).

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	M	The composition is variable-dependent on exact scenario.	H	Properties are known. Graphite steam relationships are well established.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	M	Conduction (DLOFC) dominates, these correlations are not important to final accident outcome.	M	Properties are known, complicated geometries.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H	Heat sink important to cooling fuel.	M	Basic aspects are known, but full range of possibilities will need to be defined to be confident in knowledge base.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	M	Steam will not affect reactivity much due to its low density. Corrosion effect on core components will have to be calculated—severe conditions.	M	Needs further system evaluation-specific to design-closed cycle or steam cycle...
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	M	– Can effect source term for already failed particles, dependent on many things—coated failures, temperature, etc. – Possible volume increase in particle—was	M	Relationships exist here-were used in licensing FSV (see section 14.5 FSAR). Hydrolysis of fuel particles has been studied experimentally. NOTE: this aspect is tied in to fuel qualification-this drives the rating—e.g.,

Table 12.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				shown to be accommodated at FSV. – Normally evaluated in gas reactor FSAR—not been a problem.		depends on the fuel.
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	M	Causes doubts about core structural However, burnoff calculated for FSV was small—over-design can be used to mitigate stability (see below).	M	Models exist some validation-has been investigated for some reactor grade graphites. Existing models, design conservatism probably adequate. NOTE: however, that weight on core support is high due to tall core.
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	M	Event oxidation does not likely cause concern. Function of graphite temperature, steam and hydrogen partial pressure, graphite contamination (barium) and fraction burnoff.	M	Same as above. A core thermal model will provide temps, and conditions to graphite experts to calculate.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Requires systems analysis and event scenario development.	M	Requires systems analysis and event scenario development.
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	Requires systems analysis and event scenario development.	M	Requires systems analysis and event scenario development.
10	Cavity combustion gases.		?			
12	Cavity structural performance.	Influence on ingress analysis modeling.				

Table 12.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13	Cavity filtering performance.	Affects radioactive releases.	M	Depends on credit taken for the cavity reduction of source term.	M	This is not much different than some of the LWR situations with aerosols/iodine/and noble gasses.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	M	Steam plus graphite water reaction produces CO and H_2—importance depends on severity.	H	This phenomena is known.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.1. Normal operation PIRT chart—TW

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{\text{max.fuel}}$.	H	Part of (2) and with significant fraction for both PMR and PBR, a significant effect of fuel temperature.	L	Difficult to determine core geometry.
2	Core flow distribution.	Determines fuel operating temperatures.	H	Term in energy balance equation for fuel temperature and with significant large coolant drop and significant film drop, a first order effect. Compounded by gas viscosity effect.	L	Difficult to determine core geometry with all the leakage/bypass flow paths, the stochastic nature of the pebble distribution, the fit between the stacked blocks,…an opportunity for innovative monitoring techniques.
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	???	Not sure what this ranking is referring to. Need to discuss at meeting.		
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	M	*Some effect on fuel operating temperatures.*	L	Difficult to determine core geometry.
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	M	*Some effect on fuel operating temperatures.*	L	Difficult to determine core geometry.
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	M	*Some effect on fuel operating temperatures.*	L	Difficult to determine core geometry; but they did develop hold down systems albeit for lower temperatures.
7*	*Pebble bed core bridging.*	*Problem at AVR.*	M	*Some effect on fuel operating temperatures.*	L	Difficult to determine core geometry.

Table 13.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	H	*Some effect on fuel operating temperatures.*	L	Difficult to determine core geometry. Small core in terms of number of pebbles across.
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	M	Terms are throughout the momentum balance equations for the coolant flow which with the large axial temperature drop is a first order effect on fuel temperature.	H	Helium coolant properties are well known. Full flow friction correlations are standard.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	Term in the fuel energy balance equation and with the significant film temperature drop, a first order effect.	H	Full flow heat transfer correlations are standard.
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	M	The pressure distribution across the top inlet plenum is a direct term in the momentum balance for the core flow distribution and is a first order effect on fuel temperature.	L	Uncertainties due to the upper internal structure geometry, control rod guide tubes, fuel tubes, instrumentation sheaths,…the riser distribution at the sides, should be part of a standard component test program.
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	L	Multiple primary loops and separate IHXs, depending on design, could lead to nonuniform temperature distribution across top core inlet plenum and effect distribution of core fuel temperatures but sounds like designers are going for same loop outlet temperatures.	L	Same as (11).

Table 13.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	M	The pressure distribution across the bottom outlet plenum is a direct term in the momentum balance for the core flow distribution and is a first order effect on fuel temperature.	L	Uncertainties due to the PMR support structure geometry, tubes,…the outlet pipe at one side, should be part of a standard component test program. The PBR geometry is simpler.
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	H	The PBR core void distribution sets the local coolant flow areas which is a factor in the determination of the local core coolant flow distribution and is therefore part of (2). It also has an effect on the local power peaking.	M	Aware of PBMR program, but uncertainties may well have stochastic components.
15	Effective core thermal conductivity.	Affects core maximum temperatures during operation.	H	Term in the fuel energy balance equation with temperature drop on order of coolant film drop.	M	Aware of PBMR program but on PMR side, Fort St Vrain graphite unavailable and graphite properties are variable depending upon manufacturing process.…
16	Effective fuel element thermal conductivity.	Affects fuel maximum temperatures during operation.	H	[Not recorded.]	M	
17	Core specific heat.	Affects transients.	L	Not required for steady state but needed for load changing.	M	Aware of PBMR program but on PMR side, Fort St Vrain graphite unavailable and graphite properties are highly variable depending upon manufacturing process….

Table 13.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	H	Direct term in energy balance equation for vessel wall temperature.	H	Depending upon selection of material, emissivities are well known except for life-time history behavior. Simple radiation heat transfer geometry.
19	RCCS behavior.	Affects residual heat losses, vessel temperatures.	H	Protects long term concrete temperature exposure and also for vessel/supports.	M	Water-cooled system has forced flow which reduces uncertainties. Air-cooled system has passive performance which brings up same validation questions as in the General LOFC PIRT Chart about sensitivities and uncertainties.
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*	???	Not sure what this ranking is referring to. Need to discuss at meeting.		
21-D	Power and flux profiles.	Affects core maximum temperatures.	H	The power peaking is a direct term in the energy balance equation for the peak fuel temperature.	M	Spatial dependence tied to local flux distribution. Uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burn-up…. Need validation.
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	M	Not required for steady state normal operation except for control rod worth but needed for load change and power operation stability.	H/M	Some validation still required. Global integrated effect Differences from 30 years ago: higher temperature, annular core, higher burn-up….

Table 13.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
23	Xenon buildup and oscillation.	Affects core transient behavior.	M	Not required for steady state normal operation except for control rod worth but needed for load change and power operation stability.	M	Need validation. Tied to local flux distribution. Uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burn-up…
24*	*Fuel performance modeling.*	*Fuel type dependent. crucial to design and siting; depends on performance envelope, QA/QC,…*	H	Determines the source term for the fission product release from the fuel.	?	Need to consult fuel experts.
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*	H	Part of the source term.	?	Need to consult fuel experts.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.2. General LOFC PIRT chart—TW

This chart is for general cases of loss-of-forced cooling (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	Direct factor in the energy balance equations for the fuel temperature and vessel temperature and a first order term.	M	Aware of PBMR program but on PMR side, Fort St Vrain graphite unavailable and graphite properties are variable depending upon manufacturing process….
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	H	Changes the fuel element properties with the thermal conductivity being a strong function of radiation and temperature and a first order effect on fuel temperature.	L	Very much dependent on the knowledge base for graphite so with the search for a new graphite manufacturer the uncertainties in this are large.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Inertia term in the fuel element transient energy conservation term and therefore a first order effect on the transient fuel temperature.	M	Aware of PBMR program but on PMR side, Fort St Vrain graphite unavailable and graphite properties are variable depending upon manufacturing process….
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	M	This is a direct factor in the radiation heat transfer term in the energy balance equation and therefore a first order effect on the vessel temperature but a less-than-linear power law dependence for temperature drop.	M	Depending upon choice of material there is considerable data available. What is uncertain is the effect of life-time of operation on the values. May need to be part of plant test/calibration requirements over operation period.

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.		Same as with (4), this is a direct factor in the radiation heat transfer term in the energy balance equation and therefore a first order effect on vessel temperature and also on the temperature of the concrete which keeps the vessel supports in place; less-than-linear power law dependence for temperature drop.	M	Depending upon choice of material there is considerable data available. What is uncertain is the effect of life-time history of operation on the values.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	M	This determines the effective radiative heat transfer area and is a direct factor in the radiation heat transfer term in the energy balance equation and therefore a first order effect on vessel temperature; less-than-linear power law dependence for temperature drop.	H	Numerical methods to calculate these view factors exist. In particular CFD codes such as STAR-CD have incorporated them in the code packages.
7	Reactor vessel cavity air circulation and heat transfer.	Affects upper cavity heating.	H	The upper cavity provides for vessel upper supports, so upper cavity heating of cavity concrete could have consequences. There are other scenario dependent criteria. For P-LOFC overheating of the top head seals could result in leakage paths. For air ingress accidents	L	Need scaled integral validation data. Empty cavity experimental data is a start but it is difficult to find data with the long narrow aspect ratios and in the appropriate Raleigh number range. Moreover, with the presence of the complex RCCS geometry dividing the coupling into

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				(graphite oxidation consequences) the inventory and distribution of cavity air vs light gas (helium), steam...sets the inlet boundary conditions. Discussed further in the Air Ingress PIRT In the case of water-cooled RCCS designs a larger fraction of the vessel- to-standpipe heat transfer is by natural convection in the cavity. RCCS performance is therefore affected.		at least two cavities, facing the vessel and facing the concrete and possibly more (upper and lower), the properly scaled integral data is not available.
8	Reactor vessel cavity “gray gas” (participating media).	Can affect vessel temperatures and T_{Fuel} max.	H	Radiation is a major part of the heat transfer between the vessel and the RCCS and the cavity gray gas resistance will be part of the pathway.	L	Major uncertainty at this point is the composition of the gray gas. Also distribution in reactor cavity. Depends upon scenario. Is it graphite dust, water vapor/liquid, steam, fission products…?
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	M	Same effect on fuel temperature as with (1) and (2) but is further away from the peak in the fuel temperature and influence should be mitigated by all the core heat capacity in between.	M	Aware of PBMR program but on PMR side, very much dependent on the knowledge base for graphite so with the search for a new graphite manufacturer the uncertainties in this could be large.

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	M	As with (9) further away from the peak fuel temperature but feeds directly into the energy balance equation for the vessel wall so should be a first order effect on the vessel temperature; less-than-linear power law dependence for temperature drop.	M	Depending upon choice of material there is considerable data available. What is uncertain is the effect of life-time history of operation on the values (dust…).
11	Stored (Wigner) energy releases.		L	Pure guess. Even though need graphite different from that at St Vrain, probably operating temperatures are too high for Wigner phenomenon.	M	Very much dependent on the knowledge base for graphite so with the search for a new graphite manufacturer the uncertainties in this are large.
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	*M*	*Factor in heat transfer term to water secondary, for vessel wall heat removal energy balance equation. Effect depends upon relative radiative drop vs conduction convective drop and therefore upon magnitude of fouling.*	*M*	*Uncertain in the case of the water cooling system option because it depends upon the water chemistry treatment. For the air cooled system option, there will be oxidation corrosion data depending upon structural material selection.*
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	*M*	*In addition to the effect discussed in (19) on heat transport to the ultimate heat sink, the spatial distribution also affects the "heat exchanger effectiveness" of the RCCS design. Not all*	*L*	*For ex-vessel validation of cavity/RCCS interactions refer to (7) and (19). In-vessel, this is scenario dependent but in the main, this occurs mainly with the P-LOFC where natural circulation*

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				parts of the surface area are equally effective.		*and the transition from forced-to-natural with flow stagnation and flow reversal leads to the shift in the vessel wall temperatures and the spatial heat loadings. This is discussed more in P-LOFC PIRT but the scaled integral data for the formation and stability of these flow patterns in the top head, riser, is not available.*
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	???	*Not sure what this ranking is referring to. Need to discuss at meeting.*		
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.	???	*Not sure what this ranking is referring to. Need to discuss at meeting.*		
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	*???*	*Not sure what this ranking is referring to. Need to discuss at meeting.*		
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	H	This should be evaluated in conjunction with (19). Since the air system option is always natural convection driven there is per se no transition from global forced to global natural circulation (but the air flow patterns discussed in (19) could be a function	L	*Need scaled integral validation data. As in (18) and (19), for the water cooled system, it is the combination of features which makes this system configuration/ conditions different from that for the LWRs. The geometry of an individual*

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				of start-up conditions). However, on an individual air duct basis, the local heat transfer coefficient is defined by local buoyancy effects. This affects the heat removal capability of the RCCS. The mixed convection heat transfer mode is also discussed in (19). In the case of the water system, the transition also involves system reconfiguration and this sets up the initial conditions for the combinations of flow patterns discussed in (19). So in addition to heat transfer and pressure drop correlations, it will therefore be an important factor in determining the passive heat transport to the ultimate heat sink.		*standpipe required to provide coverage to protect the concrete and at the same time optimize the radiation heat transfer and provide feed water is not standard in the LWR world. Water T/H correlations are not available in this geometry. Separate effects tests are not sufficient as it is the coupling (19) which is the focus. Scaled integral data with the coupling between the water standpipes in this geometry and the asymmetric heating are not available.*
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	H	Since the air system option always operates in the single phase mode, this is a phenomenon of the water-cooled system. In the passive mode, the reactor decay heat removal/storage capacity is provided by the latent heat of the water storage tank liquid inventory	L	Need scaled integral validation data. It is the combination of features which makes this system configuration and conditions different from those for the LWRs. The geometry of an individual standpipe required to provide coverage to protect the concrete and

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				When electric power is lost and gravity heads drive the water cooling flow on the secondary side, the subcooling is eventually lost in the water standpipes but given the height of the system the elevation head is quite significant (on the order of depending upon the design). This suppresses the boiling in the standpipe region. However, as the heated water transports upwards to the storage tank, the elevation head diminishes and a flashing point is reached. Two-phase mixture is discharged into the tank through a sparger and then through a discharge line open to the atmosphere. The degree of phase separation which occurs with the flashing in the network, and the tank/sparger effect on carryover/carryunder for the exiting quality will determine how much liquid inventory is lost with the discharge. This affects the 72 h inventory requirements. Moreover if there is stratification in		at the same time optimize the radiation heat transfer and provide feed water is not standard in the LWR world. Correlations for the suppression of boiling are not available in this geometry. Flashing in the manifolds of the piping network at this pressure range may require confirmation. BWR carryover/carryunder correlations are for separator and dryer geometries unlike the sparger /tank combination encountered here. But more than the separate effects, there is no integral validation data for the coupled effects which would require the proper scaling.

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance^1	Rationale	Knowledge level^1	Rationale
				the tank it will affect the inlet temperature condition and the heat removal capability of the standpipe system.		
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	*H*	*In the passive mode, with the low driving heads induced by the density differences from the thermal gradients, particularly in the case of the air system option, there can be various kinds of flow patterns in the system. There can be recirculation patterns between groups of air ducts/water standpipes which are connected through common chimneys or manifolds so the reactor decay absorbed in these ducts/standpipes is not transported to the ultimate heat sinks (atmosphere/water storage tanks) as intended but just recirculated in the network. This is a negative effect on the RCCS design performance. This could be exacerbated by the asymmetric RCCS spatial heating around the periphery of the reactor*	*L*	*Need scaled integral validation data. As in (18), for the water-cooled system, it is the combination of features which makes this system configuration/conditions different from that for the LWRs. The geometry of an individual standpipe required to provide coverage to protect the concrete and at the same time optimize the radiation heat transfer and provide feed water is not standard in the LWR area. Correlations for the convective heat transfer are not available in this geometry. Separate effects tests are not sufficient as it is the coupling which is focus. Scaled integral data with the coupling between the water standpipes in this geometry and the asymmetric heating are not available. This is also the case for the air-cooled system option.*

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				vessel and the increase in air viscosity with temperature. Furthermore there is a possibility of low-flow internal (3-D) recirculation patterns within each duct/standpipe. In the case of the air duct system with the back-to-front temperature gradient it could be localized mixed convection modes which lead to a subset of issue (17) regarding what heat transfer correlation and pressure drop correlations are applicable. In the case of the water annular standpipe system it could be more global with the cold central feed pipe exacerbating the local temperature gradient. Once the system goes two-phase (18) than the situation is further complicated by pressure oscillations as flashing takes place.		
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	???	Not sure what is being referred to. Need to discuss at meeting.		

Table 13.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	This is the driving force (source term in fuel energy balance equation) for all the accidents.	M	Major work has been done in the area of time dependence. Spatial dependence tied to local flux distribution. Flux uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burn-up…. Need validation.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.3. Pressurized LOFC PIRT chart—TW

This chart is for phenomena specific to the P-LOFC case; see General LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge l evel[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	Part of (3) with the major shift of the heat loads to the top of the core, vessel and cavity and the same consequences as (3).	L	The coupling between the core channels and the top plenum determines the stratification and the plume patterns and there is a need for scaled integral data which has this coupling.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	L	Significant part of heat transfer to top head but mitigated by insulation.	H	Numerical methods to calculate view factors exist. CFD codes such as STAR-CD have incorporated them in code packages.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	H	The upper cavity provides for vessel upper supports, so upper cavity heating of cavity concrete could have consequences. Overheating of the top head seals could result in leakage paths. The skewed distribution affects the “heat exchanger effectiveness” of the RCCS design. For heat exchanger effectiveness effect and RCCS parallel channel interaction refer to (19) in General LOFC PIRT Chart on heat transport to the ultimate heat sink.	L	For ex-vessel validation of cavity/RCCS interactions refer to (7) and (19) in General LOFC PIRT. During the P-LOFC, in-vessel natural circulation and the transition from forced-to-natural with flow stagnation and flow reversal leads to the shift in the vessel wall temperatures and the spatial heat loadings. The scaled integral data for the formation and stability of these flow patterns in the top head, riser,… is not available.
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	This is a part of the shift of the heat loads towards the heat loads towards the top of the core, vessel and	L	Scaled integral data is not available for the flow patterns, natural circulation and the transition from

Table 13.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge l evel[1]	Rationale
				cavity with the same consequences as (3).		forced-to–natural with flow stagnation and flow reversal. Also uncertainties in core geometry and the need for natural circulation/mixed convection correlations for low flow. Aware of the PBMR program.
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	M	Part of (4), core coolant flow distribution but could be a smaller fraction with the Reynolds number dependence of classical form losses.	L	Uncertainties in core geometry and the natural circulation/mixed convection correlations for low flow. Aware of the PBMR program.
6	Coolant flow friction/viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	M	Quasi-static “laminar” momentum balance equation terms have direct dependence on these factors.	M	Coolant properties of helium are well known but the natural circulation/mixed convection correlations for low flow for the PMR channels need data. Aware of the PBMR program.
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*	???	Not sure what this ranking is referring to. Need to discuss at meeting.		

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.4. Depressurized LOFC PIRT chart—TW

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Direct factor in the energy balance equations for the fuel temperature and vessel temperature and a first order term.	M	Aware of PBMR program but on PMR side, Fort St. Vrain graphite unavailable and graphite properties are variable depending upon manufacturing process.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	This is the driving force (source term in energy balance equation for fuel) for all the accidents.	M	Major work has been done in the area of time dependence. Spatial dependence tied to local flux distribution. Flux uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burnup…. Need validation.
3	RCCS spatial heat loadings.	Major shifts in heat load to middle of RCCS; complex geometries involved.	M	No major mechanical structure around middle of vessel. For heat exchanger effectiveness effect and RCCS parallel channel interaction refer to (19) in General LOFC PIRT Chart on heat transport to the ultimate heat sink,	L	For ex-vessel validation of cavity/RCCS interactions refer to (7) and (19) in General LOFC PIRT. In-vessel, the uncertainties in the spatial loadings for the D-LOFC is determined by the uncertainties in the decay heat distribution and the in-vessel conduction—radiation cool-down model.

Table 13.4 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	H	Determines the source term for the fission product release from the fuel.	?	Need to consult Fuel experts.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.5. Air ingress LOFC PIRT chart—TW

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	H	Agree with comment. Factor in start-up of air natural circulation for the air-graphite oxidation.	M	Air-helium data should be available(AREVA?) but other mixtures need to be examined on case-by-case basis.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	H	Agree with comment. Factor in start-up of natural circulation for the air-graphite oxidation.	M	Air-helium data should be available(AREVA?) but other mixtures need to be examined on case-by-case basis.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc. in cavity reduces radiant heat transfer; complex processes involved.	H	Radiation is a major part of the heat transfer between the vessel and the RCCS and the cavity gray gas resistance will be part of the pathway.	L	Major uncertainty at this point is the composition of the gray gas. Also distribution in reactor cavity. Depends upon scenario. Is it graphite dust, combustion products, fission products…?
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	This is an additional mechanism/mode for failing the local FP confinement properties of the kernel coatings asides from temperature alone.	?	Need to consult fuel experts.
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*	H	Damage to core structure makes it more difficult to confirm core coolable geometry.	M	Aware of PBMR program in this area but uncertainty on PMR side without Ft. St. Vrain graphite manufacturer.
6	Core oxidation modeling.	Determination of "where" in core the oxidation would take place.	M	Determines second internal heat source in addition to decay heat. Therefore contributes to determining additional	L	Aware of PBMR program in this area but uncertainty on PMR side without Ft. St. Vrain graphite manufacturer.

Table 13.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				fuel damage but also provides another mode of fuel damage and potential fuel transport out off the core.		
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	M	Interpreted as vessel-to-cavity leakage after initial blow-down. The leakage/discharge characteristics. Depending upon location and size, during the blow-down phase and beyond contributes to the determination of the cavity gas distribution (9), composition (8), the structural loads (12) and the related ex-vessel consequences which interface with the in-vessel consequences.	L	Separate effects validation data with dust and the lift-off of the normal operation plate-out during the discharge, into the cavity are not available.
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	H	Whether or not the primary helium discharge displaces significant fraction of the initial cavity oxygen/air inventory will be a boundary condition factor in the in-vessel oxidation of (6). This is part of the coupling between ex-vessel and in-vessel phenomena.	L	Ex-vessel phenomena need to be part of the validation focus, which has been mainly on in-vessel. Integral coupled validation data which set the boundary conditions for the in-vessel scenario need to be developed in the scaled geometry with the RCCS configuration.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	H	For air ingress accidents), the ex-vessel inventory and distribution of cavity air vs light gas	L	Validation data for the initial phase blow down discharge experiment into the reactor

Table 13.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				(helium),… sets the inlet boundary conditions for the in-vessel graphite oxidation consequences. After the initial jet mixing, natural convection patterns will set the ex-vessel gas composition distribution.		cavity/confinement with the scaled geometry are not available The transition to natural convection in the cavity for a mixture of gases with a hot vessel wall and a cold RCCS (particularly for the water cooled option) require validation data. Natural convection pattern data for the air inlet conditions require mocking up the various cavities in a coupled mode. Single empty cavity experiment data are available but not with the high aspect ratios and Rayleigh numbers.
10	Cavity air in-leakage.	Determines long-term oxidation rate if accident unchecked.	H	Agree with comment. The limitation on the energy release of the potential for graphite oxidation is the oxygen supply. There is the Russian experience.	L	Cavity air in-leakage uncertainties are primarily a component-testing program. Validation regarding the consequences from such leakage is discussed under each of the corresponding phenomena sections.
11	Cavity combustion gases.		M	As with (3) and (8), effects on RCCS performance and boundary conditions for the in-vessel graphite oxidation.	L	The efflux of combustion gases + combustion products and the feedback on the air ingress back in-vessel is a coupled phenomena which requires coupled validation data in the

Table 13.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						scaled geometry.
12	Cavity structural performance.	Influence on air ingress analysis modeling.	M	LB-LOCA with jet impact loadings, vibration, pressurization could lead to RCCS duct/standpipe integrity issues which could degrade RCCS performance. High temperature loading on vessel support structures, concrete… could lead to coolable configuration integrity questions.	M	Fluid structure interaction (FSI) data are needed to validate proposed suite of codes such as STAR-CFD.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	Agree with comment but can also mitigate fission product/aerosol releases which is the primary concern for public dose and safety.	L	Dust/fission product transport validation data with the appropriate scaled geometry for cavity filtering are not available.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.6. Reactivity (ATWS) PIRT chart—TW

This chart is for phenomena including LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	Fuel energy deposition rate is direct function of step reactivity insertion and whether or not it is subprompt critical.	M	Aware of PBMR pebble flow work. Complicated both mechanically and neutronically. Needs validation. Pebble flow and reconfiguration may be stochastic. Reactivity effect may be sensitive balance between changes in the four factors.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*	M	Large factor in determining individual control rod worths which are used in the control rod withdrawal ATWS.	M	Need validation. Tied to local flux distribution. Uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burn-up.
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	Interpret this as reactivity effect ranking since there is a separate Water/Steam Ingress PIRT Chart. Contributes to ramp rate.	M	Needs reactivity validation. Sensitive calculation on sign over density range. Differences from 30 years ago, annular core, higher temperature, higher burn-up.

Table 13.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects reactivity.	H	The rate of ingress and mode of ingress (flow regime) of water/steam determines the ramp rate pre-reactor scram. This defines the fuel energy deposition rate. The flow regime will affect the heat transfer correlation and possibly the hydrolysis rate in the core.	H	There is considerable work in the LWR area on flow regimes under different injection condition and also the HTGR work from 30 years ago. Only question is the temperature range.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).		H	This is the negative feedback term which turns the power peak around mitigates fuel energy deposition rate.	H/M	Some validation still required. Global integrated effect. Differences from 30 years ago: higher temperature, annular core, higher burn-up.
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	L	Plays minimal role in turning the power peak around.	M	Need validation. More localized effect than reactivity coefficient. PMR has control rod in reflector region rather than core region of 30 years ago. PBR is now annular vs solid core of 30 years ago.
7	Xenon and samarium buildup.	Determination of poison distribution.	M	Determines potential for recriticality and a return to power.	M	Need validation. Tied to local flux distribution. Uncertainties/sensitivities, especially at inner reflector interface, due to differences from 30 years ago, annular core, higher temperature, higher burn-up.
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.		Not sure what this ranking is referring to. Need to discuss at the meeting.		

Table 13.6 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9*	*Rod ejection prevention.*		???	Not sure what this ranking is referring to. Need to discuss at the meeting.		
10*	*Coolant flow restarts during ATWS.*		???	Not sure what this ranking is referring to. Need to discuss at the meeting.		

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 13.7. IHX failure (molten salt) PIRT chart—TW

Design assumptions: Molten salt (~800°C), inventory = 130,000 kg (3000 ft^3), 15,000 ft^3 in reactor, isolation valves?
Scenario: Break of IHX internal tubes, blowdown of primary to secondary, then possible ingress of molten salt (no nitrates).
Conditions: Secondary side press lower than primary (no nitrate salts), lower plenum filled with molten salt by ~X hrs with partial P/D-LOFC. He escapes by secondary relief valve out molten salt lines (confinement bypass), countercurrent flow, lots of inertia as 0.5 miles of molten salt slows down and pump coasts down.
Single failure: isolation valve fails to close.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Ingress of helium into IHX loop (part of confinement bypass).	Blowdown of primary system into secondary system, gas jet into liquid, initial circulating activity is the prime source of the public and worker dose.	H	FOM—public and worker dose. Helium flow rate in determines flow regime in pipe and liquid MS flow out into primary system.	M	Lot of air/steam-water data on countercurrent flow that may be applicable; however, does this scale well to helium–molten salt data.
2	*Fission product* transport through IHX loop (part of confinement bypass).	Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out.	H	FOM—public and worker dose. Determines activity released out of IHX relief valve, and residuals in IHX loop.	M	Lack of scrubbing data in molten salt.
3	*Helium* transport in IHX loop (part of confinement bypass).	Possible helium/molten salt countercurrent flow, blocking bubble in IHX loop.	M	FOM—public and worker dose. Affects fission product transport through IHX to relief valve and MS rate into primary.	M	Lot of air/steam-water data on countercurrent flow that may be applicable, however, does this scale well to helium–molten salt data.
4	Ingress of molten salt into primary system and RPV.	After partial blowdown, relies on items #1, 2, 3 as initial/boundary conditions.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Determines amount/mass of MS in vessel, core MS level and, therefore, the local heat loads.	M	Lot of air/steam-water data on countercurrent flow that may be applicable; however, does this scale well to helium–molten salt data.

Table 13.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Riser fill with molten salt.	Through cold duct.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Affects vessel temperatures, heat transfer to RCCS.	M	During pressure equilibration phase when helium is still discharging flow regime uncertainty. Once equilibrated should be just liquid flow with an equilibrium level.
6	Lower plenum fill with molten salt.	Through hot duct.	M	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Temperatures not much different from normal operating temperature but could enter lower head region.	M	During pressure equilibration phase when helium is still discharging flow regime uncertainty. Once equilibrated should be just liquid flow with an equilibrium level.
7	Molten salt (in cold duct)-to-core support/vessel heat transfer.		M	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Depending on design ,temperatures could be quite higher than normal operation and the other accidents covered so far. Impact on cross duct and vessel temperatures.	M	There is considerable past work on liquid metal pool and water pool heat transfer. Question is scaling.
8	Molten salt (in hot duct)-to-core support/vessel heat transfer.		M	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Temperatures not much different from normal operating temperature but could enter lower head region.	M	There is considerable past work on liquid metal pool and water pool heat transfer. Question is scaling.

Table 13.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
9	RCCS heat removal.	Heat transfer from vessel wall to RCCS and cavity.	H	FOM—vessel temps, vessel support temps, cavity temperatures. Ultimate heat sink, abnormal temperature distribution on RCCS and vessel.	L	Skewed vessel heat loading towards lower cavity and below RCCS design.

[1] H, M, or L (high, medium, or low).

Table 13.8. Water-steam ingress PIRT chart—TW

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	H	The coolant properties enter into the energy balance equation for the fuel temperature and also for the core flow rate. Affects water flow rate into core.	H	Need to go back 30 years. This was a major HTGR accident and a lot of work was done in this area. Only question is temperature range.
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	H	The heat transfer coefficient is a direct term in the core energy balance equation for the fuel. Since the coolant film drop is a significant part of the heat transfer this is a first order effect.	H	Need to go back 30 years. This was a major HTGR accident and a lot of work was done in this area. Only question is temperature range.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	H	Radiation is a major part of the heat transfer between the vessel and the RCCS and the cavity gray gas resistance will be part of the pathway.	L	Major uncertainty at this point is the composition of the gray gas. Also distribution in reactor cavity. Depends upon scenario. Is it graphite dust, steam/liquid, hydrolysis products, fission products…?
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	H	The rate of ingress and mode of ingress (flow regime) of water/steam determines the ramp rate prereactor scram. This defines the fuel energy deposition rate. The flow regime will affect the heat transfer correlation	H	There is considerable work in the LWR area on flow regimes under different injection condition and also the HTGR work from 30 years ago. Only question is the temperature range.

Table 13.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				and possibly the hydrolysis rate in the core.		
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	H	This is an additional mechanism/mode for failing the local FP confinement properties of the kernel coatings asides from temperature alone.	?	Need to consult fuel experts.
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	H	Damage to core structure makes it more difficult to confirm core coolable geometry.	M	Aware of PBMR program but on PMR side, data uncertainty without Ft. St. Vrain graphite manufacturer and looking at other grades of graphite.
7	Core (steam) oxidation modeling.	Determination of “where” in core the oxidation would take place.	H	Determines second internal heat source in addition to decay heat. Therefore, contributes to determining additional fuel damage but also provides another mode of fuel damage and potential fuel transport out off the core.	M	Aware of PBMR program, but on PMR side data uncertainty without Ft. St. Vrain graphite manufacturer and looking at other grades of graphite.
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Whether or not the primary helium discharge with steam displaces significant fraction of the initial cavity oxygen/air inventory will be a factor in the cavity performance. It should affect the heat transfer	L	Ex-vessel phenomena need to be part of the validation focus, which has been mainly on in-vessel. Integral coupled ex-vessel validation data which set the boundary conditions for the in-vessel scenario need to be developed in

Table 13.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				with the RCCS and the boundaries If in the scenario, the SCS is unavailable, this will be the passive heat removal mechanism. This is part of the coupling between ex-vessel and in-vessel phenomena.		the scaled geometry with the RCCS configuration. Higher temperatures than 30 years ago.
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	With the lifting of the relief valve, the distribution of cooler cavity air vs hot light gas(helium) and steam/liquid mixture sets a constraint condition for the ex-vessel natural convection patterns and the spatial heat transfer. Upper cavity heating vs lower cavity heating where the various support structures and flange seals could be affected.	L	Validation data for the response to the relief valve discharge into the reactor cavity/ confinement with the scaled geometry are not available. The transition to natural convection in the cavity for a mixture of gases with a hot vessel wall and a cold RCCS (particularly for the water cooled option) require validation data . Natural convection pattern data require mocking up the various cavities in a coupled mode. Single empty cavity experiment data are available but not with the high aspect ratios and Rayleigh numbers.

Table 13.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
10	Cavity combustion gases.		M	As with (8) and (9), effects are on RCCS performance.	L	The effect is a coupled phenomena which requires coupled validation data in the scaled geometry.
12	Cavity structural performance.	Influence on ingress analysis modeling.	M	Relief valve lift with jet impact loadings, vibration, pressurization could lead to RCCS duct/standpipe integrity issues which could degrade RCCS performance. High temperature loading on vessel support structures, concrete...could lead to coolable configuration integrity questions.	M	Fluid structure interaction (FSI) data are needed to validate proposed suite of codes such as STAR-CFD.
13	Cavity filtering performance.	Affects radioactive releases.	H	Can mitigate fission product/aerosol, dust…, releases which is the primary concern for public dose and safety.	L	Dust/fission product transport validation data with the appropriate scaled geometry for cavity filtering are not available. The presence of steam changes the chemistry.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	L	Raises issue of coolable core geometry.	M	Core temperatures for steam formation higher than HTGR from 30 years ago.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.1. Normal operation PIRT chart—YH

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core coolant bypass flow.	Determines active core cooling; affects $T_{max.fuel}$.	H	Determine the flow and temperature distributions in the core. Consequently, the fuel temperature.	M	The determination and calculation of the flow is dependent on many parameters such as the gaps and the changes with time due to the radiation. The effect of irradiation on the graphite.
2	Core flow distribution.	Determines fuel operating temperatures.	H	The complex flow distribution will determine the accurate predictions of the fuel and the structure temperatures within the core.	M	The complex flow distributions and patterns due to the complex core geometry as in PBR and the leakage flows in both core types of the reactors.
3*	*Core flow distribution changes due to temperature gradients.*	*Some effect on fuel operating temperatures.*	M	Affect the fuel temperature. In pebble bed this may change the local (microscopic!) flow distribution drastically.	M	It is difficult to compute the local velocity/temperature distributions under these conditions; practically for PBMR.
4*	*Core flow distribution changes due to graphite irradiation.*	*Some effect on fuel operating temperatures.*	M	Would affect the fuel temperature and it may vary with the aging as the irradiation would affect the gaps and graphite spacing!	M	It would be difficult to determine the core geometry due to the changes with the irradiation. This would require data.
5*	*Core flow distribution changes due to core barrel geometry.*	*Some effect on fuel operating temperatures.*	M	The heat transfer would change due to the core flow distribution changes and consequently, it would affect the fuel temperatures.	M	It would be difficult to determine the core geometry changes with time.
6*	*Core flow distribution due to core block stability (prismatic).*	*Problem at Fort St. Vrain.*	H	It would affect the fuel operating temperature.	M	It would be difficult to determine the core geometry.
7*	*Pebble bed core bridging.*	*Problem at AVR.*	H	It would affect the fuel temperature.	M	The geometry is difficult to determine.

Table 14.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
8*	*Pebble bed core wall interface effects on bypass flow.*	*Diversion of some core cooling flow.*	H	The local flow patterns due to wall interface effects would affect the local fuel temperature.	L	Understanding of the complex flow behavior under these conditions is missing.
9	Coolant properties—viscosity and friction effects.	Determines core temperatures.	M	These properties are important to determine the flow and temperature distributions (pressure drop and heat transfer) within the core.	H	Helium properties are known.
10	Coolant heat transfer correlations.	Determines core temperatures.	H	Important in calculation of heat transfer and consequently, the fuel temperature.	M	Large uncertainty in pebble bed reactor correlations for heat transfer.
11*	*Core Inlet flow distribution.*	*Important for core cooling calculations.*	M	Important in determination of the pressure drops and heat transfer in the core from one zone to the other.	M	Uncertainty in the calculation due to the complex geometry.
12	Thermal fluid mixing from separate loops.	Important for core cooling calculations.	M	It could led to nonuniform temperature at the core inlet plenum.	M	Uncertainty in the calculation due to the complex geometry.
13	Outlet plenum flow distribution.	Affects mixing; thermal stresses in plenum and down stream.	H	This would affect the outlet temperature to the turbine. It may cause thermal stress and affect the integrity of the supports.	M	Thermal mixing in the complex geometry of the outlet plenum needs data for validation of CFD codes. In addition turbulence structure should be studied.
14*	*Pebble flow.*	*Affects core maximum temperatures, pebble burnup; problem at THTR.*	H	This is important in calculation of the heat transfer values which would determine the fuel temperature, burnup.	L	Again local velocity patterns between the pores are amazing and complex.
15	Effective core thermal conductivity.	Effects core maximum temperatures during operation.	H	Important in calculation of the heat transfer.	M	Determination of accurate values for the thermal conductivity; consequently the heat transfer can be calculated.

Table 14.1 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
16	Effective fuel element thermal conductivity.	Effects core maximum temperatures during operation.				
17	Core specific heat.	Affects transients.	M		M	
18	Side reflector—core barrel—vessel heat transfer.	Affects residual heat losses, vessel temperatures.	M		M	
19	RCCS behavior (heat removal performance).	Affects residual heat losses, vessel temperatures.	H	Important component for heat transfer and consequently, the vessel integrity.	M	
20*	*Shutdown cooling system startup transients.*	*Can affect component thermal stresses; dependent on design and operational details.*	M	Can affect the thermal stress and cause fretting and accelerate the corrosion.	M	Material issue.
21-D	Power and flux profiles.	Affects core maximum temperatures.	H	It would be affected also with the fuel pebbles distribution in the core and bypass leakages.	M	The flux is dependent on the core configuration.
22	Reactivity-temperature feedback coefficients.	Affects core transient behavior.	M	Under the circumstances of load changes would affect the core behavior and power distribution.	H	
23	Xenon buildup and oscillation.	Affects core transient behavior.	M	Needed for transient conditions.	M	Need data for validation.
24*	*Fuel performance modeling.*	*Fuel type dependent. Crucial to design and siting; depends on performance envelope, QA/QC,…*	H	Source term. Need data.	M	Need data.
25*	*Ag-110m release and plateout.*	*Affects maintenance dose.*	M	Determine the source term.	M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.2. General LOFC PIRT chart—YH

This chart is for general cases of loss-of-forced cooling (LOFC) events; for specifics of pressurized (P-LOFC) or depressurized (D-LOFC) cases, see other tables.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core thermal conductivity (effective).	Affects T_{Fuel} max (low values) and T_{Vessel} max (high values); effective conductivity is a complex function of graphite temp and radiation terms.	H	It is an important parameter in fuel temperature calculations.	M	Thermal conductivity of graphite as a function of the irradiation duration.
2	Fuel element annealing (prismatic core).	End-of-life T_{Fuel} maximum calculations sensitive to annealing calculations; extent of annealing in given areas can be difficult to predict.	M	Affect the fuel properties. It is a function of irradiation.	M	The knowledge and characteristics of the graphite.
3	Core specific heat function.	Large core heat capacity gives slow accident response; fuel property close to that of graphite.	H	Important in heat calculations and consequently, fuel temperature.	M	Graphite properties change in the core with time due to irradiation effects on the graphite.
4	Vessel emissivity.	T^4 vessel to RCCS affects heat transfer process at accident temperatures.	H	The vessel is important factor in estimation of the radiation heat transfer and its magnitude is important to estimate the fuel temperature.	M	Depend on the material and the changes of the emissivity with the time.
5	RCCS panel emissivity.	Factor in the radiant heat transfer from vessel to RCCS.	H	Important in the heat transport from vessel wall to the panel. The integrity of the vessel is dependent on the heat transport.	M	Depend on the material and the changes of the emissivity with time.
6	Vessel to RCCS effective view factors.	Determines space-dependent heat transfer; complex geometries involved.	M	The radiation heat transfer is a function of the effective view factors.	M	Determination of the geometrical view factors are available. Verification of these factors in the codes is missing.

Table 14.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
7	Reactor vessel cavity air circulation and heat transfer + radiation.	Affects upper cavity heating.	H	The upper cavity would be affected and maybe the heat transport from the upper vessel head to the RCCS is reduced via radiation heat transport mode. The fraction between the heat transport via the convection and radiation mechanisms are different from the vessel sides and lower head under this accident condition.	L	Data is needed for validation of the computational tools. The air flow patterns in the cavity are three dimensional and complex (with circulation patterns). This flow behavior would affect the heat transfer and the nominal heat transfer correlation may not be accurate and needs to be modified.
8	Reactor vessel cavity “gray gas” (participating media).	Can affect vessel temperatures and T_{Fuel} max.	M	The cavity temperature and gray gas with aerosol particles would affect the heat transfer.	L	The flow and temperature predictions under these condition are complex to understand and to compute.
9	Reflectors: conductivity and annealing.	Affects peak fuel and vessel temperatures.	H	It would affect the fuel temperature.	M	Conductivity knowledge of graphite under the condition of the reactor is important.
10	Core barrel emissivity.	Affects peak fuel and vessel temperatures.	H	Temperature drop in the fuel elements depend also on the emissivity and its changes with time.	M	The effect of the dust on the barrel emissivity.
11	Stored (Wigner) energy releases.		M		M	
*12**	*RCCS fouling on coolant side.*	*Affects heat sink effectiveness; deterioration can be measured on-line in some designs.*	*H*	*It affects the heat transfer and also may affect the structural integrity of the system.*	M	*Here there are maybe two types of cooling (air or/and water systems). Oxidation and erosion of the panels and water pipes with*

Table 14.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
						the time is a concern due to less knowledge. The fluid accelerated erosion and corrosion!!
*13**	*RCCS spatial heat loadings.*	*Shifts in heat loadings can affect cooling effectiveness; complex geometries involved.*	M	*Vessel support integrity.*	*M*	*Lack of experimental data.*
14	RCCS failure of 1 of 2 channels.	Affects cooling effectiveness (design); complex geometries involved.	H		M	
15	RCCS failure of both channels.	Involves complex heat transfer to cavity walls.	H		L	
*16**	*RCCS panel damage from missiles.*	*Complex phenomena involved.*	H		*L*	
17	RCCS forced-to-natural circulation transitions.	Complex phenomena (more so with water coolant); crucial to function.	M	It is important in determination of the accurate values of heat transport.	M	The switching from forced to natural convection and may end also with a mixed convection regime. This needs data for validation.
18	RCCS single phase boiling transitions.	Complex phenomena; crucial to function.	M	Here subcooled boiling can exist and one side is hot and the other side of the panel is cool. This may end up with complex phenomena to understand and also to determine the cooling magnitude value.	M	Complex phenomena.
*19**	*RCCS parallel channel interactions.*	*Complex phenomena; crucial to function.*	*H*	*Various patterns of flow behavior.*	*M*	*Data is needed for understanding the phenomena and for validation of the calculations.*

Table 14.2 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
20	RCCS natural circulation in horizontal panel(s).	Complex phenomena (more so with water coolant); crucial to function.	M		M	
21	Decay heat.	Time dependence and spatial distribution major factors in T_{Fuel} max. estimate.	H	This is the driving force. The need is to enhance the cooling of the fuel elements.	M	The spatial distribution of the fuel elements or pebbles should be predicted!!!!

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.3. Pressurized LOFC PIRT chart—YH

This chart is for phenomena specific to the P-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Inlet plenum stratification and plumes.	Determines design of upper vessel head area insulation.	H	Stresses on the plenum structures due to the thermal stratification. Affect the behavior of control rod and its driving channels.	M	Forces on the support. The flow coupling of the inlet plenum and the core. This may require thermal hydraulic system code coupled with CFD program for the plenum domain. Validations of these codes are missing. Need of data.
2	Radiant heat transfer from top of core to upper vessel head.	Determines design of upper vessel head area insulation; view factor models; also affected by core top surface temperatures.	H	It is important for heat transfer from the upper vessel head.	M	Determination of the view factors is needed for calculation of the radiation heat transfer. Knowledge is fine but difficult implementation and validation.
3	RCCS spatial heat loadings.	Major shifts in heat load to top of RCCS; complex geometries involved.	M	This may cause the heating of the cavity roof which can reduce the heat transfer from the upper vessel head (cooling of the upper vessel head).	M	This could affect the heat transfer mechanisms (i.e., less radiation heat transfer due to the high temperature of the roof with respect to the normal operational conditions).
4	Core coolant flow distribution.	Dominates core heat redistribution in P-LOFC; involves low-flow correlations, flow reversals.	H	Affect the fuel temperature. Hot gas would be on the top elevation of the core. Also may affect the upper vessel structure.	M	Complex heat transfer pattern laminarization of the flow close to the wall which would decrease heat transfer from fuel. Data is needed for validation and refinement of the heat transfer correlations.

Table 14.3 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5	Core coolant (channel) by-pass flow.	Involves low-flow correlations, flow reversals.	M	This change in the flow distribution would affect the fuel temperatures. It is clear here that three-dimensional flow distributions are needed to determine the local heat transfer.	L	Low flow correlation under high temperature conditions (in addition to more complexity of the geometry in case of pebble core).
6	Coolant flow friction/ viscosity effects.	Significant effects on plumes; models for very low and reverse flows.	M	Determine the flow distributions, consequently the fuel temperatures.	M	The heat transfer under these conditions would be also in a mixed convection mode. This is known but it is difficult to be calculated accurately due to the turbulence estimations under these flow modes.
7*	*SCS startup flows—transients.*	*Thermal transients for P-LOFCs more pronounced.*	M	Affect the integrity of SCS components due to the transient behavior.	M	Validation data are needed during these transients.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.4. Depressurized LOFC PIRT chart—YH

This chart is for phenomena specific to the D-LOFC case; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Core effective thermal conductivity.	Affects T_{Fuel} max for D-LOFC.	H	Affect the heat transfer and consequently the fuel temperature.	M	Local effective thermal conductivity estimation.
2	Decay heat and distribution vs time.	Affects T_{Fuel} max for D-LOFC.	H	FOM—fuel temperature, dose. >The major concern is to dissipate the decay heat via several cooling mechanisms to maintain the fuel integrity.	M	Dependent on the accurate calculations of the peaking factors in the core,… (neutronics). Three dimensional coupling is needed between neutronics and thermal hydraulics, especially for pebble bed reactors. Uncertainty in the calculations of photon and electron scattering at the many interfaces and the boundaries. Microchemistry and microstructure changes for old fuel are unknown.
3	RCCS spatial heat (DISTRIBUTION) *loadings.*	Major shifts in heat load to middle of RCCS; complex geometries involved.	H	Structure integrity.	M	The loading can be determined. Validation is needed.
4*	*Heatup accident fuel performance modeling.*	*Crucial factor in reactor design limits; dependent on fuel type, operational history.*	M	Power level.	M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.5. Air ingress LOFC PIRT chart—YH

This chart is for phenomena specific to the D-LOFC case with air ingress; see the general LOFC and D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core.	H	Different densities between air and He mixing need diffusion of both gases in the plenum. Properties of the helium such as viscosity increases with temp (opposite of liquids) would affect the heat transfer.	M	Prediction of local flow characteristics depends on the coolant properties of the gases (as the laminarization phenomena near heated walls).
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core.	H	Determine fuel temperature.	M	Correlations at high temperature close to the fuel rods are not accurate.
3	RCCS performance with “gray gas” in cavity.	Particulates, etc., in cavity reduces radiant heat transfer; complex processes involved.	M	Radiation heat transfer mechanism is a significant part of total heat transfer. The aerosol particle would affect the heat transfer mechanisms (radiation and also convection (gas/particles). The effect on radiation is more and it may be significant depending on the concentration values and distribution.	L	The estimation of the dust concentration in the cavity and its values during the transient are not available.
4*	*Fuel performance with oxygen attack.*	*Consideration for long-term air ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.*	H	Determine fuel temperature. Changes in surface emissivity and conductivity due to oxidation would affect the fuel temperature.	M	Oxidation characteristics for irradiated fuels.

Table 14.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
5*	*Core support structures oxidation modeling.*	*Low-temperature oxidation potentially damaging to structural strength.*	M	Core support integrity.	M	Mixing and temperature distribution would affect the local structure oxidations (i.e., local oxidation may be different from a region to another in the outlet plenum).
6	Core oxidation modeling.	Determination of "where" in core the oxidation would take place.	H	Affect fuel temperature.	M	Information to calculate the onset of oxidation and distribution within the core. The oxidation can occur at the top of the core too depending on the break location.
7	Reactor vessel cavity leakage rates.	Determines cavity performance after D-LOFCs; function of gas, separation characteristics.	H	Determine the behavior of the flow and consequently oxidation phenomena once air penetrate the core.	M	Here is also the gas conditions are important.
8	Cavity gas composition and temperature.	Provides gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Would affect the corrosion and oxidation depending on the ingress flow which is dependent on the cavity composition and its state conditions.	M	The calculations of the cavity conditions and composition may be obtained the boundary conditions are defined and known. The transient condition may end to opening the confinement valves in interment (pulses) mode.
9	Cavity gas stratification and mixing.	Provides gas ingress and cold-leg conditions; needed to determine oxidation rate.	H	Would affect the ingress flow; consequently, the fuel temperature. In case the break at the top which leak hot helium to the upper level of the cavity and	M	The calculation of the flow and temperature at the region below the vessel is not accurate with conventional calculation tools. (Code

Table 14.5 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
				end-up with hot helium bubble. These conditions may affect the performance of RCCS.		calculations under this stratification conditions are not accurate due to, for example, numerical diffusions of the numerical scheme).
10	Cavity air in-leakage to the core.	Determines long-term oxidation rate if accident unchecked.	H	Cavity air in-leakage flow and its thermal state conditions would affect oxidation rate)—which would affect the fuel temperature.	M	The flow distribution and condition need to be determined to obtain flow rates in.
11	Cavity combustion gases.	Some Co formed as oxidation product.	L	Cavity pressure and temperature conditions.	M	Concentrations are not determined.
12	Cavity structural performance.	Influence on air ingress analysis modeling.	M	Fast depressurization may cause fluid-induced high forces on the structure (gas jets).	M	Fluid-induced forces and vibration should be calculated accurately. This needs coupling between fluid and structure codes.
13	Cavity filtering performance.	Affects radioactive dust releases; dust can contribute to the source term for PBMR.	H	Can release fission products and aerosol dust particles.	M	Aerosol dynamics need to be addressed under the cavity conditions.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.6. Reactivity (ATWS) PIRT chart—YH

This chart is for phenomena specific to LOFC cases with ATWS; see also general LOFC, P-, and/or D-LOFC charts as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Pebble core compaction (packing fraction) via earthquake.	Potentially sharp increase in reactivity with packing fraction; can affect reactivity feedback.	H	Challenge to reactivity control. Fuel energy deposition.	M	Neutronic calculations are available. The porosity of the packed bed during earthquake needs to be addressed.
2*	*[Prismatic] Excess reactivity (with burnable poison—BP).*	*Potential for large reactivity inputs with large excess reactivity; uncertainty depending on BP design.*	M	Determination of CR worths.	M	
3	Steam-water ingress accidents.	Positive reactivity insertions possible; complex processes involved; also decreases control rod effectiveness.	H	The effect on control rod is important.	M	Existing models are fine—validation.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects reactivity.	M	Flow regimes determine the scram. The flow regime will determine the heat transfer mode.	M	Available data. Need validation for our geometry configurations.
5	Reactivity temperature feedback coefficients (fuel, moderator, reflectors).		M/H	A negative feed back.	H	Intensive calculations are needed.
6	Control rod, scram, reserve shutdown worths.	Needed for cold shutdown validation.	M		H	
7	Xenon and samarium buildup.	Determination of poison distribution.	M	Recriticality issue.	M	The phenomena are known.
8	Scram and reserve shutdown system failure modes.	Needed for cold shutdown validation.	H		H	
9*	*Rod ejection prevention.*		H		M	
10*	*Coolant flow restarts during ATWS.*		M		M	

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

Table 14.7. IHX failure (molten salt) PIRT chart—YH

Design assumptions: Molten salt (~800°C), inventory = 130,000 kg (3000 ft^3), 15,000 ft^3 in reactor, isolation valves?
Scenario: Break of IHX internal tubes, blowdown of primary to secondary, then possible ingress of molten salt (no nitrates).
Conditions: Secondary side press lower than primary (no nitrate salts), lower plenum filled with molten salt by ~X hrs with partial P/D-LOFC. He escapes by secondary relief valve out molten salt lines (confinement bypass), countercurrent flow, lots of inertia as 0.5 miles of molten salt slows down and pump coasts down.
Single failure: isolation valve fails to close.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Ingress of helium into IHX loop (part of confinement bypass).	Blowdown of primary system into secondary system, gas jet into liquid, initial circulating activity is the prime source of the public and worker dose.	M	FOM—public and worker dose. Helium flow rate determines how much activity is transported into IHX loop.	M	Uncertainties in secondary system side conditions (operating pressure, relief valve settings) make accurate calculation of total helium into IHX loop difficult.
2	*Fission product* transport through IHX loop (part of confinement bypass).	Deposit/removal of FP, dust, scrubbing of molten salt, adsorption, plate-out.	H	FOM—public and worker dose. Determines activity released out of IHX relief valve, and residuals in IHX loop.	M	Lack of scrubbing data applicable to counter-current He–MS flow. The bounding models may be able to reduce uncertainties.
3	*Helium* transport in IHX loop (part of confinement bypass).	Possible He/molten salt countercurrent flow, blocking bubble in IHX loop.	M	FOM—public and worker dose. Affects fission product transport through IHX to relief valve.	L	The scaling to helium–molten salt data are unavailable.
4	Ingress of molten salt into primary system and RPV.	After partial blowdown, relies on items #1, 2, 3 as initial/boundary conditions.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Determines amount/mass of MS in vessel, core MS level.	L	Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.
5	Riser fill with molten salt.	Through cold duct.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. Affects vessel temperatures, heat transfer to RCCS.	L	Design dependent uncertainties such as break location, piping design, break size, secondary blowdown.

Table 14.7 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
6	Lower plenum fill with molten salt.	Through hot duct.	H	FOM—vessel temperatures, vessel support temperatures, core support temperatures structural integrity effects.	L	Uncertainty in calculating MS level and mass.
7	Molten salt (in cold duct)-to-core support/vessel heat transfer.		H	FOM—vessel temperatures, vessel support temperatures, core support temperatures. >Impact on cross duct and vessel temperatures.	L	Heat transfer calculations are more complex due to non-wetting nature of MS and trapping of helium in cavities, two-phase flow.
8	Molten salt (in hot duct)-to-core support/vessel heat transfer.		M	FOM—vessel temperatures, vessel support temperatures, core support temperatures. >Temperatures not much different from normal operating temperature.	L	Heat transfer calculations are more complex due to non-wetting nature of MS and trapping of helium in cavities, two-phase flow.
9	RCCS heat removal.	Heat transfer from vessel wall to RCCS and cavity.	H	FOM—vessel temps, vessel support temps, cavity temps. >Ultimate heat sink, abnormal temperature distribution on RCCS and vessel.	L	Skewed vessel heat loading below RCCS design.

[1] H, M, or L (high, medium, or low).

Table 14.8. Water-steam ingress PIRT chart—YH

This chart is for phenomena specific to LOFC cases with water ingress; see general LOFC chart as well.

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
1	Coolant flow properties for mixed gases in core.	Determines friction and heat transfer characteristics in core; can affect accident outcome.	M		M	
2	Heat transfer correlations for mixed gases in core.	Determines heat transfer characteristics in core; can affect accident outcome.	M	This heat transfer has an influence on fuel temperature.	M	Validation is needed for these correlation under the conditions here.
3	RCCS performance with "gray gas" in cavity.	Particulates, etc. in cavity reduces radiant heat transfer; complex processes involved.	M	Radiation is an important part in heat transport.	L	The effect of particulates in the gas and their distributions would determine the heat transport.
4	Mechanisms for water or steam ingress from SCS or PCU coolers.	Some water ingress scenarios are postulated; effects on reactivity and core degradation.	M	The scenario of the steam/water ingress would affect the heat transfer.	H	Two phase flow behavior has a lot information from LWR.
5	Fuel performance with oxygen attack.	Consideration for water ingress involving core (fueled area) oxidation; FP releases observed for high temperature exposures.	M	The effect of the oxidation. Here also the flow pattern may affect the oxidation rate.	M	
6	Core support structures oxidation modeling.	Core support structure area potential weakening.	H	The damage of core support due to oxidation.	M	This also depends on the flow/temperature distributions within the core support structural area.
7	Core (steam) oxidation modeling.	Determination of "where" in core the oxidation would take place.	M	The oxidation location and its effects may cause pebble fuel damage.	M	The flow patterns and local steam concentration would determine the degree of oxidation!!

Table 14.8 (continued)

ID No.	Issue (phenomena, process, etc.)	Comments	Importance[1]	Rationale	Knowledge level[1]	Rationale
8	Cavity gas composition and temperature.	Provides steam/gas ingress and cold-leg conditions; needed to calculate ingress flow rate and properties.	M	Affect the heat transfer with radiation and convection in the cavity.	M	Validation is needed.
9	Cavity gas stratification and mixing.	Provides steam/gas ingress and cold-leg conditions; needed to determine oxidation rate.	M	Would affect the heat transport from the vessel to RCCS.	M	Oxidation rate calculations!!
10	Cavity combustion gases.		M	Effect the RCCS performance.	H	
12	Cavity structural performance.	Influence on ingress analysis modeling.	M	The effect on the RCCS structure.	M	Fluid structure interaction issues.
13	Cavity filtering performance.	Affects radioactive releases.	H		M	Depends on the characteristics of the filters and also the locations.
14	Pressure transients from steam formation.	Potential damage to primary system structures.	M	May cause structural problems.	H	FSI is known.

*Issue not written down in the first PIRT meeting, but was discussed.

[1] H, M, or L (high, medium, or low).

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