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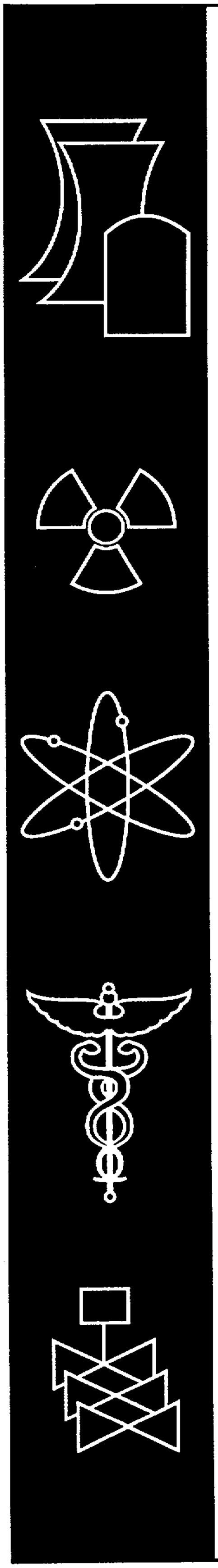

Phenomenon Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel

Los Alamos National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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Phenomenon Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel

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Abstract

In the United States, cladding embrittlement criteria and related evaluation models are used to address loss-of-coolant accidents. The embrittlement criteria are a peak cladding temperature of 1204 °C (2200 °F) and an equivalent oxidation of 17% of the cladding wall thickness calculated with the Baker-Just correlation. Evaluation models address ballooning, rupture, flow blockage, and oxidation kinetics. In the 1970s, high burnup was considered to be around 40 GWd/t (average for the peak rod). Data out to that burnup had been included in databases for codes, and regulatory decisions. It was believed that some extrapolation in burnup could be made and fuel burnups in licensed reactors up to 62 GWd/t (average for the peak rod) were permitted. By the mid 1980s, however, unique changes in pellet microstructure had been observed from vendor and international data at higher burnups along with increases in the rate of cladding corrosion. It thus became clear that other phenomena were occurring at high burnups and that continued extrapolation of transient data from the low-burnup database was not appropriate. The US Nuclear Regulatory Commission (NRC) is addressing these issues. The NRC is performing research with respect to high burnup fuel to acquire and develop the requisite understanding of the performance of high burnup fuel under accident conditions. It is also conducting research to determine if current embrittlement criteria and evaluation models are adequate for high-burnup fuel or if modifications are needed. To support these efforts, The NRC has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena occurring during selected transient and accident scenarios in both pressurized water reactors and boiling water reactors containing high burnup fuel. Because the PIRT identifies and ranks phenomena for importance, currently existing experimental data, planned experiments, computational tools (codes), and code-calculated results can be screened to determine applicability and adequacy using the PIRT results. This PIRT identifies and ranks phenomena for loss-of-coolant accidents in both pressurized and boiling water reactors. A spectrum of break sizes has been considered in preparing the PIRT.

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EXECUTIVE SUMMARY

In the United States, cladding embrittlement criteria and related evaluation models are used to address loss-of-coolant accidents (LOCA). The embrittlement criteria are a peak cladding temperature of 1204 °C (2200 °F) and an equivalent oxidation of 17% of the cladding wall thickness calculated with the Baker-Just correlation. Evaluation models address ballooning, rupture, flow blockage, and oxidation kinetics. The criteria and models are used to ensure that fuel damage does not interfere with either short-term or long-term cooling of the core.

In the 1970s high burnup was considered to be around 40-gigawatt days/metric ton (GWd/t) (average for the peak rod). Data out to that burnup had been included in databases for codes and regulatory decisions. It was believed that some extrapolation in burnup could be made, and fuel burnups in licensed reactors up to 62 GWd/t (average for the peak rod) were permitted. By the mid 1980s, however, unique changes in pellet microstructure had been observed from both vendor and international data at higher burnups along with increases in the rate of cladding corrosion. It thus became clear that additional phenomena were occurring at high burnups and that continued extrapolation of transient data from the low-burnup database was not appropriate.

The US Nuclear Regulatory Commission (NRC) is addressing these issues. It is identifying research to be done with respect to high burnup fuel to acquire and develop the requisite understanding of the performance of high burnup fuel under accident conditions. The NRC is also preparing to develop new regulatory limits for fuel damage if they are needed.

To support these efforts, the NRC has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena occurring during selected transient and accident scenarios in both pressurized water reactors (PWR) and boiling water reactors (BWR) containing high burnup fuel. Membership of the PIRT panel has been drawn from the US and international scientific community, and many of its twenty-two members are actively involved in experimental and analytical work related to the behavior of high burnup fuel under accident conditions. Because the PIRT identifies and ranks phenomena for importance, currently existing experimental data, planned experiments, computational tools (codes), and code-calculated results can be screened to determine applicability and adequacy using the PIRT results.

This LOCA PIRT has been developed for PWRs and BWRs. PIRT development becomes difficult if multiple reactor types or accident scenarios are considered simultaneously. For the LOCA PIRT, the panel elected to develop a baseline PIRT for a PWR plant and then evaluate changes to the PIRT for BWR plants. No specific PWR plant was selected. However, the primary LOCA overview information presented to the panel was for a Westinghouse 4-loop PWR. Overview information describing the response of a BWR-6 plant to a large-break LOCA was also presented to the panel. Additional information was also provided about the response of a generic BWR/4 and BWR/2 plant to the same event. Related PIRTs have been prepared for a PWR rod ejection accident and for instability power oscillations arising during an anticipated transient without scram in BWRs. The PWR and BWR fuel descriptions from these PIRTs were also used for the LOCA PIRT. The burnup of the fuel was assumed to be 62 GWd/t, the current approval limit. However, the panel was also charged with the responsibility of extending the applicability of the PIRT to cover other fuel, cladding, and reactor types and fuel burnups to 75 GWd/t.

The panel recognized that it is necessary to use a combination of experimental data (both from integral tests and from separate effects tests) and analyses (including plant transient analysis and fuel rod analysis) to resolve issues related to fuel burnup. Integral tests refer to the testing of fueled rods when subjected to conditions representative of a LOCA. Although these are the tests that most closely approximate the actual LOCA event, they are extremely expensive, so that it is financially impractical to devise a research program based solely on integral tests. Because of this, the effects of various parameters must be studied in separate-effects tests that can investigate the relevant parameters in detail. In addition, it is necessary to perform fuel rod analysis to translate the results of the integral testing to the power plants and to be able to extract data from the experimental results. Such analysis can factor in any inherent differences between the integral tests and real power plants. It is also necessary to perform analyses of plant transients that give the boundary conditions for the LOCA, as well as assessing its likelihood.

Previous PIRT efforts have recorded a single importance rank for each phenomenon. This was achievable, in part, because the typical panel consisted of 6–8 members; and such panels were usually able to reach a common view about phenomena importance in a timely manner. Given the size of the present panel, it was decided that a vote would be taken and the number of votes for each importance rank reported. Panel members voted on only those phenomena for which they had a firm opinion about importance.

The PIRT phenomena identified by the panel were grouped into four categories: (A) Plant Transient Analysis, (B) Integral Testing, (C) Transient Fuel Rod Analysis, and (D) Separate Effects Testing. For the purposes of evaluation, the panel divided the phenomena into two analytical categories (Category A, Plant Transient Analysis, and Category C, Fuel Rod Analysis) and two experimental categories (Category B, Integral Tests, and category D, Separate Effects Tests). We decided as a panel on a primary evaluation criterion, namely, cladding fragmentation. The criteria that were used to examine the possibility of cladding fragmentation were the calculated peak cladding temperature and the amount of cladding oxidation.

The panel was then divided into analytical and experimental working groups. Each working group: (1) created a list of phenomena with written definitions; (2) discussed and evaluated each phenomenon according to a set of well-defined questions, which are presented in Section 2.5; (3) ranked their importance to the primary evaluation criterion as high, medium, or low; (4) documented the rationales for the importance votes; (5) evaluated the current uncertainty in the knowledge of these phenomena as "known," "partially known," or "unknown";

and (6) evaluated whether any of the importance votes would change for other fuels or claddings and for burnups to 75 GWd/t (instead of 62 GWd/t).

The panel then analyzed the results of the PIRT effort to identify the most important outcomes. The importance rankings and rationales, combined with the uncertainty rankings and rationales, have been considered in developing the panel's perspective regarding the important issues affecting LOCAs. To provide a weighting structure to our assessment of the importance and uncertainty vote results, the panel created an importance ratio, a knowledge ratio, and related cutoff values.

The panel notes that there were a number of phenomena having importance and uncertainty values near to but not meeting the screening criteria. Some of these phenomena may also warrant additional consideration. While the screening criteria provide a useful first cut at identifying important phenomena for which the knowledge base is limited, parties analyzing or applying the PIRT results should also look at those phenomena that are near to but not meeting the screening criteria. Those applying these PIRT results should carefully examine and consider both the PIRT votes and the documented rationales.

For the four PIRT categories considered by the PIRT panel, application of the importance and uncertainty screening criteria by the panel produced the following results[1].

Plant Transient Analysis (Category A)

This category was divided into seven subcategories: (1) initial conditions, (2) transient power distribution, (3) steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood) and core spray heat transfer, (4) transient coolant conditions as a function of elevation and time, (5) fuel rod response, (6) multiple rod mechanical effects, and (7) multiple rod thermal effects.

Within the initial conditions subcategory, two of the eighteen phenomena satisfied both the importance and the knowledge screening criteria: (1) gas pressure and (2) rod free volume. Gas pressure was considered to be important because it sets the initial conditions for rod response and can affect conductance. The rod free volume influences the possible burst of the rod.

Within the transient power distribution subcategory two of the five phenomena were identified as important: (1) moderator feedback and (2) decay heat power. However, neither of these had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. The implication of the uncertainty outcome is that the panel believes that it has sufficient knowledge to adequately model each of the important phenomena identified in this category.

Within the steady state and transient cladding to coolant heat transfer subcategory, four of the eight phenomena satisfied both the importance and knowledge

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[1] Definitions of each phenomenon listed below are found in Appendices A-D of this report. The rationales for importance and uncertainty rankings are found in the same appendices.

screening criteria: (1) film boiling over a wide void fraction, (2) rewet, (3) rod-to-spacer grid thermal-hydraulic interaction, and (4) spacer grid rewetting and droplet breakup. From the importance vote justifications, it is clear that the panel recognizes that the complex processes of dryout, film boiling and rewetting are at once of great importance in determining cladding temperature and fairly unknown because fundamental models do not exist and there is large scatter of data. The influence of the spacer grids on heat transfer and rewetting was also highlighted by the panel's importance vote. The lack of data and model uncertainty in these areas were thought by the panel to be even greater than in the above two areas.

The difficulty in accurately modeling and predicting two-phase flow characteristics crucial to determining cladding temperature during the transient was evidenced by the panel's votes on the phenomena listed in the transient coolant conditions as a function of elevation and time subcategory. Five of the seven phenomena satisfied both the importance and knowledge screening criteria: (1) temperature, (2) flow rate and direction including counter current flow limitation, (3) quality, (4) void fraction, and (5) cross flow effects due to flow blockage. The common rationale given in the justifications for the importance and knowledge votes was that these coolant conditions determine cladding temperature and that the accurate prediction of the local two-phase flow behavior is difficult.

Within the fuel rod response subcategory, two of the sixteen phenomena satisfied both the importance and knowledge screening criteria: (1) burst criteria and (2) time-dependent gap-size heat transfer. The high importance attached to the burst criterion stems from the fact that tube burst can lead to substantial flow blockage and the existing correlations are outdated and require significant improvement, especially in regards to the effect of hydrogen. In the case of time-dependent gap-size heat transfer, the panel highlighted the importance of the gap in heat transfer and stressed that gap size is not well known.

Within the two subcategories dealing with multiple rod effects (mechanical and thermal effects), no phenomenon satisfied the dual screening criteria. In the thermal effects subcategory, radiative heat transfer from the rod to channel, to the water and to the inner channel were considered to be important but well known.

Each of the above listed phenomena in the Plant Transient Analysis category meeting the dual screening criteria has been flagged by the panel as a candidate for additional consideration.

Integral Testing (Category B)

This category includes phenomena related to the testing of fuel rods in a test reactor such as Halden or Phebus or in an electrically heated facility. This category was divided into three subcategories: (1) fuel rod selection, (2) conduct of test, and (3) parameters and variables measured.

Within the fuel rod selection subcategory, a single characteristic from among the four fuel and ten cladding characteristics satisfied both the importance and knowledge screening criteria. That characteristic is the fuel burnup. This characteristic was highlighted because burnup is the focus of the test and a high burnup rod should be selected to facilitate discovery of phenomena not yet recognized and so that unknown effects are not overlooked. As fabricated wall-thickness should also be considered given its importance ranking and proximity to the knowledge ratio screening criterion cutoff value.

Within the conduct of test subcategory, three characteristics satisfied both the importance and knowledge screening criteria: (1) plateau temperature, (2) cooldown, quench, and rewet rate initiation, and (3) whether the test specimen contained fuel or was void of fuel. A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The plateau temperature (temperature of period 2) was thought to be very important because it affects oxidation and hydrogen pickup kinetics, which ultimately determine the survivability of the cladding. In the same manner, the rate of cooldown and quench (temperature history of stages 3 and 4) was thought to be crucial to determining cladding response. Finally the presence of fuel was thought to be an important feature of LOCA simulation tests because of the effects of fuel bonding.

The parameters and variables measured subcategory was further divided into a consideration of online measurements and post-test examination. None of the ten online measurements were judged by the panel to meet both the importance and knowledge screening criteria. One of the eight post-test measurements (fuel relocation, residual bonding, and dispersal) satisfied both the importance and knowledge screening criteria. Determination of the amount of fuel released from the fuel rod during the test and the location to which it moved or dispersed were highlighted by the panel as possibly the only way to quantify a potentially significant effect of the transient.

Each of the above listed characteristics in the Integral Testing category meeting the dual screening criteria has been flagged by the panel as a candidate for additional consideration.

Transient Fuel Rod Analysis (Category C)

This category consists of six subcategories: (1) initial conditions, (2) transient boundary conditions, (3) fuel rod response, (4) multiple rod mechanical effects, (5) properties, and (6) transient cladding-to-coolant heat transfer.

Within the initial conditions subcategory, eight of the twenty-five conditions satisfied both the importance and the knowledge screening criteria: (1) gas pressure, (2) gas composition, (3) cladding oxidation on both the inner and outer cladding surfaces, (4) hydrogen concentration, (5) hydrogen distribution, (6) porosity distribution, (7) rim size, and (8) spallation and cracking of the oxide layer.

Within the transient boundary conditions subcategory, two of the three conditions satisfied both the importance and knowledge screening criteria: (1) transient cladding-to coolant heat transfer and (2) transient coolant conditions. The first phenomenon was voted high because it helps determine cladding temperature during the quench phase and hence quench speed, quenched cladding microstructure and cladding survivability. The time dependent coolant conditions also change the heat transfer coefficient and by extension cladding temperature.

Within the fuel rod response subcategory, six of the twenty-seven conditions satisfied both the importance and knowledge screening criteria: (1) gap heat resistance, (2) oxide heat resistance, (3) magnitude of the cladding oxidation on both the inner and outer cladding surfaces, (4) size of burst opening, (5) burst criteria, (6) and time of burst. With the first three phenomena, the panel highlighted the effect of gap heat resistance (especially during ballooning) and oxide thickness (both prior and during the transient) on heat transfer, and by extension on cladding temperature. The last three phenomena relating to fuel rod bursting affect the cladding temperature and amount of fuel dispersal and flow blockage.

The single condition in the multiple rod mechanical effects subcategory, rod-to-rod and rod-to-channel thermal and mechanical interactions satisfied neither the importance or knowledge screening criteria.

Within the properties subcategory, none of the six properties satisfied both the importance and knowledge screening criteria.

Within the transient cladding-to-coolant heat transfer subcategories, each of the two conditions in the subcategory satisfied both the importance and knowledge criteria: (1) rod-to-spacer grid thermal-hydraulic interaction and (2) spacer grid rewetting and droplet breakup. The panel believed that both phenomena have significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature.

Each of the above listed conditions in the Transient Fuel Rod Analysis category meeting the dual screening criteria has been flagged by the panel as a candidate for additional consideration.

Separate Effect Testing (Category D)

This category collects the phenomena related to separate effect testing. It is important to have these tests to facilitate translation of the results of the integral tests and to help explore the possible variations in parameters. To evaluate separate-effects experiments that could provide information on the behavior of high burnup fuel during a LOCA, the panel considered not only experiments currently being conducted, but also other experiments that could be useful.

The experimental subgroup discussed and defined a list of experiments that should be considered, the information that could be gleaned from such experiments, and how they should be conducted. The subgroup then voted for the experiments in the list with respect to their potential value to assessing fuel behavior during a LOCA.

The ranking produced the order in which the experiments are listed here, with the highest ranked listed first. The subgroup then developed subcategories for each of these experiments, considering both the conduct of the test and the parameters to be studied. The subgroup created definitions and voted on the subcategories according to the evaluation criteria, provided justifications, and assessed uncertainties.

Those considering use of the results derived from the screening criteria, as applied to Category D, should exercise additional care for two reasons. First, the number of panel members voting was often small. Thus, the importance and knowledge ratio values were more sensitive to a single panel member's vote than is the case when more panel members voted. Second, more than ten of the phenomena satisfied one screening criterion but were excluded from this summary because their calculated ratios for the remaining screening criterion were exactly 75, i.e., they were not greater to or less than 75 as required by the specific criterion.

This category was divided into six subcategories identified by different separate effect test types: (1) oxidation rate, oxygen distribution, and effect of chemistry on solubility, (2) quench tests, (3) phase equilibria and transformation kinetics-chemistry effects, (4) mechanical properties at high temperature, e.g., ≥ 300 °C, (5) mechanical properties at low temperature, e.g., < 300 °C, and (6) simulation of fuel relocation. Within each test type, specimen selection, conduct of the test, and post-test examination were used to further collect test parameters and characteristics.

These subcategories are discussed in more detail below.

Oxidation Rate, oxygen distribution, effect of chemistry on solubility. This is a separate effects test to measure the high temperature oxidation kinetics used in zirconium alloys used for fuel cladding. These kinetics will result in a particular oxygen distribution in the cladding and will be affected by the altered solubilities brought about by different chemistry. The importance of this test is that it can determine the amount of oxidation given a temperature history. As such it would be valuable for the analysis of integral tests and for oxidation predictions in codes.

In the specimen selection the subgroup felt that the alloy type chosen was very important for the outcome of the test. This is because previous tests have shown that the high temperature oxide layer forms differently on different alloys. For the during the test subcategory, oxygen potential was considered to be highly important to the test outcome, since this is the boundary condition that determines specimen oxidation. The test temperature and time and the weight gain measurement during the test, the latter a primary measure of oxidation, were both considered to be highly important, although better known.

During the post-test examination, the determination of the oxide thickness, characteristic alpha-beta morphology and oxygen distribution were considered to be highly important, as they relate to the basic parameters measured by the test. Their knowledge ratios were near to, but did not satisfy, the cutoff value. These measurements are clearly candidates for additional consideration should the test be conducted.

Quench tests, quench rate and quench temperature. These are tests that attempt to determine the rewetting temperature and the thermal shock resistance of cladding after high temperature oxidation.

From the specimen selection phenomena, it was clear that the specimen configuration is important to the outcome of such tests. The subgroup singled out two items: axial constraints and whether the test is conducted with empty or full cladding as having high importance and a low knowledge ratio. The test specimen fittings are designed to simulate in-reactor fuel rod axial constraints, but can affect the test outcome. The thermal inertia of the pellets can have a significant impact on the temperature history of the cladding during the transient.

For the conduct of the test subcategory, the cladding temperature at the time of water insertion (quench) occurs was considered of high importance and with low knowledge ratio. This affects the metallurgical morphology of the cladding. Whether quench occurs before or after the alpha to beta transformation occurs influences the magnitude of the thermal stresses and the properties of the prior beta phase. The other factor that met the dual criteria was the pre-thinning of the cladding designed to simulate the oxidation related thinning prior to ballooning.

Finally, whether the cladding fragments at the end of the test is considered of major importance because cladding fragmentation determines the risk of fuel dispersal and subsequent coolability concerns.

Phase Equilibria. This category refers to experiments designed to measure fundamental phase equilibria in the systems of interest, as well as phase transformation kinetics that can provide fundamental data relevant to the analysis of cladding behavior during LOCA transients. These include high temperature oxidation experiments to measure the rate of beta phase formation, and the influence of various parameters on alpha-beta phase equilibria. The selection of the alloy was thought to be of great importance because elements such as Sn and Nb affect the alpha-beta phase boundaries. The determination of hydrogen and oxygen solubilities in the alpha and beta phases were thought to be important for modeling efforts, and the determination of retained beta and transformed beta morphology was thought to be important because this was one of the objects of the test.

Mechanical properties at high temperature (>300 °C). This category refers to mechanical tests conducted at high temperature to measure the creep and burst behavior of the cladding during the transient. Specimen selection for alloy and initial thermomechanical treatment satisfied the dual criteria for importance and knowledge. In addition, the measurements of load and displacements, which is essentially the object of the test, and the determination of the post-test strain were given high importance rankings and knowledge ratios of 80%, indicating what the panel thought was most relevant were this test to be conducted.

Mechanical properties at low temperature (<300 °C). In this section, five tests were identified as possibly having enough relevance to assess LOCA behavior: axial tensile, ring tensile, ring compression, impact, and bending (seismic) tests. The panel judged that the seismic test had the greatest relevance to assessing LOCA behavior, by addressing the ability of the fuel rod to withstand a post-LOCA seismic event without shattering. The panel identified how such a test, a four point bending test, should be conducted. In the specimen selection, the alloy type was thought to affect hydrogen content and hydrogen distribution, which in turn affects cladding ductility. This was also the rationale for voting pre-existing and transient hydrogen content as being of high importance. The presence or absence of ballooning in the tested rod was thought by the panel to affect the ability of the fuel rod to withstand the seismic event. In addition, the panel thought that the strain rate and the application of the appropriate bending moment were crucial to the outcome of the test. The rod should clearly be tested for integrity after the test, since this is one of the main test objectives, and measuring the amount of hydrogen will allow the analysis of the results.

Fuel Relocation. The fuel relocation subcategory refers to a separate effects test to measure the effect of fuel relocation during ballooning on the temperature and mechanical evolution of the fuel rod. Within the simulation of fuel relocation subcategory, two of the five specimen selection parameters (burnup and chemical and mechanical bonding), two of the eight conduct of test parameters (internal pressure and moles of gas and balloon size and burst size) and two of the six post-test examination parameters (granularity of dispersed material and strain profile of cladding) satisfied both the importance and knowledge screening criteria.

Each of the above listed conditions in the Separate Effect Testing category meeting the dual screening criteria has been flagged by the panel as a candidate for additional consideration.

Related tutorial discussions and descriptions of existing codes and databases that are relevant to the above categories are also presented in the appendices.

Companion PIRT reports have been prepared for rod ejection accidents in PWRs containing high burnup fuel (NUREG/CR-6742) and power oscillations without scram in BWRs containing high burnup fuel (NUREG/CR-6743)

An NRC staff report that seeks to utilize these PIRT results has also been issued (NUREG-1749).

FOREWORD

In the design and licensing of light-water reactors, it is postulated that a small set of low probability accidents will occur, and it is required that the reactor be able to accommodate or mitigate their consequences without affecting the public health and safety. The most severe in this set of postulated accidents in terms of challenging both the reactor and its associated systems is the large-break loss-of-coolant accident. Small-break loss-of-coolant accidents are also postulated. The characteristics of these accidents serve to set the requirements for a number of the reactor's safety systems, including the emergency core cooling system and the design of the containment.

In addition to the loss-of-coolant accidents, the other important class of postulated accidents has been the reactivity accidents. These include PWR rod-ejection accidents, BWR rod-drop accidents, and BWR power oscillations without scram. In these accidents, energy is deposited in the fuel and causes rapid heating that may damage or even destroy the fuel if the power burst is sufficiently energetic. Consideration of reactivity accidents has led to fast-acting reactor control systems as well as reactor core designs with inherently negative power and void coefficients.

In the mid 1990s, the NRC learned that regulatory criteria, which have been used to ensure benign behavior of these accidents, might not be adequate at high burnups. Further, there were questions at least in principle about the effect on these criteria of new cladding alloys being introduced by the industry. Faced with these concerns, the NRC took several actions to make sure that reactor safety is maintained, that public confidence is not eroded, and that no unnecessary regulatory burden is imposed.

One of the actions was the initiation of research programs to investigate the effects of high burnup and new cladding alloys. To ensure that these research programs were well planned and to get insights on resolving related issues, the NRC sought the advice of a large number of experts. This was done in the form of a structured elicitation process that was used to develop phenomenon identification and ranking tables (PIRTs) for the postulated accidents mentioned above. The PIRT information was then used to make sure that NRC's research programs, which were addressing the burnup and alloy issues, were well planned. Four reports collectively describe the results of this expert elicitation and the implications of the information received for follow-on NRC fuel research. The following is one of those reports, and this report makes reference to the others.

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- Ralph Meyer of the NRC's Office of Nuclear Regulatory Research played a key role in planning and facilitating the panel's understanding of needs, as well as providing invaluable assistance in each of the panel's meetings.
- Harold Scott, Farouk Eltawila, and Frank Odar of the NRC's Office of Nuclear Regulatory Research helped create the programmatic elements that supported this effort.
- Arthur Motta and Kenneth Peddicord served as chairs of working groups. To facilitate the PIRT effort, panel members served on one of two working groups. The working group for Categories A and C focused on analytical issues and was chaired by Kenneth Peddicord. The working group for Categories B and D focused on experimental issues and was chaired by Arthur Motta. The working group chairpersons were responsible for planning and facilitating discussions and documenting the identification and ranking outcomes of the working group.
- Several introductory and valuable presentations were made to the panel. Lawrence Hochreiter, Mitchell Nissley, and Bert Dunn, all panel members, prepared and presented information on the "PWR Loss of Coolant Accident (LOCA): Impact of High Burnup Fuel." Jens Anderson, a panel member, presented information on the "BWR LOCA." Michael Billone and Hee Chung or Argonne National Laboratory presented a "Cladding Phenomena Overview."
- Gerald Potts and Arthur Motta, panel members, made significant contributions to Section 2.2, Description of Fuel and Cladding State. Arthur Motta, with assistance from panel member Joe Rashid prepared the original write-up for the PWR RIA report. Gerald Potts revised this information so that it was applicable to BWR fuel.
- The Electric Power Research Institute suggested industry participants for panel membership. These individuals represented a cross section of the nuclear power industry. EPRI also sponsored the participation of Joe Rashid on the PIRT panel. The Advisory Committee on Reactor Safeguards suggested international participants for panel membership. With the exception of several university and private consultant members of the panel, the panel members were responsible for the expenses associated with their participation. The contributions of these institutions and individuals are gratefully acknowledged.
- Alain Mailliat of the French Institute for Nuclear Safety and Protection attended the PIRT panel meetings and participated in our discussions.

Acronyms

BWR	Boiling Water Reactor
DNB	Departure from nucleate boiling
ECCS	Emergency core cooling system
ECR	Equivalent cladding reacted
EOL	End of life
EPRI	Electric Power Research Institute
GDC	General Design Criterion
LOCA	Loss-of-coolant accident
LWR	Light-Water Reactor
MOX	Mixed oxide fuel
NRC	United States Nuclear Regulatory Commission
NSRR	Nuclear Safety Research Reactor
PCMI	Pellet-cladding mechanical interaction
PIRT	Phenomena Identification and Ranking Table
PWR	Pressurized Water Reactor
RCS	Reactor Coolant System

1. INTRODUCTION

The United States (US) Nuclear Regulatory Commission (NRC) has commissioned the formation of a Phenomena Identification and Ranking Table (PIRT) panel to identify and rank the phenomena occurring during selected transient and accident scenarios in pressurized water reactors (PWR) and boiling water reactors (BWR) containing high burnup fuel. The panel has prepared PIRTs for the following three scenarios: (1) PWR rod ejection accident, (2) BWR instability power oscillations arising in an anticipated transient without scram, and (3) PWR and BWR loss-of-coolant accidents (LOCAs). In the remainder of this report, the authors documents the findings of the High Burnup Fuel PIRT panel for the PWR and BWR LOCA. Additional reports have been issued for the remaining scenarios.[1-1, 1-2]

The report is organized into five sections and contains nine supporting appendices.

- Section 1, Introduction, summarizes the issues associated with high burnup fuel, provides an overview of the PIRT process, identifies the members of High Burnup Fuel PIRT panel, and identifies the objectives of the PIRT effort.
- Section 2, PIRT Preliminaries, describes elements of the PIRT process, as applied to the high burnup fuel issue, which lay the foundation for the identification and ranking of phenomena.
- Section 3, PWR and BWR LOCA PIRTs, contains the PIRT tables.
- Section 4, Databases, describes the experimental and analytical databases used by the panel during the development of the PWR and BWR LOCA PIRT.
- Section 5, Additional Panel Insights, documents PIRT panel insights in two areas, technical and procedural.

Important supporting information is provided in the remaining appendices.

- Appendix A contains the phenomena descriptions and rationales for Category A, Plant Transient Analysis.
- Appendix B contains the phenomena descriptions and ranking rationales for Category B, Integral Testing.
- Appendix C contains the phenomena descriptions and ranking rationales for Category C, Transient Fuel Rod Analysis.
- Appendix D contains the phenomena descriptions and ranking rationales for Category D, Separate Effect Testing.
- Appendix E contains descriptions of the applicable experimental databases.

- Appendix F contains descriptions of the fuel and cladding states at high burnup for PWR fuel.
- Appendix G contains descriptions of the fuel and cladding states at high burnup for BWR fuel.
- Brief experience summaries for each panel member are provided in Appendix H.
- Appendix I contains tutorial presentations made to the PIRT panel that are considered to have historical value.

1.1. Background

The NRC's research program is focusing on events that have significant risk. Because risk derives from both probability and consequence, data about each contributor is needed. The radiological consequence of an accident in a nuclear power plant is most directly associated with fuel melting. Therefore, the NRC is examining design basis accidents that involve fuel damage criteria, the purpose of the criteria being to prevent the progression of an accident into a severe accident with serious radiological consequences.

The NRC is screening events by considering two classes. The first is the class of events in which too much power is generated and the second is the class of events in which there is insufficient cooling.

In earlier PIRT efforts, a PWR reactivity-related accident and a BWR accident with instability power oscillations arising during an anticipated transient without scram were considered.[1-1, 1-2] These two accidents were representative of a class of events in which too much power is generated. In this report, PWR and BWR LOCAs are considered. The PWR and BWR LOCAs are representative of the class of events in which there is insufficient cooling. A spectrum of break sizes has been considered for each reactor type.

In the United States, regulatory criteria have been developed for ensuring the Emergency Core Cooling System (ECCS) can adequately cool the core following a LOCA. Five specific design acceptance criteria have been specified for the ECCS.[1-3] The five criteria are: (1) the calculated maximum peak cladding temperature shall not exceed 2200 °F, (2) the calculated local oxidation of the cladding shall nowhere exceed 0.17 times the local cladding thickness before oxidation, (3) the total amount of hydrogen generated shall not exceed 0.01 (1%) of the total amount which could be generated from all the cladding which surrounds the fuel, (4) calculated changes in core geometry shall be such that the core remains amenable to cooling, and (5) after any calculated successful operation of the ECCS, systems shall be in place to maintain the calculated core temperature at an acceptably low value and decay heat shall be removed for an indefinite period of time as required by the long-lived radioactivity remaining in the core.

In the 1970s when the regulatory criteria and related analytical methods were being established, high burnup was considered to be around 40 GWd/t (average for the peak rod). Data out to that burnup had been included in databases for codes and regulatory decisions, and it was believed that some extrapolation in burnup could be made. Fuel burnups in licensed reactors up to 62 GWd/t (average for the peak rod) were permitted. By the mid 1980s, however, unique changes in pellet microstructure had been observed from both vendor and international data at higher burnups along with increases in the rate of cladding corrosion (breakaway oxidation). It thus became clear that additional phenomena were occurring at high burnups and that continued extrapolation of transient data from the low-burnup database was not appropriate.

By the 1990s, large amounts of oxidation (corrosion) were accumulating on Zircaloy fuel that was being operated to higher burnups. In the U.S. a defacto limit of 100 microns of oxide thickness was implemented. At this level, however, as much as 14% of the cladding wall thickness could be oxidized and the obvious question was raised about the effect of pre-accident corrosion and associated hydrogen uptake on the allowable oxidation during the accident. The NRC, as an interim measure, interpreted the allowable 17% total oxidation to include pre-accident corrosion thus sharply limiting the amount of oxidation permitted during the LOCA transient.

To address the question of total oxidation and the adequacy of related evaluation models for high-burnup fuel, the NRC established a testing program at Argonne National Laboratory with EPRI cooperation. The NRC also expanded its collaboration with researchers in France, Japan, and Russia to include information exchanges on LOCA-related research.

Although the test and analytical programs underway provide valuable data for an interim assessment, these programs have also provided enough understanding of the related phenomena to know that the current database has substantial limitations. To address these uncertainties in a cost-effective manner, the NRC will continue to participate in experimental programs through international agreements as well as code-related efforts within the US.

The NRC has embarked on efforts to address two important needs. The first need is to identify the research to be done by the NRC and industry with respect to high burnup fuel to acquire and develop the requisite understanding of the performance of high burnup fuel under accident conditions. The second need, as previously stated, is to develop revised regulatory limits for fuel damage if they are needed. The PIRT documented in this report is a tool that will be used by the NRC in addressing these two needs. The PIRT presented in this report can be visualized as a lens through which existing experimental data and planned experiments can be examined. Because the PIRT both identifies and ranks phenomena for importance, existing experimental data and planned experiments can be viewed through the PIRT lens to determine adequacy. Likewise, both computational tools (codes) and code-calculated results can be viewed through the PIRT lens to determine applicability and adequacy.

The role of the PIRT in addressing the needs identified above is illustrated in Fig. 1-1. In reality, the acquisition of knowledge and understanding is not a once-through process. Rather, the process is inevitably iterative in nature, e.g., improved modeling leads to improved code-calculated results and refined experiments contribute to an improved experimental database.

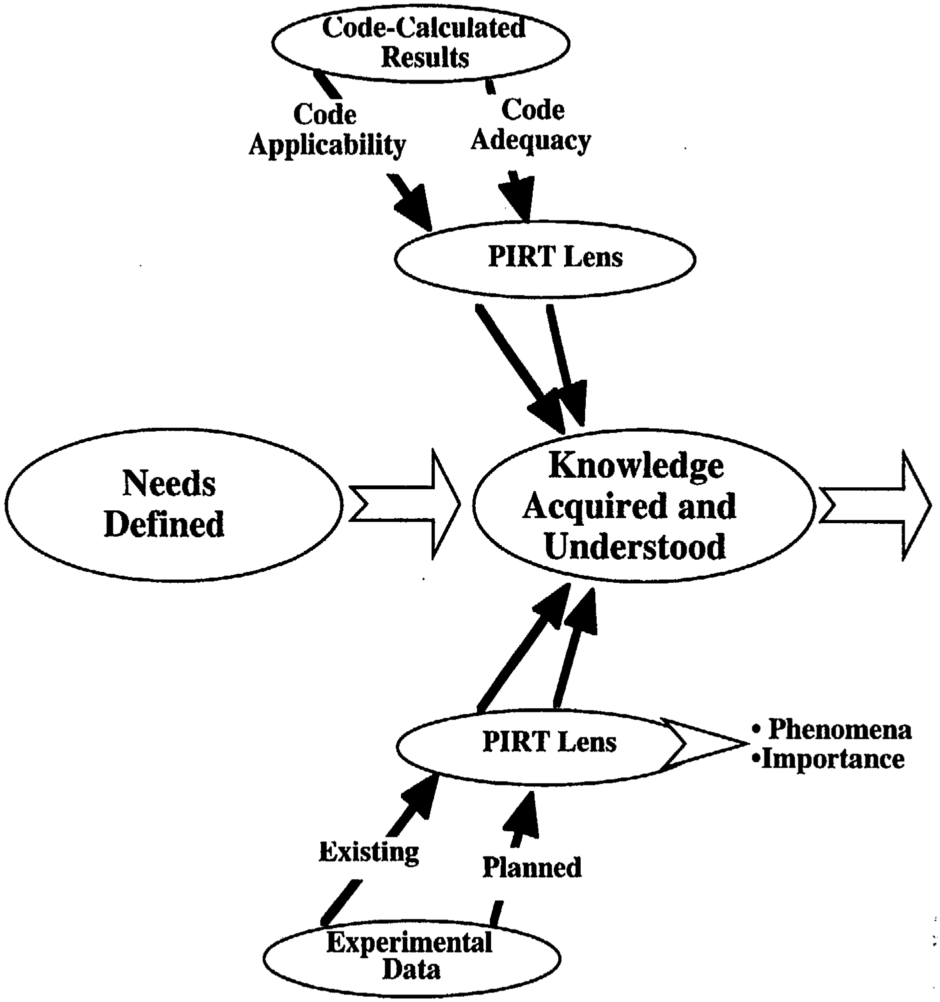
There are many specific questions that must be answered while addressing the NRC's needs. As answers are collected and issues resolved, the knowledge and understanding required to satisfy the NRC's needs is obtained. It must be noted that the PIRT is just one of several tools and approaches used to ensure the requisite knowledge is acquired and understood.

1.2. PIRT Panel Membership

The panel members were selected after considering each candidate's background related to plant type, accident scenarios, and technical expertise, e.g., materials science, reactor kinetics and physics, thermal-hydraulics, etc. It was decided that one PIRT panel would be formed rather than creating a separate PIRT panel for each plant type and scenario. This approach minimizes the startup time for a new PIRT panel and permits the ongoing panel members to utilize the insights gained in the initial PIRT efforts for subsequent PIRT efforts. Representatives of each US reactor vendor, utilities, and members of the international community were asked to participate.

The High Burnup Fuel panel members participation in the PWR and BWR LOCA PIRT were as follows:

- Carl A. Alexander, Battelle Memorial Institute;
- Jens G. M. Andersen, Global Nuclear Fuel, Inc.;
- John A. Blaisdell, Westinghouse Electric Company (Combustion Engineering Nuclear Power LLC);
- Bert Dunn, Framatome Technologies, Inc.;
- Derek B. Ebeling-Koning, Westinghouse Electric Company (Combustion Engineering Nuclear Power LLC);
- Toyoshi Fuketa, Japan Atomic Energy Research Institute;
- Georges Hache, French Institute for Protection and Nuclear Safety;
- Lawrence Hochreiter, The Pennsylvania State University;
- S. E. "Gene" Jensen, Siemens Power Corporation;
- Siegfried Langenbuch, Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) mbH;
- Fred Moody, Consultant;



Note: The PIRT will be just one of several tools or approaches used to ensure the requisite knowledge is acquired and understood.

Fig. 1-1. Use of PIRTs to address NRC need

- Authur Motta, The Pennsylvania State University
- Mitchell E. Nissley, Westinghouse Electric Company;
- Katsuhiro Ohkawa, Westinghouse Electric Company;
- Kenneth Peddicord, Texas A&M University;
- Gerald Potts, Global Nuclear Fuel, Inc.;
- Joe Rashid, Anatech Corporation;
- Richard Rohrer, Nuclear Management Company;
- James S. Tulenko, University of Florida;
- Keijo Valtonen, Finnish Center Radiation and Nuclear Safety;
- Nicolas Waeckel, Electric Power Research Institute; and
- Wolfgang Wiesenack, Halden Reactor Project

The facilitator for the High Burnup Fuel PIRT panel was Brent E. Boyack, Los Alamos National Laboratory. Brief experience summaries for each panel member and the panel facilitator are presented at the end of this volume in Appendix F.

1.3. PIRT Overview

The PIRT process has evolved from its initial development and application[1-4, 1-5, 1-6] to its description as a generalized process.[1-7] A PIRT can be used to support several important decision-making processes. For example, the information can be used to support either the definition of requirements for related experiments and analytical tools or the adequacy and applicability of existing experiments and analytical tools.

This information is important because it is neither cost effective or required to assess each feature of an experiment or analytical tool in a uniform fashion. The PIRT methodology brings into focus those phenomena that dominate, while identifying all plausible effects to demonstrate completeness.

A simplified description of the PIRT process, as applied to the development of the PWR and BWR LOCA PIRT for high burnup fuel, is illustrated in Fig. 1-2 and described as follows.

1. Define the issue that is driving the need, e.g., licensing, operational, or programmatic. The definition may evolve as a hierarchy starting with federal regulations and descending to a consideration of key physical processes.

2. Define the specific objectives of the PIRT. The PIRT objectives are usually specified by the sponsoring agency. The PIRT objectives should include a description of the final products to be prepared.

3. Define the hardware and equipment scenario for which the PIRT is to be prepared. Generally, a specific hardware configuration and specific scenario are specified. Experience gained from previous PIRT efforts indicates that any

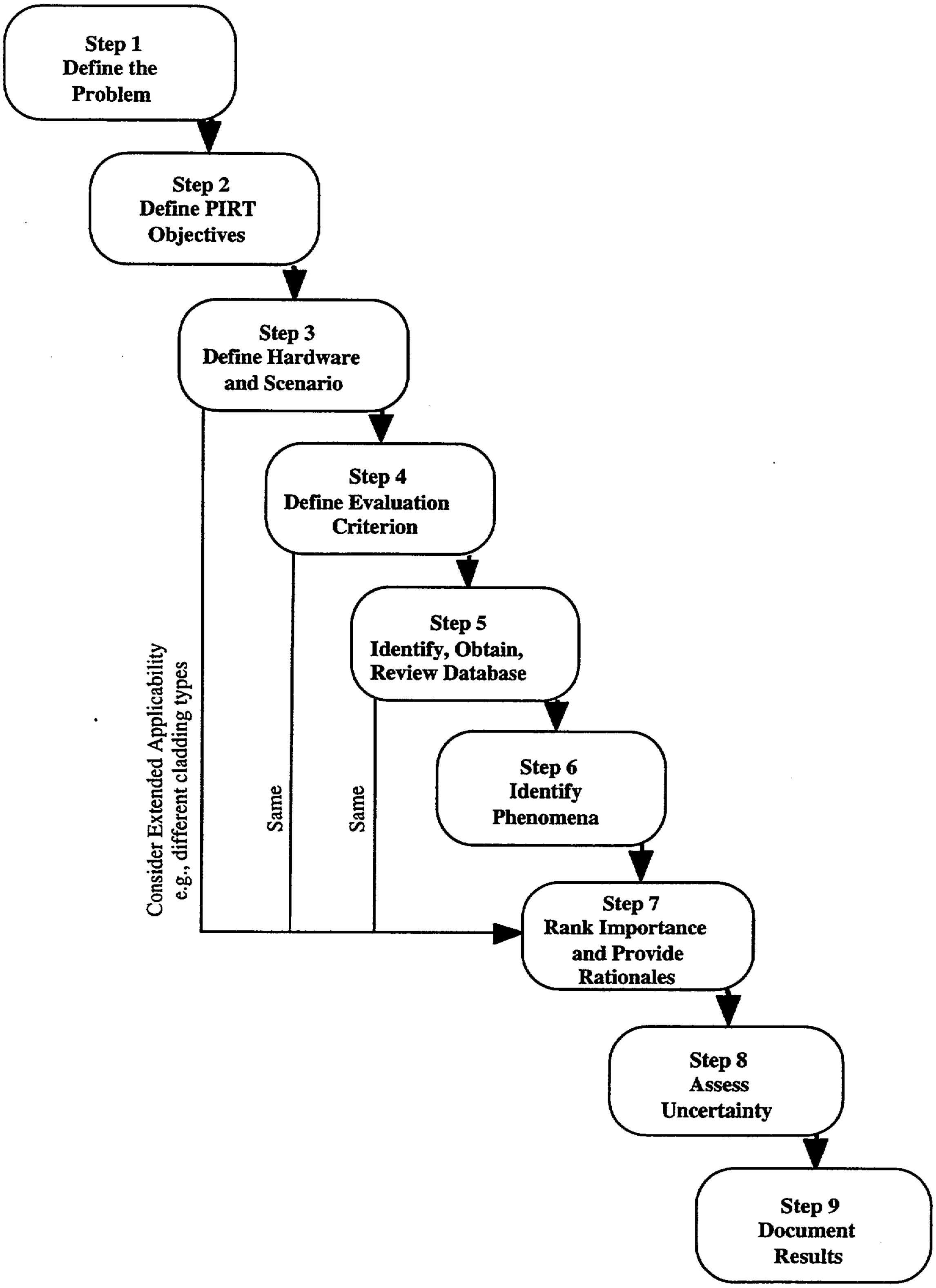


Fig. 1-2. Illustration of PWR and BWR LOCA PIRT process.

consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed as illustrated in Fig. 1-2.

4. Define the primary evaluation criterion. The primary evaluation criterion is the key figure of merit used to judge the relative importance of each phenomenon. It must, therefore, be identified before proceeding with the ranking portion of the PIRT effort. It is extremely important that all PIRT panel members come to a common and clear understanding of the primary evaluation criterion and how it will be used in the ranking effort. For the PWR and BWR LOCA PIRT effort, the primary evaluation criterion is derived from regulatory requirements.

5. Compile and review the contents of a database that captures the relevant experimental and analytical knowledge relative to the physical processes and hardware for which the PIRT is being developed. Each panel member should review and become familiar with the information in the database.

6. Identify all plausible phenomena. A primary objective of this step is completeness. In addition to preparing the list of phenomena, precise definitions of each phenomenon should be developed and made available to the PIRT panel to ensure that panel members have a common understanding of each phenomenon.

7. Develop the importance ranking and associated rationale for each phenomenon. Importance is ranked relative to the primary evaluation criterion adopted in Step 5. For PIRT panels having 6–8 members, importance discussions usually lead to a single importance rank for a given phenomenon. For PIRT panels having more members such as the present case (see Section 1.2), it has been determined that voting on importance is more efficient. With a large panel, individual members may be experts in some of the phenomena identified but be less familiar with others. To deal with this reality, panel members are informed that they need vote only if they feel they have sufficient understanding of the importance of the phenomena. Panel members must take care to focus solely on importance relative the primary evaluation criterion when voting. The degree of knowledge or understanding of the phenomenon is handled separately in the next step.

8. Assess the level of knowledge, or uncertainty, regarding each phenomenon. This is new step in the evolving PIRT process. It was not included, for example, in a recent generalized description of the PIRT process.[1-7] By explicitly addressing uncertainty, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT panel members to assign high importance to a phenomenon for which it is concluded that there is significantly less than full knowledge and understanding.

9. Document the PIRT results. The primary objective of this step is to provide sufficient coverage and depth that a knowledgeable reader can understand what was done (process) and the outcomes (results). The essential results to be documented are the phenomena considered and their associated definitions, the importance of each phenomena and associated rationale for the judgement of importance, the level of knowledge or uncertainty regarding each phenomenon and associated rationale, and the results and rationales for any assessments of extended applicability for the baseline PIRT. Other information may be included as determined by the panel or requested by the sponsor.

As presented in Fig. 1-2, the PIRT process proceeds from start to end without iteration. In reality, however, the option to revisit any step is available and is sometimes used in the PIRT development process.

1.4. PIRT Objectives

The PIRT panel was organized to develop a PIRT for a PWR or a BWR containing high burnup fuel and experiencing a loss-of-coolant accident. The PIRT was developed and documented so that it could be used to help guide future NRC-sponsored analytical, experimental, and modeling efforts conducted as part of its program to assess and revise if necessary the LOCA embrittlement criteria and related evaluation models. An NRC staff report that strives to utilize these PIRT results has also been issued.[1-8]

1.5. References

1-1. B. E. Boyack et al., "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6742 (September 2001).

1-2. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6743 (September 2001).

1-3. Code of Federal Regulation, Title 10 (January 1, 2000), Part 50.

1-4. TPG (Technical Program Group), "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," EG&G Idaho, Inc. document NUREG/CR-5249 (1989).

1-5. TPG (Technical Program Group), "Quantifying Reactor Safety Margins: Application of CSAU to a LBLOCA," *Nuclear Engineering and Design* **119** (1990): B. E. Boyack et al., Part 1: An overview of the CSAU Evaluation Methodology; G. E. Wilson et al., Part 2: Characterization of Important Contributors to Uncertainty; W. Wulff et al., Part 3: Assessment and Ranging of Parameters; G. S. Lellouche et al., Part 4: Uncertainty Evaluation of LBLOCA Analysis Based on TRAC-PF1/MOD1; N. Zuber et al., Part 5: Evaluation of Scale-Up Capabilities of Best Estimate Codes; I. Catton et al., Part 6: A Physically Based Method of Estimating PWR LBLOCA PCT.

1-6. R. A. Shaw, T. K. Larson, and R. K. Dimenna, "Development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic Phenomena During a PWR LBLOCA," EG&G Idaho, Inc. report NUREG/CR-5074 (1988).

1-7. G. E. Wilson and B. E. Boyack, "The Role of the PIRT Process in Experiments, Code Development, and Code Applications Associated with Reactor Safety Analysis," *Nuclear Engineering and Design* **186**, 23–37 (1998).

1-8. R. O. Meyer, "Implications from the Phenomena Identification and Ranking Tables (PIRTS) and Suggested Research Activities for High Burnup Fuel, US Nuclear Regulatory Commission document NUREG-1749 (September 2001).

2. PIRT PRELIMINARIES

Several important preliminary steps must be completed in advance of the identification and ranking efforts of the PIRT process. The PIRT objective was defined and documented in Section 1.4. During the PIRT development process, each PIRT is developed for a specific plant or vendor design and scenario because both the occurrence of phenomena and processes and the importance of phenomena and processes are plant and scenario specific.

The plant and fuel designs selected for this PWR and BWR LOCA PIRT development are discussed in Section 2.1.

Descriptions of the selected fuel types for this PIRT and their states at high burnup prior to a LOCA event are described in Section 2.2.

The accident scenarios selected for the LOCA PIRT are discussed in Section 2.3. Fuel and cladding behavior during the event are described in Section 2.3.2. In a departure from the standard PIRT process, the PIRT panel grouped the phenomena under consideration into categories associated with code and experimental activities. Four categories were defined for the PIRT. The panel broadened the definition of the term "phenomena," as it appears in the PIRT acronym, to include phenomena, processes, conditions, and properties. This approach was taken to facilitate the panel's involvement in both the development of the PIRT and consideration of the PIRT's application to

- modifications that might be needed in plant transient codes for licensing analysis,
- experimental derivation of a quantitative behavior criterion, and
- development of transient fuel rod codes that might be introduced into regulatory assessment.

The PIRT panel performed the ranking effort relative to a primary evaluation criterion. Therefore, it is important that this criterion be explicitly defined, as is done in Section 2.4.

The categories of phenomena are discussed in Section 2.5.

The phenomena ranking scale is described in Section 2.6, with an accompanying discussion of the voting process and voting rationale.

Panel efforts in the areas of extended PIRT applicability and uncertainty evaluation are provided in Sections 2.7 and 2.8, respectively.

2.1. Selected Plant and Fuel

The LOCA PIRT has been developed for both PWR and BWR reactors. However, PIRT development becomes very difficult if the panel considers more than a single reactor type when developing the baseline LOCA PIRT. For the LOCA PIRT, the panel decided to develop the baseline PIRT for a PWR plant and then evaluate changes to the baseline PWR LOCA PIRT as part of evaluating "Extended Applicability" for the PIRT. In this manner, the PWR LOCA PIRT was extended to BWR plants. These results are reported in the PIRT tables presented in Section 3.

2.1.1. PWR Plant

No specific PWR plant was selected for the PWR element of the LOCA PIRT. However, the primary LOCA overview information presented to the PIRT panel was for a Westinghouse 4-loop PWR. The coolant piping is arranged in a 4x4 configuration consisting of four hot legs, four steam generators, four coolant pumps, and four cold legs.

The primary coolant system of a Westinghouse PWR[2-1] consists of a multi-loop arrangement arrayed around the reactor vessel as shown in Fig. 2-1. In a typical four-loop configuration, each loop has a vertically oriented steam generator and a coolant pump. The coolant flows through the steam generator within an array of U-tubes that connect inlet and outlet plenum located in the bottom of the steam generator. The system's single pressurizer is connected to the hot leg of one of the loops.

During normal operation, the inlet nozzles connected to the cold legs communicate with an annulus formed between the inside of the reactor vessel and the outside of the core support barrel. Coolant entering this annulus flows downward into the inlet plenum formed by the lower head of the reactor vessel. Here it turns upward and flows through the core into the upper plenum, which communicates with the reactor vessel outlet nozzles connected to the hot legs.

With the exception of beginning of life plant startup, a reactor core usually contains a mixture of new fuel assemblies, i.e., newly fabricated fuel assemblies being introduced into the reactor core for the first time, and assemblies that have resided in the core for various lengths of time. During its time of residence in the core, the fuel undergoes burnup, that is, the nuclear-reactor fuel is consumed. Thus, burnup is a measure of nuclear reactor fuel consumption, expressed as the amount of energy produced per unit weight of fuel. For the present PIRT, the fuel with the highest burnup is assumed to have a burnup of 62 gigawatt days/metric ton (GWd/t). A description of high burnup fuel is provided in the following section.

Although a specific plant and fuel type are generally selected, the panel recognizes the desirability of extending the applicability of the PIRT developed for the specified plant and fuel. Accordingly, the panel elected to perform a preliminary screening of the phenomena identified for the selected plant, fuel and cladding to other plants

[Westinghouse (W), Babcock and Wilcox (B&W), Combustion Engineering (CE), and General Electric], array sizes (e.g., 8x8, 9x9, 16x16 or 17x17), fuel types [mixed-oxide (MOX) fuel utilizing fissile plutonium], cladding types introducing niobium (Nb), having reduced tin (Sn) content [ZIRLO, Duplex, M5, etc., or Zirconium liners], and burnup to 75 GWd/t.

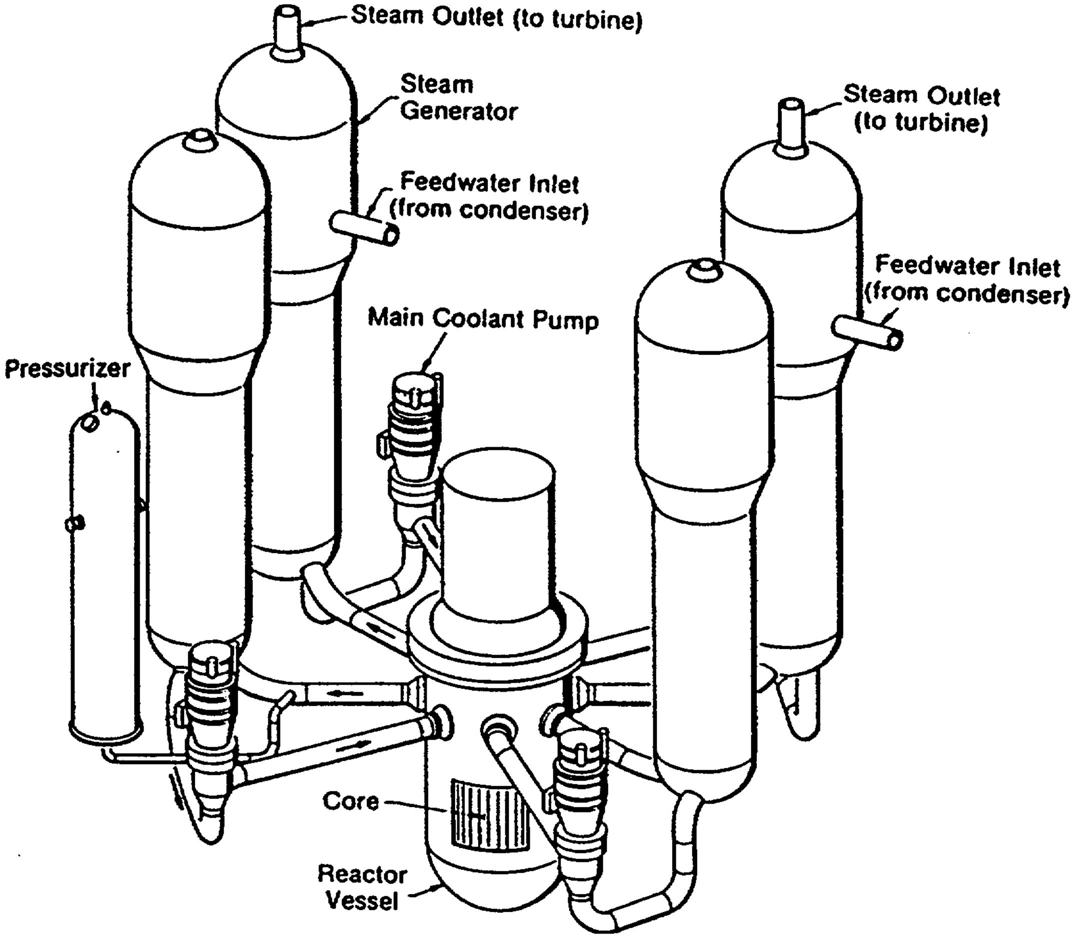


Fig. 2-1. PWR primary system arrangement.

2.1.2. BWR Plant

As described in Section 2.1, the panel decided to develop the baseline PIRT for a PWR plant and then evaluate changes to the baseline PWR LOCA PIRT as part of evaluating "Extended Applicability" for the PIRT.

To prepare for evaluating the extended applicability of the PIRT, the panel received overview information regarding the response of BWR plants to a spectrum of LOCAs. Details were first provided for the response of a generic BWR/6 plant to a large-break LOCA, after which additional information was provided about the response of a generic BWR/4 and BWR/2 plant to the same event.

The steam and recirculation water flow paths in a BWR[2-1] are shown in Fig. 2-2. The steam-water mixture first enters steam separators after exiting the core. After subsequent passage through steam dryers located in the upper portion of the reactor vessel, the steam flows directly to the feedwater system. The water, which is separated from the steam, flows downward in the periphery of the reactor vessel

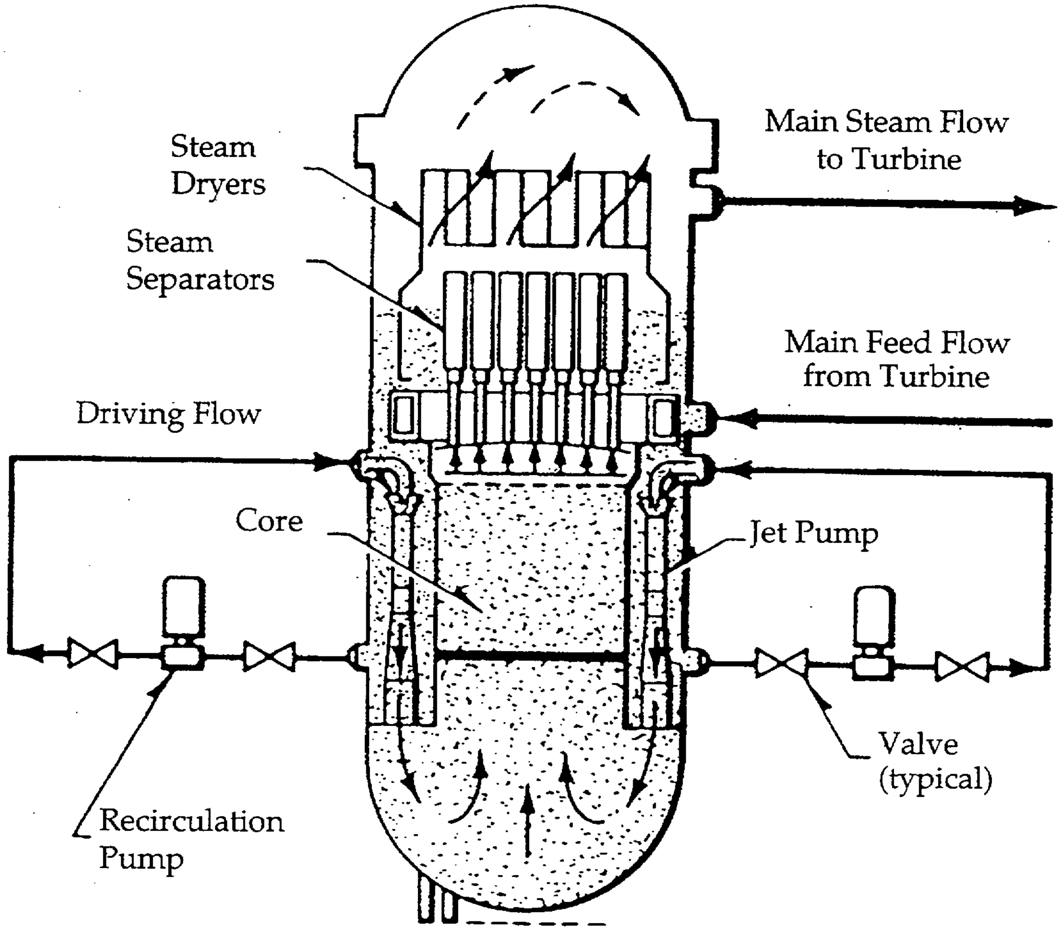


Fig. 2-2. Steam and recirculation water flow paths in the BWR.

and mixes with the incoming main feed flow from the turbine. This combined flow stream is pumped into the lower plenum through jet pumps mounted around the inside periphery of the reactor vessel. The jet pumps are driven by flow from recirculation pumps located in relatively small-diameter external recirculation loops, which draw flow from the plenum just above the jet pump discharge location. The fuel is uranium dioxide (UO_2) and the cladding is zircaloy-2 with a zirconium-based inner liner. Each fuel assembly has several fuel rods with a burnable poison, gadolina (Gd_2O_3) mixed in solid solution with UO_2.

2.2. Description of Fuel and Cladding State at High Burnup

Related PIRTs have been prepared for a PWR rod ejection accident[2-2] and for instability power oscillations arising during an anticipated transient without scram in BWRs.[2-3] In each case, a description of the anticipated fuel and cladding state just prior to the event was prepared. These descriptions are also applicable to the PWR and BWR LOCA events and are repeated in this document. The description of PWR fuel and cladding at high burnup is provided in Appendix F; the description of BWR fuel is presented in Appendix G.

2.3. Accident Scenario

Brief descriptions of three LOCA scenarios are presented below. The scenarios are for the PWR large-break LOCA, PWR small-break LOCA, and the BWR LOCA. Fuel and cladding behavior during a LOCA are also described.

2.3.1. PWR Large-Break LOCA

The design basis accident is a double-ended guillotine break in a cold leg between the reactor coolant pump and the reactor vessel.

The blowdown period (0 – 30 s) is the result of a break in the coolant system through which the primary coolant is expelled. Within a fraction of a second after the break, the core voids and goes through departure from nuclear boiling. The negative void reactivity rapidly shuts down the core. With the diminished cooling and the redistribution of stored energy, the cladding heats up. Interactions between the pump and the break dynamics cause intermittent flow reversals. The primary system pressure rapidly decreases and the high-pressure safety injection begins, but most of this flow is lost out the break. Injection from the cold-leg accumulators begins but much of the injected flow is swept around the downcomer, into the broken-loop cold leg and out the break. As the blowdown progresses an increasing amount of the accumulator-injected coolant stays in the downcomer and some water begins to enter the lower plenum. The average blowdown peak cladding temperature (PCT) during the blowdown phase of the large-break LOCA is approximately 1500 °F and the PCT at 95% confidence is about 1750 °F, assuming a loss-of-offsite power and the worst single failure assumption for the emergency core cooling system.

The refill period occurs between 30 and 40 s following the start of the LOCA. The primary pressure has decreased to a level at which the low-pressure injection system activates and begins to inject water into the system. The lower plenum begins to fill with accumulator water as coolant bypass diminishes. While refilling of the lower plenum is underway, however, the core heats up in a near adiabatic mode due to decay heat. Some fuel rods swell and burst, causing blockage of some of the flow channels during refill.

The reflood period occurs between 40 and 200 s; it begins at the time when the lower plenum has filled and the core begins to refill. Water injected by the accumulators fills the downcomer and creates the driving head for refilling the core. The lower elevations of the core quench, generating a two-phase mixture that provides some cooling to the upper elevations of the core. However, the fuel rods continue to heat up until the quench front begins to move upward through the core. Some additional number of fuel rods may burst during the reflood period. Zirconium-water reactions can occur for high temperature regions of the core. As the quench front continues to advance, the fuel rod upper elevations are cooled by a dispersed non-equilibrium two-phase mixture of superheated steam and entrained droplets. Eventually, there is sufficient cooling in advance of the quench front to terminate the increase in cladding temperature and the PCT is reached. The average reflood PCT during this period is approximately 1680 °F and the PCT at 95% confidence is about 1975 °F. The maximum amount of cladding oxidized at a given location during this phase of the LOCA is about 10% for beginning of life UO_2 fuel and the total oxidation is less than 1%.

2.3.2. PWR Small-Break LOCA

Breaks with flow areas typically less than 1-ft^2 and greater than 3/8 in. span the category of small breaks. A small break is sufficiently large that the primary system depressurizes to the high-pressure safety injection set point and a safety injection or "S" signal is generated, automatically starting the High-Pressure Safety Injection (HPSI) system. Breaks smaller than 3/8-inch in diameter do not depressurize the reactor coolant system because the reactor charging flow can replace the lost inventory. The control rods shut down the reactor such that only decay heat is generated in the core.

The limiting small-break LOCA is determined by the inter-play between core power level, the axial power shape, break size, the high-head safety injection performance, and the pressure at which the accumulator begins to inject. The limiting break is one that is large enough that the high-pressure safety injection system cannot make-up the mass loss from the reactor system but small enough that the reactor system does not quickly depressurize to the accumulator set point. This combination of circumstances leads to a core uncovery.

For Westinghouse plants, the limiting breaks are typically in the 2-4 inch range. A spectrum of break sizes has been calculated for a Westinghouse three-loop plant. Calculations were performed assuming both fresh fuel and fuel with burnup between 30 and 54 GWd/t. These calculations are thought to accurately display the effect of burnup on fuel performance.

With fresh fuel, a three-inch break was found to produce the highest PCTs for breaks in the range of 2 to 6 inches. The PCT of 1830 °F occurred at approximately 1480 s.

The core average cladding oxidation was 0.5%. No bursting of the fuel is predicted for fresh fuel.

The available calculated results for fuel that has been in the reactor indicate that as burnup increases, some of the fuel will burst and experience double-sided cladding reactions. However, the burnup reduces the linear heat rate such that the calculated PCTs are below those for fresh fuel and are, therefore, less limiting. At 54 GWd/t, the hot rod PCT is predicted to be approximately 1500 °F.

2.3.3. BWR LOCA

The design basis accident for a BWR/6 is a double-ended break in the suction-side of the recirculation line.

Shortly after the break, the reactor scrams, typically on drive flow pressure. Because of the large flow reductions immediately following the LOCA caused by the depressurization, there is a rapid increase in the core average void fraction. The negative void reactivity rapidly shuts down the core. The flow reverses in the broken loop jet pump. With the flow reversal all the drive flow to that jet pump is lost and one-half the drive flow that is supporting the core flow is lost.

A loss of offsite power is also assumed. Thus, there is no power to the recirculation pump, which means that the intact loop pump also starts to coast down. The coast-down time of the pump is on the order of 10-15 seconds. With the loss of pumped flow, there is an almost instantaneous and large reduction in the core flow, which causes an early boiling transition in the core, typically within one second after the break.

The cladding temperature rapidly increases; the resulting blowdown peak cladding temperature is dominated by the stored energy in the fuel.

Valves are closed to isolate the system, typically within four seconds after the LOCA. System depressurization and loss of liquid inventory continue. As a result of the loss of inventory, the water level in the downcomer decreases and as the water level eventually drops down to the top of the jet pump. This opens a flow path through which steam can flow to the break. The rate of depressurization increases following jet pump uncovery.

During normal operation, the inlet subcooling at the bottom of the core is 20 °F. With the rapid depressurization, there is a large amount of flashing of the fluid in the lower plenum, this occurring at approximately 10 s. This causes a large increase in the coolant flow through the core, quenching the fuel, and returning the cladding temperature to the saturation temperature.

As the LOCA and depressurization continue, the level inside the core region decreases, as well as forming a level in the lower plenum region. The flow into the core is limited and the core uncovery leads to a second boiling transition. That typically happens at approximately 20 seconds into the transient.

Within 35-40 s following the LOCA, the high pressure core spray system begins to deliver coolant to the top of the core, the time being determined by the time to start the diesel generator that drives the high pressure core spray system. The low-pressure injection begins when the system pressure drops below the shutoff head for the pumps, typically on the order of about 200 psi.

A second transition and core heatup begins in the period 20-35 s. This heatup is terminated by the operation of the BWR-6 safety systems.

The BWR-6 has one high-pressure coolant system, one low-pressure core spray system, and three low-pressure coolant injection (LPCI) systems injecting into the bypass region. The worst single failure for the BWR-6 is the failure of one of the diesel generators that will drive two of the LPCI systems. The outcome of this failure is that the system behavior is based on the availability of the high-pressure core spray, the low-pressure core spray and one LPCI system that injects into the bypass region.

Given the operation of these systems, the core refills before the lower plenum. The refilling and reflooding processes restores the liquid inventory in the core and quenches the core in the period 100-150 s following the LOCA. Throughout the transient, the best-estimate peak cladding temperature for nominal conditions is approximately 800 °F. The upper bound estimate for a 95%-95% upper bound is approximately 1200-1300 °F.

For the BWR/4, the ECC configuration is slightly different. However, The early part of the transient is very similar to the BWR/6. These differences cause the core reflood during the refilling and reflooding phase of the LOCA to take somewhat longer than in a BWR/6. This results in a somewhat higher peak cladding temperature for the BWR/4, with the peak cladding temperature for nominal conditions being approximately 1000 °F and the upper bound estimate approximately 1400-1500 °F.

The BWR/2 is the older-generation BWR without jet pumps. The core cannot be reflooded. The peak cladding temperature is controlled by a balance between decay heat and the core spray heat transfer. Typically, the peak cladding temperature occurs late in the transient, perhaps 600-800 s following the LOCA. Quenching of the fuel rods is also very slow. The upper bound peak cladding temperature for the BWR/2 is approximately 1700 °F. For these plants, cladding oxidation, rather than PCT, may be limiting.

For the purposes of this PIRT, the panel did not differentiate between BWR small-break and large-break LOCAs. The BWR is designed to automatically convert postulated small-breaks that would uncover the core into a large-break through the activation of an Automatic Depressurization System (ADS). The ADS opens several of the standard safety relief valves, causing a controlled depressurization with system response quite similar to that for a postulated large break in the reactor steam line.

2.3.4. Fuel and Cladding Behavior During a LOCA

Reactor power drops quickly when the coolant (moderator) is lost, but the fuel pellets have stored heat because of their heat capacity and radionuclide decay continues to provide an additional heat source. Consequently, the cladding temperature increases with time and the fuel pellet temperature decreases with time as the fuel and cladding temperatures tend to equilibrate. A qualitative plot of cladding temperature response to this transient is shown in Fig. 2-3. A more quantitative plot of cladding temperature evolution with time is shown in Fig. 2-4, which presents an idealized temperature profile that is being used for LOCA testing at Argonne National Laboratory. Following along this temperature profile, several important phenomena are identified.

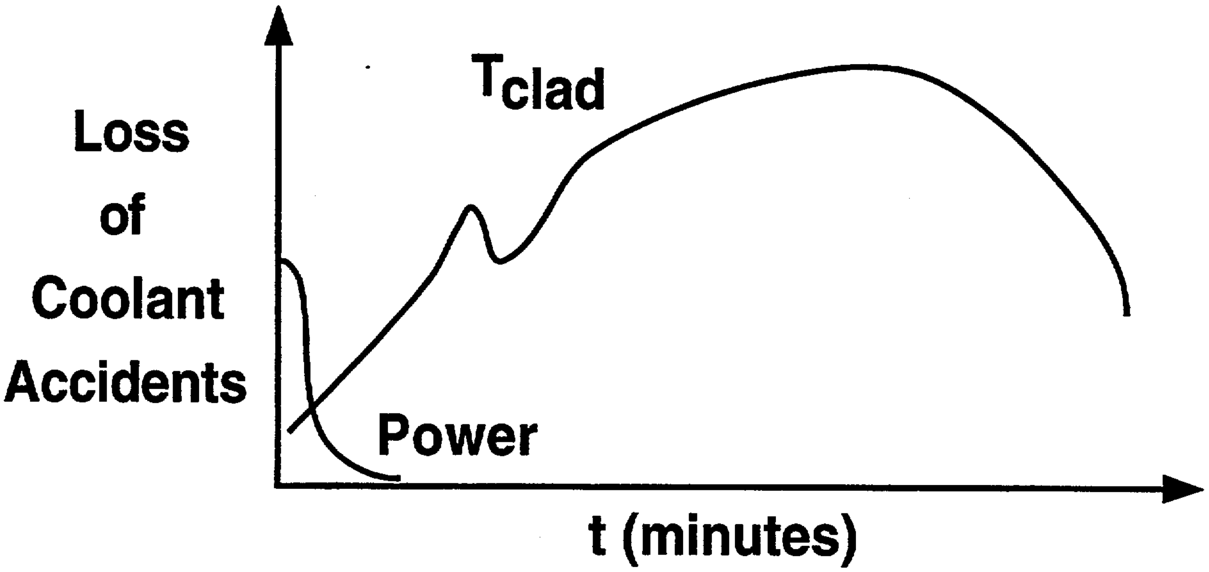


Fig. 2-3. Qualitative plot of fuel rod power and cladding temperature during a LOCA

As the cladding temperature reaches about 800 °C (1472 °F), ballooning of the cladding will take place because of the positive pressure differential and the elevated temperature. After reaching the ultimate tensile stress of the cladding, the ballooning process becomes unstable and rupture follows quickly. The extent of the ballooned region is of course important because large balloons would form blockages that might interfere with long-term cooling. Figure 2-5 shows the extent of ballooning deformation at the location of the burst for different degrees of azimuthal temperature variation.

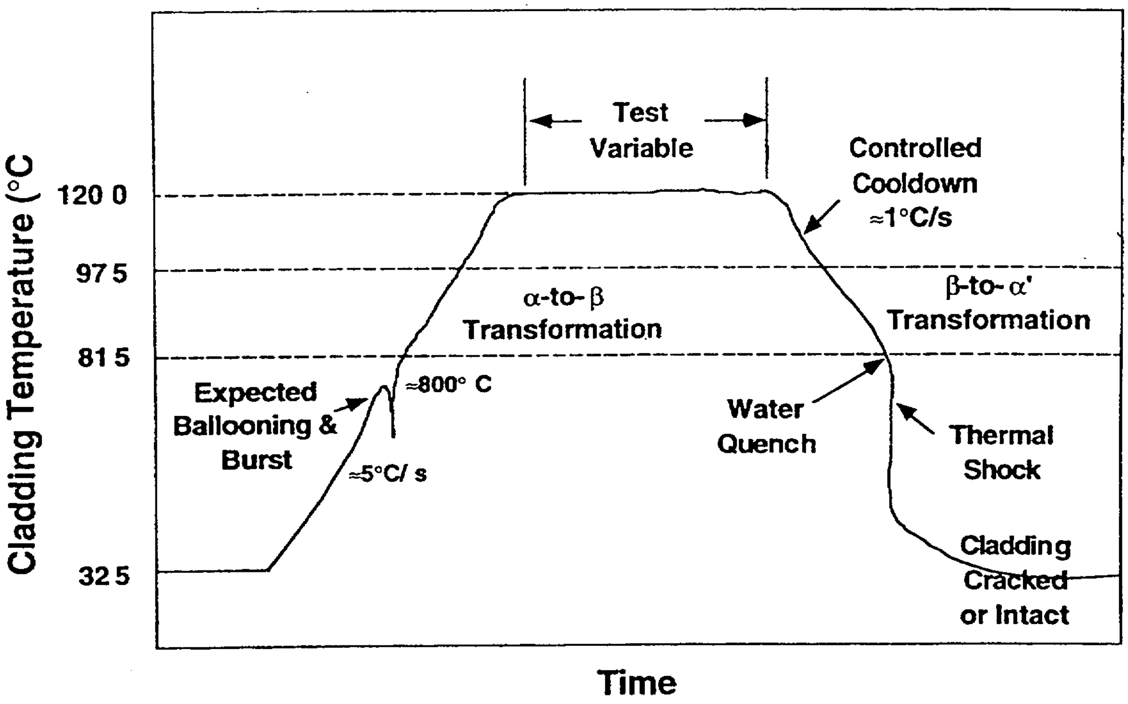


Fig. 2-4. Cladding temperature profile that is planned for LOCA testing at Argonne National Laboratory.

Following rod burst, cladding temperature continues to rise to as much as 1200 °C (2200 °F limit from 10 CFR 50.46), a temperature at which most of the cladding oxidation will take place. During this ascent in temperature, two important phenomena can take place. One is the relocation of pellet fragments into the ballooned region as seen in early tests in the PBF (PBF-LOC Program), FR-2, and SILOE (FLASH experiment) test reactors. This relocation of fuel material will increase the heat source in the ballooned region of the fuel and decrease the fuel-cladding gap. The other phenomenon is the phase transition in the Zircaloy cladding from the low temperature alpha phase to the high temperature beta phase. Figure 2-6 shows the phase diagram for these changes. A higher oxygen content makes the cladding material more susceptible to thermal shock and post quench failures.

At the end of the high temperature period, at which time as much as 17% of the original Zircaloy cladding may be oxidized (17% limit from 10 CFR 50.46), cooldown and quenching will occur. Because of reductions in ductility during the oxidation process, the thermal shock during quenching may fragment the cladding, or other mechanical loads may fragment the cladding after it has been fully quenched.

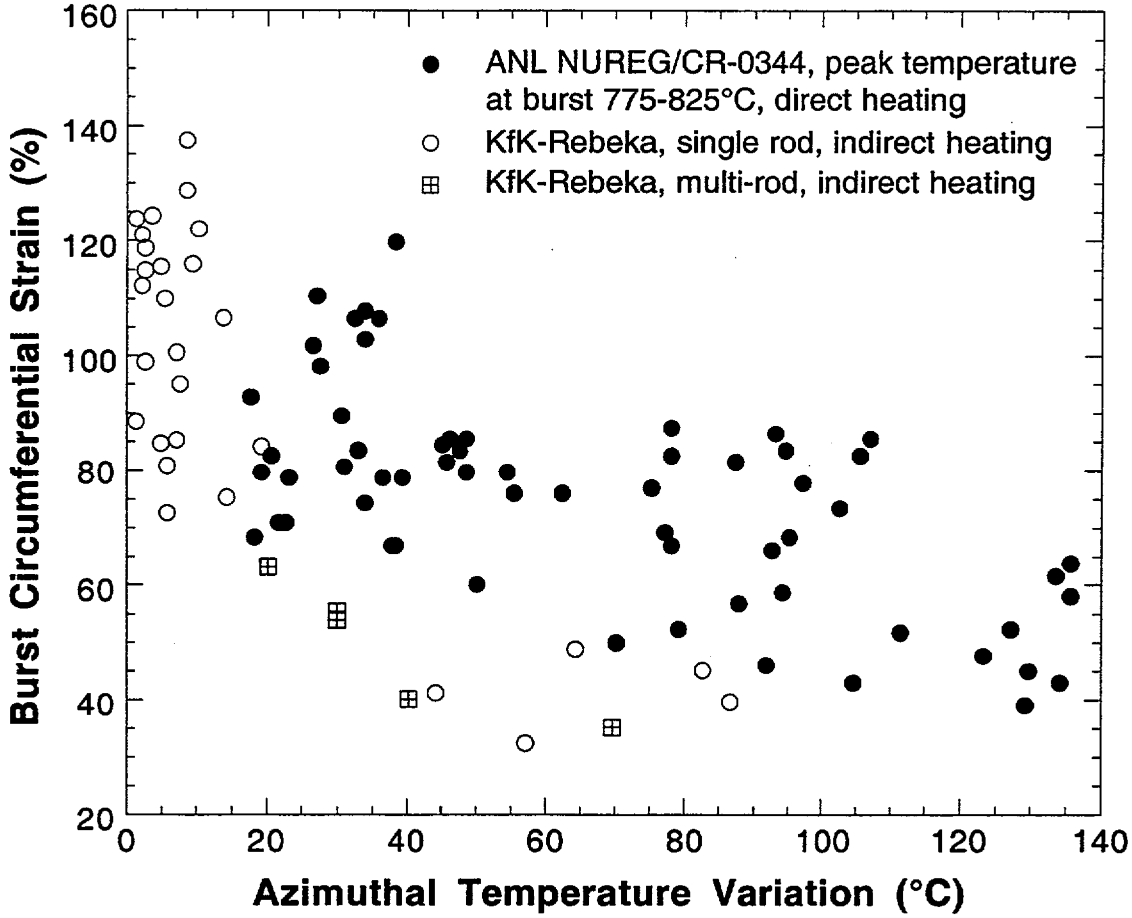


Fig. 2-5. Burst strain versus azimuthal temperature difference for Zircaloy cladding tubes ruptured in simulation tests.

Figure 2-7 shows the microstructure and oxygen content prior to the LOCA transient. Here you see a large alpha-phase layer that has low oxygen content and high strength and ductility. Hydride stringers are shown in the cladding as discussed in connection with the reactivity accidents, but these hydrides would dissolve at subsequent high cladding temperatures during a LOCA. Figure 2-8 shows the microstructure and oxygen content right after the relatively slow cooldown but before the water quench. When the transition back through the beta to-alpha phase occurs, the alpha phase forms two layers. One alpha layer, right next to the oxide on both the OD and ID surfaces, has a very high oxygen content and has very low strength and ductility. This alpha layer cannot carry any significant load. The other layer, sometimes called the alpha-prime or prior-beta layer, has low oxygen content and forms the surviving load-bearing thickness of the cladding. Whether fragmentation will occur depends largely on the thickness of this alpha-prime or prior-beta layer.

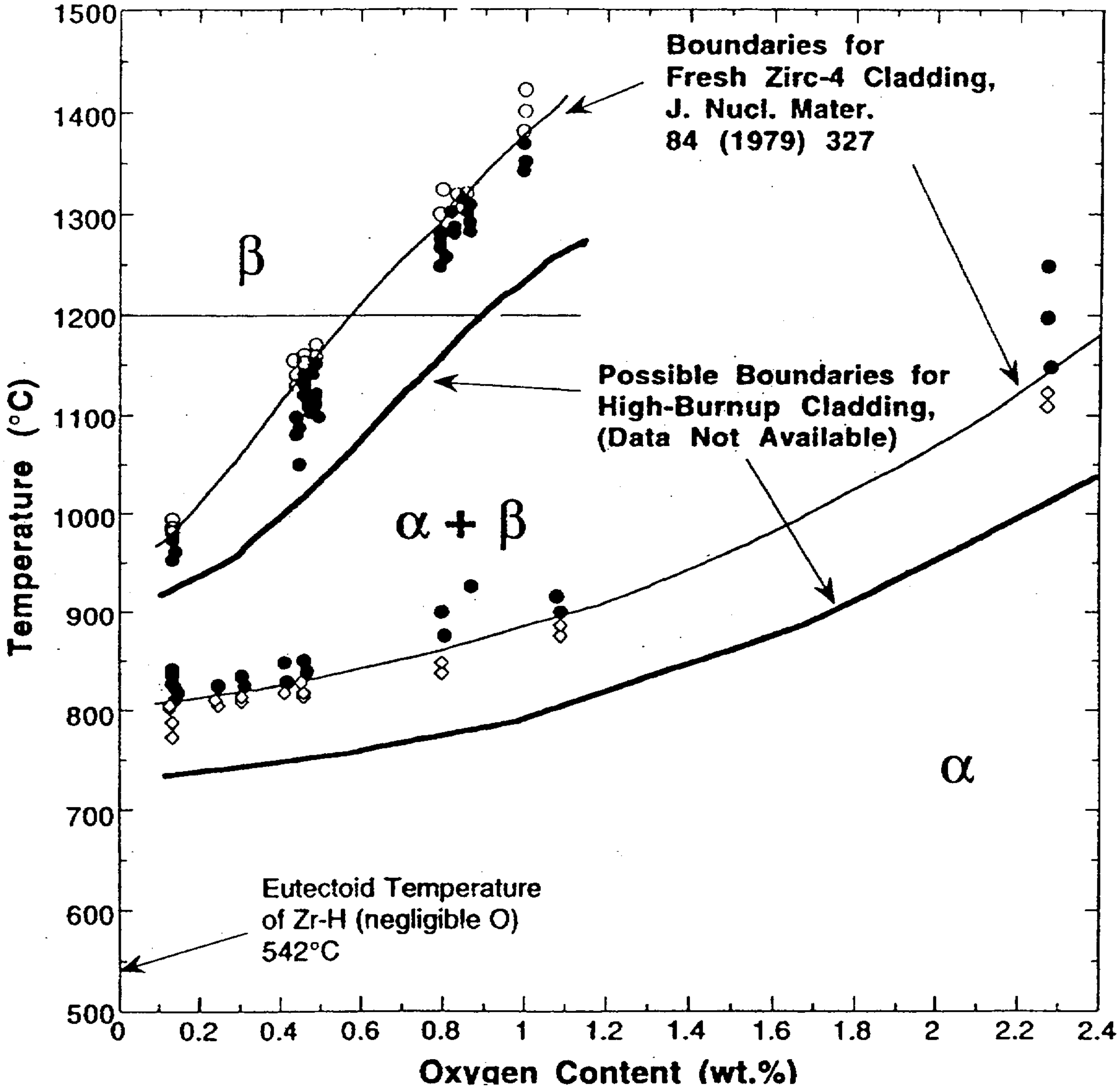


Fig. 2-6. Phase diagram for Zircaloy containing oxygen

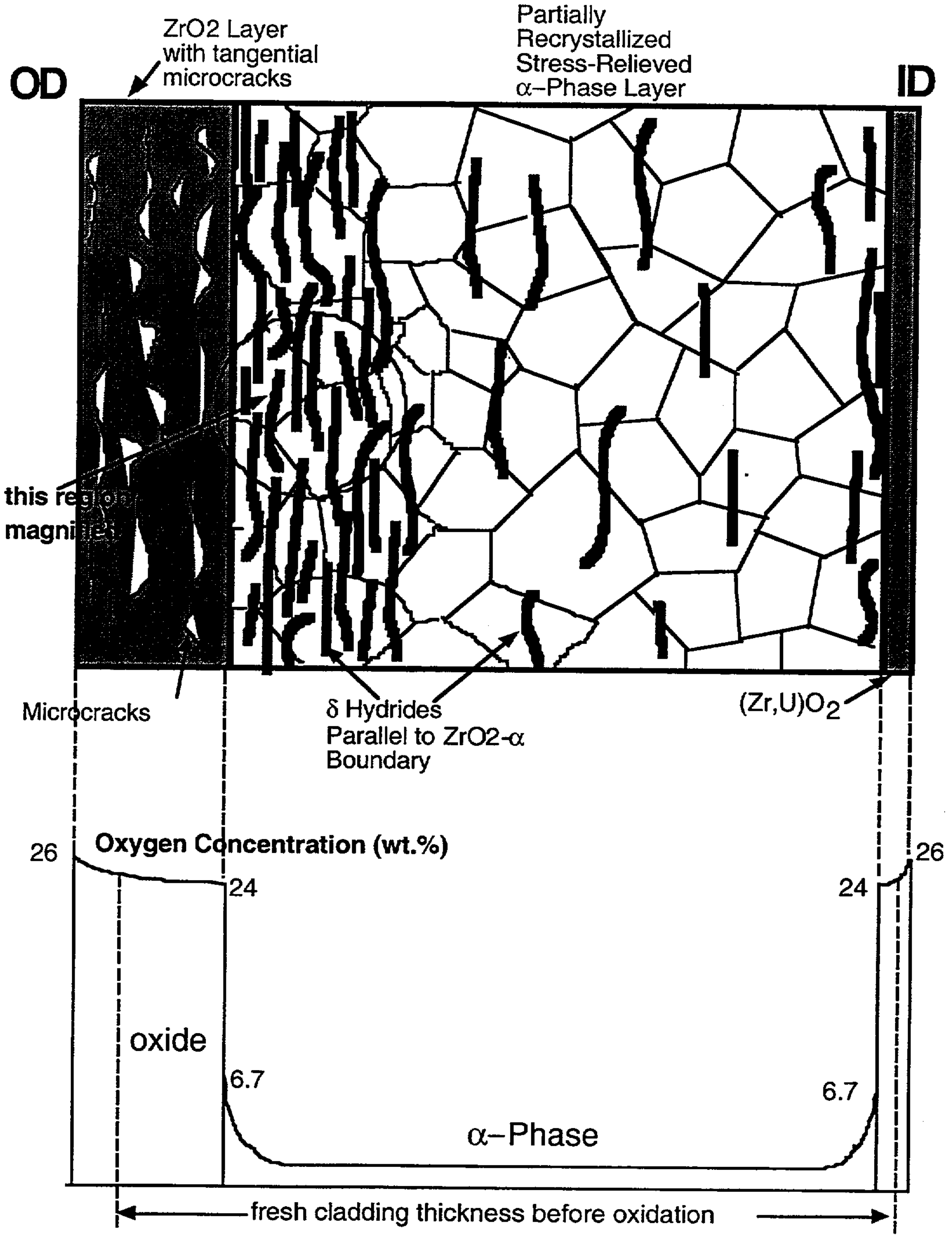


Fig. 2-7. Radial distribution of phases and oxygen concentration in Zircaloy prior to a LOCA transient.

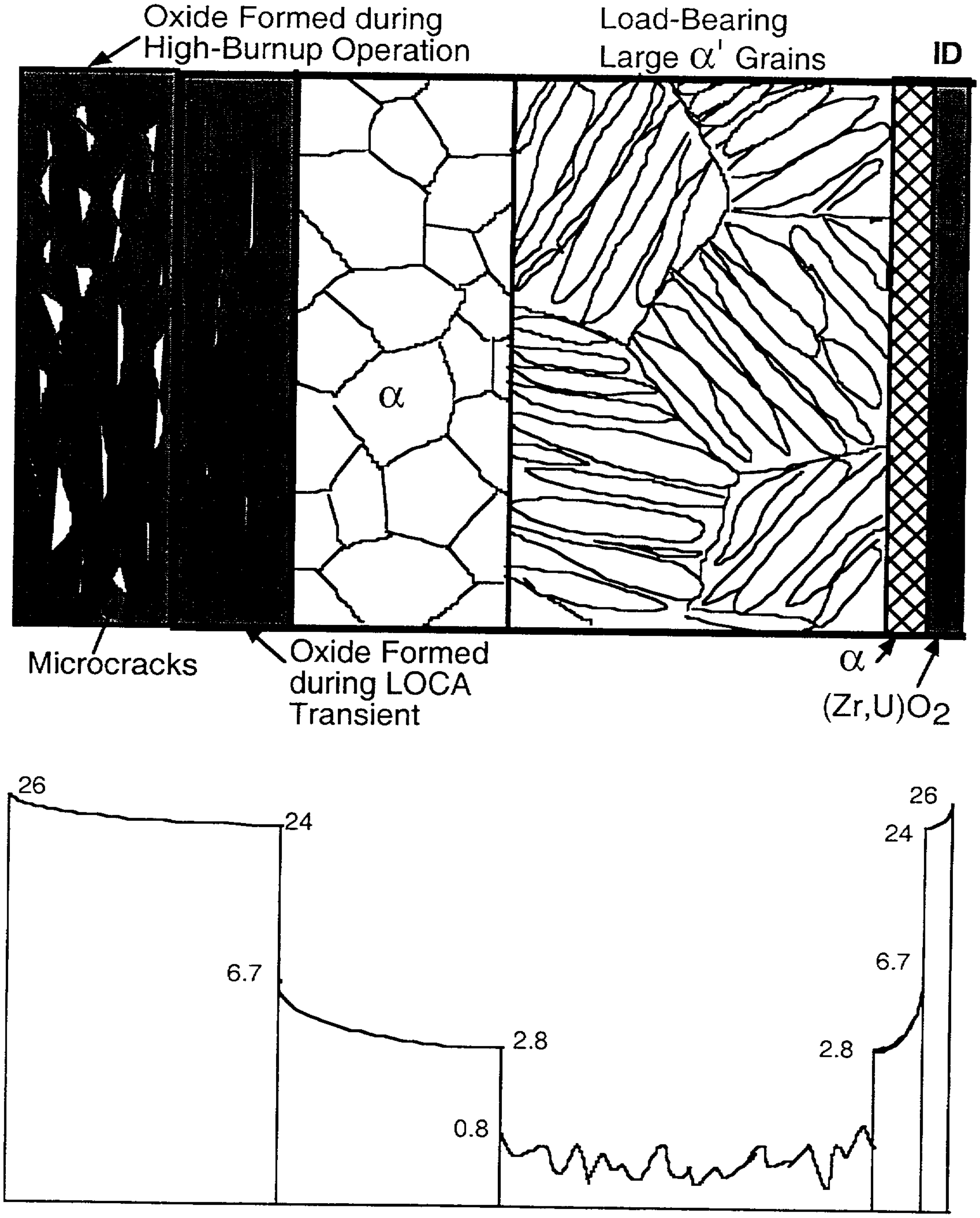


Fig. 2-8. Radial distribution of phases and oxygen concentration in Zircaloy after initial cooling from the peak cladding temperature but before the water quench.

2.4. Primary Evaluation Criterion

The main concern in the case of LOCA accidents is that they might lead to the loss of core coolability if not mitigated. At the high temperatures that can be encountered during a LOCA, the fuel rods can balloon, rupture, and oxidize. Upon cooling, the cladding must retain sufficient ductility to preclude fragmentation and collapse. This precludes the loss of coolable core geometry.

It has been the traditional approach in reactor licensing to ensure that cladding fragmentation does not occur; therefore, the primary evaluation criterion was chosen to be cladding fragmentation. The criteria that were used to examine the possibility of cladding fragmentation were the calculated peak cladding temperature and the amount of cladding oxidation.

2.5. Categories of Phenomena

The panel recognized that, in order to resolve a LOCA issue by avoiding cladding fragmentation, use will likely be made of a combination of analysis and experimental data. Given this reality, the panel generated a list of phenomena classified broadly into two analytical categories (Plant Analysis and Fuel Rod Analysis) and two experimental categories (Integral Experiments and Separate Effect Tests).

The four PIRT categories are as follows:

A. Plant Transient Analysis category includes the phenomena related to the plant-specific reactor kinetics, reactivity, and thermal-hydraulic response for the plant, as well as the transient thermal analysis of the fuel rod.

B. Integral Tests category includes the phenomena related to the integral testing of fuel rods, such as performed at the Japan Atomic Energy Research Institute (JAERI), in progress in the Phebus reactor, and planned at Argonne National Laboratory (ANL) and in the Halden reactor. This category is divided into fuel rod selection and conduct of the test.

C. Transient Fuel Rod Analysis category includes the phenomena and outcomes of calculations of transient fuel rod behavior such as performed by codes such as FRAPTRAN, FALCON, SCANAIR and FRETA.[2-4]

D. Separate Effect Tests category includes the important phenomena relevant to high- and low-temperature mechanical properties, phase transformations, fuel relocation, oxidation kinetics, cladding quenching, and seismic response in the post-accident condition.

The panel discussed at length the questions to be asked to determine the importance vote recorded in Section 3. For the most part the questions asked were as follows:

<u>Category A: Plant Transient Analysis</u>

Are the results of the code-calculated outcome (e.g., calculated peak cladding temperature) sensitive to either this initial condition or to this phenomenon? If the answer is "yes," rank this item "high."

Category B: Integral Testing

If integral tests were conducted to observe heat up, ballooning, bursting, oxidation, and quenching, is this phenomenon of high, medium, or low importance?

Category C: Transient Fuel Rod Analysis

Are the results of the code-calculated outcome (e.g., cladding strain) sensitive to either this initial condition or to this phenomenon? If the answer is "yes," rank this item "high."

Is it important to the understanding and analysis derived from the code calculation that this parameter be calculated?

Category D: Separate Effect Tests

If separate-effect tests were performed to measure oxidation rate, effects of quench, phase transformations, mechanical properties, seismic response, and fuel relocation, is this phenomenon of high, medium, or low importance?

2.6. Phenomenon Ranking Scale

It was decided that the low, medium, and high rank scheme should be adopted based upon past experience with the PIRT process.

- High = The phenomenon or process has dominant impact on the primary evaluation criterion, i.e., cladding fragmentation, within the context of plant transient analysis, experimental testing, or transient fuel rod analysis. The phenomenon should be explicitly and accurately modeled in code development and assessment efforts. The phenomenon should be explicitly considered in any experimental programs.
- Medium = The phenomenon or process has moderate influence on the primary evaluation criterion. The phenomenon should be well modeled, but accuracy may be somewhat compromised in code development and assessment efforts. The phenomenon should also be considered in any experimental programs.
- Low = The phenomenon or process has small effect on the primary evaluation criterion. The phenomenon should be represented in the code, but almost any model will be sufficient. The phenomenon should be considered in any experimental programs to the extent possible.

Previous PIRTs have recorded a single importance rank for each phenomenon, with the option of recording any exceptions by a panel member with respect to a particular importance rank on a given phenomenon. The assignment of a single importance rank for a given phenomenon was achievable, in part, because the typical panel consisted of six to eight members. Such panels were usually able in a timely manner to debate and move to a common view regarding phenomena importance.

The present panel has more than 20 members and the process of debating to a single importance rank for a given phenomenon was not deemed feasible. Given this situation, it was decided that a vote would be taken and the number of votes for each importance rank reported.

Panel members were asked to vote on only those phenomena for which they have a firm opinion about importance. Generally, the panel member's understanding of importance is understood to arise from direct experience. However, the panel members were free to vote based upon experience in related fields that permitted the panel member to see implications across different fields. Practically, this meant that not all of the panel members recorded ranking votes on some phenomena.

The rationales for voting "High," "Medium," or "Low" for each phenomenon in each of the four categories described in Section 3.1 are recorded in Appendices A through D.

2.7. Extended PIRT Applicability

Recognizing that the value of the PIRTs would be enhanced if the applicability of the PIRTs to other reactor, fuel, cladding types, and higher burnups was assessed, the panel has considered and evaluated the applicability of the reactor- and fuel-specific PIRT to other reactor, fuel, cladding types, and higher burnups. The evaluation consisted of asking whether the importance ranks recorded for a given phenomenon would change for a different fuel array, specifically 8x8 or 17x17; or chamfer, or MOX, designated (F) in tables 3-1 to 3-4; a different cladding type from various vendors, e.g., GE and Siemens, designated (C); a different reactor type, e.g., B&W, C-E, or BWR/2 – BWR/6, designated (R); and extended burnup to 75 GWd/t, designated (B). If the answer was "yes," an entry was made and the rationale reported. The outcome of the extended PIRT applicability assessment is reported as part of the PIRT tabulation.

2.8. Uncertainty Evaluation

The NRC requested that the panel consider the uncertainty relative to the panel's understanding of the phenomena. The panel did so for each phenomena by assigning uncertainty for the phenomena to one of three categories: "known" meaning approximately 75-100% of full knowledge and understanding of the phenomenon, "partially known" meaning approximately 25-75% of full knowledge and understanding of the phenomenon, and "unknown" meaning 0-25% of full knowledge and understanding of the phenomenon. The outcome of the uncertainty assessment was recorded and is reported as part of the PIRT tabulation.

2.9. References

2-1. N. E. Todreas and M. S. Kazimi, Nuclear Systems I Thermal Hydraulic Fundamentals, Hemisphere Publishing Corporation (1990).

2-2. B. E. Boyack et al., "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6742 (September 2001).

2-3. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6743 (September 2001).

2-4. M. Uchida, "Application of a Two-Dimensional Ballooning Model to Out-Pile and In-Pile Simulation Experiments," *Nuclear Engineering and Design* 77, 37-47 (1984).

3. PWR AND BWR LOCA PIRTS

Four PIRT tables are presented in this section, one each for Plant Transient Analysis, Integral Testing, Transient Fuel Rod Analysis, and Separate Effect Testing. The PIRT has been developed for PWR and BWR LOCA events in plants containing high burnup fuel. The plant and fuel, description of fuel and cladding state at high burnup, and accident scenario are described in Sections 2.1, 2.2, and 2.3, respectively. The selection of the four PIRT categories, as well as the phenomena definitions, is patterned after the PIRTs developed for a PWR rod ejection accident[3-1].

These PIRTs represent the informed judgment of the PIRT panel members regarding both the phenomena that are expected to occur during the scenario, and the relative importance of those phenomena. The importance of each phenomenon was evaluated relative to the primary evaluation criteria presented in Section 2.4, namely, cladding fragmentation. As discussed in Section 2.6, a vote was taken on the importance of each phenomenon and the number of panel members voting for "High," "Medium," and "Low" tabulated. The rationale for each vote has also been documented as discussed in Section 2.6.

The panel recognized that the phenomena lists presented in two related PIRT reports for reactivity transients[3-1, 3-2] primarily address low-temperature PCMI failure, and this is especially true for Categories C and D. Panel members concluded that fuel behavior for a high-temperature scenario for BWR power oscillations without scram would involve ballooning, rupture, oxidation, and fragmentation that would be quite similar to fuel behavior during a loss-of-coolant accident (LOCA). It was thus concluded that high-temperature behavior would be addressed only once, and the results would be recorded in this report on LOCA phenomena.

In addition to identifying and ranking phenomena, the applicability of the ranking vote for each phenomenon to other reactor, fuel and cladding types and to fuel burnups of 75 GWd/t was assessed as discussed in Section 2.7. Finally, the panel considered uncertainty relative to the panel's understanding of each phenomenon as discussed in Section 2.8.

3.1 Category Descriptions

Phenomena have been identified and ranked for importance relative to the evaluation criterion in each of the four following categories.

3.1.1. Category A: Plant Transient Analysis

The Plant Transient Analysis category includes the phenomena related to the plant-specific reactor kinetics and reactivity response for the plant, as well as the transient thermal analysis of the fuel rod, that are deemed relevant for understanding and predicting fuel behavior during PWR and BWR LOCAs. The PIRT for Plant Transient Analysis is provided in Table 3-1. This PIRT examines the phenomena that impact the calculation of heat transfer during LOCAs and the calculation of peak cladding temperature and cladding oxidation during the event.

3.1.2. Category B: Integral Testing

The Integral Testing category includes the phenomena related to the integral testing of fuel rods. This category is further divided into three subcategories: fuel rod selection, conduct of the test, and parameters and variables measured. Fuel rod selection includes the initial conditions that are considered to be of importance in selecting fuel rods for use in integral tests, both in terms of capturing the important physical characteristics and in terms of assuring prototypicality of the testing. The Conduct of the test category captures the test features (either experimental design or test conditions) that the panel deemed important for the integral tests. Parameters and variables measured identifies measurements taken either on-line or during Post-Test-Examination. The PIRT for Integral Testing is provided in Table 3-2.

3.1.3. Category C: Transient Fuel Rod Analysis

The Transient Fuel Rod Analysis category includes the phenomena and outcomes of calculations of transient fuel rod behavior predicting the fuel behavior in reactor integral tests and in separate effect tests. These calculations are performed with codes such as FRAPTRAN, FALCON, SCANAIR.[3-1, Appendix F] and FRETA.[3-3] This category is divided into seven sub-categories that may require modeling in the codes. The first (initial conditions) captures the characteristics of the fuel and cladding before the transient. The remaining five sub-categories (transient boundary conditions, fuel rod response, multiple rod mechanical effects, properties, and transient cladding-to-coolant heat transfer) simulate the loading and the thermal, mechanical response of the fuel and cladding that need to be modeled by the code to assess cladding behavior during a LOCA. The PIRT for Transient Fuel Rod Analysis is provided in Table 3-3.

3.1.4. Category D: Separate Effect Testing

The Separate Effect Testing category was developed by considering the types of separate effect experiments that might be conducted to develop needed data. The panel defined six test types and the phenomena associated with each. Prior to voting on the phenomena themselves, the panel voted on the importance of each test type. The order of presentation of the test types in Table 3-4 is the order of importance assigned by the working group that developed Category D. The number of votes for each test type is presented in column 1 of Appendix D. The test types are briefly described below.

- Oxidation rate, oxygen distribution, effect of chemistry on solubility. Such tests would measure the steam oxidation kinetics at high temperature in Zirconium alloys used for cladding.

- Quench tests, including quench rate and time of quench. These tests would determine the thermal shock resistance of cladding when quenched after high-temperature oxidation.
- Phase equilibria and transformation kinetics (chemistry effects). These tests would measure phase equilibria and phase transformation kinetics to provide fundamental data relevant to the cladding behavior during LOCA events.
- Mechanical properties at high temperature, e.g., ≥ 300 °C. These tests would be designed to investigate creep and burst behavior of cladding at high temperature. Creep, burst and uniaxial tests are envisioned.
- Mechanical properties at low temperature, e.g., < 300 °C. These tests would include post oxidation and quench ductility tests. Seismic tests would address the ability of the fuel rod to withstand a post-LOCA seismic event using the four-point bending test.
- Simulation of fuel relocation. These tests would balloon and burst a high burnup rod and determine the fuel relocation and posttest thermal conductivity.

3.2. Structure of the PIRT Tables

The structure of each PIRT-results table is:

- Column 1—Subcategory, a collector for related phenomena. An importance vote is taken at the subcategory level only if there are no phenomena associated with the subcategory.

- Column 2— Phenomenon being ranked.

- Column 3 — Phenomenon importance rank. The number of panel members voting for High (H), Medium (M), and Low (L) are tabulated in the respective columns. The total number of panel members voting on given phenomena varies as discussed in Section 2.5. The ranking scale is also described in Section 2.5. The importance ranking (IR) is also tabulated here and described below in Sect. 3.4.

- Column 4 — Extended applicability assessment. Panel assessment of whether the importance assessment for the base case appearing in column 3 will be altered for other fuel, cladding, reactor types, or fuel with a burnup of 75 GWd/t. A "Y" or "yes" communicates that the importance ranking will be altered while an "N" or "no" indicates that importance ranking will not be altered.

- Column 5 —Uncertainty evaluation. The number of panel members voting for known (K), partially known (PK), or unknown (UK) is tabulated in the respective columns. The definitions for K, PK, and UK are appended to the table. The knowledge ratio (KR) is also tabulated here and described below in Section 3.4.

3.3. Phenomena Descriptions and Ranking Rationales

Phenomena descriptions and ranking rationales are given in tabular form in Appendices A-D. Appendix A presents all the descriptions and rationales for Category A, plant transient analysis. Appendix B presents all the descriptions and rationales for Category B, integral testing, and so forth. These large tables are, in effect, annotated versions of the PIRT tables that will follow in this section.

3.4. Panel Analysis of PIRT Results

The panel has examined the results of the PIRT effort to identify the most important outcomes. The panel's observations are summarized by category below. The importance rankings and rationales, combined with the uncertainty rankings and rationales, have been considered in developing the panel's perspective regarding the important issues affecting PWR and BWR LOCAs.

The panel notes that our approach to developing PIRTs for high burnup fuel evolved during the course of the PIRT effort. This was due to several factors. First, the membership of this PIRT panel was much larger than previous PIRT panels. Given the size of the panel, it was more difficult to have sufficient exchanges to develop a common understanding of processes and definitions. For example, we note that two different questions were answered at different points of the PIRT process as the uncertainty rankings, i.e., K, PK, or UK, were developed. One was "How well do we know the parameter in question?" and the other was "How well do we know the *effect* of the parameter in question on transient behavior?" As both questions were addressed at various times, we have identified which question the panel was addressing when knowledge or uncertainty regarding each phenomenon subcategory was addressed.

To provide a weighting structure to our assessment of the importance and uncertainty vote results, we created the Importance Ratio (IR) and the Knowledge Ratio (KR). This was accomplished by assigning a value of 1 to a "High" or "Known" vote, a value of 0.5 to "Medium" or "Partially Known" vote and a value of zero to a "Low" or "Unknown" vote.

The importance ratio is:

$$IR = 100 \times (H + M/2)/(H+M+L),$$

where H, M and L stand for the number of high, medium and low votes and the knowledge ratio is:

$$KR=100 \times (K + PK/2)/(K+PK+UK),$$

where K, PK and UK stand for the number of known, partially known and unknown votes respectively.

We applied the importance ratio, IR, by considering any phenomenon with an importance ratio, IR, greater than 75 to be highly important.

We applied the knowledge ratio, KR, by considering any phenomenon with a knowledge ratio of less than 75 to have associated with a significant *lack of knowledge,* i.e., the closer the KR value is to zero, the greater the lack of knowledge.

The cutoff values for the IR and KR are arbitrary, but the panel believes that use of these cutoff values does adequately convey the panel's perspective regarding those phenomena for which the importance is high relative to the evaluation criterion but for which there is a significant lack of knowledge. Partial knowledge generally indicates a large uncertainty in the knowledge about a given parameter. In safety analyses this uncertainty is considered by making bounding assumptions for these parameters.

The panel also notes, however, that there were a number of phenomena having IR and KR values near to but not meeting the screening criteria. Some of these phenomena may also warrant additional consideration. While the screening criteria provide a useful first cut at identifying important phenomena for which the knowledge base is limited, parties analyzing or applying the PIRT results should also look at those phenomena near to but not meeting the screening criteria.

3.4.1. Category A: Plant Transient Analysis

This category consists of seven subcategories: "Initial conditions," "Transient power distribution," "Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood) and core spray heat transfer," "Transient coolant conditions as a function of elevation and time," "Fuel rod response," "Multiple rod mechanical effects," and "Multiple rod thermal effects."

Within the "Initial conditions" subcategory, gap size, gas pressure, burnup distribution, coolant conditions, rod free volume, initial stored energy-fuel, rod axial power distribution, fuel assembly peaking factors and fuel cycle design were judged as being of high importance by the panel, i.e., each has an IR greater than 75. Of the above, gas pressure and rod free volume have knowledge ratios that are sufficiently low, i.e., KR less than 75, to flag them as candidates for additional consideration. Gas pressure was considered to be important because it sets the initial conditions for rod response and can affect conductance. The rod free volume influences the possible burst of the rod.

Within the "Transient power distribution" subcategory, moderator feedback and decay heat power were identified as being highly important. However, neither of these had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. The implication of the uncertainty outcome is that the panel believes that it has sufficient knowledge to adequately model each of the important phenomena identified in this category.

Within the steady state and transient cladding to coolant heat transfer and core spray heat transfer subcategory, each phenomenon, with the exception of radiation heat transfer to coolant, was judged as being of high importance by the panel. Film boiling over a wide void fraction, rewet, rod-to-spacer grid thermal-hydraulic interaction, and spacer grid rewetting and droplet breakup have knowledge ratios that are sufficiently low to flag them as candidates for additional consideration. From the importance vote justifications, it is clear that the panel recognizes that the complex processes of dryout, film boiling and rewetting are at once of great importance in determining cladding temperature and fairly unknown because fundamental models do not exist and there is large scatter of data. The influence of the spacer grids on heat transfer and rewetting was also highlighted by the panel's importance vote. The lack of data and model uncertainty in these areas were thought by the panel to be even greater than in the above two areas.

Within the "Transient coolant conditions as a function of elevation and time" subcategory, temperature, flow rate and direction, quality, void fraction, and cross flow effects due to flow blockage satisfied the dual criteria for IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration. The common rationale given in the justifications for the importance and knowledge votes was that these coolant conditions determine cladding temperature and that the accurate prediction of the local two-phase flow behavior is difficult.

Within the "Fuel rod response" subcategory, burst criteria, location of burst and time-dependent gap-size heat transfer satisfied the dual criteria for IR and KR. These phenomena are, therefore, flagged as candidates for additional consideration. The high importance attached to the burst criterion stems from the fact that tube burst can lead to substantial flow blockage and the existing correlations are outdated and require significant improvement, especially in regards to the effect of hydrogen. In the case of time-dependent gap-size heat transfer, the panel highlighted the importance of the gap in heat transfer and stressed that gap size is not well known.

Within the "Multiple rod mechanical effects" subcategory, no phenomenon was identified as being either highly important or lacking knowledge. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

Within the "Multiple rod thermal effects" subcategory, several phenomena were identified as being highly important but none satisfied the dual criteria for IR and KR. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

We note that many of the phenomena considered in fuel rod response are also considered by the experimental group in sections B and D, from the point of view of the effect that these phenomena have on the likelihood of cladding fragmentation. In this section they are only considered in how they would affect the plant transient analysis.

3.4.2 Category B: Integral Testing

This category includes phenomena related to the testing of fuel rods in a test reactor such as Halden or Phebus or in an electrically heated facility. This category consists of three subcategories: "Fuel rod selection," "Conduct of test," and "Parameters/variables measured."

Within the "Fuel rod selection" subcategory, fuel burnup and cladding as-fabricated wall thickness were judged as being of high importance by the panel. Of these two phenomena, fuel burnup had a knowledge level sufficiently low to flag it as a candidate for additional consideration. However, the knowledge ratio for as-fabricated wall thickness was just above the cutoff value so this phenomenon may also warrant additional consideration. Fuel burnup was voted as being of high importance not because a specific degradation mechanism was identified that could affect the results of the test, but, rather, because the panel believed that since the focus of the experimental effort is to determine the fuel safety at high burnup, high burnup fuel must be used. The high vote for "as-fabricated fuel thickness" was justified high impact of this parameter on the size of the remaining load bearing ligament after oxidation. For a given oxidation thickness and a given amount of high temperature oxidation, an initially thin-walled cladding will have less load bearing material, than a thicker one.

Within the "Conduct of test" subcategory, plateau temperature, cooldown and quench and rewet rate initiation, and fuel or non-fuel testing configuration satisfied the dual criteria for IR and KR. These phenomena are flagged as candidates for additional consideration. The high vote for plateau temperature was justified by the high impact of this parameter on the oxidation rate. The higher the oxidation rate at high temperature for a given time, the greater the extent of oxygen embrittlement and the higher the probability of failure upon quenching. Cooldown and quench and rewet rate initiation refers to the final part of the temperature history shown in Figure 2.4, during which the material temperature decreases from the plateau temperature to the alpha region. The transformation structure and cladding properties such as quench resistance and impact resistance depend on the cooldown rate, and thus this parameter has a sizable impact on the test outcome. The panel also recognized that the presence or absence of fuel inside the cladding during the integral tests can have a major impact on test outcome.

Within the "Parameters and variables measured" subcategory, Post-Test-Examination for fuel relocation and residual bonding and dispersal satisfied the dual criteria for IR and KR. This phenomenon is, therefore, flagged as a candidate for additional consideration. We also note that two additional parameters judged as important by the panel, online measurement of clad temperature and Post-Test-Examination for prior beta thickness, had knowledge ratios slightly above the knowledge ratio screening criteria. These phenomena may also warrant additional consideration.

We note several items in Category B that are judged to be essential to integral testing, e.g., having a well-defined oxygen potential, careful measurement of the temperature, influence of axial constraints, etc., whose effects are fairly well-known. These parameters, while they need to be well controlled, do not need to be studied per se.

In the conduct of the test category, there are several items that are highly important (IR > 93%) and only partially known, although KR is not lower than 75%. For the online measurements subcategory, these were cladding temperature as function of position, i.e., (r, θ, z), and determination of the time of failure. It is important to make these measurements if possible, but the panel concluded that the exact determination of these quantities is not essential.

Similarly, for post test measurements, several items having a knowledge ratio greater than 75%: were considered highly important. They are measurement of the equivalent cladding reacted at failure section (ECR), post-test metallography, and determination of the prior beta thickness. These should be determined, even though they may not be absolutely essential to the outcome of the test. Two items in the post test measurements met the dual criteria of IR and KR. The first is the determination of any fuel relocation, residual bonding and fuel dispersal. There is clearly significant uncertainty associated with such complex processes, and they are the major outcome of the test. The second is the measurement of the total hydrogen and oxygen in the sample after the test. This is needed to properly interpret the test.

3.4.3. Category C: Transient Fuel Rod Analysis

The "Transient Fuel Rod Analysis" category consists of six subcategories: "Initial conditions," "Transient boundary conditions," "Fuel rod response," "Multiple rod mechanical effects," "Properties," and "Transient cladding-to-coolant heat transfer."

Within the "Initial conditions" subcategory, gas pressure, gas composition, cladding oxidation, hydrogen concentration, hydrogen distribution, porosity distribution, rim size, and spallation and cracking of the oxide layer satisfied the dual criteria for importance and knowledge. These phenomena are, therefore, flagged as candidates for additional consideration.

Within the "Transient boundary conditions" subcategory, transient cladding-to-coolant heat transfer and transient coolant conditions satisfied the dual criteria for importance and knowledge. These phenomena are, therefore, flagged as candidates for additional consideration. The first phenomenon was voted high because it helps determine cladding temperature during the quench phase and hence quench speed, quenched cladding microstructure and cladding survivability. The time dependent coolant conditions also change the heat transfer coefficient and by extension cladding temperature.

Within the "Fuel rod response" subcategory, heat resistances in the gap and oxide, cladding oxidation magnitude, size of burst opening, burst criteria, and time of burst satisfied the dual criteria for importance and knowledge. These phenomena are, therefore, flagged as candidates for additional consideration. With the first three phenomena, the panel highlighted the effect of gap heat resistance (especially during ballooning) and oxide thickness (both prior and during the transient) on heat transfer, and by extension on cladding temperature. The last three phenomena relating to fuel rod bursting affect the cladding temperature and amount of fuel dispersal and flow blockage.

Within the "Multiple rod mechanical effects" subcategory, the single phenomenon was identified as being neither highly important nor lacking knowledge. It was not, therefore, flagged as a candidate for additional consideration. We note that many of the phenomena considered here are also considered in the experimental Categories B and D and in Category A. One element of the fuel response, i.e., likelihood of cladding fragmentation upon quenching, was not considered in this section and is considered in more detail in the experimental sections.

Within the "Properties" subcategory, no phenomenon was identified as being both highly important and lacking knowledge. No phenomenon in this subcategory was, therefore, flagged as a candidate for additional consideration.

Within the "Transient cladding-to-coolant heat transfer" subcategory, rod-to-spacer thermal-hydraulic interactions and spacer grid rewetting and droplet breakup satisfied the dual criteria for importance and knowledge. These phenomena are, therefore, flagged as candidates for additional consideration. The panel believed that both phenomena have significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature.

3.4.4. Category D: Separate Effect Testing

This category collects the phenomena related to separate effect testing. It is important to have these tests to facilitate translation of the results of the integral tests and to help explore the possible variations in parameters. To evaluate separate-effects experiments that could provide information on the behavior of high burnup fuel during a LOCA, the panel considered not only experiments currently being conducted, but also other experiments that could be useful.

The experimental subgroup discussed and defined a list of experiments that should be considered, the information that could be gleaned from such experiments, and how they should be conducted. The subgroup then voted the experiments in the list as to their potential in providing value to assessing fuel behavior during a LOCA.

The ranking produced the order in which the experiments are listed here, with the highest ranked listed first. The subgroup then developed subcategories for each of these experiments, considering both the conduct of the test and the parameters to be studied. The subgroup created definitions and voted on the subcategories according to the evaluation criteria, provided justifications, and assessed uncertainties.

Those considering use of the results derived from the screening criteria, as applied to Category D, should exercise additional care for two reasons. First, the number of panel members voting was often small. Thus, the importance and knowledge ratio values were more sensitive to a single panel member's vote than is the case when more panel members voted. Second, more than ten of the phenomena satisfied one screening criterion but were excluded from this summary because their calculated ratios for the remaining screening criterion were exactly 75, i.e., they were not greater to or less than 75 as required by the specific criterion.

As discussed in Section 3.1.4, this category was divided into six subcategories identified by different separate effect test types: (1) oxidation rate, oxygen distribution, and effect of chemistry on solubility, (2) quench tests, (3) phase equilibria and transformation kinetics (chemistry effects), (4) mechanical properties at high temperature, e.g., ≥ 300 °C, (5) mechanical properties at low temperature, e.g., < 300 °C, and (6) simulation of fuel relocation. Within each test type, specimen selection, conduct of the test, and post-test examination were used to further collect test parameters and characteristics. The panel also identified parameters that should be measured in a separate effect test to aid in the interpretation of the test and to develop a mechanistic understanding of the failure process.

In the summary findings that follow, the screening criteria, i.e., importance ratio greater than 75 and knowledge ratio less than 75 are largely observed. However, users of the PIRT findings for this category should carefully review Table 3-4 because there are more than 15 phenomena for which either the IR or KR screening criterion is satisfied and the remaining importance ratio value, while failing the screening criterion, is close to the screening criterion value.

We note that the items flagged below according to our dual criteria of high IR and low KR, should be considered only if the test itself is deemed important enough to be conducted. That is, if this test is to be conducted, then the highly ranked parameters are important. We note that the first two subcategories listed below, i.e., oxidation rate and quench, were considered to be of greater importance by the subgroup members than the remaining four subcategories.

Oxidation Rate, oxygen distribution, effect of chemistry on solubility. This is a separate effect test to measure the high temperature oxidation kinetics in zirconium alloys used for fuel cladding. The kinetics will result in a particular oxygen distribution in the cladding and will be affected by the altered solubilities brought about by different chemistry. The importance of this test is that it can determine the amount of oxidation given a temperature history. As such it would be valuable for the analysis of integral tests and for oxidation predictions in codes.

Within the "Oxidation rate" subcategory, (1) specimen selection: alloy type and (2) conduct of test: oxygen potential, oxygen satisfied the dual criteria for importance and knowledge.

The subgroup felt that specimen selection, i.e., the alloy type chosen, was very important for the outcome of the test. This is because previous tests have shown that the high temperature oxide layer forms differently on different alloys.

For test conduct, oxygen potential was considered to be highly important to the test outcome, because this is the boundary condition that determines specimen oxidation. Although better known, the test temperature and time and the weight gain measurement during the test were each considered to be highly important. Weight gain measurement provides a primary measure of oxidation

During post test examination, the determination of the oxide thickness, characteristic alpha-beta morphology and oxygen distribution were considered to be highly important (IR = 100%), because they relate to the basic parameters measured by the test. Oxygen distribution was considered to be the one with the greatest uncertainty (KR = 75%) but the others were not too far off (80 and 88%). This indicates that the subgroup felt these were important measurements to make if the test is to be conducted.

Quench tests, quench rate and quench temperature. These are tests that attempt to determine the rewetting temperature and the thermal shock resistance of cladding after high temperature oxidation.

From the specimen selection phenomena rankings, it is clear that the specimen configuration is important for the outcome of the tests. The subgroup singled out two items: axial constraints and whether the test is conducted with empty or full cladding as having high importance and a low knowledge ratio. The test specimen fittings are intended to simulate in-reactor fuel rod axial constraints and can affect the test outcome. The thermal inertia of pellets simulates the effect of the fuel and can have a significant impact on the temperature history of the cladding during the transient.

For the conduct of the test subcategory, the cladding temperature at the time the insertion of water (quench) occurs was considered of high importance but not well known. This affects the metallurgical morphology of the cladding. Whether quench occurs before or after the alpha to beta transformation takes place influences the magnitude of the thermal stresses and the properties of the prior beta phase. The other factor that met the dual criteria was the pre-thinning of the cladding designed to simulate the oxidation related thinning prior to ballooning.

Finally, whether the cladding fragments or does not at the end of the test is considered of major importance because cladding fragmentation determines the risk of fuel dispersal and subsequent coolability concerns.

Phase equilibria and transformation kinetics (chemistry effect). This category refers to experiments designed to measure fundamental phase equilibria in the systems of interest, as well as phase transformation kinetics that can provide fundamental data relevant to the analysis of cladding behavior during LOCA transients. These include high temperature oxidation experiments to measure the rate of beta phase formation and the influence of various parameters on alpha-beta phase equilibria.

Within the "Phase equilibria and transformation kinetics (chemistry effect)" subcategory, The selection of the alloy was thought to be of great importance because elements such as Sn and Nb affect the alpha-beta phase boundaries. The determination of hydrogen and oxygen solubilities in the alpha and beta phases were thought to be important for modeling efforts, and the determination of retained beta and transformed beta morphology was thought to be important because this was one of the objects of the test. These phenomena are, therefore, flagged as candidates for additional consideration.

Mechanical properties at high temperature (>300 °C). This category refers to mechanical tests conducted at high temperature to measure the creep and burst behavior of the cladding during the transient.

Specimen selection for alloy and initial thermomechanical treatment satisfied the dual criteria for importance and knowledge. This phenomenon is flagged as a candidate for additional consideration. In addition, the measurements of load and displacements, which is essentially the object of the test, and the determination of the post-test strain were given high importance rankings and knowledge ratios of 80%, indicating what the panel thought was most relevant were this test to be conducted.

Mechanical properties at low temperature (<300 °C). In this section, five tests were identified as possibly having enough relevance to assess LOCA behavior: axial tensile, ring tensile, ring compression, impact, and bending (seismic) tests. The panel judged that the seismic test had the greatest relevance to assessing LOCA behavior, by addressing the ability of the fuel rod to withstand a post-LOCA seismic event without shattering. The panel identified how such a test (four point bending test) should be conducted.

Within the "Mechanical properties at low temperature" subcategory, specimen selection for alloy type, pre-existing and transient hydrogen content and distribution, and ballooning satisfied the dual criteria for importance and knowledge. The alloy type was thought to affect hydrogen content and hydrogen distribution, which in turn affects cladding ductility. This was also the rationale for voting pre-existing and transient hydrogen content as being of high importance. The presence or absence of ballooning in the tested rod was thought by the panel to affect the ability of the fuel rod to withstand the seismic event.

For test conduct, temperature, strain rate, ASTM specification, and appropriate bending moment satisfied the dual criteria for importance and knowledge. The panel thought that the strain rate and the application of the appropriate bending moment were crucial to the outcome of the test.

For Post-Test-Examination, characterization of integrity and local hydrogen satisfied the dual criteria for importance and knowledge. The rod should clearly be tested for integrity after the test, since this is one of the main test objectives, and measuring the amount of hydrogen will allow the analysis of the results.

These phenomena are flagged as candidates for additional consideration.

Fuel Relocation. The fuel relocation subcategory refers to a separate effect test to measure the effect of fuel relocation during ballooning on the temperature and mechanical evolution of the fuel rod.

Within the "Simulation of fuel relocation" subcategory, specimen selection for burnup and chemical and mechanical bonding satisfied the dual criteria for importance and knowledge. For test conduct (1) internal pressure and moles of gas and (2) balloon size and burst size satisfied the dual criteria for importance and knowledge. For Post-Test-Examination, granularity of dispersed material and strain profile of the cladding satisfied the dual criteria for importance and knowledge. These phenomena are flagged as candidates for additional consideration.

3.5. References

3-1. B. E. Boyack et al., "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6742 (September 2001).

3-2. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6743 (September 2001).

3-3. M. Uchida, "Application of a Two-Dimensional Ballooning Model to Out-Pile and In-Pile Simulation Experiments," *Nuclear Engineering and Design* 77, 37-47 (1984).

Table 3-1. PWR and BWR LOCA. CATEGORY A – PLANT TRANSIENT ANALYSIS PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Initial conditions	Gap size	7	0	0	100	N	N	N	N	7	0	0	100
	Gas pressure	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**7**	**0**	**50**
	Gas composition	1	6	0	57	Y	N	N	N	0	7	0	50
	Pellet and cladding dimensions	0	7	0	50	N	N	N	N	7	0	0	100
	Burnup distribution	7	0	0	100	N	N	N	N	7	0	0	100
	Cladding oxidation (ID & OD)	0	0	7	0	N	N	N	N	0	7	0	50
	Coolant conditions	7	0	0	100	N	N	N	N	7	0	0	100
	Rod free volume	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**7**	**0**	**50**
	Gas communication (full)	0	2	5	14	N	N	N	Y	0	7	0	50
	Gadolinium distribution (conductivity effect)	0	0	7	0	N	N	N	N	7	0	0	100
	Initial stored energy-fuel	7	0	0	100	N	N	N	N	7	0	0	100
	Initial stored energy-structures	7	0	0	100	N	N	N	N	7	0	0	100
	Initial core pressure drop (grids)	0	0	7	0	N	N	N	N	7	0	0	100
	Pellet radial power distribution	0	0	7	0	N	N	N	N	7	0	0	100
	Rod axial power distribution	7	0	0	100	N	N	N	N	7	0	0	100
	Fuel assembly peaking factors	7	0	0	100	N	N	N	N	7	0	0	100
	Pin peaking factors	0	1	6	7	N	N	Y	N	7	0	0	100
	Fuel cycle design	7	0	0	100	N	N	N	N	7	0	0	100
Transient power distribution	Moderator feedback	7	0	0	100	N	N	N	N	7	0	0	100
	Decay heat power	7	0	0	100	N	N	N	N	7	0	0	100

Table 3-1. PWR and BWR LOCA. CATEGORY A – PLANT TRANSIENT ANALYSIS PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Transient power distribution (cont)	Fuel temperature feedback	0	0	7	0	N	N	N	N	7	0	0	100
	Delayed neutron fraction	0	0	7	0	N	N	N	N	7	0	0	100
	Fractional energy deposition in moderator and structures	0	0	7	0	N	N	Y	N	7	0	0	100
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood) and core spray heat transfer	Single phase convection	7	0	0	100	N	N	N	N	7	0	0	100
	Subcooled boiling, nucleate boiling, bulk boiling, and forced convection vaporization	7	0	0	100	N	N	N	N	7	0	0	100
	Critical heat flux/dryout	7	0	0	100	Y	N	N	N	7	0	0	100
	Film boiling over a wide void fraction (inverted annular, dispersed flow)	7	0	0	100	N	N	N	N	0	7	0	50
	Radiation heat transfer to coolant	0	0	7	0	N	N	N	N	7	0	0	100
	Rewet	7	0	0	100	N	N	N	N	0	7	0	50
	Rod-to-spacer grid thermal-hydraulic interaction	6	1	0	93	Y	N	N	N	0	7	0	50
	Spacer grid rewetting and droplet breakup	7	0	0	100	Y	N	N	N	0	0	7	0
Transient coolant conditions as a function of elevation and time	**Temperature**	7	0	0	100	N	N	N	N	0	7	0	50
	Flow rate/directions (CCFL)	7	0	0	100	N	N	N	N	0	7	0	50

Table 3-1. PWR and BWR LOCA. CATEGORY A – PLANT TRANSIENT ANALYSIS PIRT

		Importance[**]				Applicability[†,††]				Uncertainty[§,§§]			
Subcategory	Phenomenon[*]	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Transient coolant conditions as a function of elevation and time (cont)	**Quality**	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**7**	**0**	**50**
	Void fraction	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**7**	**0**	**50**
	Pressure	7	0	0	100	N	N	N	N	7	0	0	100
	Partial vapor pressure	0	0	7	0	N	N	N	N	7	0	0	100
	Cross flow effects due to flow blockage	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**7**	**0**	**50**
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	5	0	0	100	N	Y	N	N	5	0	0	100
	Direct gas pressure loading	5	0	0	100	N	N	N	N	3	2	0	80
	Thermal deformation of pellet and cladding	0	0	5	0	N	N	N	N	5	0	0	100
	Elastic deformation of cladding	0	3	2	30	N	N	N	N	5	0	0	100
	Heat resistances in fuel, gap and cladding	5	0	0	100	N	N	N	N	5	1	0	92
	Axial and radial temperature distributions	5	0	0	100	N	N	N	N	5	1	0	92
	Metal-water reaction heat addition	0	1	5	8	N	N	N	N	5	0	0	100
	Cladding oxidation magnitude	0	0	5	0	N	N	N	N	4	1	0	90
	Cladding temperature	5	0	0	100	N	N	N	N	3	2	0	80
	Burst criteria	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Cladding phase changes	0	4	1	40	N	N	N	N	5	0	0	100
	Time of burst	1	4	1	50	N	N	N	N	0	5	0	50
	Location of burst and blockage	5	0	0	100	N	N	N	N	4	2	0	83
	Fuel relocation	0	2	4	17	N	N	N	N	0	0	5	0

Table 3-1. PWR and BWR LOCA. CATEGORY A – PLANT TRANSIENT ANALYSIS PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Fuel rod response (cont)	**Time dependent gap-size heat transfer**	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**1**	**5**	**0**	**58**
	Thermal and mechanical properties of pellet and cladding	5	0	0	100	N	N	N	N	5	0	0	100
Multiple rod mechanical effects	Rod-to-rod mechanical interactions	0	1	4	10	N	N	N	N	0	0	4	0
	Rod bow between spacer grids	0	0	4	0	N	N	N	N	0	0	4	0
Multiple rod thermal effects	Rod-to-rod radiative heat transfer	0	0	4	0	N	N	Y	N	4	0	0	100
	Rod-to-channel box radiative heat transfer	4	0	0	100	N	N	NA	N	4	0	0	100
	Rod-to-spacer grid local heat transfer	1	4	0	60	N	N	N	N	0	4	0	50
	Rod-to-guide tube radiative heat transfer	0	0	4	0	N	N	NA	N	4	1	0	90
	Rod-to-water rod radiative heat transfer	4	1	0	90	N	N	N	N	5	0	0	100
	Rod-to-inner channel radiative heat transfer	4	1	0	90	N	N	N	N	5	0	0	100

[*] Descriptions for the phenomena listed in the Plant Transient Analysis PIRT are provided in Appendix A.

[**] The rationale for each High, Medium and Low rank are documented in Appendix A.

[†] The column numbers are related to the following issues related to extended applicability

F = Fuel array, i.e., 8x8 or 17x17 rods in a fuel assembly, chamfer, or MOX
C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
R = Reactor type, e.g., B&W, CE, BWR/2 through /6.
B = Burnup to 75 GWd/t.

Data were received by ballot: "N" was entered if no one voted "Yes"; otherwise, the number of "Yes" votes was entered.

[††] The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3 through 5, are documented in Appendix A.

[§] The definitions for Known, Partially Known, and Unknown used by the panel are as follows.

K = Known; approximately 75%-100% of full knowledge and understanding
PK = Partially known; 25%-70% of full knowledge and understanding
UK = Unknown; approximately 0%-25% of full knowledge and understanding

[§§] The rationale for the assessment of uncertainty is found in Appendix A.

Table 3-2. PWR and BWR LOCA. Category B – Integral Testing PIRT

			Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Fuel rod selection	**Fuel**	**Burnup**	**5**	**1**	**0**	**92**	**N**	**N**	**N**	**N**	**0**	**6**	**0**	**50**
		PU agglomerates (MOX fuel only)	1	0	6	14	NA	N	N	N	6	0	1	86
		Duty cycle	0	4	3	29	N	N	N	N	4	3	0	79
		Fuel type (absorbers, additives	0	3	4	21	NA	N	N	N	0	4	2	33
	Cladding:	Pre-existing oxidation (thickness, type, uniformity f[θ])	2	4	1	57	N	N	N	N	6	1	0	93
		Spalling	0	3	4	21	N	N	N	N	2	5	0	64
		Total hydrogen	3	4	0	71	N	N	N	N	4	3	0	79
		Hydrogen distribution	0	1	5	8	N	N	N	N	5	1	0	92
		Surface conditions (crud)	0	1	5	8	N	N	N	N	5	1	0	92
		Fluence/radiation damage	0	1	5	8	N	N	N	N	5	1	0	92
		Initial residual deformation (hourglassing, creepdown)	0	2	4	17	N	N	N	N	0	5	1	42
		Chemical bonding	1	4	1	50	Y	N	N	N	0	5	1	42
		As-fabricated wall thickness	3	1	0	88	N	Y	N	N	2	2	0	75
	Cladding Alloy type:	Alloy composition Microstructure/2nd phase particle Initial cold work Liner/nonliner clad	2	4	1	57	N	NA	N	N	0	4	2	33

Table 3-2. PWR and BWR LOCA. Category B – Integral Testing PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Conduct of test	**Plateau temperature (plus variations)**	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**3**	**4**	**0**	**71**
	Temperature ramp	3	4	0	71	N	N	N	N	4	3	0	79
	Time at temperature	7	0	0	100	N	N	N	N	7	0	0	100
	Cooldown/quench/rewet rate initiation: (Clad temperature level, mass flow rate, pump or gavity feed, quality, subcooling)	**6**	**1**	**0**	**93**	**N**	**N**	**N**	**N**	**2**	**5**	**0**	**64**
	Plenum volume	1	5	0	58	N	N	N	N	6	1	0	93
	Internal pressure	3	3	0	75	N	N	N	N	4	3	0	79
	Attachments	1	6	0	57	N	N	N	N	5	2	0	86
	Temperature measurement	7	0	0	100	N	N	N	N	6	1	0	93
	Gas composition	0	1	6	7	N	N	N	N	7	0	0	100
	Design test such that axial and azimuthal temperature gradients are known	3	4	0	71	N	N	N	N	4	2	0	83
	Single rod versus bundle	1	3	3	36	N	N	N	N	0	6	0	50
	Fuel/nonfuel	**7**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**2**	**5**	**0**	**64**
	Water chemistry	0	6	1	43	N	N	N	N	7	0	0	100
	Coolant flow conditions	0	3	4	21	N	N	N	N	6	1	0	93
	Heating source (internal or external, type, electrical, radiant, neutronic)	3	4	0	71	N	N	N	N	6	1	0	93
	Specimen length	2	5	0	64	N	N	N	N	6	1	0	93

Table 3-2. PWR and BWR LOCA. Category B – Integral Testing PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Conduct of test (cont)	Specimen constraints (grids, spacers, structures)	7	0	0	100	N	N	N	N	5	2	0	86
	Temperature effects of fuel relocation	3	3	1	64	Y	N	N	N	4	3	0	79
	Fuel stored energy	1	3	3	36	N	N	N	N	5	2	0	86
Parameters/variables measured	Online: Clad temperature f(θ , z, t)	7	0	0	100	N	N	N	N	4	3	0	79
	Fuel temperature f(z, t)	0	4	3	29	N	N	N	N	4	2	1	71
	Time of failure	6	1	0	93	N	N	N	N	5	2	0	86
	Time of fuel relocation	2	2	3	43	N	N	N	N	0	6	1	43
	Fuel dispersal	0	5	2	36	N	N	N	N	0	3	3	25
	Internal pressure (value and axial communication)	3	3	1	64	N	N	N	N	2	5	0	64
	Hydrogen release/evolution	0	3	4	21	N	N	N	N	5	2	0	86
	Fission product release	1	4	2	43	N	N	N	N	5	0	2	71
	Steam consumption	2	1	4	36	N	N	N	N	4	3	0	79
	Strain measurement	2	3	2	50	N	N	N	N	4	3	0	79
	Post-Test Examination: ECR at failure location (burst and/or thermal shock)	7	0	0	100	N	N	N	N	5	2	0	86
	Remaining prior beta thickness	6	1	0	93	N	N	N	N	4	3	0	79
	Cladding strain	3	4	0	71	N	N	N	N	4	2	0	83
	Fuel relocation, residual bonding and/or dispersal	7	0	0	100	Y	N	N	N	0	3	2	30

Table 3-2. PWR and BWR LOCA. Category B – Integral Testing PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Parameters/variables measured (continued)	Metallography (oxide thickness microstructure, prior beta, hydrides, and cladding thinning)	7	0	0	100	N	N	N	N	5	2	0	86
	Chemistry (Total hydrogen and oxygen content)	7	0	0	100	N	N	N	N	4	2	0	83
	Oxide spallation and delamination during test	0	1	6	7	N	N	N	N	3	2	0	80
	Fission gas distribution	0	2	4	17	Y	N	N	N	0	3	0	50

*Descriptions for the phenomena listed in the Plant Transient Analysis PIRT are provided in Appendix B.

**The rationale for each High, Medium and Low rank are documented in Appendix B.

†The column numbers are related to the following issues related to extended applicability

F = Fuel array, i.e., 8x8 or 17x17 rods in a fuel assembly, chamfer, or MOX
C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
R = Reactor type, e.g., B&W, CE, BWR/2 through /6.
B = Burnup to 75 GWd/t.

Data were received by ballot: "N" was entered if no one voted "Yes"; otherwise, the number of "Yes" votes was entered.

††The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3 through 5, are documented in Appendix B.

§The definitions for Known, Partially Known, and Unknown used by the panel are as follows.

K = Known; approximately 75%-100% of full knowledge and understanding
PK = Partially known; 25%-70% of full knowledge and understanding
UK = Unknown; approximately 0%-25% of full knowledge and understanding

§§The rationale for the assessment of uncertainty is found in Appendix B.

TABLE 3-3. PWR AND BWR LOCA. CATEGORY C – TRANSIENT FUEL ROD ANALYSIS PIRT

		Importance[**]				Applicability[†,††]				Uncertainty[§,§§]			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Initial conditions	Gap size	5	0	0	100	N	N	N	N	5	0	0	100
	Gas pressure	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Gas composition	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Pellet and cladding dimensions	5	0	0	100	N	N	N	N	5	0	0	100
	Burnup distribution	5	0	0	100	N	N	N	N	5	0	0	100
	Cladding oxidation (ID + OD)	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**2**	**4**	**0**	**67**
	Hydrogen concentration	**5**	**0**	**1**	**83**	**N**	**N**	**N**	**N**	**2**	**3**	**0**	**70**
	Hydrogen distribution	**5**	**0**	**1**	**83**	**N**	**N**	**N**	**N**	**2**	**3**	**0**	**70**
	Fast fluence	5	0	0	100	N	N	N	N	5	0	0	100
	Porosity distribution	**5**	**0**	**1**	**83**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Rim size	**5**	**0**	**1**	**83**	**Y**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Pellet radial power distribution	0	5	0	50	N	N	N	N	5	0	0	100
	Rod axial power distribution	5	0	0	100	N	N	N	N	5	0	0	100
	Fuel-clad gap friction coefficient/bonding	0	3	2	30	N	N	N	Y	0	5	0	50
	Surface conditions (rewet)	1	0	5	17	N	N	N	N	5	1	0	92
	Coolant conditions (P, T, α, x, mdot)	5	0	0	100	N	N	N	N	5	0	0	100
	Rod free volume	5	0	0	100	N	N	N	N	5	0	0	100
	Gas communication (resistance)	0	1	5	8	N	N	N	N	5	0	0	100
	Pu cluster size (MOX only)	0	0	5	0	NA	N	N	N	5	0	0	100
	Pellet cracking representation	0	5	0	50	N	N	N	N	5	1	0	92

TABLE 3-3. PWR AND BWR LOCA. CATEGORY C – TRANSIENT FUEL ROD ANALYSIS PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Initial conditions (cont)	Gadolinium distribution (conductivity effect)	0	5	0	50	Y	N	N	N	5	0	0	100
	Initial stored energy	5	0	0	100	N	N	N	N	5	0	0	100
	Initial core pressure drop (grids)	0	0	5	0	N	N	N	N	5	0	0	100
	Spallation of oxide layer, cracking	**5**	**1**	**0**	**92**	**N**	**Y**	**N**	**N**	**0**	**5**	**0**	**50**
	Pellet shape	0	0	5	0	N	N	N	N	5	1	0	92
Transient boundary conditions	**Transient cladding-to-coolant heat transfer (all phases: blowdown refill, reflood and steady state)**	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
	Transient and steady state power distributions	5	0	0	100	N	N	N	N	5	0	0	100
	Transient coolant conditions	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**0**	**50**
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	5	0	0	100	N	N	N	N	4	1	0	90
	Direct gas pressure loading	5	0	0	100	N	N	N	N	5	0	0	100
	Quench loading of clad	0	3	2	30	N	N	N	N	5	1	0	92
	Thermal deformation of pellet and cladding	0	0	5	0	N	N	N	N	5	0	0	100
	Elastic deformation of cladding	0	4	1	40	N	N	N	N	5	0	0	100
	Fission gas release	0	0	5	0	N	N	N	N	5	0	0	100
	Pellet swelling	0	0	5	0	N	N	N	N	5	0	0	100
	Axial and radial temperature distributions	5	0	0	100	N	N	N	N	5	0	0	100
	Heat resistances - fuel	5	0	0	100	N	N	N	N	4	2	0	83
	Heat resistances —gap	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**6**	**0**	**50**

TABLE 3-3. PWR AND BWR LOCA. CATEGORY C – TRANSIENT FUEL ROD ANALYSIS PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Fuel rod response (cont)	Heat resistances— clad	1	5	0	58	N	N	N	N	5	0	0	100
	Heat resistances —oxide	**5**	**1**	**0**	**92**	**N**	**Y**	**N**	**N**	**0**	**5**	**0**	**50**
	Cladding azimuthal temperature distributions	1	5	0	58	N	N	N	N	0	6	0	50
	Cladding oxidation magnitude (ID/OD)	**5**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**2**	**4**	**0**	**67**
	Metal-water reaction heat addition	5	1	0	92	N	N	N	Y	6	0	0	100
	Size of burst opening	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**1**	**42**
	Burst criteria	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**1**	**5**	**0**	**58**
	Cladding phase changes	6	0	0	100	N	N	N	N	6	0	0	100
	Time of burst	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**6**	**0**	**50**
	Location of burst	6	0	0	100	N	N	N	N	4	2	0	83
	Spacer grid constraint	1	3	2	42	N	N	N	Y	0	6	0	50
	Pellet to cladding bonding	2	4	0	67	N	N	N	N	0	6	0	50
	Localized effects	0	0	5	0	N	N	N	Y	0	0	5	0
	Biaxiality	0	2	3	20	N	N	N	N	5	0	0	100
	Fuel relocation	1	5	0	58	Y	N	N	N	0	6	0	50
	Grain boundary decohesion	0	0	5	0	N	N	N	N	0	5	0	50
	Evolution of pellet stress state	0	0	5	0	N	N	N	N	5	0	0	100
Multiple rod mechanical effects	Rod-to-rod and rod-to-channel thermal and mechanical interactions	1	5	0	58	N	N	Y	N	5	0	0	100

TABLE 3-3. PWR AND BWR LOCA. CATEGORY C – TRANSIENT FUEL ROD ANALYSIS PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Properties	Fracture stress of oxide	0	0	5	0	N	N	N	N	5	0	0	100
	Yield stress in compression	0	0	5	0	N	N	N	N	5	0	0	100
	Heat capacities of fuel and cladding	5	0	0	100	N	N	N	N	5	0	0	100
	Thermal conductivities of fuel and cladding	5	0	0	100	N	N	N	N	5	0	0	100
	Strain rate effects	0	0	5	0	N	N	N	N	5	0	0	100
	Anisotropy	0	0	5	0	N	N	N	N	5	0	0	100
Transient cladding-to-coolant heat transfer	**Rod-to-spacer grid thermal-hydraulic interaction**	5	0	0	100	N	N	N	N	0	5	0	50
	Spacer grid rewetting and droplet breakup	5	0	0	100	N	N	N	N	0	5	0	50

*Descriptions for the phenomena listed in the Plant Transient Analysis PIRT are provided in Appendix C.

**The rationale for each High, Medium and Low rank are documented in Appendix C.

†The column numbers are related to the following issues related to extended applicability

F = Fuel array, i.e., 8x8 or 17x17 rods in a fuel assembly, chamfer, or MOX
C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
R = Reactor type, e.g., B&W, CE, BWR/2 through /6.
B = Burnup to 75 GWd/t.

Data were received by ballot: "N" was entered if no one voted "Yes"; otherwise, the number of "Yes" votes was entered.

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TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Oxidation rate, oxygen distribution, effect of chemistry on solubility	**Specimen selection:** **Alloy type**	**3**	**2**	**0**	**80**	**N**	**NA**	**N**	**N**	**2**	**2**	**1**	**60**
	Specimen Selection: Thickness and morphology of pre-existing oxide	1	2	2	40	N	NA	N	N	2	3	0	70
	Specimen Selection: Burnup, including fluence	3	1	1	70	N	N	N	NA	1	4	0	60
	Specimen Selection: Pre-existing hydrogen content and distribution	1	3	1	50	N	NA	N	NA	2	2	0	75
	Conduct of Test-During Test **Oxygen potential**	**3**	**1**	**0**	**88**	**N**	**N**	**N**	**N**	**1**	**2**	**0**	**67**
	Conduct of Test-During Test Temperature and time	5	0	0	100	N	N	N	N	2	2	0	75
	Conduct of Test-During Test Total steam pressure	1	3	1	50	N	N	N	N	3	1	0	88
	Conduct of Test-During Test Weight gain	4	1	0	90	N	N	N	N	5	0	0	100
	Conduct of Test-During Test Steam consumption	1	2	2	40	N	N	N	N	3	2	0	80
	Conduct of Test-During Test One-sided vs. two-sided	2	3	1	58	N	N	N	N	2	3	0	70
	Conduct of Test—Post-Test-Examination Oxide thickness	5	0	0	100	N	N	N	N	3	1	0	88
	Conduct of Test—Post-Test-Examination Characteristic α–β morphology	5	0	0	100	N	N	N	N	3	2	0	80

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

Subcategory	Phenomenon[*]	Importance[**]				Applicability[†,††]				Uncertainty[§,§§]			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Oxidation rate, oxygen distribution, effect of chemistry on solubility (cont)	Conduct of Test—Post-Test-Examination Oxygen distribution	5	0	0	100	N	N	N	N	2	2	0	75
	Conduct of Test—Post-Test-Examination Hydrogen pickup and distribution	4	2	0	83	N	N	N	Y	3	2	0	80
Quench tests, quench rate, Tquench, etc.	Specimen Selection: Hydrogen content and distribution	3	2	0	80	N	N	N	N	2	2	0	75
	Specimen Selection: Alloy type	2	2	1	60	Y	N	Y	N	1	2	1	50
	Specimen Selection: Thickness and morphology of pre-existing oxide	3	3	0	75	N	N	N	N	3	1	1	70
	Specimen Selection: Burnup	2	2	0	75	Y	N	N	N	2	2	1	60
	Conduct of Test—During Test **Axial constraints**	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**5**	**1**	**42**
	Conduct of Test—During Test Azimuthal quenching	1	3	1	50	N	N	N	N	0	4	1	40
	Conduct of Test—During Test **Empty/full**	**4**	**2**	**0**	**83**	**N**	**N**	**N**	**Y**	**1**	**4**	**0**	**60**
	Conduct of Test—During Test One-sided vs. two-sided	2	4	0	67	N	N	N	N	1	4	0	60
	Conduct of Test—During Test Cooldown before quench	6	0	0	100	N	N	N	N	4	2	0	83

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Quench tests, quench rate, Tquench, etc. (cont)	**Conduct of Test—During Test** **Clad temperature at time of quench**	**5**	**1**	**0**	**92**	**N**	**N**	**N**	**N**	**3**	**4**	**0**	**71**
	Conduct of Test—During Test Cycling of quenching	1	2	3	33	N	N	N	N	0	2	3	20
	Conduct of Test—During Test Temperature history	4	2	0	83	N	N	N	N	3	3	0	75
	Conduct of Test—During Test **Pre-thinning of cladding**	**4**	**2**	**0**	**83**	**N**	**N**	**N**	**N**	**1**	**5**	**0**	**58**
	Conduct of Test—During Test Quench mass flow rate	0	1	3	13	N	N	N	N	0	4	0	50
	Conduct of Test—Post-Test-Examination Equivalent cladding reacted (ECR) at location of failure	7	0	0	100	N	N	N	N	4	2	0	83
	Conduct of Test—Post-Test-Examination Metallography	6	0	0	100	N	N	N	N	3	2	0	80
	Conduct of Test—Post-Test-Examination **Fragment/non-fragment**	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**2**	**3**	**0**	**70**
	Conduct of Test—Post-Test-Examination Characterization of tubing integrity	3	5	0	69	N	N	N	N	2	3	0	70

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Phase equilibria and transformation kinetics-chemistry effects	Specimen selection: Hydrogen content and distribution	4	1	0	90	N	Y	N	Y	3	2	0	80
	Specimen Selection: **Alloy type**	**4**	**1**	**0**	**90**	**N**	**N**	**Y**	**N**	**2**	**3**	**0**	**70**
	Specimen Selection: Oxygen content	3	3	0	75	N	N	N	N	4	1	0	90
	Specimen Selection: Fluence	0	2	3	20	N	Y	N	N	2	3	0	70
	Determination of hydrogen and oxygen solubilities in α and β phases as a function of hydrogen, oxygen, and temperature for relevant alloys	**4**	**1**	**0**	**90**	**N**	**Y**	**N**	**Y**	**1**	**4**	**0**	**60**
	Determination of time constants for limiting mechanisms for phase transformation during heating as a function of hydrogen, heating rate and cooling rate	3	1	1	70	N	N	N	N	2	3	0	70
	Determination of diffusion coefficient of oxygen in individual phases	1	1	1	50	N	N	N	N	2	1	0	83
	Determination of the retained β and transformed β-phase morphology and oxygen plus hydrogen redistribution during **β - α transformations (cooling), including Niobium-rich alloys**	**2**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**2**	**0**	**50**

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Mechanical Properties at high temperature, e.g., ≥ 300 •C Creep, burst and uniaxial tests	Specimen Selection: Pre-existing oxide	1	2	1	50	N	N	N	N	4	0	0	100
	Specimen Selection: Alloy and initial thermo-mechanical treatment	5	1	0	92	N	Y	N	N	2	2	1	60
	Specimen Selection: Hydrogen content	2	4	0	67	N	Y	N	N	1	4	0	60
	Specimen Selection: Fluence (radiation damage)	1	1	3	30	N	N	N	N	3	2	0	80
	Conduct of Test-During Test Strain profile as a f(r, θ, z, t)	4	1	0	90	N	N	N	N	3	1	0	88
	Conduct of Test-During Test Pressure as f(t)	5	0	1	83	N	N	N	N	3	2	0	80
	Conduct of Test-During Test Temperature as f(t)	5	0	0	100	N	N	N	N	4	1	0	90
	Conduct of Test-During Test Temperature profile as f(θ) and f(z)	4	1	0	90	N	N	N	N	3	2	0	80
	Conduct of Test-During Test Open (actively pressurized) or closed	5	0	1	83	N	N	N	N	4	1	0	90
	Conduct of Test-During Test Biaxiality ratio	5	2	0	86	N	N	N	N	2	2	0	75

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

Subcategory	Phenomenon*	Importance[**]				Applicability[†,††]				Uncertainty[§,§§]			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
	Conduct of Test-During Test Load and displacements, i.e., σ and ε behavior	5	0	0	100	N	N	N	N	3	2	0	80
	Conduct of Test-During Test Strain rate	2	1	0	83	N	N	N	N	2	1	0	83
	Conduct of Test-During Test Circumferential (hoop)/axial (ring)	5	1	0	92	N	N	N	N	2	1	0	83
	Conduct of Test—Post-Test-Examination Post-test strain	8	0	1	89	N	N	N	N	3	2	0	80
Mechanical Properties at low temperature, e.g., ≤ 300 •C Post oxidation and quench ductility test	Test types (1) Axial tensile (2) Ring tensile (3) Ring compression (4) Impact (5) Bending Note: The question answered by the ranking-"Is it of H, M, or L importance which of the five tests is selected?"	4	1	1	75	N	N	N	N	1	3	0	63
	Specimen Selection: **Alloy type**	**4**	**0**	**0**	**100**	**N**	**Y**	**N**	**N**	**1**	**1**	**2**	**38**
	Specimen Selection: Thickness and morphology of pre-existing and transient oxides	3	1	0	88	N	N	N	N	3	0	1	75
	Specimen Selection: Burnup	2	1	1	63	N	N	N	N	2	1	1	63
	Specimen Selection: **Pre-existing and transient hydrogen content and distribution**	4	0	0	100	N	N	N	N	2	1	1	63
	Specimen Selection: **With or without ballooning**	4	0	0	100	N	N	N	N	1	2	0	67

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
	Conduct of Test—During Test Temperature	3	0	1	75	N	N	N	N	0	4	0	50
	Conduct of Test—During Test Strain rate (displacement ratio)	3	1	0	88	N	N	N	N	0	3	0	50
	Conduct of Test—During Test ASTM specification	2	1	0	83	N	N	N	N	1	3	0	63
	Conduct of Test—During Test Appropriate bending moment	4	0	0	100	N	N	N	N	1	3	0	63
	Conduct of Test—During Test Cycling	3	0	1	75	N	N	N	N	1	3	0	63
	Conduct of Test—Post-Test-Examination Characterize integrity	4	0	0	100	N	N	N	N	1	1	2	38
	Conduct of Test—Post-Test-Examination Characterize local hydrogen	4	0	0	100	N	N	N	Y	1	2	0	67
Simulation of fuel relocation	**Specimen Selection: Burnup**	4	0	0	100	Y	N	N	N	1	3	0	63
	Specimen Selection: Fuel type (MOX)	2	1	1	63	N	N	N	N	1	2	1	50
	Specimen Selection: Alloy type	2	2	1	60	N	N	N	N	2	1	1	63
	Specimen Selection: Chemical and mechanical bonding	4	0	0	100	N	N	N	N	0	3	1	38
	Specimen Selection: Cracking	2	0	2	50	N	N	N	N	1	3	0	63
	Conduct of Test—During Test With or without blowdown	0	1	2	17	N	N	N	N	0	1	2	17

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

Subcategory	Phenomenon*	Importance**				Applicability†,††				Uncertainty§,§§			
		H	M	L	IR	F	C	R	B	K	PK	UK	KR
Simulation of fuel relocation (cont)	Conduct of Test—During Test Blowdown temperature transients for fuel and cladding	2	0	1	67	N	N	N	N	1	2	0	67
	Conduct of Test—During Test Pre- and post-burst test phases (2)	1	3	0	63	N	N	N	N	1	3	0	63
	Conduct of Test—During Test **Internal pressure and moles of gas**	**3**	**1**	**0**	**88**	**N**	**N**	**N**	**N**	**0**	**4**	**0**	**50**
	Conduct of Test—During Test Flow induced vibration	0	2	2	25	N	N	N	N	0	2	1	33
	Conduct of Test—During Test Exterior rod constraints	1	1	2	38	Y	N	N	N	0	4	0	50
	Conduct of Test—During Test **Balloon size and burst size**	**4**	**0**	**1**	**80**	**N**	**N**	**N**	**N**	**1**	**2**	**0**	**67**
	Conduct of Test—During Test Length	2	1	1	63	N	N	N	N	1	3	0	63
	Conduct of Test—Post-Test-Examination **Granularity of dispersed material**	**3**	**1**	**0**	**88**	**N**	**N**	**N**	**N**	**0**	**4**	**0**	**50**
	Conduct of Test— **Post-Test-Examination** Thermography	1	0	2	33	N	N	N	N	0	2	1	33
	Conduct of Test—**Post-Test-Examination** Thermal diffusivity of rubble bed	1	1	1	50	N	N	N	N	0	2	1	33
	Conduct of Test—Post-Test-Examination **Strain profile of cladding as $f(\theta,z)$**	**3**	**1**	**0**	**88**	**N**	**N**	**N**	**N**	**1**	**3**	**0**	**63**
	Conduct of Test—**Post-Test-Examination** Burst size	3	0	1	75	N	N	N	N	2	2	0	75
	Conduct of Test—**Post-Test-Examination** Material balance (in-rod and dispersed)	2	0	2	50	N	N	N	N	1	2	1	50

TABLE 3-4. PWR AND BWR LOCA. CATEGORY D – SEPARATE EFFECT TESTING PIRT

[*] Descriptions for the phenomena listed in the Plant Transient Analysis PIRT are provided in Appendix D.

[**] The rationale for each High, Medium and Low rank are documented in Appendix D.

[†] The column numbers are related to the following issues related to extended applicability

F = Fuel array, i.e., 8x8 or 17x17 rods in a fuel assembly, chamfer, or MOX
C = Cladding types from various vendors, e.g., GE and Siemans, barrier-type or not.
R = Reactor type, e.g., B&W, CE, BWR/2 through /6.
B = Burnup to 75 GWd/t.

Data were received by ballot: "N" was entered if no one voted "Yes"; otherwise, the number of "Yes" votes was entered.

[††] The rationale for "Y" entries, meaning cases in which the importance ranking will be altered from the base case rankings in columns 3 through 5, are documented in Appendix D.

[§] The definitions for Known, Partially Known, and Unknown used by the panel are as follows.

K = Known; approximately 75%-100% of full knowledge and understanding
PK = Partially known; 25%-70% of full knowledge and understanding
UK = Unknown; approximately 0%-25% of full knowledge and understanding

[§§] The rationale for the assessment of uncertainty is found in Appendix D.

4. DATABASES

Although identification and ranking of processes and phenomena rely heavily on the expertise of the PIRT panel, both of these efforts proceed best when there are comprehensive databases of information upon which judgements are based. The experimental databases used by the PWR and BWR LOCA PIRT panel are documented in Section 4.1. More detailed descriptions of the experimental databases are provided in Appendix E. The analytical databases used by the panel are documented in Section 4.2. More detailed descriptions of the analytical databases are provided in Ref. 4-1, Appendix F. Additional information considered by the panel is presented in Section 4.3.

4.1. Experimental Databases

A variety of separate effect and integral experimental programs seeking a better understanding of the phenomena occurring in high burnup fuel during a PWR rod ejection accident have been conducted or are in the process of being conducted. That information was summarized in the PWR rod ejection report PIRT report.[4-1] Although some of the information therein may be of value, it is specific to PWR fuel, cladding and conditions. Additional tests with BWR fuel were summarized in the BWR ATWS PIRT report.[4-2] Test programs delivering data that is directly applicable to the PWR and BWR LOCA PIRT panel are summarized in this section and more detailed descriptions of these experimental programs are presented in Appendix E.

4.1.1. Separate Effect Tests

Separate effect tests are experiments in which a limited number of physical phenomena of interest occur, and detailed high-quality data are obtained under closely controlled conditions. Separate effect tests cover a spectrum of tests from the most fundamental, to those investigating interactions between phenomena and hardware in a specific region of a physical system.

In the following paragraphs, brief descriptions of the separate effect tests considered by the PWR and BWR LOCA PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

Cladding Tests (United States). Argonne National Laboratory (ANL) and the Pennsylvania State University (PSU) are working together on a program to investigate cladding properties at high burnups. Mechanical-properties testing is being done under both LOCA conditions and reactivity accident conditions. The objectives of the tests at relatively high temperatures and low strain rates appropriate for LOCA conditions are two-fold: to understand the degradation in cladding failure behavior at high burnup and to obtain stress-strain relationships that will serve as inputs to codes. A ring tensile specimen design has been developed and tested at ANL to generate tensile properties in the hoop direction. A related ring specimen design was developed and tested at PSU to provide a nearplane-strain stress state that approximates the stress state produced by expanding fuel pellets during a reactivity accident. Similar testing will be done on axial tensile specimens electromachined from de-fueled portions of irradiated fuel rods and from non-irradiated tubing specimens. These tests will be performed over the same temperature range (up to 1000 °C) and strain-rate range as the ring-stretch tests mentioned above. Low temperature mechanical property tests are also planned on pre-oxidized (post-quench) specimens. Oxidation kinetics and phase transformation characteristics are also being measured on high-burnup specimens. These tests are further described in Appendix E-1.

Cladding Mechanical Property Tests (Japan). Mechanical property tests for fuel cladding have been carried out at the Japan Atomic Energy Research Institute (JAERI) by applying different testing methods and specimen configurations according to the test objectives. Ring tensile, axial tensile, and tube burst tests have all been conducted. The most general and reliable method to quantitatively examine the mechanical property of materials is the uniaxial tensile test. Therefore, this method is used to examine the mechanical property changes arising with the temperature transients expected in LOCAs. The data will be used to evaluate results from thermal shock tests. Similar tests are planned with oxidized and hydrided specimens and high burnup specimens. The modified ring tensile test with machined specimens, currently under development at JAERI, may prove to be advantageous, e.g., specimen volume. These tests are further described in Appendix E-1.

LOCA Separate Effect Tests (France). Two types of separate tests programs have been carried out at Commissariat à l'Energie Atomique (CEA). The primary purpose of the EDGAR program and the TAGCIS-TAGCIR-HYDRAZIR-CINOG programs series is to evaluate the following separate phenomena which are supposed to occur together during a prototypical LOCA transient. The EDGAR program will examine phase transformations, cladding ballooning and rupture during the dry-out phase. The TAGCIS-TAGCIR-HYDRAZIR-CINOG program series will examine oxidation kinetics and thermal shock quenching behavior of different kind of cladding materials during the heating and cooling phases. After the quench phase, some of the samples are mechanically tested at low temperature (ring compression tests, bending tests or fracture toughness tests). These programs are further described in Appendix E-1.

4.1.2. Integral Tests

Integral tests for high burnup fuel are experiments which investigate behavior in the fuel rod exposed to conditions simulating the environment that would be experienced in a reactor core undergoing the given transient.

In the following paragraphs, brief descriptions of the integral tests considered by the PWR and BWR LOCA PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

LOCA Tests (United States). The primary purpose of these tests is to evaluate the performance of high burnup fuel relative to the NRC cladding embrittlement criteria defined in 10CFR50.46. Within the Argonne National Laboratory test plan, the LOCA integral tests will be conducted on fuel rod segments (300 mm long) with the as-irradiated cladding outside- and inside-diameter oxide layers and the fuel intact. In this way, the high burnup effects of the oxide layers, the associated hydrogen pickup due to waterside corrosion, and the fuel cladding contact and/or bonding will be present in the tests. As the planned tests with high burnup fueled cladding are first-of-a-kind relative to previous tests that have been conducted, there are other important responses that will be studied to resolve the effects of high burnup operation on LOCA-relevant phenomena. For some tests, the temperature rise is sufficient to cause the cladding to balloon and burst. These tests will provide data on the circumferential magnitude and axial extent of the ballooning, the geometry of the burst, possible fuel particle relocation to the ballooned and burst region, and the effects of these phenomena on the circumferential and axial temperature profile. To the extent practical, these phenomena will be observed, described and quantified. In terms of post-test analyses, the equivalent cladding reacted (ECR), the phase distribution and the hydrogen content will be measured in the ballooned-and-burst region and either in the thermal-quench-failed region (if different from the ballooned-and-burst region) or in a non-ballooned, non-burst, non-failed axial location for the tests in which thermal-shock failure does not occur. The ECR values based on data will be compared to the calculated ECR values to determine the degree of conservatism associated with the models. These tests are further described in Appendix E-2.

LOCA Tests (Japan). This test series investigates the behavior of high burnup fuel under LOCA conditions. Pre-hydrided, pre-oxidized, and irradiated claddings, as well as high burnup claddings, are tested. Oxide layer thickness, hydrogen content, and the circumferential increase by ballooning are measured in the post-test examination to characterize the cladding failure. Failure-bearing capability will be evaluated based on ECR values calculated both from oxidation temperature-time and measured oxide layer thickness. Tests have already been performed with artificially hydrided cladding (non-irradiated) to examine the separate effect of hydrogen absorption during operation. Test results indicate that the restriction of the cladding shrinkage during quench has a large influence on the failure boundary for the oxidized condition and an even stronger effect in pre-hydrided claddings. Preparation of high burnup cladding test specimens is now in progress. The tests with high burnup PWR fuel claddings (about 42 MWd/kgU) are to be started in 2002. These tests are further described in Appendix E-2.

BWR Transient Dryout and Rewet Tests (United States). The power oscillation instability and the LOCA have been identified as key events for the evaluation of fuel performance for a BWR. In an instability event the BWR will be at low flow for natural circulation and experience power oscillations. During these oscillations, the high power fuel bundles may undergo periodic boiling transition and rewet following each power pulse. As long as the peak cladding temperature remains below the minimum film boiling temperature, rewet will occur and excessive fuel heat-up is avoided. However, if the cladding temperature exceeds the minimum film boiling temperature [approximately 600 °C (1100 °F)] following a power pulse, the fuel may not rewet and substantial fuel heat-up can occur. The prediction of transient dryout and rewet is essential for the evaluation of the fuel performance for a power oscillation event. Additional information on the BWR transient dryout and rewet tests is provided in Appendix E-2.

Dryout Effects on High Burnup Fuel (Halden Reactor Project-Norway). The objective of the dry-out test series was to provide information on the consequences for fuel of short-term dry-out incidents in a BWR. The experimental method employed was to expose fuel rod with different burnups to single or multiple dry-out events; to follow this by either unloading or continued operation in the reactor; and to finish with post irradiation examination and testing with emphasis on fuel clad properties. Additional information on the test series is provided in Appendix E-2.

4.2. Analytical Databases

The experimental data derived from the programs described in the previous section are valuable in their own right because they provide insights into the basic physical processes occurring in a reactor should high burnup fuel undergo a LOCA. The data play an equally if not more important role when applied to the validation of physical models of high burnup fuel behavior. Once physical models are developed that include all the highly important processes and phenomena, incorporated in an integrated computer model, and validated, the resulting code can be used to predict the behavior of high burnup fuel in a reactor undergoing a LOCA.

The modeling features of three representative computer codes currently being developed, validated, and used to predict the behavior of high burnup fuel undergoing a reactivity transient were described in Appendix F of the PWR rod ejection PIRT report [4-1] and will not be repeated in this report. Each of the codes simulates the following aspects and their coupling: (1) fuel and clad mechanical behavior, (2) fission gas transient behavior, and (3) the thermal behavior of the system (fuel, gap, clad, and coolant).

The FRAPTRAN code is the NRC's single-rod fuel performance analysis program. It calculates the response of single-fuel rods to operational transients and hypothetical accidents. Features of the FRAPTRAN code are described in Ref. 4-1, Appendix G, Table G-2.

The FALCON code is a utility-sponsored finite-element-based best-estimate analysis program designed to compute the transient thermal and mechanical behavior of a light water reactor fuel rod during both normal and off-normal events. Features of the FALCON code are described in Ref. 4-1, Appendix G, Table G-1.

The SCANAIR code is an ISPN (France) thermal-mechanical analysis program for modeling the behavior of PWR irradiated fuel rod during fast power transients. Features of the SCANAIR code are described in Ref. 4-1, Appendix G, Table G-3.

The FRETA-B code[4-3] has also been used to analyze fuel behavior during LOCA events. The FRETA code analyzes LWR fuel behavior during accidents, particularly LOCAs. FRETA can be used to simultaneously model multiple fuel rods in a bundle, including the interactions between the individual fuel rods. The modeling feature of the FRETA-B computer code was not evaluated by the PIRT panel, as was the case with the previously discussed codes.

4.3 Additional Information

Additional information describing the thermal-hydraulic and neutronic processes and phenomena expected to occur in either a PWR or BWR during a LOCA was presented to the panel during the PIRT process. The information presented to the panel is found in Appendix I.

4.4. References

4-1. B. E. Boyack et al., "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6742 (September 2001).

4-2. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6743 (September 2001).

4-3. M. Uchida, "Application of a Two-Dimensional Ballooning Model to Out-Pile and In-Pile Simulation Experiments," *Nuclear Engineering and Design* 77, 37-47 (1984).

5. ADDITIONAL PANEL INSIGHTS

Through the course of the PWR and BWR LOCA PIRT activity, the panel developed important insights. These insights are briefly summarized in this section.

5.1. Technical Insights

1. Descriptions of three transient fuel rod analysis codes, FRAPTRAN, FALCON, and SCANAIR were provided to the PIRT panel at the time the PIRT for rod ejection accidents in PWRs containing high burnup fuel was being developed. The features and capabilities of each code were cross-correlated with a list of phenomena occurring in the fuel pellet, pellet-cladding gap, cladding, and coolant. The tabulated results provided an excellent yet concise overview of the modeling features of each code. These results are found in Ref. 5-1, Appendix F. Although the above codes were reviewed within the context of the PWR rod ejection accident, this information is thought to be of use when considering these codes for other applications.

2. Very little data exist about the state of fuel at burnups approaching 75 GWd/t. Consequently, the PIRT applies most directly to burnups of 62 GWd/t. The panel did assess the applicability of its phenomenon importance rankings at 75 GWd/t and this information is tabulated in each of the PIRT tables in Section 3. In addition, the panel also addressed the question of what additional information is needed to justify increasing the burnup limit from 62 to 75 GWd/t. This information is provided in Ref. 5-1, Appendix H. It should be noted that at the time the panel members responded, they were developing the PIRT for rod ejection accidents in PWRs containing high burnup fuel.

5.2. Procedural Insights

1. For a given PIRT effort, it is important that the phenomena list be defined and organized such that it benefits the users. For the present PIRT, the term phenomena was broadly defined to include phenomena, processes, conditions, properties, and code- and experiment-related factors in two code-focused categories and two experimental-focused categories. Although this definition was much broader than previous PIRT development efforts, it served the purpose of identifying and ranking items germane to the needs of the participants.

2. The most useful primary evaluation criteria were found to be those that are not only physically based but also are most closely and directly linked to the phenomena that have been identified and are being ranked. Hence, somewhat more conservative criteria related to fuel damage were used rather than loss of core coolability.

3. It was vitally important that the panel had clear and agreed-upon phenomena definitions in place before ranking discussions were held. Having access to commonly held definitions ensures that each individual panel member and the collective panel is assessing importance from a common foundation. These definitions are given in Appendices A through D.

4. The panel reached a common understanding of the rationale to be used in assessing importance before proceeding with the ranking effort. These rationales are given in Appendices A through D.

5. Various phenomena are linked in a cause-effect relationship. The question arose whether a panel should consider the importance of each phenomenon individually or within the concept of linkages. The panel decided that the best approach was to treat each phenomenon individually.

6. Consideration of experimental data, if available, was highly desirable. The value of this exposure is enhanced if presented by those with a high level of technical expertise related to the data. Therefore, expert tutorials were presented to the panel and these tutorials are given in Appendix I.

7. Consideration of code-calculated results, if available, was also highly desirable, assuming that the adequacy, limitations, and applicability of the code were also presented. The value of this exposure is enhanced if presented by those with a high level of technical expertise related to the code, code-calculated results, and adequacy and applicability of the code. Such presentations were included in the tutorials.

8. As various rationales were recorded, significantly different and contradictory rationales were sometimes expressed. These differences were not immediately explored due to time constraints. However, for those phenomena that became candidates for significant expenditures of effort or resources, these differing viewpoints were revisited.

9. Written ballots are a less-effective means of collecting information from panel members than real-time voting at panel meetings. The reason is that panel members do not have the benefit of hearing and addressing as a group the logical basis for each issue. Therefore, most of the voting was done during panel meetings.

10. The recording and extraction of rationales from the meeting transcript proved to be a workable but difficult procedure. The oral rationales were often provided as urged by the meeting facilitator in response to an effort to complete agenda items. Because of the size of the PIRT panel, insufficient time was spent developing a better joint understanding of a number of the stated rationales.

11. Breakout groups proved to be an effective approach to improving the PIRT findings. The breakout groups were smaller and consisted of panel members having expertise in the portions of the document being reviewed. The smaller groups provided the panel members a better forum for expressing their opinions. The use of breakout (working) groups on subsequent large-panel PIRT efforts is highly recommended.

12. A refinement of the PIRT process by which the panel explicitly addresses the frequency of occurrence of a particular phenomenon is needed. On occasion, the panel knew that a particular process or phenomenon was highly unlikely. This knowledge appears to have been reflected in the importance vote on occasion.

5.3. References

5-1. B. E. Boyack et al., "Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6742 (September 2001).

APPENDIX A

CATEGORY A
PLANT TRANSIENT ANALYSIS

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-1, Plant Transient Analysis PIRT. Entries in the Table A-1, columns 1 and 2, follow the same order as in Table 3-1. Table A-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table C-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-1.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered.

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gap size	Distance between pellet outside and inside clad diameters. H(7) Affects the rate of energy release from the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): There is a lot of in-pile data available and the data reveals that the gap is closed or nearly closed for high burnup. PK(0): No votes UK(0): No votes
Initial conditions	Gas pressure	Pressure of the gas in the rod. H(7) Sets the initial conditions for response of the cladding and can affect clad conductance. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Cumulative fission gas release is not well known. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas composition	Composition of the gas in the rod (mole fractions of the fill and fission gas components). H(1) Affects gap heat transfer coefficient and heat release from fuel. M(6) Solid contact is majority of gap conductance. L(0) No votes Fuel: Y No rationale provided. Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in composition at higher burnup. UK(0): No votes
Initial conditions	Pellet and cladding dimensions	Characteristic physical dimensions, as a function of burnup. H(0) No votes M(7) Assumes that we have separated the pellet and clad dimensions from the gap and the dimensions are well known. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Design values are well controlled and can be predicted with acceptable accuracy. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Burnup distribution	Radial and axial burnup magnitude and distribution in the core. H(7) Determines the power distribution and fuel conditions at initiation of the accident. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from the calculations during the fuel cycle. PK(0): No votes UK(0): No votes
Initial conditions	Cladding oxidation (ID & OD)	The amount of prior zirconium oxide on both the inside and outside cladding surfaces. H(0) No votes M(0) No votes L(7) Does not affect the overall system response. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in the amount and structure of the oxide at high burnup. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Coolant conditions	Thermal-hydraulic conditions in the core including pressure, temperature, quality, void fraction, and mass flow rate. H(7) Has a significant impact on determining the outcome of the transient. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known and characterized for a plant. PK(0): No votes UK(0): No votes
Initial conditions	Rod free volume	The plenum and other free volumes within the fuel rod occupied by the gas. H(7) Can affect fuel rod burst and blockage as well as the timing of the blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Larger scatter in the data reflecting the effect of cracks opening in the pellet. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas communication (full)	The ability of the gas in the free volume to move axially within the fuel rods, thereby providing uniform gas pressure. H(0) No votes M(2) No communication would lead to very high local pressures. L(5) Time scale of accident is sufficient long to allow communication. Fuel: N Clad: N Reactor: N Burnup: Y – higher burnup can cause fuel-clad bonding which could decrease resistance to heat transfer. K(0): No votes PK(7): Large uncertainty, but some data are available. UK(0): No votes
Initial conditions	Gadolinium distribution (conductivity effect)	The spatial distribution of gadolinium within the core, which affects the thermal conductivity of the fuel rods. H(0) No votes M(0) No votes L(7) Small effect on conductivity, which has a smaller effect on system response. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known accurately from calculations. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial stored energy-fuel	The total energy content of the fuel rods at initial power conditions before the LOCA. H(7) Determines fluid conditions that lead to the peak cladding temperature during blowdown; also affects reflood. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from calculations. PK(0): No votes UK(0): No votes
Initial conditions	Initial stored energy-structures	The total energy content of structures within the vessel at initial power conditions before the LOCA. H(7) Can affect the heat release to the coolant, particularly for small LOCA and large LOCA at low pressure. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from plant calculations. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial core pressure drop (grids)	The initial axially varying pressure within the core. H(0) No votes M(0) No votes L(7) Does not have a significant effect on the transient as an initial condition. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from data. PK(0): No votes UK(0): No votes
Initial conditions	Pellet radial power distribution	The radial distribution of the power produced in the fuel rods. H(0) No votes M(0) No votes L(7) Distribution of energy within fuel is not important; amount of energy is important. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from calculations for fuel pins. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Rod axial power distribution	The magnitude and axial distribution of the power produced in the fuel rod. H(7) Has a significant impact on the peak cladding temperature as it affects the location of the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from plant analysis calculations. PK(0): No votes UK(0): No votes
Initial conditions	Fuel assembly peaking factors	A fuel assembly's power compared to the core average (radial peaking factor). H(7) Has significant effect on peak cladding temperature, and allowable KW/foot determines the hot assembly average rod. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Design parameter is well known. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pin peaking factors Note: for codes in which the detached rod model is combined with the thermal-hydraulic code, e.g., BWR TRAC, this factor is more important.	Pin power distribution within an assembly. H(0) No votes M(1) Important for rod-to-rod radiation for BWR. L(6) Not important for hydraulic calculation for the system. Fuel: N Clad: N Reactor: Y – ranked higher for BWRs. Burnup: N K(7): Design parameter is well known. PK(0): No votes UK(0): No votes
Initial conditions	Fuel cycle design	H(7) Determines the reactor power distribution and burnup. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): This is a result of the design process and well known; it can be accurately calculated given the plant state. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Moderator feedback	Reactivity feedback from moderator density and density changes in active channels. These changes are a result of direct deposition to the coolant and heat transfer from the cladding. H(7) Shuts down the plant due to voids for LBLOCAs in PWRs and BWRs. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Can be accurately calculated given the plant state. PK(0): No votes UK(0): No votes
Transient power distribution	Decay heat power	The power produced due to decay reactions of actinides and fission products. H(7) This is the significant heat source to be considered because 97-99% of the energy is deposited in the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Accurately known from tests. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Fuel temperature feedback	Reactivity feedback from fuel temperature changes. This effect results from the heating of the fuel and associated neutronic effects, in particular the Doppler effect, and heat transfer from the fuel rod cladding. H(0) No votes M(0) No votes L(7) Not significant as compared to the void coefficient, which shuts down the plant. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known well from temperature distribution. PK(0): No votes UK(0): No votes
Transient power distribution	Delayed neutron fraction	The fraction of fission neutrons that are not emitted instantaneously, designated beta (β). H(0) No votes M(0) No votes L(7) Not a significant contributor to core power for a LOCA. Fuel: N Clad: N Reactor: N Burnup: N K(7): Known from core physics. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient power distribution	Fractional energy deposition in moderator and structures	The fraction of total fission and decay energy that is deposited directly in the coolant and the structures. H(0) No votes M(0) No votes L(7) Very small fraction (1% - 2.6%) is deposited outside of the fuel in other structures. Fuel: N Clad: N Reactor: Y – a BWR has more structures and thus, the phenomenon could be more important. Burnup: N K(7): Can be accurately calculated. PK(0): No votes UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Single phase convection	Heat transfer from fuel outer surface to adjacent single-phase liquid or vapor. H(7) Primary heat transfer mode for small-break LOCA and also for large-break LOCA for dispersed flow film boiling. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known, ample data. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Subcooled boiling, nucleate boiling, bulk boiling, and forced convection vaporization	Heat transfer to adjacent liquid resulting in the formation of vapor at nucleation sites on the cladding surface or in the bulk liquid. H(7) Significant heat transfer mechanism for covered regions for small breaks in BWRs as well as during a PWR reflood. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Well known, ample data. PK(0): No votes UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Critical heat flux/dryout	The heat flux that causes vaporization sufficient to prevent liquid from arriving at the heated surface. H(7) Affects the timing of DNB/dryout and the resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: Y – Fuel-assembly design-type dependent. Clad: N Reactor: N Burnup: N K(7): Well known, can predict with sufficient accuracy. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Film boiling over a wide void fraction (inverted annular, dispersed flow)	Heat transfer from the cladding outer surface through an adjacent vapor film to the liquid at a rate sufficient to prevent direct liquid to cladding contact. H(7) This is the regime in which the peak cladding temperature occurs. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): No fundamental models exist and there is a lot of scatter in the data. UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Radiation heat transfer to coolant	Radiative thermal energy transport to the surrounding vapor/liquid environment. H(0) No votes M(0) No votes L(7) Not a significant effect for the transient analysis calculations. Fuel: N Clad: N Reactor: N Burnup: N K(7): This is a well-known phenomenon. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Rewet	Heat transfer occurring from liquid contact with the cladding surface after dryout; occurs when the surface temperature has decreased to the minimum film boiling point. H(7) Determines the boundary conditions for either good or bad cooling. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Large uncertainty in the models that exist. All models will predict rewet, but the timing could be off significantly. The uncertainty is toward the lower end of the PK range. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Rod to spacer-grid thermal-hydraulic interaction	The enhanced convective heat transfer effects downstream of the spacer grids due to mixing and flow redistribution for single- or two-phase flows. H(6) Can significantly affect peak cladding temperature, ballooning shape, and distribution. M(1) Lower order effect compared to the more dominant heat transfer modes. L(0) No votes Fuel: Y – Fuel assembly type dependent. Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Lots of scatter in data; no really good models, the uncertainty is towards the lower end of the PK range. UK(0): No votes
Steady state and transient cladding to coolant heat transfer (blowdown, refill, reflood, and core spray heat transfer)	Spacer grid rewetting and droplet breakup	The wetting of spacer grids, which enhances the interfacial heat transfer at and downstream of the spacer grids. H(7) Has a significant effect on the vapor temperature, which directly affects the peak cladding temperature. M(0) No votes L(0) No votes Fuel: Y – Fuel assembly design directly affects this phenomenon. Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(7): Insufficient data to develop models to predict phenomenon.

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Temperature	Temperatures of the gas and liquid phases of coolant flowing along the fuel rod. H(7) Determines the local heat transfer coefficient sink temperature and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): For two-phase conditions, the degree of non-equilibrium is not well known. UK(0): No votes
Transient coolant conditions as a function of elevation and time	Flow rate/directions (CCFL)	Flow rate and direction of gas and liquid phases flowing along the fuel rod (including crossflow and counter current flow limiting effects). H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Quality	The mass flow fraction of steam (gas) in the two-phase mixture flowing along the fuel rod. H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes
Transient coolant conditions as a function of elevation and time	Void fraction	The volume fraction of steam (gas) in the two-phase mixture. H(7) Determines the local heat transfer and resulting peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): Accurate predictions of the local two-phase flow behavior is difficult. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Pressure	The absolute total pressure in the coolant channel along the rod. H(7) Affects the coolant properties, which in turn determine the heat transfer, emergency core cooling flows, high-pressure safety injection, etc. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Effects are well known. PK(0): No votes UK(0): No votes
Transient coolant conditions as a function of elevation and time	Partial vapor pressure	The partial steam pressure in the coolant channel along the rod. H(0) No votes M(0) No votes L(7) Not expected to be an important phenomenon in the core. Fuel: N Clad: N Reactor: N Burnup: N K(7): Assumes that non-condensable concentrations in the coolant due to fuel failure are known. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient coolant conditions as a function of elevation and time	Cross flow effects due to flow blockage	The extent to which axial flow along the rod is diverted from the associated fuel subchannel due to pressure gradients and deformation of the rods. H(7) Affects the flow in the hot assembly, which directly impacts the calculated peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(7): At the low end of PK due to the limited amount of data available. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	Irreversible changes in cladding dimensions caused by pressure differentials or mechanical loadings at high temperatures. If cladding burst occurs, the final plastic deformation at the burst location is characterized by the burst strain. H(5) This model is needed to predict the flow blockage. M(0) No votes L(0) No votes Fuel: N Clad: Y – Model needs to be specific to the cladding type. Reactor: N Burnup: N K(5): A large amount of data and modeling experience exists to support this vote. Material model is affected by high burnup but this is addressed as a separate item. PK(0): No votes UK(0): No votes
Fuel rod response	Direct gas pressure loading	The combination of available fission gas combined with the fill gas in determining an internal pressurization. H(5) This defines the loading mechanism that drives the cladding deformation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Based upon the validity of the perfect gas law used in the system code. PK(2): Large uncertainty in the prediction of gas release for a given burnup. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Thermal deformation of pellet and cladding	Reversible changes in pellet and cladding dimensions caused by thermal expansion. H(0) No votes M(0) No votes L(5) This is a second order effect. Fuel: N Clad: N Reactor: N Burnup: N K(5): Easy to calculate accurately. PK(0): No votes UK(0): No votes
Fuel rod response	Elastic deformation of cladding	Reversible changes in cladding dimensions caused by pressure differentials or mechanical loadings. H(0) No votes M(3) This calculation determines the initial conditions for a plastic deformation calculation. L(2) Second order effect compared to the plastic deformation. Fuel: N Clad: N Reactor: N Burnup: N K(5): Easy to calculate accurately; textbook basis. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Heat resistances in fuel, gap, cladding, and oxide	The resistances offered by the fuel, gap, and cladding to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) This governs the thermal response that determines the energy release to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Modeling method is well known. PK(1): Large scatter in data; depends on power history, pellet cracking, etc. UK(0): No votes
Fuel rod response	Axial and radial temperature distributions	Axial and radial temperature distributions, as used to determine pellet properties and gas temperatures. H(5) This determines the heat from the fuel to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): No rationale recorded. PK(1): Depends on model and associated accuracy. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Metal-water reaction heat addition	The additional heat generated in the cladding due to metal-water reactions. H(0) No votes M(1) Depends on temperature level. L(5) The heat addition to the system calculation due to metal-water reaction is a very small component of the total heat transport. Fuel: N Clad: N Reactor: N Burnup: N K(5): Available models are sufficiently accurate. PK(0): No votes UK(0): No votes
Fuel rod response	Cladding oxidation magnitude (ID/OD)	Thickness of oxide layers on inner and outer surfaces of cladding. H(0) No votes M(0) No votes L(5) Not important for a system code. Fuel: N Clad: N Reactor: N Burnup: N K(4): This can be calculated with adequate accuracy. PK(1): Temperature is not calculated with adequate accuracy. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding temperature	The cladding thermal state (temperature) as used in determining cladding properties and leading to cladding deformation. H(5) Significant for determining key response such as flow blockage and heat flow to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Assuming that plant and boundary conditions are known, we can calculate cladding temperature to within 30%. PK(2): Boundary conditions are not well known. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Burst criteria	Combinations of physical parameters, which are expected to cause cladding, burst. For example, NUREG-0630 correlates burst temperature as a function of engineering hoop stress and heatup rate. H(5) Can be the source of substantial flow blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Outdated data; correlations require signification improvement, particularly at high burnup where the hydrogen dependency must be better characterized. UK(0): No votes

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding phase changes	Change in the cladding microstructure from alpha phase (low temperature) to the alpha + beta phase, to beta phase (high temperature). The phase change energy of transformation can effectively increase the cladding specific heat over the transition temperature range. The phase change affects ductility resulting in significant effects of plastic deformation (creep rate and burst). Changes in cladding alloy or hydrogen content affect the transition temperature changes. H(0) No votes M(4) Affects the thermal/mechanical properties. L(1) Second-order element. Fuel: N Clad: N Reactor: N Burnup: N K(5): Phase changes are well known. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time of burst	The amount of time elapsed between initiation of the LOCA and the predicted cladding burst. H(1) Burst time directly affects peak cladding temperature. M(4) Causes significant flow blockages. L(1) Second order effect. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Factors influencing or determining the time of burst are not well known. UK(0): No votes
Fuel rod response	Location of burst and blockage	The axial position at which cladding burst and flow blockage occur. H(5) Supplies the boundary conditions for the rod calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Given the power shape, the location can be determined with adequate accuracy. PK(2): Some factors in determining the location have uncertainties. Grid effects affect burst location and the amount of blockage. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fuel relocation	Movement of pellet fragments into a region where cladding plastic deformation (ballooning or burst) has occurred. Fuel relocation changes the local linear heat rate and affects gap conductance and fuel thermal resistance. H(0) No votes M(2) Could have an impact on the parameters to be calculated (low medium stated) L(4) Small local effect on system analysis. Could make the calculation burst node limiting. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(5): Limited data available.

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time dependent gap-size heat transfer	The gap size is a result of plastic, thermal, and elastic deformation. The heat transfer across the gap is a function of gap size, conductance of the gas mixture, and the temperatures of the pellet outside diameter and cladding inside diameter (radiative heat transfer).; H(5) Primary heat transfer path for transporting heat from the fuel to the coolant. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(1): Approach to calculation of gap conductance is well known, given the input parameters. PK(5): Overall heat transfer coefficient for gap is well known but the gap size is not well known. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Thermal and mechanical properties of pellet and cladding	The thermal and mechanical properties of the pellet and cladding, e.g., heat capacity, conductivity, yield stress, and creep, are needed to calculate the temperature and deformation response of the fuel rod. H(5) Governs the thermal and mechanical response of the pellet and cladding. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): A large database exists but there are incomplete data at higher burnup and temperature ranges. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod mechanical effects	Rod-to-rod mechanical interactions	Interaction between two or more rods, including guide tubes, water rods, and channels. Occurs when one or all rods are deformed due to swelling or bowing, including mechanical contact and conduction heat transfer., such that the rods are in physical contact. H(0) No votes M(1) Depends on the number of rods, how close they are, and if they can cause local blockage. L(4) Local effect has a secondary impact on system transient. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(4): No rationale recorded.
Multiple rod mechanical effects	Rod bow between spacer grids	Bowing of a fuel rod due to axially constrained thermal expansion. H(0) No votes M(0) No votes L(4) Local effect; not important for system response. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(0): No votes UK(4): No rationale recorded.

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-rod radiative heat transfer	Thermal radiation heat transfer between fuel rods. H(0) No votes M(0) No votes L(4) Important for hot-rod but not for system performance. Fuel: N Clad: N Reactor: Y – This is a dominant phenomenon for BWR bundle temperature calculations. Burnup: N K(4): Given the temperature distribution, the radiation heat transfer is well known. PK(0): No votes UK(0): No votes
Multiple rod thermal effects	Rod-to-channel box radiative heat transfer	Thermal radiation heat transfer between a fuel rod and the channel box in a BWR. H(4) Very important heat transfer mechanism for determining the MAPHGR limit in BWRs M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: NA Burnup: N K(4): Given the temperature distribution, the radiation heat transfer is well known. PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-spacer grid local heat transfer	Heat transfer between a fuel rod and a spacer grid due to thermal radiation and conduction heat transfer. H(1) Directly affects heat transfer on the cladding, which determines the blockage location and the degree of co-planar blockage. M(4) Grid affects rewet of fuel rod; contributes to heat transport from fuel. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(4): Working group participants stated "Data is available to indicate the temperature during LOCA conditions." During the document review, a panel member commented that this data is not available. UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-guide tube radiative heat transfer	Thermal radiation heat transfer between a fuel rod and a guide tube (PWR). H(0) No votes M(0) No votes L(4) Local effect; more important for hot rod peak cladding temperature calculation. Fuel: N Clad: N Reactor: NA Burnup: N K(4): Working group participants stated "Data is available to indicate the temperature during LOCA conditions." During the document review, a panel member commented that this data is not available. PK(1): Guide tubes are usually not modeled. UK(0): No votes
Multiple rod thermal effects	Rod-to-water rod radiative heat transfer	Thermal radiation heat transfer between a fuel rod and a water rod (BWR). H(4) Important heat sink during spray cooling; more important for hot rod peak cladding temperature calculation. M(1) Second order effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data is available to indicate the temperature during LOCA conditions." PK(0): No votes UK(0): No votes

Table A-1. PWR and BWR LOCA. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod thermal effects	Rod-to-inner channel radiative heat transfer	Thermal radiation heat transfer between a fuel rod and the inner channel box (BWR). H(4) Important heat sink during spray cooling; more important for hot rod peak cladding temperature calculation. M(1) Second order effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data is available to indicate the temperature during LOCA conditions." PK(0): No votes UK(0): No votes

APPENDIX B

CATEGORY B
INTEGRAL TESTING

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-2, Integral Testing PIRT. Entries in the Table B-1, columns 1 and 2, follow the same order as in Table 3-2. Tables B-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table B-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-2.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered

There were several phenomena for which no importance rank was recorded. In such cases "No rationale recorded" is entered.

Table B-1. PWR and BWR LOCA. Category B – Integral Testing

Subcategory	Phenomena		Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel	Burnup	Amount of nuclear fuel that has been consumed in fuel pellets used in the test article in, for instance, GWd/t. H(5) This is the focus of the test and a high burnup rod should be selected so as to facilitate discovery of phenomena not yet recognized and so that unknown effects are not overlooked. Fuel morphology (fragmentation, rim characteristics, bonding, etc.) is important. M(1) Burnup is not important per se, but individual physical effects such as oxidation or rod internal pressure are important. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena		Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel	PU agglomerates (MOX fuel only)	For the selected fuel rod containing MOX, the degree and type of agglomerates (clusters) of plutonium should be characterized, e.g., agglomerate size. H(1) May affect the amount of fine grain material after relocation M(0) No votes L(6) The presence of agglomerates are not considered to be important to LOCA outcome. Fuel: NA Clad: N Reactor: N Burnup: N K(6): Judgement PK(0): No votes UK(1): Judgement
Fuel rod selection	Fuel	Duty cycle	For the selected fuel rod, the history of burnup accumulation should be known. H(0) No votes M(4) Operating history sets many parameters that can influence test results. May affect the fuel cracking and the cladding corrosion and hydrogen pickup. L(3) There is no unique duty and all must be covered in order to determine the rupture strain results. Fuel: N Clad: N Reactor: N Burnup: N K(4): Code, data PK(3): Code, data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena		Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel	type (absorbers, additives)	Some fuel vendors have different kinds of burnable absorbers in the rod. Various absorbers and additives should be considered when selecting fuel rods for refabrication followed by testing. H(0) No votes M(3) Additives may cause an attack on the cladding that could have unknown effects on the experimental results. Gadolinium may affect rim size. L(4) There is no evidence that possible impacts exist. Fuel: NA Clad: N Reactor: N Burnup: N K(0): No votes PK(4): Data, Judgement UK(2): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Pre-existing oxidation (thickness, type, uniformity f[θ])	Extent and characteristics of pre-existing clad oxidation. H(2) High levels of oxidation indicates hydrogen in the metal and a different morphology. The rate of high temperature oxidation will be affected by these. Also remaining nonoxidized material is affected. M(4) No barrier effect was observed in the French tests nor, possibly, in the Japanese tests. Azimuthal changes may occur. Oxidation characteristics are less important than associated hydrogen pickup. However, nonprototypical fabrication conditions may artificially enhance its impact. For example, oxide layer produced under gaseous mixture of noble gas and steam is dense and protective, while oxide layer produced under irradiation is defective and not protective). L(1) To date sufficient French and Japanese testing has been completed to show that this phenomenon is not important. Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Spalling	Peeling of the oxide layer (high or low amounts) from the cladding leaving the underlying material exposed to the coolant. Can lead to a local cold spot and hydride blister formation H(0) No votes M(3) The clad under a spalled region is of questionable quality because there is less protection to the cladding under a spalled region. May affect azimuthal burst due to hydrogen content. However, after alpha to beta transformation, hydrogen will be in solution in the beta phase. L(4) The amount of spalled material is small and hydrogen blisters will dissolve. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK(5): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Total hydrogen	Total amount of hydrogen in the cladding. H(3) When solubility of oxygen in the beta phase of zirconium is high, the ability of the cladding to handle loads is diminished. The microstructure of the beta phase and its brittleness is affected. Affects burst (alpha to beta phase transformation), oxygen solubility in the beta phase, and post-quench ductility. M(4) Available information suggests hydrogen is not affecting quench behavior but may effect post quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data (Japanese and French testing) PK(3): Data, Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Hydrogen distribution	Spatial distribution of the hydrogen, including local hydride formations in the cladding (hydride rim) and including hydride blisters. H(0) No votes M(1) May affect burst (alpha to beta transformation). However, after this transformation, hydrogen will be in solution in the beta phase. L(5) The preexisting hydrogen distribution will be erased by the temperature excursion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, judgement PK(1): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Surface conditions (crud)	The presence of nodular corrosion, delamination, crud, scratches, and other irregularities. H(0) No votes M(1) May affect thermal-hydraulic behavior. During the document review process, a panel member commented that T_{min} will be affected. L(5) Crud is not a significant factor in heat transfer and may have a small effect on swelling and rupture. A rod with representative surface conditions should be tested. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, calculations, judgement PK(1): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Fluence/radiation damage	Material damage caused by the time-integrated particle flux to which the cladding is exposed (Energy > 1.0 Mev, i.e., fast fluence). H(0) No votes M(1) At 62 GWd/t, the major factor is hydrogen pickup. The important at 75 GWd/t is uncertain. L(5) All radiation damage is annealed out during the temperature excursion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data, calculations, judgement PK(1): Data, judgement UK(0): No votes
Fuel rod selection	Cladding: Initial residual deformation (hourglass, creepdown)	Dimension condition after irradiation. H(0) No votes M(2) Uncertainty exists about the effects on ballooning and burst of cladding and gas communication (includes combined fuel and cladding effects). L(4) Residual stresses are annealed out during the transient. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Data, calculations UK(1): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: Chemical bonding	Bonding (adhesion) between fuel and cladding at high burnup H(1) May affect burst and timing of relocation. M(4) When the bond is strong, there may be an effect on ballooning and burst, clad temperature at burst, and thermal shock resistance. L(1) Cracking during cool down reduces the effect. Fuel: Y (1): MOX Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Judgement UK(1): Judgement
Fuel rod selection	Cladding: As fabricated wall thickness	Self defined. H(3) The thinner the initial wall thickness, the thinner the ligament after reactor exposure and the thinner the beta phase, as shown by the JAERI data. May have a different stress. M(1) Although there may be a difference in behavior, there may not be an impact relative to the 17% oxidation criterion. L(0) No votes Fuel: N Clad: Y Reactor: N Burnup: N K(2): Data (Japanese), judgement PK(2): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding Alloy type: Alloy composition Microstructure/2nd phase particle Initial cold work Liner/nonliner clad	Characteristics of a candidate cladding alloy to be considered and documented during the selection process, given the same oxidation characteristics. H(2) Swelling and rupture results for claddings differ for nonirradiated claddings. If the annealing effect is valid, this should hold for irradiated claddings as well. May affect burst (beta-favoring and alpha-favoring additions) and also oxygen distribution and hydrogen pickup. M(4) There could be differences in behavior (swelling and rupture, oxidation rates, quench behavior and alpha to beta transformation) but these are likely to be small. L(1) Low impact on high temperature oxidation rate. No need for specific integral tests. Issues addressed through separate effect tests. Fuel: N Clad: NA Reactor: N Burnup: N K(0): No votes PK(4): Data UK(2): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Plateau temperature (plus variations)	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The plateau temperature corresponds to period (2) as defined above. H(7) Solubility of the oxide in the beta phase increases susceptibility to brittle fracture. Consideration should be given to verifying that high temperature is not the worst case (see BAW-10277). In-reactor LOCA transient may exhibit a first thermal peak that may anneal the cladding and affect the clad strain and burst behavior. May affect oxygen distribution and hydrogen pickup. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(3): Data, calculations PK(4): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Temperature ramp	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The temperature ramp corresponds to period (1) as defined above. H(3) Ramp will create different effects on phase change kinetics and other issues. Creep depends on the time-temperature history. Affects burst. M4) Ramp rates between 2 and 50 °C/s do not significantly affect strain results and will not affect oxidation. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Time at temperature	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. This phenomenon is the time from the start to the end of phase 3. H7) Controls the amount of oxidation M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Cooldown/quench/rewet rate initiation: (Clad temperature level, mass flow rate, pump or gravity feed, quality, subcooling)	A LOCA simulation will consist of a time versus temperature profile which consists of (1) an initial heatup period, (2) a period during which the temperature will be nearly constant, (3) a period of relatively slow cooling, and (4) a quench. The cooldown/quench/rewet rate initiation corresponds to periods (3) and (4) as defined above. H(6) Transformation structure and the properties of the transform material depend on cooling rate. A representative cooling rate should be used. H. Chung has shown that slow cooled specimens exhibit higher quench and impact resistances than fast cooled specimens. M(1) Same as the rationale for high but the impact is not large. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): Data PK(5): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Plenum volume	A volume incorporated into the test article to be representative of internal pressure, amount of gases available, accommodate fuel expansion, and avoid end-effect. H(1) Provides the driving force for ballooning, burst, and partly for relocation. M(5) Poor plenum design can affect outcome, e.g., internal pressure and ballooning, but these may not affect quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data, judgement PK(1): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Internal pressure	The total pressure in the test specimen gap at the start of in-reactor testing resulting from the introduction of the fill gas at the time the test specimen was prepared. H(3) The pressure should be representative of the LOCA if the test is to be prototypical. Provides the driving force for ballooning, burst, and partly for relocation. M(3) The gas pressure should be representative of the transient but its impact is moderate. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data, judgement PK(3): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Attachments	Any item, e.g., instrumentation, affixed to the test article. H(1) The potential for affecting the outcome of the test is high so care must be taken to properly design and utilize attachments. M(6) The risk of artificial behavior is high for swelling and rupture but it is unlikely that there will be any effect on oxidation. Impact to be reduced as much as possible by adequate technology. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Data, judgement UK(0): No votes
Conduct of test	Temperature measurement	Self defined H(7) The temperature is needed to draw conclusions from the test and to correlate results, e.g., amount of oxidation and embrittlement. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Gas composition	The composition of the gas in the gap and the plenum resulting from the introduction of the fill gas at the time the test specimen was prepared. H(0) No votes M(1) For in pile tests, the impact is believed to be small. L(6) There is no interaction with gas composition; second order parameter. Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Design test such that axial and azimuthal temperature gradients are known	Instrumentation would be provided to measure the temperature variation around the circumference of the test fuel rod at one or more axial levels. H3) Impact on burst strain is significant and is needed if the results are to be adequately understood. M(4) This is very difficult to do. There will be multiple gradients. The impact on ECR will not be large. Affects burst in single fresh rod experiments with cold shroud; importance is reduced in experiments with heated shroud or in bundle experiments and also at low burnups. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Data, judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Single rod versus bundle	The phenomenon is best expressed as a question, namely, is it possible to characterize the needed phenomena in a single rod test article or is it necessary to conduct some testing in a bundle? High votes mean that a bundle test is needed while Low means a single rod tests will suffice. The evaluation is based on the effect of high burnup considering the availability of single rod to bundle tests at low burnup. H(1) Some bundle testing is necessary for: (1) providing prototypical azimuthal temperature gradients, (2) providing radial constraints on ballooning development, and (3) avoiding non-prototypical fuel fragment escape from the balloon. M(3) A lot unknown interactions occur between rods, rods limit the strains of other rods. It would be well if they were better understood. L(3) Bundle effects can arise but it is not clear how large these effects are. This should be addressed in other types of experiments that can include rod bow. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Data. judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Fuel/nonfuel	The importance of having fuel in the cladding (fuel) or being able to test absent the fuel in the cladding (nonfuel). H(7) Data from fueled rods will provide information on bonding and bowing of high burnup fuel. Fuel is important because it can determine the azimuthal temperature gradient in the cladding. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): Data, judgement PK5): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Water chemistry	The chemical characteristics of the coolant used in the test are to be well characterized, e.g., oxygen potential is to be known. H(0) No votes M(6) Deviation within a range of water chemistries will not be that significant or cause significant effects. L(1) Test data confirms that there is very little difference in results over a reasonable range of water conditions. Fuel: N Clad: N Reactor: N Burnup: N K(7): Data PK(0): No votes UK(0): No votes
Conduct of test	Coolant flow conditions	Pressure, temperature, flow rate, quality, etc. H(0) No votes M(3) Coolability affects the clad temperature, which affects strain, location and timing. The oxide is not affected. L(4) Flow affects clad temperature and that will be measured. Fuel: N Clad: N Reactor: N Burnup: N K(6): Data PK(1): Data UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Heating source (internal or external, type, electrical, radiant, neutronic)	Heating will vary depending upon test type. This phenomenon focuses on the nature of the heating and its prototypicality with the intent of determining the degree to which the heating method is prototypical or nonprototypical affects the conclusions that can be drawn from the test. H(3) Azimuthal temperature variations can be caused by the heat source and that may affect strain. The quenching process may be different with internal heating and heat capacities. M(4) Cladding temperature can be controlled to overcome the effect of the source on cladding parameters. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data and calculations PK(1): Data and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Specimen length	The appropriate length of the test article such that the data delivered from the test is useable. H(2) The length of anticipated test sections is sufficient to both rupture and pre-rupture strains. M(5) Assumes some intelligence on the part of the experimental team. Little concern that sample will be too short. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Data and calculations PK(1): Data and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Specimen constraints (grids, spacers, structures)	The degree to which mechanical setup used to hold the test article in place is prototypical H(7) Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data (JAERI) and judgement PK(2): Data UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Temperature effects of fuel relocation	Change in local cladding due to relocation of internal heat source (pellets) H(3) May cause hot spots that change selling and rupture, oxidation, and brittleness results. M(3) Less important for high burnup fuel because of fuel and clad bonding. L(1) Second order effect. Fuel: Y (1): For MOX fuel, the temperature effect will be more important because of the larger fraction of fine grain material. Clad: N Reactor: N Burnup: N K(4): Calculations PK(3): Calculations UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Fuel stored energy	The fuel stored energy, which depends upon the fuel temperature, amount of fuel, and fuel physical properties, should be known. Of the above, the fuel temperature is the parameter that must be measured during the test. H(1) Possible effects of debonding of clad and fuel and heat capacity of fuel will make it difficult to quench. M(3) Same reason as for high but felt to be less important, even a 2nd order effect. L(3) The temperatures are controlled during the test and that is the most important impact. Fuel: N Clad: N Reactor: N Burnup: N K(5): Calculations PK(2): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Clad temperature f(z, t)	Measurement of the time varying cladding temperature as a function of azimuthal and axial location. H(7) This is the most important parameter characterizing behavior and it should be measured to the extent possible. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes
Parameters/variables	Online: Fuel temperature f(z, t)	Measurement of the time-varying fuel temperature as a function of axial location. H(0) No votes M(4) Difficult to obtain but desirable data. It provides a sensibility check of the experiment. L(3) Clad temperature is monitored and controlled and will reflect fuel temperature. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(2): Data and judgement UK(1): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Time of failure	The time resolution of test rod burst failure occurrence. H(6) This information is needed to interpret and understand the tests and relating them to correlations. M(1) If burst occurs within the anticipated range, it will not effect oxidation or quench behavior. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data and calculations PK(2): Calculations and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Time of fuel relocation	The time resolution of the time of initial movement of fuel following either ballooning or test rod failure. H(2) Determines the time that more power is available to heat the clad. M(2) It is more important to know that material moves than when it moves. Movement in an electrically heat test would be much less important or significant than in a nuclear test. L(3) For this test, with known clad temperature, knowing when relocation occurs will not effect the results. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Calculations UK(1): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Fuel dispersal	Measurement of the movement of fuel particles out of the cladding and into the coolant during a burst. H(0) No votes M(5) Will not affect the test but may be important to understanding and setting regulations. In a single pin test will be overestimated. Needs to be quantified. L(2) No drive to expel fuel and there is no current data on this. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(3): Judgement UK(3): Judgement
Parameters/variables	Online: Internal pressure (value and axial communication)	The pressure at two axial locations within the fuel rod is sought to characterize the axial transport of gases. H(3) Needed for correlation to swell rupture correlations. M(3) Desirable but difficult to measure for axial communication of gases. L(1) No influence on tests being run. Only affects ballooning and burst to second order. Fuel: N Clad: N Reactor: N Burnup: N K(2): Data and calculations PK(5): Judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Hydrogen release/evolution	The release of hydrogen to the steam. H(0) No votes M(3) Provides a marker for the evolution of the oxide versus time and as a check on kinetics correlations. L(4) Errors in this measurement will be high and the measurement is not needed to verify kinetics. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Judgement UK(0): No votes
Parameters/variables	Online: Fission product release	Detection of the time at which fission gases escape from the fuel rod into the test channel. H(1) Good source for determining the onset of failure. M(4) Important to know but we only know about long-lived isotopes. L(2) It has nothing to do with outcomes and won't add to in-reactor understanding. Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(0): No votes UK(2): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	Online: Steam consumption	The measurement of steam consumption is equivalent to oxidation monitoring. H(2) This data can be used to determine the time rate of oxidation. M(1) This data can be used to check German information on ECR. L(4) Accuracy is bad; this parameter does not affect the outcome of the test. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(3): Judgement UK(0): No votes
Parameters/variables	Online: Strain measurement	Measurement of the time-dependent variation of clad hoop strain during the test. H(2) Will provide added data on creep and burst; strain away from the rupture is important for creating a bundle simulation. M(3) Useful to understand results but can be obtained from separate effect tests. L(2) Does not affect outcome and the data obtained from separate effect tests is much better. Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: ECR at failure location (burst and/or thermal shock)	Following the test, post irradiation examination (PTE) is performed on the fuel rod to determine the outcome of the test on various measurable features. Definition needed. H(7) ECR is key data needed to interpret the test results. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data PK(2): Data and judgement UK(0): No votes
Parameters/variables	PTE: Remaining prior beta thickness	H(6) A critical item of data needed for test interpretation. M(1) Some what less a critical result; failure is more important. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(3): Data and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Cladding strain	End state cladding strain. H(3) Can be cross-correlated to separate effect tests. M(4) Useful data but only as it provides confirmatory data for separate effect tests. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data PK(2): Data and judgement UK(0): No votes
Parameters/variables	PTE: Fuel relocation, residual bonding and/or dispersal	The amount of fuel that moved during the test and the location to which it was moved or dispersed is determined. H(7) May be the only way to quantify a potentially significant effect. M(0) No votes L(0) No votes Fuel: Y (1): Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample. Clad: N Reactor: N Burnup: N K(0): No votes PK(3): Calculations and judgement UK(2): Judgement

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Metallography (oxide thickness microstructure, prior beta, hydrides, and cladding thinning)	The end state of the listed parameters are measured. H(7) Needed to properly interpret the test. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Data and calculations PK(2): Data and judgement UK(0): No votes
Parameters/variables	PTE: Chemistry (Total beta hydrogen and oxygen content)	The listed end state parameters are measured. H(7) Needed to properly interpret the test. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Data and calculations PK(2): Data and judgement UK(0): No votes

Table B-1. PWR and BWR LOCA. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Parameters/variables	PTE: Oxide spallation and delamination during cooldown	The listed end state parameters are measured. H(0) No votes M(1) No rationale available L(6) Does not affect the outcome of the test. Phenomena are inconsequential. Fuel: N Clad: N Reactor: N Burnup: N K(3): Data PK(2): Judgement UK(0): No votes
Parameters/variables	PTE: Fission gas distribution	The listed end state parameter is measured. H(0) No votes M(2) Releases in rim and MOX agglomerates could affect pressure or filling of balloon with fuel. L(4) Characterizes release but has no impact on the outcome of the test. Fuel: Y (1): Low temperature burst strains are affected by constraints. Japan has shown effects on brittle fracture. The constraints should be prototypical and avoid over constraining the sample. Clad: N Reactor: N Burnup: N K(0): No votes PK(3): Data and judgement UK(0): No votes

APPENDIX C

CATEGORY C
TRANSIENT FUEL ROD ANALYSIS

PHENOMENA DESCRIPTIONS AND RATIONALES FOR IMPORTANCE RANKING, APPLICABILITY, AND UNCERTAINTY

This appendix provides a description for each phenomenon appearing in Table 3-4, Transient Fuel Rod Analysis PIRT. Entries in the Table C-1, columns 1 and 2, follow the same order as in Table 3-3. Table C-1, column 3, also documents the PIRT-panel developed rationales for three types of Panel findings.

First, rationales are provided for the importance (High, Medium, or Low) assigned by the panel to each phenomenon. Because importance ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular rank, i.e., High, Medium or Low. If there were no votes for a given importance rank, "No votes" is entered.

Second, the PIRT panel considered the applicability of the baseline PIRT to a broader set of circumstances, e.g., different fuel arrays, cladding types, reactor types, and burnups to 75 GWd/t. The specific question addressed by the PIRT panel was as follows: "Could the importance ranking assigned for the given phenomenon in the baseline PIRT be for different for other fuel arrays, cladding types, reactor types, or burnups?" If this question is answered with a "no", the following entry appears in Table C-1: "Baseline PIRT importance rank is applicable." If this question is answered with a "yes", the rationale is entered. Additional details are presented in the footnotes to Table 3-4.

Third, the PIRT panel considered the current state of knowledge or uncertainty regarding each phenomenon. The phenomenon is characterized as "known (K)" if approximately 75-100% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "partially known (PK)" if between 25-75% of full knowledge and understanding of the phenomenon exists. The phenomenon is characterized as "unknown (UK)"if less than 25% of full knowledge and understanding of the phenomenon exists. Because the uncertainty ranking was established by a vote of the panel members, a rationale is provided whenever one or more panel members voted a particular uncertainty, i.e., known, partially known, or unknown. If there were no votes for a given uncertainty level, "No votes" is entered.

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gap size	Distance between pellet outside and inside clad diameters. H(5) Affects the rate of energy release from the fuel. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): There is a lot of in-pile data available and the data reveals that the gap is closed or nearly closed for high burnup. PK(0): No votes UK(0): No votes
Initial conditions	Gas pressure	Pressure of the gas in the rod. H(6) Sets the initial conditions for response of the cladding and can affect clad conductance; also affects burst and blockage. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes. PK(5): Cumulative fission gas release is not well known. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas composition	Composition of the gas in the rod (mole fractions of the fill and fission gas components). H(5) This parameter contributes to establishing initial fuel stored energy. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Detailed gas release model can generate more accurate gas composition but the accuracy remains at 30%. UK(0): No votes
Initial conditions	Pellet and cladding dimensions	Characteristic physical dimensions, as a function of burnup. H(5) More important for hot rod calculation than for system calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Design values are well controlled and can be predicted with acceptable accuracy. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Burnup distribution	The radial and axial burnup magnitude and distribution in the fuel rod. H(5) Establishes peaking factors – very important. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Known from the calculations during the fuel cycle. PK(0): No votes UK(0): No votes
Initial conditions	Cladding oxidation (ID + OD)	The amount of prior zirconium oxide on both the inside and outside cladding surfaces. H(6) Thermal resistance effect – establishes starting point and can influence degree to which criteria are satisfied; also affects peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): For a single rod, initial oxide thickness can be calculated with adequate accuracy. PK(4): There is a moderate amount of uncertainty in oxidation over 60 GWd/t. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Hydrogen concentration	The average hydrogen concentration in the cladding specified as the initial condition. H(5) Establishes initial ductility of cladding. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(2): Hydrogen concentration can be accurately calculated from the oxide thickness. PK(3): Same as rationale for K but less certain about accuracy. UK(0): No votes
Initial conditions	Hydrogen distribution	The local distribution of hydrogen in the cladding and hydride orientation specified as the initial condition. H(5) Establishes initial ductility of cladding. Not modeled in most codes at present time. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(2): Hydrogen distribution can be directly correlated to the oxide thickness. PK(3): Same as rationale for K but less certain about accuracy. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Fast fluence	Time integrated fast neutron flux to which the cladding is exposed. H(5) Establishes cladding properties. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Fluence history is well known. PK(0): No votes UK(0): No votes
Initial conditions	Porosity distribution	The porosity distribution, including the rim, specified as the initial condition that is used to calculate the thermal conductivity and the fission gas transient behavior. H(5) Affects the conductivity of the pellet and the amount of fission gas release; affects the power distribution. M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Sufficient data exist for 62 MWd/t but data are incomplete for higher burnups. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Rim size	Width of zone at outer periphery of pellet characterized by high porosity, high local burnup and plutonium content, and small grain structure containing fission gases in tiny closed pores specified as the initial condition. H(5) Affects radial power distribution and radial temperature distribution (stored energy) M(0) No votes L(1) Second order effect on peak cladding temperature. Fuel: Y: Rim size not as important for MOX fuel. Clad: N Reactor: N Burnup: N K(0): No votes PK(5): For the purpose of LOCA analysis, enough data exists to characterize the rim size adequately. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pellet radial power distribution	The radial magnitude and distribution of the power produced within the fuel rod, including the effect of plutonium in the rim region. H(0) No votes M(5) Determines radial distribution of stored energy; not as important as axial distribution. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Can be calculated with adequate accuracy. PK(0): No votes UK(0): No votes
Initial conditions	Rod axial power distribution	The axial distribution of the power produced in the fuel rods. H(5) Dominant factor in determining peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Power shapes are conservatively set or calculated. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Fuel-clad gap friction coefficient/bonding	The friction coefficient between the pellet and cladding specified as an initial condition to represent the initial-state of interaction between the two (includes chemical bonding between the fuel and cladding as appropriate. H(0) No votes M(3) Affects heat transfer (beneficial) and could affect the degree of ballooning. L(2) Not a dominant effect during LOCAs. Fuel: N Clad: N Reactor: N Burnup: Y: For higher burnup, more bonding is present. K(0): No votes PK(5): Phenomenon is known but well enough known to be used for a LOCA calculation. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Surface conditions (rewet)	Conditions, e.g., roughness, on the outer surface of the cladding as they affect interaction with the coolant, particularly during rewet. H(1) Affects cladding rewetting and quench location which directly affects peak cladding temperature. M(0) No votes L(5) Does not affect the peak cladding temperature calculation as rewet occurs after the peak cladding temperature is attained. More important for system response and energy release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Surface roughness of cladding in the core at the initiation of the LOCA is well known. PK(1): Large scatter in data. Material dependent and surface condition dependent. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Coolant conditions	Thermal-hydraulic conditions in the coolant channel, including pressure, temperature, quality, void fraction and mass flow rate. H(5) Determines the heat transfer coefficient. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Fluid conditions at the initiation of the LOCA are well known. PK(0): No votes UK(0): No votes
Initial conditions	Rod free volume	The plenum and other free volumes within the fuel rod occupied by the gas. H(5) Can affect the magnitude of burst and blockage as well as timing. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): For a given rod, the free volume can be calculated within 25%. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Gas communication (resistance)	The ability of the gas in the free volume to move axially within the fuel rods, thereby providing uniform gas pressure. H(0) No votes M(0) No votes L(5) Time scale is too long for this to be important. Fuel: N Clad: N Reactor: N Burnup: N K(5): Based on burst data but note that tests were conducted with fresh fuel. PK(1): Uncertainty in the phenomenon. UK(0): No votes
Initial conditions	Pu cluster size (MOX only)	The size and distribution of Plutonium rich agglomerates in MOX fuel. H(0) No votes M(0) No votes L(5) Within expected distribution, the effect is 2nd or 3rd order. Fuel: NA Clad: N Reactor: N Burnup: N K(5): Well characterized. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Pellet cracking representation	Radial and circumferential cracks within the pellet. H(0) No votes M(5) Affects conductivity, stored energy, and gap conductance. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Adequately known. PK(1): Due to uncertainty. UK(0): No votes
Initial conditions	Gadolinium distribution (conductivity effect)	The spatial distributions of gadolinium within the fuel rod that affects the thermal conductivity of the fuel pellets. H(0) No votes M(5) Currently gadolinium rods are not limiting, but they become limiting when the gadolinium burns out in future designs. L(0) No votes Fuel: Y: Gadolinium designed for high burnup could change the ranking to high. Clad: N Reactor: N Burnup: N K(5): Well characterized. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Initial stored energy	The total energy content of the fuel rods initial power conditions before the LOCA. H(5) This phenomenon establishes the starting point. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Known from plant calculations. PK(0): No votes UK(0): No votes
Initial conditions	Initial core pressure drop (grids)	The initial axially-varying pressure within the fuel channel. H(0) No votes M(0) No votes L(5) Does not influence heat transfer coefficients, which were previously calculated in system analysis. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Initial conditions	Spallation of oxide layer, cracking	Separation and loss of the cracked oxide layer from the outer surface of the cladding. H(5) Can create weak spots which may result in early ballooning and rupture; creates hydride lens (weak spot). M(1) Rods that are at high burnup usually are not peak cladding temperature limited. L(0) No votes Fuel: N Clad: Y: Could be less important if there is a cladding material that doesn't oxidize as much. Reactor: N Burnup: N K(0): No votes PK(5): Spallation of oxide layer is random and cannot be predicted accurately. UK(0): No votes
Initial conditions	Pellet shape	Changes to the pellet shape from its initial state such as dished or chamfered ends, barreling or hourglassing as they affect the cladding response. H(0) No votes M(0) No votes L(5) 2nd order effect. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(1): Due to pellet cracking. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient boundary conditions	Transient cladding-to-coolant heat transfer (all phases: blowdown refill, reflood and steady state)	Flow-regime-dependent total heat transfer coefficient (including convection and radiation) and fluid temperature for blowdown, refill, and reflood phases. H(5) These are the set of controlling phenomena that determine how the cladding will respond. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): There are uncertainties associated with the input to the two-phase heat transfer coefficients and the heat transfer coefficients themselves. UK(0): No votes
Transient boundary conditions	Transient and steady state power distributions	Provides the spatial and temporal power and stored energy distributions in the fuel rod. H(5) Major source of energy that drives the peak cladding calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Decay heat is well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient boundary conditions	Transient coolant conditions	Spatial and temporal variation of the coolant conditions within the fuel channel. H(5) Establishes the heat sink. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): There are uncertainties associated with the input to the two-phase heat transfer coefficients and the heat transfer coefficients themselves. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Plastic deformation of cladding (thinning, ballooning and burst)	Irreversible changes in cladding dimensions caused by pressure differentials or mechanical loadings at high temperatures. If cladding burst occurs, the final plastic deformation at the burst location is characterized by the burst strain. H(5) Affects gap heat transfer, inside and outside oxidation, and location of the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Given temperatures and pressures, cladding plastic deformation can be calculated with adequate accuracy. PK(1): Same as K but uncertainty is larger. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Direct gas pressure loading	The combination of available fission gas combined with the fill gas in determining an internal pressurization. H(5) A driver in determining clad strain and burst. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Universal gas law`is adequate. PK(0): No votes UK(0): No votes
Fuel rod response	Quench loading of clad	Thermal loading due to quenching of the fuel rod by the coolant. H(0) No votes M(3) Could determine long-term coolability. L(2) Assumes we stay below 17% criterion. Fuel: N Clad: N Reactor: N Burnup: N K(5): Temperature distribution in the cladding can be calculated. PK(1): Gap conductance is variable during the process. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Thermal deformation of pellet and cladding	Reversible changes in pellet and cladding dimensions caused by thermal expansion. H(0) No votes M(0) No votes L(5) Not significant compared to plastic deformation. Fuel: N Clad: N Reactor: N Burnup: N K(5): Temperature distribution can be accurately calculated. PK(0): No votes UK(0): No votes
Fuel rod response	Elastic deformation of cladding	Reversible changes in cladding dimensions caused by pressure differentials or mechanical loadings. H(0) No votes M(4) Not the dominant effect. L(0) Not the dominant effect but even lower influence. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fission gas release	The release of fission gas during a transient through the pellet into the free volume. H(0) No votes M(0) No votes L(5) Temperature below threshold for fission gas release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Fuel temperature below the threshold. PK(0): No votes UK(0): No votes
Fuel rod response	Pellet swelling	Fission gas contribution to the swelling of the pellet. H(0) No votes M(0) No votes L(5) Temperature below threshold for fission gas release. Fuel: N Clad: N Reactor: N Burnup: N K(5): Well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Axial and radial temperature distributions	Radial and axial variation in temperature. H(5) Determines the heat transfer rate to the cladding and coolant and the peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the boundary conditions, heat conduction analysis method is well established and accurate. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Heat resistances in fuel	The resistances offered by the fuel to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Used in determining the temperature response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Known well at locations other than the burst location, even at the burst location the fuel resistance is well known prior to the burst. PK(2): During ballooning, the possibility of fuel relocation increases the uncertainty. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in gap	The resistances offered by the gap to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Used in determining the temperature response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): During ballooning, the possibility of fuel relocation increases the uncertainty. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in clad	The resistances offered by the clad to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(1) A key part of the calculation of heat flux. M(5) A small contribution to heat resistance. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): Heat resistance of cladding is well known at possible temperatures. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
	Heat resistances in oxide	The resistances offered by the oxide to the flow of thermal energy from regions of high temperature to regions of lower temperature. The resistance is dependent upon path length and thermal conductivity, which change with burnup and other processes, e.g., the buildup of oxide on the cladding surfaces. H(5) Can be a large contribution considering effects of oxide delamination. M(1) High burnup rods are not peak cladding temperature limiting. L(0) No votes Fuel: N Clad: Y: Effect can be smaller if new cladding does not oxidize as readily. Reactor: N Burnup: N K(0): No votes PK(6): Relatively high uncertainty due to delamination. UK(0): No votes
Fuel rod response	Cladding azimuthal temperature distributions	Circumferential variation in temperature. H(1) Determines when burst occurs and the degree of blockage. M(5) Can affect timing and degree of strain at burst. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): High uncertainty in predicting fragmentation. High uncertainty in predicting azimuthal temperature distributions. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding oxidation magnitude (ID/OD)	Change in cladding oxidation during the transient. H(5) Can be limiting for those cases that are ruptured node limited – also affects meeting the local oxidation limit. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(2): For a given set of conditions, oxidation can be calculated with adequate accuracy. PK(4): Uncertainty in initial oxidation and uncertainty in application to complex situations. UK(0): No votes
Fuel rod response	Metal-water reaction heat addition	The additional heat generated in the cladding due to metal-water reactions. H(5) Can be important above certain temperature for inside and outside oxidation. M(1) Effect is small unless cladding temperatures exceed 2200 °F. Phenomenon is exponential with temperature. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: Y: Less important for high burnup. K(6): Mechanism is well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Size of burst opening	Geometry of the burst region. H(6) An important phenomenon as it affects the degree of blockage and fuel dispersal and relocation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Evidence to indicate that the burst opening is smaller for high burnup. UK(1): Not known sufficiently well to calculate.
Fuel rod response	Burst criteria	Combinations of physical parameters that are expected to cause cladding burst. For example, NUREG-0630 correlates burst temperature as a function of engineering hoop stress and heatup rate. H(6) Determines the timing and location of cladding burst – affects the calculation of peak cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(1): The state of the art is such that the burst criteria can be accurately calculated. PK(5): The current criteria do not include the important time effect. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Cladding phase changes	Change in the cladding microstructure from alpha phase (low temperature) to the alpha + beta phase, to beta phase (high temperature). The phase change energy of transformation can effectively increase the cladding specific heat over the transition temperature range. The phase change affects ductility resulting in significant effects of plastic deformation (creep rate and burst). Changes in cladding alloy or hydrogen content affect the transition temperature changes. H(6) All these effects determine cladding material properties that determine the degree of strain and the timing of the burst. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(6): Given the temperature, the phase transition is well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Time of burst	The amount of time elapsed between initiation of the LOCA and the predicted cladding burst. H(6) Has a significant impact on peak cladding temperature calculation. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Temperature range in which burst occurs takes place during a limited period of the LOCA transient (quickly). UK(0): No votes
Fuel rod response	Location of burst	The axial position at which cladding burst and flow blockage occur. H(6) Has a significant impact on peak cladding temperature calculation. Has a significant impact on peak cladding temperature calculation and depends on grid location. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(4): Burst location is dominated by power shape. PK(2): There are other factors that enter into the determination of the burst location. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Spacer grid constraint	Constraints imposed by the grids on cladding deformations. H(1) Spacer grids determine the amount of cooling which in turn determines where the blockage occurs and the degree of co-planar blockage. M(3) Might calculate the wrong burst location if ignore grid. L(2) The limiting location is usually not a grid location – a 2nd order effect. Fuel: N Clad: N Reactor: N Burnup: Y: Less important for higher burnup. K(0): No votes PK(6): Analytical capability exists to be able to calculate with adequate accuracy. No code can calculate this. UK(0): No votes
Fuel rod response	Pellet to cladding bonding	Absence of a gap between the fuel and the cladding due to the bonding of the pellets to the cladding. H(2) May reduce the effect of inside oxidation. M(4) Not believed to be a dominant effect. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): Insufficient data. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Localized effects	Stress risers within the cladding at discrete locations, arising from various sources, including the pellet shape as well as undetected defects in the cladding. H(0) No votes M(0) No votes L(5) Data used to judge effects of rod failure already includes this effect. Fuel: N Clad: N Reactor: N Burnup: Y: Localized effect increases with burnup. K(0): No votes PK(0): No votes UK(5): Defects occur at random.
Fuel rod response	Biaxiality	The dependence of cladding deformation and burst on the multi-dimensional stress state. H(0) No votes M(2) Affects deformation during ballooning phase. L(3) a small effect on ballooning per existing analyses. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the temperature of the cladding, this behavior can be calculated with accuracy. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Fuel relocation	Movement of pellet fragments into a region where cladding plastic deformation (ballooning or burst) has occurred. Fuel relocation changes the local linear heat rate and affects gap conductance and fuel thermal resistance. H(1) It is plant dependent. If the plant is burst node limited, this can make the event worse. M(5) Has a modest impact on the local linear heat rate. L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(6): A limited amount of data available. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod response	Grain boundary decohesion	Separation of grains under the effect of gas bubble pressure when cladding confinement is lost. H(0) No votes M(0) No votes L(5) Not important for a LOCA. Fuel: Y: It is not possible to take the same burndown credit for MOX fuel as can be done for UO_2 fuel. Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Insufficient data exists to apply to situations other than those that have been directly observed. UK(0): No votes
Fuel rod response	Evolution of pellet stress state	Changes in pellet stresses due to the time-dependent temperature, pellet cladding interactions, internal gas bubble pressure, etc. H(0) No votes M(0) No votes L(5) Not important for LOCA event. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given the conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Multiple rod mechanical effects	Rod-to-rod and rod-to-channel thermal and mechanical interactions	The thermal and mechanical effects of adjacent rods and/or channel box on the fuel rod being modeled in the code. H(1) More important in CE designs due to large guide thimbles. M(5) Medium importance for BWRs (radiation). L(0) No votes Fuel: N Clad: N Reactor: Y: More important for BWRs. Burnup: N K(5): Mechanical interaction is ranked low and is less known. Heat transfer is well known. PK(0): No votes UK(0): No votes
Properties	Fracture stress of oxide	The tensile strength of the zirconium oxide. H(0) No votes M(0) No votes L(5) Offers no additional strength to cladding. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Yield stress in compression	Yield strength of the cladding as it affects rod deformations due to axial constraints. H(0) No votes M(0) No votes L(5) Rods don't go into compression mode. Fuel: N Clad: N Reactor: N Burnup: N K(5): Given conditions, this phenomenon can be accurately calculated. PK(0): No votes UK(0): No votes
Properties	Heat capacities of fuel and cladding	Self explanatory. H(5) Used to determine fuel and cladding thermal response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): The properties are well known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Thermal conductivities of fuel and cladding	Self explanatory. H(5) Used to determine fuel and cladding thermal response. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(5): The properties are well known. PK(0): No votes UK(0): No votes
Properties	Strain rate effects	Strain rate effects as they change the stress strain curve in terms of affecting the yield stress and the deformation behavior in the plastic regime. H(0) No votes M(0) No votes L(5) Strain rate is low during LOCA. Fuel: N Clad: N Reactor: N Burnup: N K(5): The material response is adequately known. PK(0): No votes UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Properties	Anisotropy	The variation of cladding properties along the different coordinate directions. H(0) No votes M(0) No votes L(5) Anisotropy disappears with fluence. Fuel: N Clad: N Reactor: N Burnup: N K(5): This effect is well known. PK(0): No votes UK(0): No votes
Transient cladding-to-coolant heat transfer	Rod-to-spacer grid thermal hydraulic interaction	The enhanced convective heat transfer effects downstream of the spacer grids due to mixing and flow redistribution for single or two-phase flows. H(5) Has significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Data are available but more data are needed. UK(0): No votes

Table C-1. PWR and BWR LOCA. Category C – Transient Fuel Rod Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Transient cladding-to-coolant heat transfer	Spacer grid rewetting and droplet breakup	The wetting of spacer grids, which enhances the interfacial heat transfer at and downstream of the spacer grids. H(5) Has significant impact on axial variation of heat transfer coefficient and calculation of cladding temperature. M(0) No votes L(0) No votes Fuel: N Clad: N Reactor: N Burnup: N K(0): No votes PK(5): Incomplete droplet breakup data. UK(0): No votes