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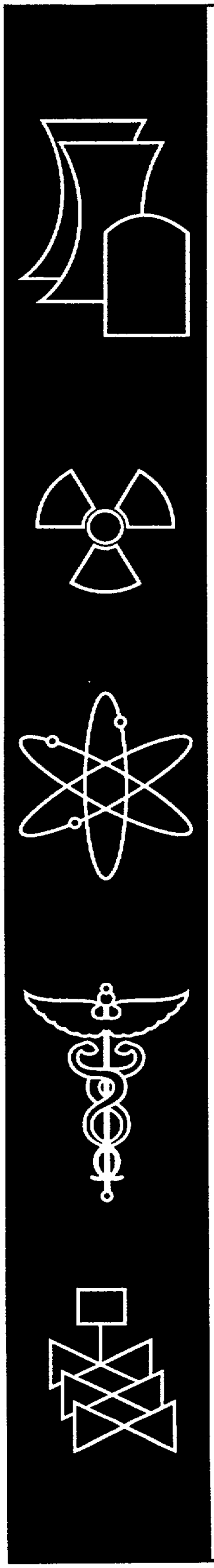

# Phenomenon Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel

Los Alamos National Laboratory

**U.S. Nuclear Regulatory Commission**
**Office of Nuclear Regulatory Research**
**Washington, DC 20555-0001**

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# Phenomenon Identification and Ranking Tables (PIRTs) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel

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## Abstract

In the United States, two types of regulatory criteria have been used in safety analyses to address reactivity accidents. One criterion is a limit of 280-cal/g fuel on peak fuel-rod enthalpy. The other criterion consists of several threshold values that are used to indicate cladding failure. 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 criteria, 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. It 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. The NRC is also preparing to develop a new criterion to replace the current 280-cal/g coolability limit. 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 instability power oscillations arising during an anticipated transient without scram in boiling water reactors containing high burnup fuel. The initiating event is a trip of both recirculation line pumps.

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# EXECUTIVE SUMMARY

In the United States, two types of regulatory criteria have been used in safety analyses to address reactivity related accidents. One criterion is a limit of 280-cal/g fuel on peak fuel-rod enthalpy. This limit was developed to (1) ensure coolability of the core after such an accident and (2) preclude the energetic dispersal of fuel particles into the coolant. The other criterion consists of several threshold values that are used to indicate cladding failure, that is, the occurrence of a breach in the cladding that would allow fission products to escape.

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 criteria, 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.

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 (BWRs) containing high burnup fuel. Membership of the PIRT panel has been drawn from the US and international scientific community and many of its sixteen 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 PIRT identifies and ranks phenomena for an accident scenario in a General-Electric-Company designed BWR/5, the LaSalle County Unit #2 (LaSalle-2). The fuel is uranium dioxide and the cladding is Zircaloy-2 with a zirconium-based inner liner at a burnup of 62 GWd/t. The transient scenario selected as the basis for the reactivity-related BWR PIRT is a trip of both recirculation pumps with a failure to scram. This scenario is suggested by the recirculation pump trip event at LaSalle-2 nuclear power station in March 9, 1988, which resulted in plant power and flow oscillations. The scenario considered by the PIRT panel is power oscillations without scram in a BWR containing high burnup fuel. Although a specific plant and fuel have been selected, the panel was 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.

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 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. Thus, 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), for the purposes of evaluation. We decided as a panel on a primary evaluation criterion, namely, cladding failure with significant fuel dispersal.

The panel was then divided into analytical and experimental working groups that (1) created a list of phenomena with written definitions; (2) discussed and evaluated each phenomenon; (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," and "unknown"; and (6) evaluated whether any of the importance votes would change for other fuels or claddings and for burnups up 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 power oscillations without scram accidents. 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 also notes, however, 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 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 the panel voting results produced the following results[1].

**Plant Transient Analysis (Category A)**

This category was divided into four subcategories: (1) calculation of power history during event, (2) calculation of rod fuel enthalpy increase during event, (3) calculation of fuel to coolant heat transfer, and (4) calculation of core and system hydraulics.

Three of the four phenomena in the calculation of power history subcategory were identified as important. They are: (1) moderator feedback, (2) fuel temperature feedback, and (3) fuel cycle design. However, none of these three had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. This indicates that the panel believes that sufficient knowledge exists to calculate the power history.

Three of the seven phenomena in the calculation of rod fuel enthalpy increase during event subcategory were identified as important. They are: (1) heat resistances of the fuel, gap, and cladding, (2) heat capacities of the fuel and cladding, and (3) rod peaking factors. However, none of these three had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. This indicates that the panel believes that sufficient knowledge exists to calculate fuel enthalpy.

Within the calculation of fuel to coolant heat transfer subcategory, four phenomena satisfied both the importance and the knowledge screening criteria. They are: (1) subcooled boiling, (2) dryout, (3) film boiling over a wide void fraction range, and (4) rewet. Having met the dual screening criteria, each of the above listed phenomena has been flagged by the panel as a candidate for additional consideration.

Within the calculation of core and systems hydraulics subcategory, two phenomena satisfied both the importance and the knowledge screening criteria. They are: (1) void fraction due to direct moderator heating and (2) flow blockage. Having met the dual screening criteria, each of the above listed phenomena has been flagged by the panel as a candidate for additional consideration.

We should note that, contrary to the practice elsewhere in the PIRT document, the importance of the phenomena in this section have been considered in an "absolute" sense rather than specifically at high burnup.

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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.

### Integral Testing (Category B)

This category includes phenomena related to the testing of fuel rods in a test reactor such as NSRR or Halden or in an electrically heated facility. The panel considered two scenarios when considering integral testing for the reasons described in Section 3.4.2.

Low Temperature Failures. In this scenario, the cladding has low ductility and could fail by pellet-cladding mechanical interaction (PCMI). Through-wall cracks could propagate and fuel particles could be dispersed, possibly resulting in a degraded coolable geometry and flow blockages that could degrade core cooling.

High Temperature Failures. In this scenario, the cladding survived the low temperature PCMI phase. However, in high power channels, the critical heat flux may be exceeded. The high cladding temperature may lead to oxidation, ballooning, rupture and fragmentation.

Both the low temperature and high temperature phases are subdivided into two subcategories, "Fuel rod selection" and "Conduct of the test."

The panel did not assess uncertainty for the phenomena identified for integral testing. Therefore, the phenomena identified below passed only the screening criterion for importance.

***Low Temperature Phase.*** Within the fuel rod selection subcategory, six phenomena satisfied the importance-screening criterion, one associated with the fuel and five with the cladding. The fuel-related phenomenon was burnup. The cladding-related phenomena are: (1) type of oxidation, (2) extent of oxide spalling and hydride blisters, (3) cladding type, (4) amount of hydrogen, and (5) cladding integrity.

Within the conduct of test subcategory, nine phenomena satisfied the importance screening criterion and none was associated with the specimen design. The nine judged to be important during the test are: (1) fuel enthalpy increase, (2) total number of pulses, (3) power drop, (4) on-line pressure pulse measurement, (5) on-line fission-product measurement, (6) on-line cladding deformation measurement, (7) time and location of failure, (8) cladding temperature, and (9) cladding elongation.

Because both the energy deposition rate and the overall energy deposition are much smaller than occur during a rod ejection accident, the loading during pellet-cladding mechanical interaction (PCMI) is also smaller. The PCMI loading occurs after the cladding temperature has increased and when the cladding is more ductile. Because of this the likelihood of a fuel failure like that occurring in a rod ejection accident is much smaller.

The following importance votes reflect the panel's views on how each parameter would affect the outcome of the test, if the tests were conducted. However, it was the opinion of the panel that low temperature fuel failures are unlikely in the case of a BWR power oscillations without scram.

*High Temperature Phase.* Within the fuel rod selection subcategory, one phenomenon satisfied the importance-screening criterion; it was the thermal inertia of the fuel. None of the cladding phenomena satisfied the importance screening criterion.

Within the conduct of test subcategory, fifteen phenomena satisfied the importance screening criterion, five were associated with the specimen design and ten were judged to be important during the test.

The important specimen design selection characteristics are (1) length, (2) grid and constraints, (3) attachments, (4) single rod versus bundle, and (5) channel boundary conditions. The parameters judged to be important during the test are: (1) flow oscillation characteristics, (2) average power level, (3) coolant heat transfer, (4) steam quality, (5) steam quality measurement, (6) vapor temperature, (7) vapor temperature measurement, (8) cladding temperature, (9) DNB and rewet detection, and (10) mass flow rate.

It is particularly remarkable that none of the variables associated with the exact power history and cycling (period of cycles, pulse height, pulse shape, number of cycles, etc.) were thought to be of high importance. Thus the high temperature fuel rod failures during a power oscillation without scram event will be controlled by parameters similar to those that control a loss-of-coolant accident (LOCA).

### Transient Fuel Rod Analysis (Category C)

This category consists of seven subcategories. They are: (1) initial conditions, (2) mechanical loading to cladding, (3) fuel and cladding temperature changes, (4) cladding deformation, (5) pellet deformation mechanisms, (6) forcing functions, and (7) multiple fuel rod and coolant channel interactions.

Within the initial conditions subcategory, a single phenomenon, thickness of oxide layer and surface condition (rewet), satisfied both the importance and the knowledge screening criteria.

Within the mechanical loading subcategory, three characteristics satisfied both the importance and the knowledge screening criteria. They are: (1) pellet thermal expansion, including expansion due to fuel melting, (2) pellet-cladding contact, and (3) fission gas induced pellet swelling.

Within the fuel and cladding temperature changes subcategory, three characteristics satisfied both the importance and the knowledge screening criteria. They are: (1) heat resistances in fuel, gap, and cladding, (2) transient cladding-to-coolant heat transfer coefficient for oxidized cladding, and (3) transient oxidation and energy source.

Within the cladding deformation subcategory, one characteristic, cladding temperature, satisfied both the importance and the knowledge screening criteria.

Within the pellet deformation mechanisms subcategory, the sole characteristic in the subcategory, i.e., fracture stress, yield stress in compression, plastic deformation, grain boundary decohesion, pellet cracking, and evolution of pellet stress state, satisfied both the importance and the knowledge screening criteria.

Within the forcing functions subcategory, each of the two listed characteristics, transient power distribution and coolant conditions, satisfied both the importance and the knowledge screening criteria.

Within the multiple fuel rod and coolant channel interactions subcategory, one characteristic, rod-to-channel interactions, satisfied both the importance and the knowledge screening criteria.

Each of the above listed characteristics 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 includes phenomena related to testing for the mechanical properties of high burnup BWR cladding with respect to failures at low temperatures. Separate effect tests and phenomena specifically related to high temperature oxidation are discussed and ranked in the LOCA PIRT (NUREG/CR-6744).

This category was divided into two subcategories: (1) Specimen selection and (2) Test conditions. The panel did not assess uncertainties for this category.

Within the specimen selection subcategory, two characteristics satisfied the importance screening criterion: (1) extent of oxide spalling and related hydride blisters and (2) hydride orientation,

Within the test conditions subcategory, five conditions satisfied the importance screening criterion. They are: (1) cladding integrity, (2) stress state imposed on specimen, (3) cycling conditions, (4) tensile specimen design, and (5) burst specimen design.

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 loss-of-coolant accidents in PWRs and BWRs containing high burnup fuel (NUREG/CR-6744)

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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## Acknowledgments

Several organizations, individuals, and resources were instrumental in supporting the PIRT panel efforts. Although the PIRT panel maintained an independent and separate perspective, the panel acknowledges the help received from the following individuals:

- 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 & C focused on analytical issues and was chaired by Kenneth Peddicord. The working group for Categories B & 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. David Diamond of Brookhaven National Laboratory presented "BWR ATWS Events with Large Oscillations." Jens Andersen, a panel member, presented "BWR ATWS Overview-ATWS Stability." Keijo Valtonen, a panel member, presented a BWR overview. Martin Zimmermann of the Paul Scherrer Institute presented "Power Oscillations During BWR ATWS: What Can Be Learned from Old Analysis at PSI?" Wolfgang Wiesenack of the Halden Reactor Project presented "The Halden Reactor Project Fuels & Materials Programme" as well as information on dryout and pellet-cladding mechanical interactions.
- 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 rod ejection accident report. Gerald Potts revised this information so that it was applicable to BWR fuel and the power oscillations without scram event.
- The Electric Power Research Institute (EPRI) 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.

## Acronyms

| | |
|---|---|
| ATWS | Anticipated Transient Without Scram |
| BWR | Boiling water reactor |
| CDC | Capsule Driver Core |
| CHF | Critical heat flux |
| DNB | Departure from nucleate boiling |
| EOL | End of life |
| GDC | General Design Criterion |
| IGR | Impulse Graphite Reactor |
| 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 |
| PCT | Peak cladding temperature |
| PIE | Post irradiation examination |
| PIRT | Phenomena Identification and Ranking Table |
| PWR | Pressurized water reactor |
| RCS | Reactor coolant system |
| SPERT | Special Power Excursion Reactor Tests |
| TMI | Three Mile Island |

# 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 (PWRs) and boiling water reactors (BWRs) containing high burnup fuel. The panel prepared PIRTs for the following three scenarios: (1) PWR rod ejection accident , (2) BWR power oscillations without scram, and (3) PWR and BWR loss-of-coolant accidents (LOCA). The remainder of this report collects and documents the findings of the High Burnup Fuel PIRT panel for the BWR power oscillations without scram accident. Additional reports have been issued for the remaining scenarios.[1-1, 1-2]

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

- Section 1, Introduction, summarizes the issues associated with high burnup fuel, provides an overview of the PIRT process, identifies the members of the 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, that lay the foundation for the identification and ranking of phenomena.
- Section 3, BWR power oscillation without scram PIRTs, contains the PIRT tables.
- Section 4, Databases, describes the experimental and analytical databases used by the panel during the development of the 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 Categories B1 and B2, Integral Testing (low temperature phenomena and high temperature phenomena).
- 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 describes the experimental programs whose data comprise the majority of the experimental database used by the panel in preparing the BWR power oscillations without scram PIRT.

- Brief experience summaries for each panel member are provided in Appendix F.
- Finally, Appendix G contains tutorial presentations that were given to the PIRT panel.

## 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 fuel melting and 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 coolant.

In an earlier PIRT effort, a PWR reactivity-related accident was considered.[1-1] In this report, a BWR reactivity accident is considered. The PWR rod ejection accident and this PIRT effort focus on the class of events in which too much power is generated. In a subsequent PIRT effort, the PIRT panel considered PWR and BWR loss of coolant accidents as representative of the class of events in which there is insufficient coolant.[1-2]

This PIRT identifies and ranks phenomena for instability power oscillations arising during an anticipated transient without scram in boiling water reactors containing high burnup fuel. The initiating event is a trip of both recirculation pumps.

NRC regulations for suppression of reactor power oscillations state: "the reactor core and associated coolant, control, and protection systems shall be designed to assure that power oscillation which can result in conditions exceeding specified acceptable fuel design limits are not possible or can be reliably and readily detected and suppressed." [1-2]

A review of this issue led to rule making and issuance of 10CFR50.62, "Requirements for the Reduction of Risk from Anticipated Transients without Scram (ATWS) Events for Light-Water Cooled Nuclear Power Plants." The issuance of this regulation in 1984 resulted in modifications at all US BWRs and generic safety analysis of the event to confirm that the modifications provided the desired degree of prevention and mitigation. In an assessment performed after the La Salle event, an energy deposition criterion was selected, with a maximum value of 280 cal/gm set as the upper limit (NEDE-32047). This value was borrowed from the regulatory limits used for PWR rod-ejection accidents.

In late 1993, a test simulating a PWR rod-ejection accident was run in the Cabri test reactor in France. This test produced cladding failure at a peak fuel-rod enthalpy of about 30-cal/g fuel (15 cal/g fuel enthalpy rise). Fragmented fuel particles were dispersed from the fuel rod in this test, and enhanced fission-product release was observed. A short time later, in 1994, a similar test in the Nuclear Safety Research Reactor (NSRR) in Japan produced cladding failure at a peak fuel-rod enthalpy of about 60 cal/g fuel. These values were so far below the 280 cal/g coolability limit that the NRC initiated an investigation into this situation and issued an Information Notice to licensees.[1-3] The NRC regulatory staff then performed a review of the safety significance of this situation and concluded that there was no significant impact on public health and safety because of the low probability of the event and the high likelihood that core coolability would be maintained, although there might be some increase in the fuel damage fraction.

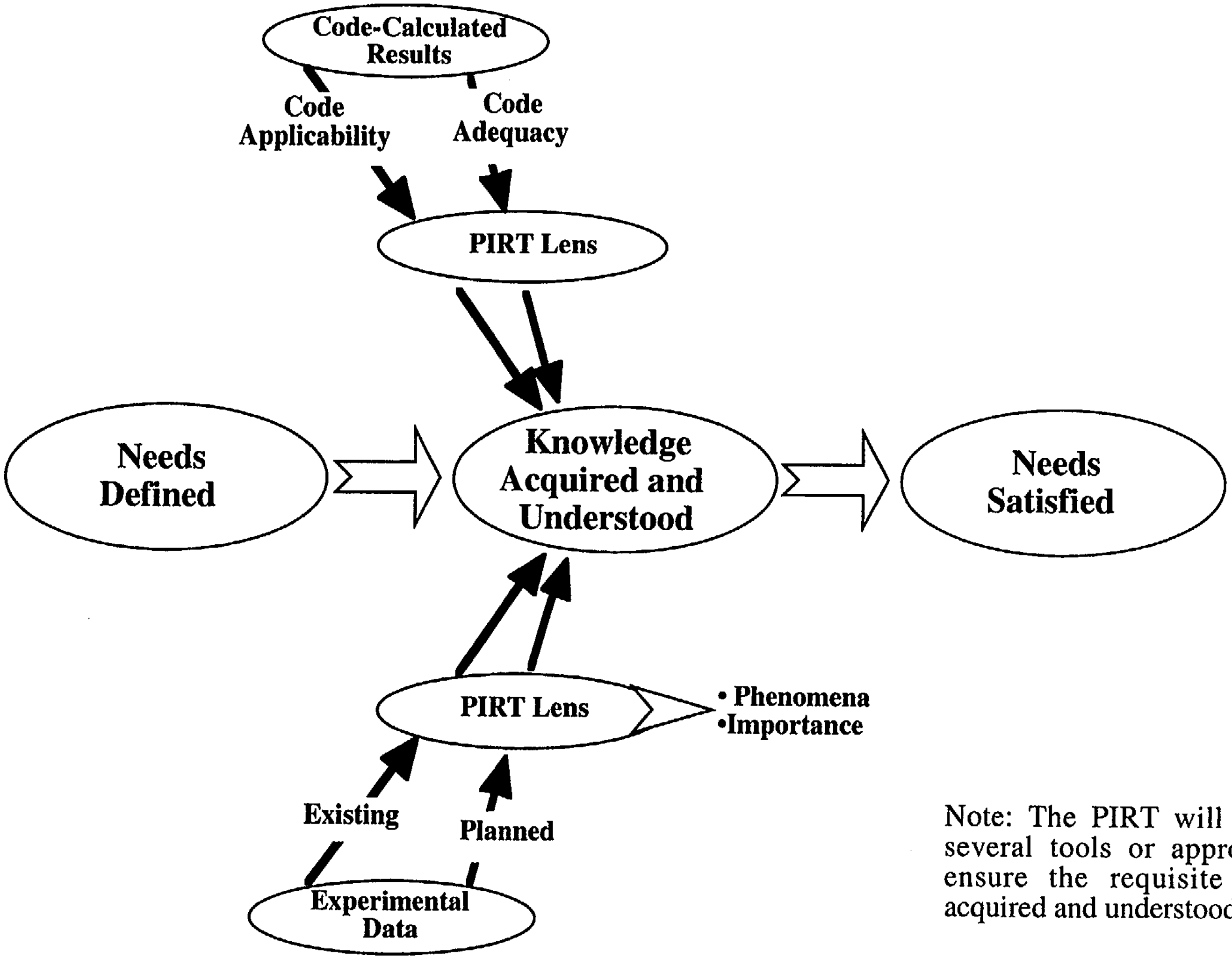
Notwithstanding this conclusion, there is still the question of the adequacy of NRC's regulatory criteria for this type of accident, and there are unanswered questions about the behavior of fragmented fuel particles and fission products released during such an event. Revised regulatory guidance is being considered for high-burnup fuel and new fuel rod designs, especially those with new cladding alloys.

The NRC entered into formal agreements with France (Cabri test reactor), Japan (NSRR test reactor), and Russia (IGR test reactor) to obtain data from current programs. The NRC also initiated generic plant calculations and an assessment of the test data and plant calculations.

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 new regulatory limits for fuel damage. 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



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 needs.

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 NRC's needs will be obtained. It must be noted that the PIRT will be 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 participating in the BWR power oscillation PIRT were as follows:

- Carl Alexander, Battelle Memorial Institute;
- Jens Andersen, Global Nuclear Fuel, Inc.;
- Bert Dunn, Framatome Technologies, Inc.;
- Toyoshi Fuketa, Japan Atomic Energy Research Institute;
- Lawrence Hochreiter, The Pennsylvania State University;
- Robert Montgomery, Anatech Corporation;
- Fred Moody, Consultant;
- Arthur Motta, The Pennsylvania State University;
- Kenneth Peddicord, Texas A&M University;
- Gerald Potts, Global Nuclear Fuel, Inc.;
- Doug Pruitt, Siemens Nuclear Power Corporation;
- Joe Rashid, Anatech Corporation;
- Richard Rohrer, Nuclear Management Company;
- James Tulenko, University of Florida;
- Keijo Valtonen, Finnish Center Radiation and Nuclear Safety; 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 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 nor required to assess each feature of an experiment or analytical tool in a uniform fashion. The PIRT methodology brings into focus the 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 BWR power oscillation PIRT for high burnup fuel, is illustrated in Fig. 1-2 and described below.

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 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 BWR power oscillation 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.

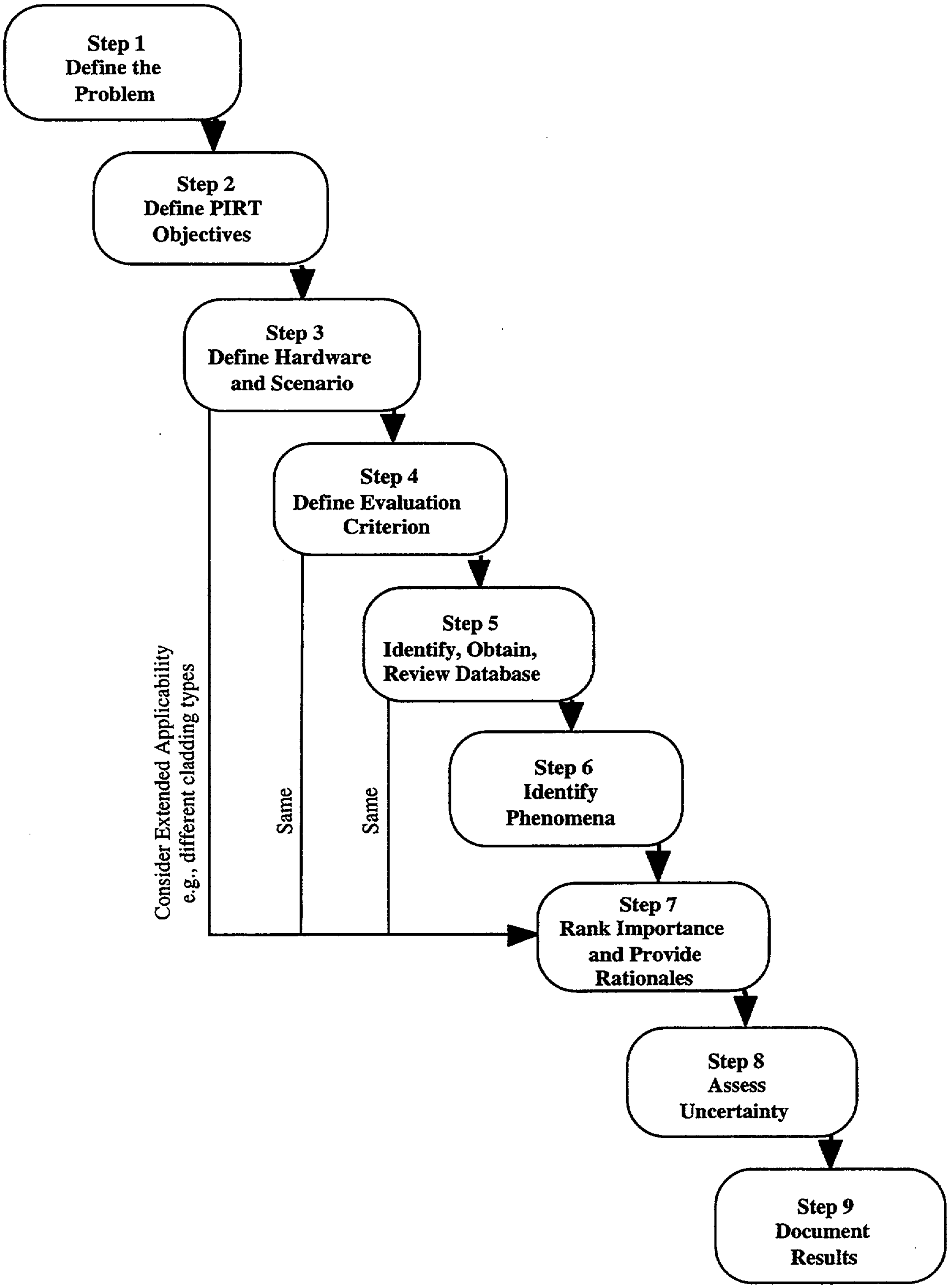


Fig. 1-2. Illustration of PIRT process for BWR power oscillations without scram.

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 4. 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 a 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 BWR containing high burnup fuel and experiencing power oscillations without scram. 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 develop a new criterion to replace the 280 cal/g criterion of Regulatory Guide 1.77 that has been used in the assessment of BWR power oscillations. An NRC staff report that strives to utilize these PIRT results has also been issued.[1-9]

## 1.5. References

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1-2. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6744 (September 2001).

1-3. US Nuclear Regulatory Commission, "Reactivity Insertion Transient and Accident Limits for High Burnup Fuel," NRC Information Notice 94-64 (August 31, 1994).

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 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 design selected for this BWR PIRT development are discussed in Section 2.1. Because the phenomena of interest during BWR power oscillations occur within a brief period following accident initiation, emphasis is placed on the fuel design for this PIRT effort and the associated coolant conditions. Descriptions of the selected fuel type for this PIRT and its state at high burnup prior to an oscillation event are described in Section 2.2.

The accident scenario selected for the BWR PIRT is discussed in Section 2.3. The behavior of the plant following the accident initiating event is discussed in Section 2.3.1. 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 (1) modifications that might be needed in plant transient codes for licensing analysis, (2) experimental derivation of a quantitative fuel enthalpy criterion, and (3) 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 reference plant selected for this PIRT is LaSalle County Unit #2 (LaSalle-2), which is a General-Electric-designed BWR/5 rated at 1036 MWe (net). The steam and recirculation water flow paths in a BWR are shown in Fig. 2-1[2-1]. 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 turbine system. The water, which is separated from the steam, flows downward in the periphery of the reactor vessel and mixes with the incoming main feed flow from the feedwater system. 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 core contains 764 fuel assemblies with fuel rods arranged in a 8x8 configuration. 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 $UO_2$.

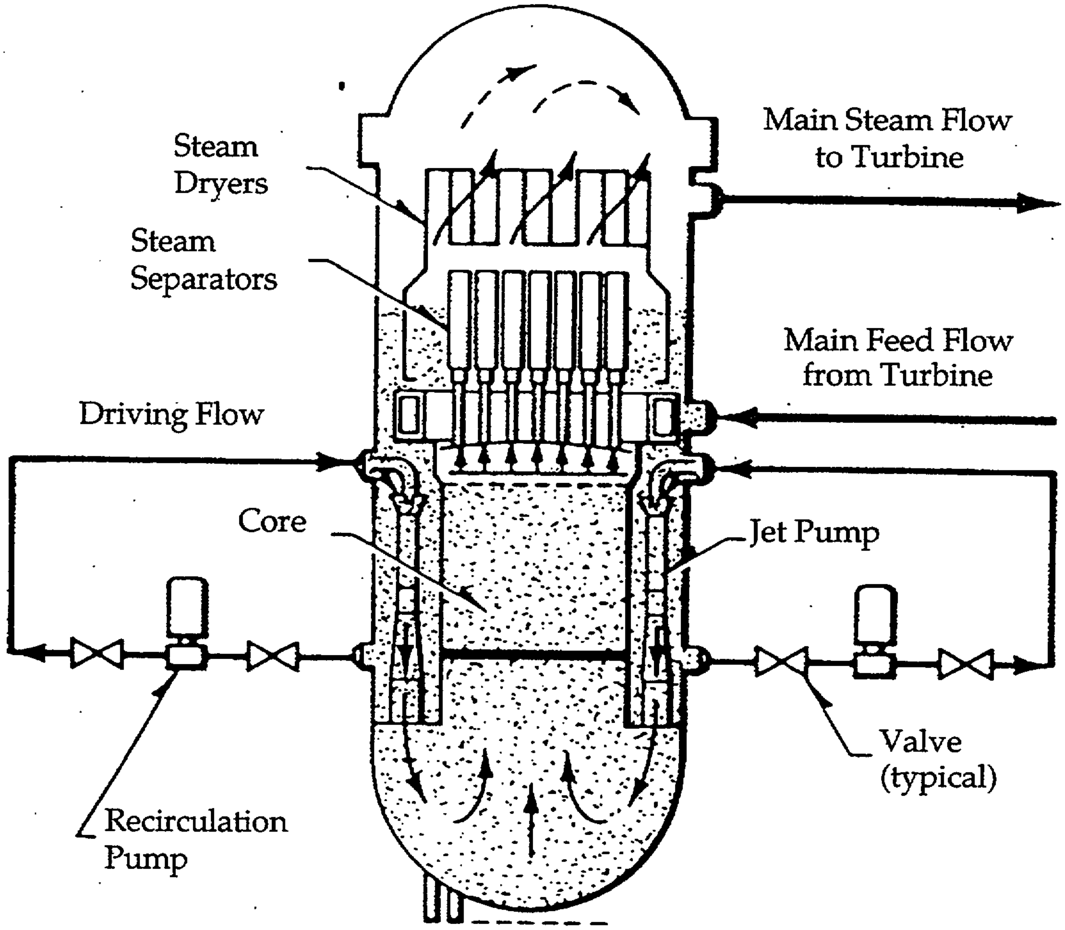

Fig. 2-1. Steam and recirculation water flow paths in the BWR.

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 have been selected, the panel recognizes the desirability of extending the applicability of the PIRT 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 [BWR/2-/6], fuel arrays [8x8, 9x8, 10x10], cladding types from other reactor vendors [Ge, Siemens], and burnup to 75 GWd/t.

### 2.2. Description of Fuel and Cladding State at High Burnup

During irradiation, the fuel and cladding experience changes in geometry, material macrostructure and microstructure, mechanical properties, and other physical and performance characteristics. It is considered that some of these changes could possibly affect the fuel rod's ability to maintain its integrity when subjected to an accident. Figure 2-2 presents a qualitative characterization of some of these fuel and cladding changes. These changes, which occur generally gradually over the life of the fuel rod, can represent initial conditions for the accident.

Of the many changes experienced by the fuel and cladding, it is important to discern which of these are of greatest importance in determining fuel rod behavior during the power oscillations. Some of the more important phenomena are presented and discussed below, recognizing that the list may not be inclusive. The changes to the fuel and cladding indicated in Figure 2-2 are possible, and have been observed, in both pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types, although to varying extents. Recognizing that the power oscillations are a BWR event, the following discussion will attempt to clarify the applicability of the various phenomena as currently recognized in modern commercial BWR fuel.

#### 2.2.1. Cladding Changes

The cladding material applied in BWRs is Zircaloy-2, most predominately in the annealed, fully recrystallized condition with a zirconium-based inner liner, although cold-worked stress relieved material and non-liner applications also exist. The zirconium liner can contain varying amounts of alloy additions, intended for post-defect corrosion resistance. The primary change mechanisms identified for the cladding are waterside corrosion, hydriding, and radiation damage.

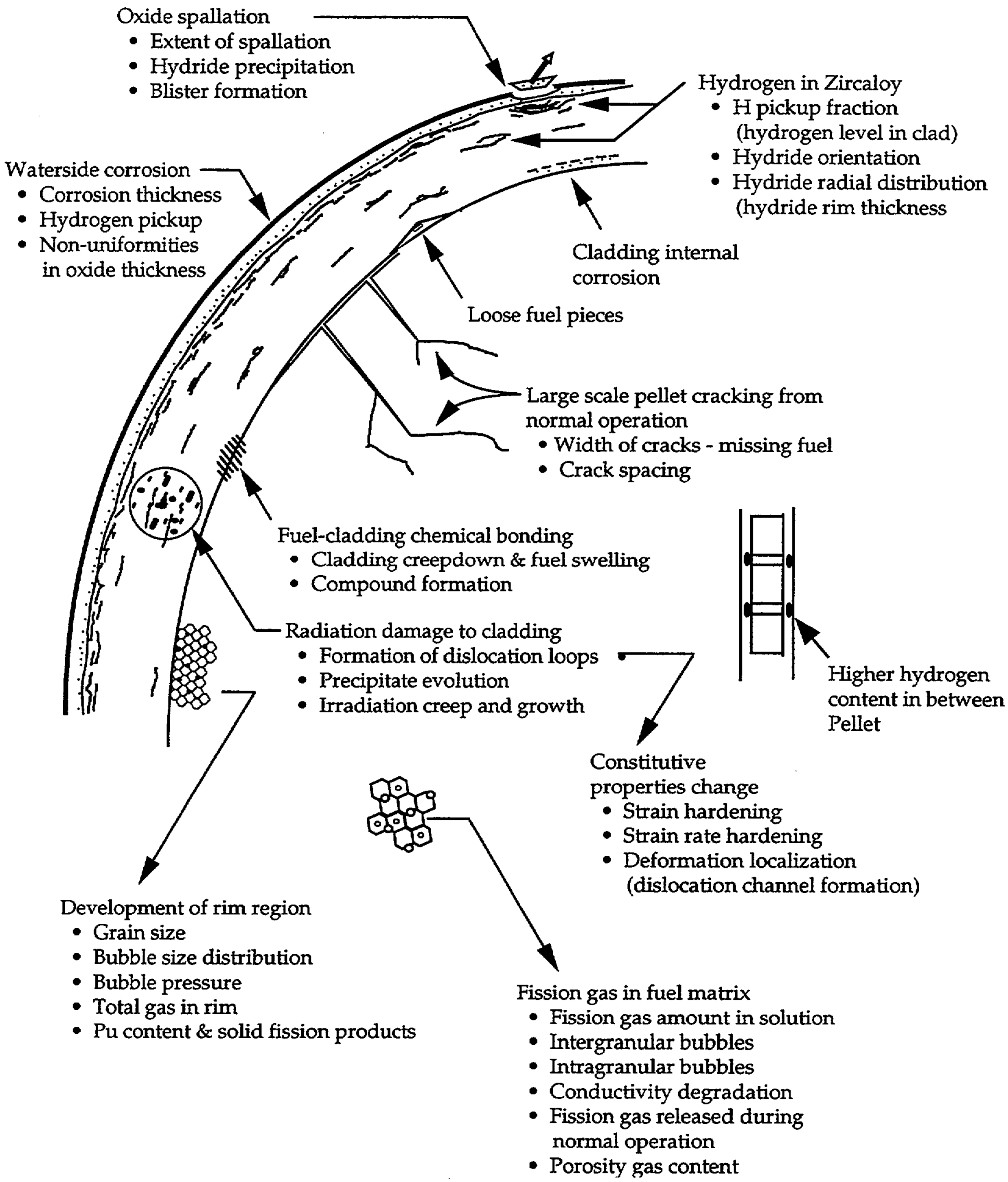

Fig. 2-2. Fuel and Cladding State

***Cladding corrosion*** occurs through direct exposure of the cladding outer surface to a high temperature, highly oxidizing environment enhanced by the radiation field. The effects of cladding corrosion are wall thinning, increased heat transfer resistance, and cladding hydrogen absorption. In general, the BWR suppliers have progressively refined the cladding material processing to minimize the occurrence of nodular corrosion, thereby resulting in a generally uniform corrosion morphology. Where cladding corrosion distributions are typically peaked at the higher elevations in PWRs, the corrosion distributions are generally more uniform along the fuel rod length in a BWR, with possible peaking at the lower elevations. Circumferential variations in cladding oxide layer thickness are observed in BWRs, but are generally minor in magnitude. Where cladding corrosion thicknesses up to or greater than 100 μm has been observed in PWRs, BWR cladding corrosion is significantly less, typically less than 50 μm at exposures up to ~62 GWd/t peak rod average exposure, as observed to date.

An important consideration is oxide layer cracking, delamination, and spalling. Oxide layer cracking and delamination can lead to an acceleration in the oxide layer growth rate. Spalled oxide regions result in a cooler cladding metal temperature during operation than exists under the adjacent unspalled oxide regions. The presence of such "cold spots" can promote redistribution of any hydrogen absorbed from the cladding outer surface corrosion process, thereby leading to hydride localizations and even bulk hydride formation (observable as bulges or blisters) in the outer region of the cladding. Such bulk hydride formation regions are highly embrittled and are often accompanied by partial cladding cracks even in the absence of applied loading by the fuel pellets (caused simply by the volume expansion associated with the conversion of zirconium to zirconium hydride). With modern cladding materials, significant accelerated corrosion and spalling is not typically observed in BWRs. This is in contrast to PWRs where accelerated corrosion and spalling are seen.

Corrosion localizations have been observed at fuel assembly spacer locations, adjacent to Inconel components (typically referred to as "shadow corrosion"). Although accelerated localized corrosion, leading to fuel rod failure, has occurred at one BWR with an earlier cladding material type, in general, the available characterizations indicate that this localization develops relatively quickly, but then remains relatively stable, at least to exposure levels characterized to date (~62 GWd/t peak rod average exposure).

BWRs operate with several water chemistry options: Hydrogen Water Chemistry, Zinc Injection, and Noble Metal Chemical Addition. To date, no unacceptable changes in the cladding corrosion performance have been observed under these water chemistry options.

In summary, in BWRs with modern cladding, the primary effects of interest from the corrosion process are (1) wall thinning, (2) increased heat transfer resistance, and (3) the effects of corresponding hydrogen pickup.

***Hydriding*** occurs as hydrogen, liberated by the cladding outer surface corrosion process, is absorbed into the cladding. Typically, less than 20% of the hydrogen generated by the corrosion reaction is absorbed by the cladding. This absorbed hydrogen generally precipitates as circumferentially oriented zirconium hydride stringers when the amount of absorbed hydrogen exceeds the solubility level. Available testing has demonstrated no adverse influence of hydrogen on elevated temperature irradiated Zircaloy ductility (total elongation) for hydrogen contents up to at least 850 ppm(2-2). At higher hydrogen levels, something in excess of 1000 ppm, the cladding ductility can be reduced at operating temperatures. Most typically, BWR cladding hydrogen content is <200 ppm, as characterized at ~50 GWd/t rod average exposure for modern BWR cladding materials. Although higher levels (less than 600 ppm) have been observed in older cladding types at elevated exposures (up to ~65 GWd/t rod average exposure), even this level is below that required to significantly affect the cladding mechanical properties.

BWR fuel typically demonstrates relatively low hydrogen concentration. As a result, dense hydride rims or extreme hydride localization at pellet-pellet interfaces do not occur. However, a tendancy for hydride accumulations toward the cladding outer surface or near pellet-pellet interfaces has been seen. This is in contrast to PWRs where much higher hydride concentrations are observed.

In summary, in BWRs with modern cladding, the primary considerations with cladding hydrogen content are (1) the impact, if any, on the cladding mechanical properties, and (2) the effect of hydride localizations to form weak, damage-susceptible regions. In general, these considerations have not been found to be significant for the hydrogen contents observed in modern BWR cladding to date.

***Radiation Damage*** to the cladding material occurs as a direct consequence of exposure to fast neutrons. This radiation damage is manifested as radiation-induced dislocation loops, both <a> and <c> type that form from the agglomeration of point defects. Although the overall <a> dislocation density saturates very early in life, the <c> type dislocations evolve over a more extended period of time. The effect of this damage is a strengthening of the material, with a corresponding reduction in ductility, and increased irradiation-induced stress-free growth (occurs in the absence of an applied stress). Additionally, microchemical changes occur as the irradiation induces intermetallic precipitate amorphization and dissolution, which can alter the mechanical properties, corrosion resistance and possibly also the hydrogen pickup of the cladding material.

In addition to irradiation-induced growth of the cladding material, irradiation also induces cladding creep in response to the applied fuel rod internal-external pressure difference and pellet expansion loadings.

In summary, the primary considerations relative to cladding radiation damage are (1) radiation hardening and the corresponding mechanical properties impact, and (2) deformation caused by irradiation-induced growth and creep.

### 2.2.2 Fuel Changes

***Fission Products.*** During normal operation, solid and gaseous fission products are generated within the $UO_2$ fuel pellet. The solid fission products generally remain at the birthsite and result in progressive swelling of the fuel material with irradiation exposure. Gaseous fission products are more mobile and distribute largely into five separate inventories: (1) gas dissolved in the $UO_2$ matrix, (2) gas in intragranular (matrix) bubbles, (3) gas in intergranular (on grain boundaries) bubbles (4) gas released to the fuel rod void volume and (5) gas in fuel porosity. The amount of gas dissolved in the $UO_2$ matrix is limited by the solubility in $UO_2$. Gaseous fission product inventories (3), and to a lesser extent (2) and (5), under high temperature low restraint conditions, can also result in fuel swelling with consequent pellet-cladding contact. Inventory (6) is referred to as fission gas release (FGR) and produces an increase in the fuel rod internal pressure and corresponding cladding loading. The exact partitioning of the fission gases among the identified inventories is dependent primarily on the fuel pellet microstructure and thermal operating history.

***Rim Formation.*** As a result of Uranium-238 resonance neutron capture at the $UO_2$ pellet periphery, the amount of plutonium formed in the fuel pellet is greater at the pellet periphery than in the center. This plutonium buildup causes a significant increase in the fission rate at the pellet periphery, relative to the fission rate in the bulk of the pellet. At elevated exposures, the result of this elevated fission rate is to produce a highly porous, fine grained structure. This altered structure region is called the **rim region.** The size of the rim region increases relatively progressively with increased exposure above ~40-45 GWd/t pellet average exposure. The primary considerations with the formation of the rim region are (1) possible increased fission gas release, (2) possible increased resistance to heat transfer, and (3) possible increased gaseous swelling under high rim temperature conditions. It is noted that the pellet rim may provide a cushion, or lubricating, effect that may reduce the consequences of pellet-cladding mechanical interaction.

***Fuel restructuring and macrocracking.*** During the initial rise to power, the thermal stresses caused by the pellet radial temperature gradient cause the pellet to crack (primarily radially). With the release of strain energy, the cracked pellet segments relocate outwards toward the cladding (called fuel relocation or restructuring). With continued irradiation, additional outward movement of the pellet segments can occur. At approximately mid-life exposures, the combined effects of pellet relocation, fuel irradiation swelling, and cladding creepdown result in a closed pellet-cladding gap. From this point, (1) a reduction in the fuel pellet expansion (such as caused by a power decrease) can result in partial gap opening, and (2) additional fuel expansion (by progressive fuel swelling or as a result of a power increase) can cause pellet radial cracks to (partially) close, thereby increasing the effective pellet stiffness, and imposing loading and deformation of the cladding. No particular change in this behavior is expected at elevated exposures.

***Microcracking.*** During a reactivity pulse where the pellet rim can experience significant heatup, and in the absence of significant constraint provided by the cladding, gas bubble expansion at the grain boundaries (most notably at the pellet rim) could lead to grain boundary cracking (decohesion). The result would be a release of fission gases to the fuel rod void volume with an increase in the fuel rod internal pressure and applied cladding pressure loading, with a subsequent reduction in the local pellet expansion. In the presence of significant cladding constraint, gas bubble expansion would be suppressed with a corresponding reactive increased loading of the cladding, likely with no significant fission gas release until release of the applied hydrostatic stress such as would occur on cooling. Additional pellet cracking can also occur on cooling, resulting in additional fission gas release, but correspondingly also reducing the gaseous swelling potential for the next heatup cycle.

***Pellet-Cladding Interface.*** With the onset of pellet-cladding contact, a bond layer develops between the fuel pellet and the cladding. At elevated exposure, the magnitude (bond layer thickness) and extent (circumferential and axial surface coverage) increases. The development of this bond layer affects the ability of the pellet and cladding to move independently (effective friction), and thereby affects load transfer from the pellet to the cladding and the subsequent cladding stress state. The bond layer can fracture during cooldown or power reductions, leading to an intermediate state.

### 2.3. Accident Scenario

The transient selected as the basis for the reactivity-related BWR PIRT is a trip of both recirculation pumps with a failure to scram. This event is suggested by the recirculation pump trip event at LaSalle-2 nuclear power station in March 9, 1988. Following the initiating event, the plant experienced power and flow oscillations. These high amplitude power oscillations continued for about four minutes until an automatic scram (trip) occurred because of high neutron power, i.e., detection of a power level of 118% on the average power range monitor.

The selected accident scenario closely, but not exactly, follows the LaSalle-2 event. These conditions were established for a BWR stability analysis performed with the Brookhaven National Laboratory Engineering Plant Analyzer.[2-3] The detailed results presented in Section 2.3.1 are from Ref. 2-3.

At the time the initiating event occurs, the plant is assumed to be at 84.2% of full power (2808 MWt). The system pressure is 6.878 MPa (1007.5 psia), and the core inlet flow is 75% of full flow (10,204 kg/s; $80.87\times10^6$ lbm/hr).

In Section 2.3.1, a description of the plant behavior following trip of both recirculation pumps with failure to scram is presented. Other than the kinetics element of the total plant behavior, the focus of the PIRT activity is on the fuel and cladding behavior. A detailed description of the BWR recirculation pump trip with failure to scram event focusing on the fuel and cladding behavior is presented in Section 2.3.2.

### 2.3.1. Plant Behavior

The event was initiated from the conditions described in Section 2.3. As described in Ref. 2-3, both recirculation pumps trip at time zero to initiate the event. With the loss of forced circulation, the core flow rapidly decreases from 75% to about 29% of normal full flow (Fig. 2-3). With the power near its operating level at event initiation and reduced core flow, vapor generation increases in the core (Fig. 2-4), negative reactivity is inserted due to the voiding (Fig. 2-5), and the reactor power drops rapidly from 84.2% to 40%. This flow and neutronic state exists by 0.5 min after event initiation. Shortly thereafter, i.e., about 0.8 min, a naturally circulating core flow at 29% of normal full flow has been established.

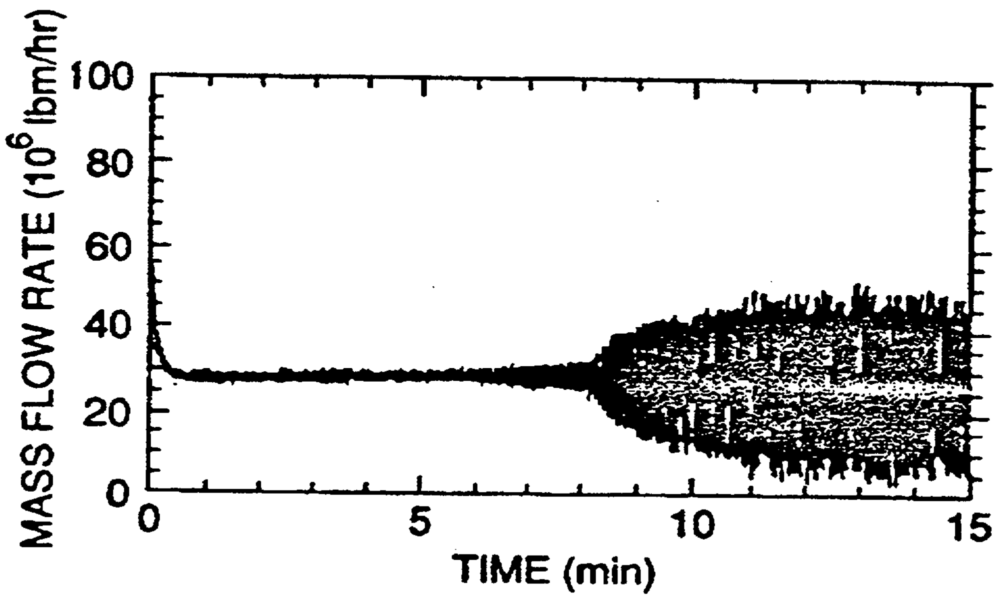

Fig. 2-3. Core-average inlet coolant flow rate.

Modulated core power oscillations begin about 5.5 min after event initiation (Fig. 2-6). Relative power is the power relative to nominal full power, hence, 1.0 is equivalent to 100% of nominal power. For the LaSalle simulation shown in the figure, 3335 MW is the nominal power. The relative average power is the running average of the relative power over a 60 s interval. Shortly thereafter, the power and flow oscillations begin to grow rapidly. By 7.0 min after event initiation, a power level of 118% is reached and the reactor trip signal that would normally occur is assumed to fail. Nine minutes after recirculation pump trip, the oscillation reaches its maximum of 1,300%. By 12 min, the power oscillations have attained a limit cycle.

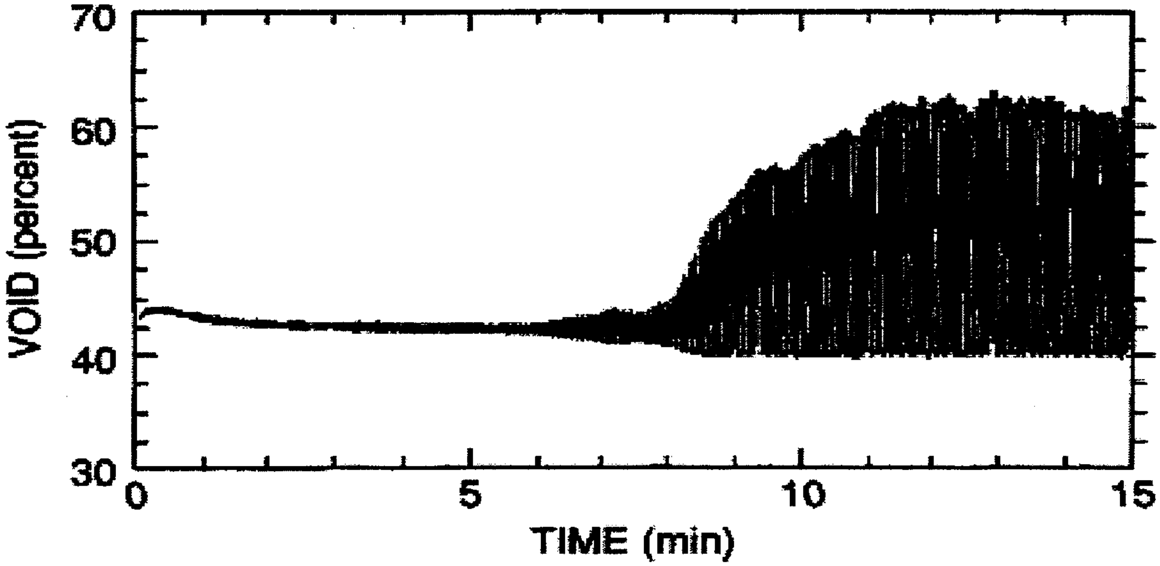

Fig. 2-4. Core-average void fraction.

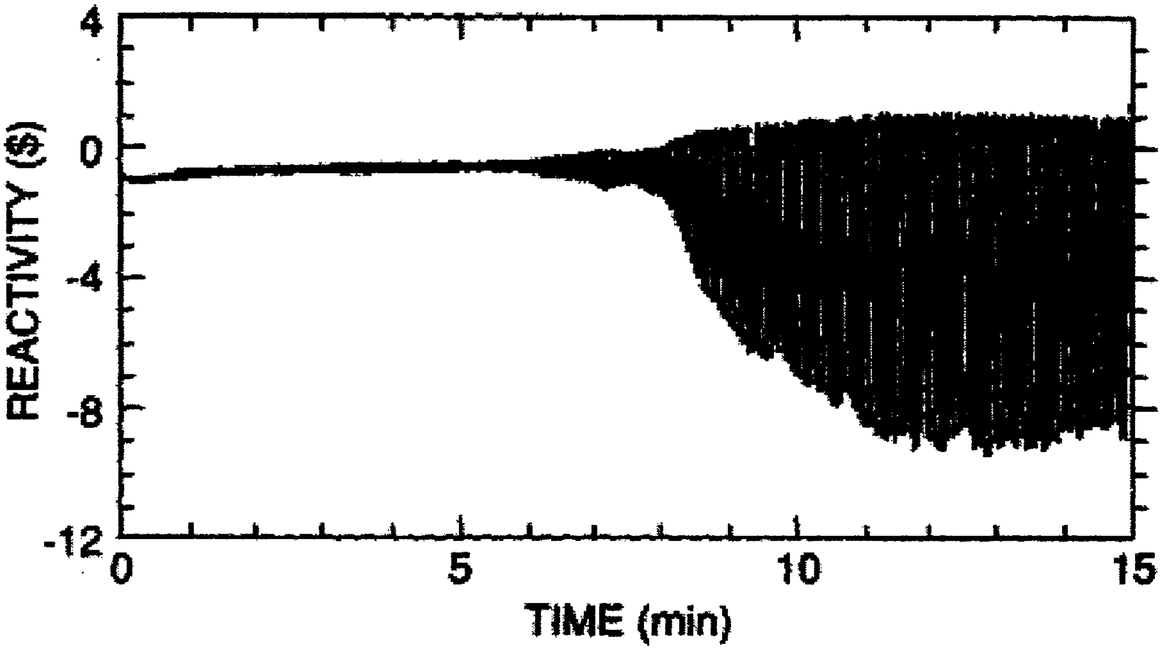

Fig. 2-5. Void reactivity.

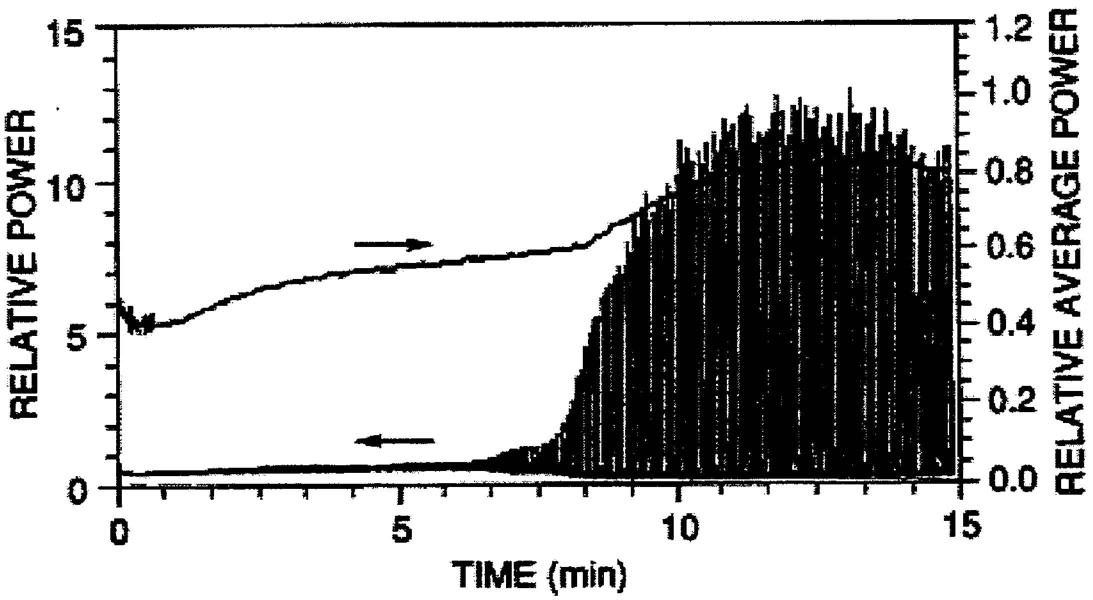

Fig. 2-6. Core relative and relative average power.

From the time when the oscillations begin until the limit cycle is attained, the fuel centerline and cladding surface temperature increase (Fig. 2-7). During this period,

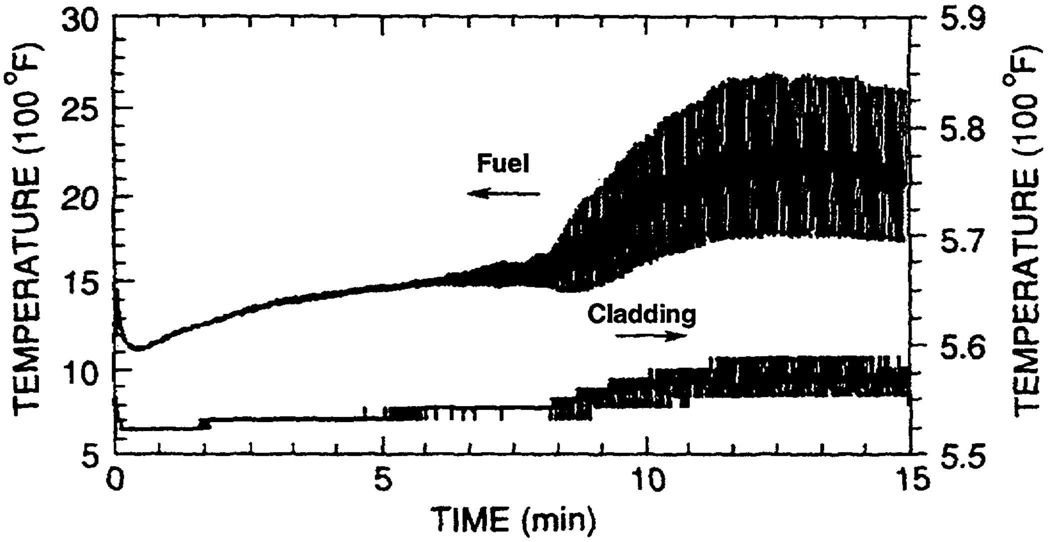

Fig. 2-7. Fuel centerline and cladding surface temperature (0.5-m axial location).

The fuel centerline temperature increases from 927 °C (1700 °F) to 1480 °C (2696 °F); the cladding temperature experiences only a small increase from 290 °C (554°F) to 296 °C (564 °F).

The analysis producing these temperature results did not include an extended period of cladding dryout. Should an extended period of dryout occur, some portions of the core would experience significantly higher temperatures and fuel expansion, fission gas release, and melting could induce cladding ballooning, oxidation, pellet-cladding mechanical interaction and failure.

High burnup assemblies are normally shuffled to the outer periphery of the core where the fission power is much lower than in the center of the core where low burnup fuel resides. Should boiling transition occur, it is expected to occur in the regions of the core fueled by low burnup fuel. High burnup fuels are unlikely to experience boiling transition.

Beginning at 12 minutes, automatic and operator actions are taken that cause soluble boron to be delivered to the core; the core power decreases to decay heat level by approximately 20 minutes after event initiation.

### 2.3.2. Fuel and Cladding Behavior during Power Oscillations Without Scram

The processes that occur during BWR power oscillations with failure to scram and that may result in cladding failure are illustrated in Fig. 2-8. Phenomena discussed in this section and appearing in Fig. 2-8 appear in **bold type**.

The BWR event scenario includes reactivity insertions occurring in rapid succession, with the behavior characterized by the following elements: (1) the magnitude of the reactivity insertions is small, (2) the pulse width is wide (typically 300 ms), (3) the time between pulses is small relative to the fuel thermal time constant, (4) compensating power reductions of similar magnitude also occur, and (5) the event is initiated from ~40 % power so that an established temperature profile exists that is significant in magnitude to the thermal energy added by the power oscillations. The result is not a large temperature excursion, or series of excursions, but instead a progressive increase in temperature, where the fuel thermal time constant effectively mitigates the power oscillations to produce a temperature history that could be simulated by a single, more gradual power increase.

In order to gain additional perspective regarding BWR fuel behavior during a power oscillation event with failure to scram, a comparison is made to a PWR rod ejection-type event. The following discussion describes the similarities and differences between these two events and corresponding fuel performance.

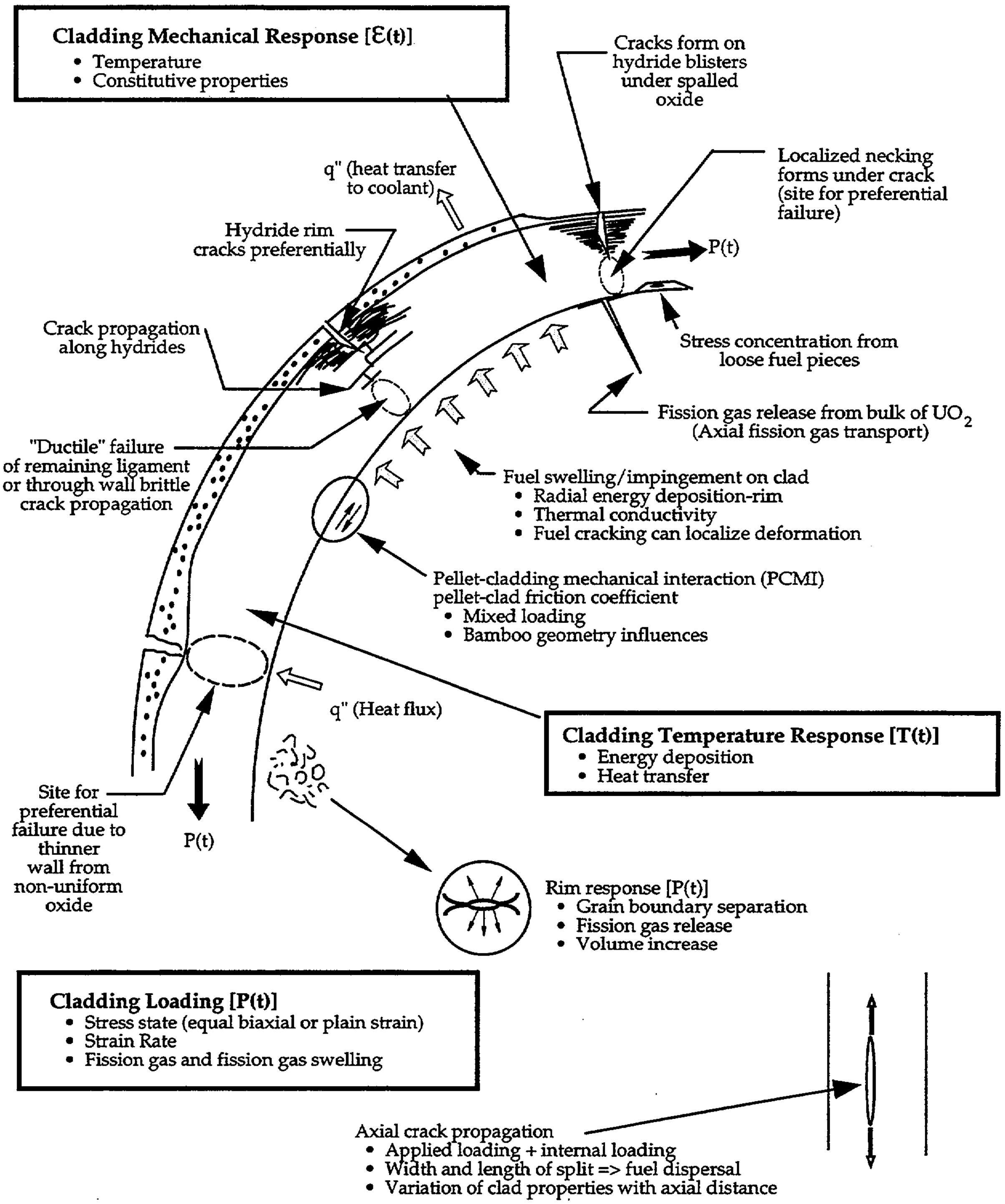

Fig. 2-8. Phenomena during an accident leading to cladding failure.

Initially, for the BWR event, the reactor is operating at full power. With the initiation of the event, the coolant pumps trip, and the reactor power is rapidly reduced to ~40 % of rated power. The effect of this power reduction is to reduce fuel temperatures and correspondingly increase the pellet-cladding gap through fuel thermal contraction. The reactor power then begins to oscillate, with essentially zero net added power (the average reactor power over the oscillation period remains ~40 % of rated power). The power oscillations, however, occur sufficiently quickly relative to the fuel thermal time constant, that sufficient time does not exist between power increases to permit the fuel to transfer all of the energy to the coolant since the last power increase, so that the fuel temperature gradually rises. A qualitative plot of cladding temperature response to this transient is shown in Fig. 2-9.

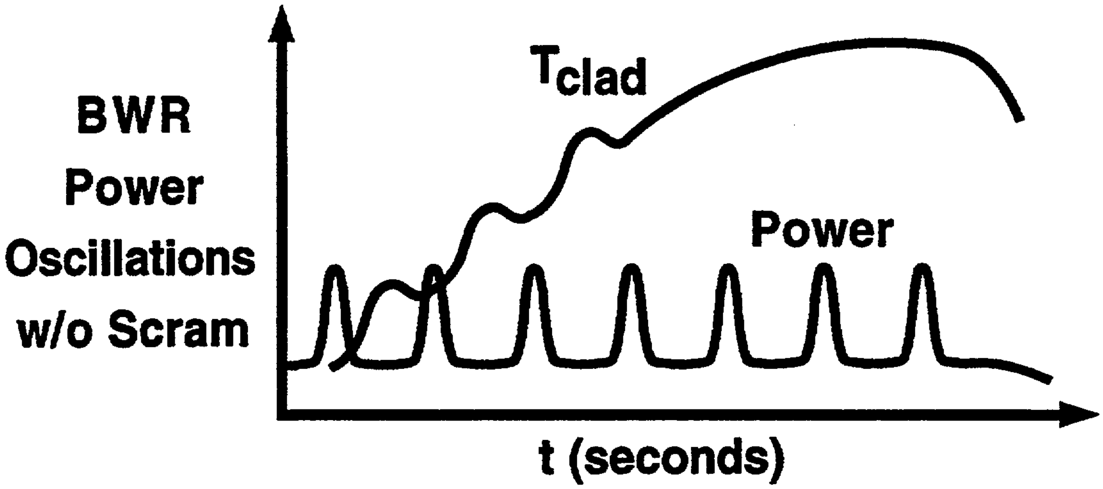

Fig. 2-9. Cladding temperature response to BWR power oscillations without scram.

In the BWR event, a parabolic radial temperature distribution exists at the 40% rated power condition. With this established temperature profile, the power pulses result in modest changes in the existing parabolic temperature distribution. The pellet rim does not experience a significant temperature increase, and does not approach the pellet centerline temperature. As a result, pellet thermal expansion occurs relatively slowly and **pellet rim gaseous swelling** occurs to either a small extent or not at all.

With the fuel temperature increase that occurs during the BWR power oscillations, fuel thermal expansion increases and the pellet-cladding gap begins to close. At some time during the event, the fuel temperature increase could be sufficient to overcome the net thermal contraction that occurred during the power reduction to the 40% rated power condition, so that **pellet-cladding contact** could occur leading to increased cladding stresses and deformation.

To the extent that the fuel thermal expansion is not sufficient to close the gap and develop pellet-cladding contact, then also, fuel temperatures have not sufficiently increased beyond the prior steady-state full power condition and significant **additional fission gas release** will not occur. To the extent that fuel thermal expansion is sufficient to close the gap and develop pellet-cladding contact, and sufficient cladding restraint remains (for example, the cladding has not entered boiling transition so that cladding temperatures have not elevated to the point of significantly reducing the cladding effective strength), then a hydrostatic stress is developed within the fuel and significant fission gas release will not occur until that stress is relieved (such as would occur through subsequent cooldown). To the extent that the cladding does enter boiling transition and elevated cladding temperatures develop, additional fission gas release may occur depending on the absolute temperature and time at temperature. With additional fission gas release, the fuel rod internal pressure increases and the cladding internal pressure loading increases. It is noted that the fuel most likely to experience boiling transition during the power oscillation event is the lower exposure fuel that is less likely to exhibit an overpressure condition (fuel rod internal pressure greater than the coolant system pressure). Therefore, the pressure increase due to fission gas release in this case would be favorable since it will not lead to cladding ballooning, but will instead impede cladding collapse onto the fuel column.

At sufficiently high temperatures, for example as the fuel approaches melting temperatures, and under elevated temperature and low constraint conditions provided by the cladding, gaseous swelling may occur in the higher temperature regions of the fuel and, in conjunction with the volumetric expansion of the fuel as it melts, may lead to additional cladding deformation (as well as increased fission gas release). With further heatup, cladding melting may occur.

In summary, the primary cladding loading, P(t), occurs through normal fuel pellet thermal expansion, with little, or no, contribution from pellet rim (or otherwise) gaseous swelling and fission gas release until very elevated fuel temperatures are produced (approaching fuel melting).

### 2.4. Primary Evaluation Criterion

The main concern in the case of BWR power oscillations without scram is that they might lead to a loss of core coolability. There are two main scenarios whereby this could happen:

1. Low-Temperature Failures. In this scenario, the cladding has low ductility and could fail by PCMI. Through-wall cracks could propagate and fuel particles could be dispersed, possibly resulting in a degraded coolable geometry and flow blockages that could degrade core cooling.

2. High Temperature Failures. In this scenario, the cladding survived the low temperature PCMI phase. However, in high power channels, the critical heat flux may be exceeded. The high cladding temperature may lead to oxidation, ballooning, rupture and fragmentation.

Given these scenarios, it is possible to associate the primary evaluation criterion with several significant physical phenomena associated with the sequence. These are:

A. Cladding failure

B. Fuel dispersal leading to flow blockages

C. Channel blockage leading to loss of geometry

The panel further concluded that in the low-temperature failure scenario, core coolability can be ensured by either: (a) accepting cladding failure as a possibility, and ensuring that any accumulation of dispersed fuel does not lead to channel blockage or (b) ensuring that the cladding does not fail in a severe manner with attendant fuel dispersal. Approach (a) would require knowledge of the type of failure, the complex fuel-coolant interactions that would create a particular size distribution of fuel particles, and the subsequent interaction of the fuel particles with the grid spacers to create channel blockage. Conducting the needed experiments and developing and certifying analytical tools for approach (a) was thought to be an extremely challenging undertaking. It was felt that the regulatory burden would be more easily met using approach (b), because experiments and analytical tools could focus on fuel-rod behavior, with particular emphasis on cladding behavior. The primary evaluation criterion was thus chosen to be "cladding failure with significant fuel failure."

Regarding the high temperature failure scenario, the prevailing opinion of the panel members was that the fuel behavior would be similar to that during a LOCA, which is addressed in the companion LOCA PIRT document.[2-4] Moreover, the scenario is believed to be relevant for fuel with low to medium burnup only.

### 2.5. Categories of Phenomena

The panel recognized that, in order to resolve reactivity-accident issue by avoiding severe cladding failure, 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). It was also recognized that, contrary to other PIRT exercises, this list contained many initial conditions that were relevant to the testing or to the behavior of the fuel in case of an accident. For this case, uncertainties reflect only our state of knowledge about the characterization of the parameter, and thus were not voted on by the panel.

The four PIRT categories are as follows:

A. 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.

B. Integral Tests category includes the phenomena related to the integral testing of fuel rods, such as performed at Halden and NSRR. 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 and SCANAIR.

D. Separate Effect Tests category includes the important phenomena relevant to high- and low-temperature cladding mechanical properties,

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:

Category A: Plant Transient Analysis

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

Category B: Integral Testing

Low temperature failures: If an integral test were to be conducted to investigate low temperature PCMI fuel behavior during BWR power oscillations, is this phenomenon of high, medium, or low importance?

High temperature failures: If we were to conduct an integral in-pile or out-of-pile test to evaluate the effect of power and flow oscillations on transient critical heat flux (CHF) and the rewet temperature ($T_{rewet}$) for the BWR power oscillations, 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 a separate test were to be conducted to investigate low temperature PCMI fuel behavior during a BWR power oscillations, is this phenomenon of high, medium, or low importance?

## 2.6. Phenomena 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 failure with significant fuel failure, 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 16 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, a 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 a 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" 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 either a different fuel array, specifically 8x8, 9x9, or 10x10, 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., BWR/2 – BWR/6, designated (R), and extended burnup to 75 GWd/t. 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. S. B. Wisner, R. B. Adamson, "Combined Effects of Radiation Damage and Hydrides on the Ductility of Zircaloy-2", *Nuclear Engineering and Design* **185** 33-49 (1998).

2-3. W. Wulff, H. S. Cheng, A. N. Mallen, and U. S. Rohatgi, "BWR Stability Analysis with the BNL Engineering Plant Analyzer," Brookhaven National Laboratory document NUREG/CR-5816 (October 1992).

2-4. B. E. Boyack et al., "Phenomena Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6744 (September 2001).

# 3. BWR POWER OSCILLATION WITHOUT SCRAM PIRTS

Four PIRT tables are presented in this section, one each for Plant Transient Analysis, Integral Tests, Fuel Rod Transient Analysis, and Separate Effect Tests. The PIRT has been developed for a BWR power oscillation without scram event in the LaSalle-2 nuclear power station assuming the core contains high burnup, Zircaloy-clad, $UO_2$ fuel. The event is initiated by a recirculation pump trip. 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 failure with significant fuel failure caused by power oscillations without scram. 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 that are presented in this section primarily address low-temperature PCMI failure, and this is especially true for Categories A and C. From further discussions, the prevailing opinion of the panel members was 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 by panel members that high-temperature behavior would be addressed only once, and the results would be recorded in the section of the companion NUREG LOCA report for high burnup fuel.[3-2]

It is useful to contrast the panel's deliberations in the BWR power oscillations without scram case to those in the PWR rod ejection accident case. In either case, fuel failure can occur at either low or high temperature. The low temperature failures in the case of BWR power oscillations without scram occur by a similar mechanism to that which occurs during a rod ejection accident. The differences are mainly that (1) the rate of reactivity insertion is much smaller during BWR power oscillations without scram, (2) the overall deposited energy is much less, (3) the reactivity insertion is cyclic with a frequency determined by the thermal-hydraulic and neutronic response, and (4) the BWR cladding is typically less oxidized and hydrided than PWR cladding. Because of these factors, the panel's overall evaluation is that low temperature failures are much less likely during BWR power oscillations without scram than during a PWR rod ejection accident.

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 and the transient thermal analysis of the fuel rod, that are deemed relevant for understanding and predicting fuel behavior during BWR power oscillations without scram. The PIRT for Plant Transient Analysis is provided in Table 3-1. This PIRT examines the phenomena that impact the calculation of power history during the power oscillations without scram and the calculation of fuel enthalpy increase during the event.

### 3.1.2. Category B: Integral Testing

The Integral Testing category includes phenomena related to the testing of fuel rods in a test reactor such as NSRR or Halden or in an electrically heated facility. For the BWR power oscillations, this category is further subdivided into two parts. The first part is for integral tests that focus on low-temperature failures. These tests focus on the low temperature PCMI fuel behavior. The second part is for integral tests that focus on high-temperature behavior -- in particular on the effect of power and flow oscillations, transient critical heat flux (CHF), and the rewet temperature ($T_{rewet}$).

This subcategory is further divided into fuel rod selection and conduct of the test. Fuel rod selection includes the initial conditions that are thought 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 parameters to be measured) that the panel deemed important for the integral tests. The PIRTs for low-temperature and high-temperature integral tests are provided in Tables 3-2 and 3-3, respectively.

### 3.1.3. Category C: Fuel Rod Transient Analysis

The Transient Fuel Rod Analysis category includes the phenomena and outcomes transient fuel rod behavior calculations that predict the fuel behavior in reactor integral tests and in separate effect tests. These calculations are performed with codes such as FRAPTRAN, FALCON and SCANAIR.(See Section 4 and Appendix F of 3-1). This category is divided into seven subcategories that may require modeling in the codes. The first subcategory (initial conditions) captures the characteristics of the fuel and cladding before the transient. The remaining six subcategories (mechanical loading to the cladding, fuel and cladding temperature changes, cladding deformation, pellet deformation mechanisms, forcing functions, and multiple fuel rod and coolant channel interactions) simulate the loading, and the thermal, mechanical response of the fuel and cladding that need to be modeled by the code to assess fuel failure during power oscillations without scram. The PIRT for Transient Fuel Rod Analysis is provided in Table 3-4. Phenomena specifically related to high-temperature ballooning, bursting, and oxidation are discussed and ranked in the companion NUREG LOCA report for high burnup fuel.[3-2]

### 3.1.4. Category D: Separate Effect Testing

The Separate Effect Testing category includes phenomena related to testing for the mechanical properties of high burnup BWR cladding. The category is divided into subcategories, specimen selection and conduct of the test. Specimen selection refers to the selection of reactor-exposed samples for mechanical testing. The test conditions subcategory refers to test parameters that are deemed to be of importance to the test outcome. The PIRT for Separate Effect Testing is provided in Table 3-5. This PIRT examines the phenomena that impact the selection and testing of specimens for mechanical properties measurement. Separate effect tests and phenomena specifically related to high temperature ballooning, bursting, and oxidation are discussed and ranked in the companion NUREG LOCA report for high burnup fuel.[3-2]

We note that separate effect tests on fuel pellet performance should also be considered in constructing experimental research programs. The fact that they are not included here does not imply that the panel believes they are unimportant.

### 3.2. Structure of the PIRT Tables

The structure of each PIRT-results table is as follows:

- 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 that is being ranked;

- Column 3 — Phenomenon importance rank 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 a given phenomenon varies, as discussed in Section 2.5. The ranking scale is described in Section 2.6. The importance ranking (IR) is also tabulated here and described below in Section 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.); and

- 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. See references in Section 2.7 for additional details. The knowledge ratio [KR] is also tabulated here and described below in Section 3.4.).

Some of the phenomena and vote entries in the PIRT tables have been entered in bold type. These phenomena are those that met the screening criteria for importance and uncertainty as described in Section 3.4.

### 3.3. Phenomena Descriptions and Ranking Rationales

Appendices A–D give in tabular form phenomena descriptions and ranking rationales. 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 analyzed 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 BWR power oscillations.

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 a "Medium" or "Partially Known" vote, and a value of 0.0 to a "Low" or "Unknown" vote.

The importance ratio (IR) is:

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

where H, M and L stand for the number of high, medium and low votes;

and the knowledge ratio (KR) is:

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

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 be 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 adequately identifies those phenomena that are, at the same time, both most important and highly uncertain due to a significant lack of knowledge.

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 the phenomena that are near to but not meeting the screening criteria.

### 3.4.1. Category A: Plant Transient Analysis

This category consists of four subcategories, (1) calculation of power history during the event, (2) calculation of pin fuel enthalpy increase during the event, (3) calculation of fuel to coolant heat transfer, and (4) calculation of core and system hydraulics."

We should note that, contrary to the practice elsewhere in the PIRT document, the importance of the phenomena in this section have been considered in an "absolute" sense rather than specifically at high burnup. That is, the phenomena were not necessarily dependent upon burnup and should be modeled any BWR oscillation event.

Within the "Calculation of power history during the event" subcategory, moderator feedback, fuel temperature feedback, and fuel cycle design were judged as being of high importance by the panel, i.e., each has an IR greater than 75. However, no phenomenon judged as highly important had a corresponding knowledge ratio that was sufficiently low, i.e., KR less than 75, to flag it as a candidate for additional consideration.

Within the "Calculation of pin fuel enthalpy increase during event" subcategory, heat resistances, heat capacities, and pin peaking factors were judged as being of high importance by the panel. However, no phenomenon judged as highly important had a corresponding knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the "Calculation of fuel to coolant heat transfer" subcategory, subcooled boiling; nucleate boiling, bulk boiling, and forced convection vaporization; dryout; film boiling; and rewet were judged as being of importance by the panel. With the exception of the phenomenon "nucleate boiling, bulk boiling, and forced convection vaporization", each of the remaining four phenomena judged as highly important had a corresponding knowledge ratio that was sufficiently low, i.e., KR less than 75, to flag it as a candidate for additional consideration.

The "Calculation of core and system hydraulics" subcategory was further divided into phenomena occurring in the bypass, core, and downcomer regions of the reactor vessel. Bypass void fraction due to direct moderator heating was identified as highly important. Core void distribution, frictional pressure drop, form pressure drop, and flow blockage were judged as being of high importance by the panel. Downcomer condensation heat transfer and jet pump or internal pump loss were also identified as being highly important. Of the seven phenomena judged as being highly important, only two, bypass void fraction due to direct moderator heating and core flow blockage, were judged to have a knowledge ratio that was sufficiently low to warrant additional consideration. However, it is noted that the first, bypass void fraction due to direct moderator heating, still had a relatively high knowledge ratio. In contrast, the knowledge ratio for core flow blockage was quite low.

In summary, the panel identified six neutronic and twelve thermal-hydraulic phenomena of high importance. All highly important neutronic phenomena were judged by the panel to be well known while the knowledge ratio for six of the thermal-hydraulic phenomena were judged to be sufficiently low to warrant additional consideration.

### 3.4.2 Category B: Integral Testing

This category includes phenomena related to the testing of fuel rods in a test reactor such as NSRR or Halden or in an electrically heated facility. As discussed in Section 3.1.2, this category is further subdivided into two parts. The first part is for integral tests that focus on the phenomena of low-temperature failures as listed in Table 3-2. The second part is for integral tests that focus on the phenomena high-temperature failures as listed in Table 3-3.

The philosophy adopted by the panel for the deliberations concerning Category B (integral testing) for BWR power oscillations without scram was somewhat different from that adopted in the corresponding sections of the PWR rod ejection accident report. This is because, in contrast to the case for the PWR rod ejection accident case, there are currently no integral or separate effect experiments either ongoing or scheduled, to address fuel rod behavior during BWR power oscillations without scram. As a result, the panel engaged in a brainstorming session to generate possible experiments that could provide insight into the likelihood of fuel failures or possible loss of coolable geometry during a BWR power oscillations without scram event. The panel then ranked these "thought experiments" and provided a general evaluation of how these experiments should be conducted, what parameters should be varied, and what should be measured, *assuming that the experiments would be performed.* Given the conjectural nature of the experiments, it was felt that it would not be worthwhile to assess uncertainty of each parameter in the conduct of test subcategory because the uncertainties on whether such experiments should be conducted in the first place is much greater.

The panel identified many parameters that should be measured in an integral test to aid in the interpretation of the test, to develop mechanistic understanding of the failure process, and to characterize fuel dispersal should it occur. Both the low temperature and high temperature phases are subdivided into two subcategories, "Fuel rod selection" and "Conduct of the test." The panel did not assess uncertainty for the "Fuel rod selection" subcategory for the "Low Temperature Phase" (see below) because it was felt that once a fuel rod was selected its properties could be characterized to a high degree of certainty.

### Low Temperature Phase

The first subcategory focuses on pretest characteristics of the fuel rod associated with the fuel rod selection process, i.e., fuel or cladding, which can affect the test outcome. The second category focuses on the conduct of the test in two areas: specimen design and phenomena occurring "during the test".

For the fuel rod selection subcategory, one fuel-condition characteristic (burnup) was judged by the panel as being of high importance. Five cladding-related characteristics were also judged by the panel as being of high importance. They are: type of oxidation, extent of oxide spalling and hydride blisters, cladding type (liner/non-liner), amount of hydrogen, and integrity.

For the conduct of test subcategory, none of the specimen-design characteristics were judged by the panel as being of high importance. However, three specimen-design characteristics (length, attachments, and constraints) had marginal importance ratios of 70%. Nine phenomena occurring during the test were judged by the panel as being of high importance. They are: fuel enthalpy increase, total number of pulses, power drop, pressure pulse measurement on-line, fission product measurement on-line, cladding deformation measurement on-line, time and location of failure, cladding temperature, and cladding elongation.

From the above panel findings, the following can be summarized regarding integral testing for the low temperature phase of BWR power oscillations without scram:

1. Those phenomena that most directly characterize high burnup fuel (e.g., burnup, cladding type and integrity, amount of hydrogen and hydride blisters, and oxide spalling) are the most important factors to be considered in selecting fuel rods for testing.
2. Phenomena that directly characterize the oscillatory phenomena associated with the BWR event should be simulated and measured during integral testing.
3. To the extent feasible, instrumentation should be incorporated and measurements taken that characterize the processes and phenomena occurring during the test.

Here, as well as in ranking the phenomena listed in Category D, the panel emphasized the importance of testing material that is certified to be without flaws.

### High Temperature Phase

The subcategory construct for the high temperature phase is identical to that for the low temperature phase but the phenomena identified for this phase are not identical.

For the fuel rod selection subcategory, one phenomenon, thermal inertia, was judged by the panel as being of high importance.

For the conduct of test subcategory, five of the specimen-design characteristics were judged by the panel as being of high importance. They are: length, grid and constraints, attachments, single rod versus bundle, and channel boundary conditions. Ten phenomena occurring during the test were judged by the panel as being of high importance. They are: flow oscillation characteristics, average power level, coolant heat transfer, steam quality, steam quality measurement, vapor temperature, measure vapor temperature, cladding temperature, DNB and rewet detection, and mass flow rate.

From the above panel findings, the following can be summarized regarding integral testing for the high temperature phase of a BWR power oscillations without scram accident:

1. In contrast to the low temperature phase testing, fuel rod selection was judged to be of medium importance because these parameters have only a modest effect on heat transfer.
2. In contrast to the low temperature phase testing, specimen design was judged to be of high importance because it has a strong effect on coolant conditions and heat transfer.
3. To the extent feasible, instrumentation should be incorporated and measurements taken that characterize the processes and phenomena occurring during the test.

### 3.4.3. Category C: Transient Fuel Rod Analysis

This category includes phenomena related to testing for the mechanical properties of high burnup BWR cladding with respect to failures only at low temperatures. This may not be the most limiting set of conditions for BWR power oscillations, i.e., PCMI failures that would occur at high temperatures. This category consists of seven subcategories: initial conditions, mechanical loading to cladding, fuel and cladding temperature changes, cladding deformation, and pellet deformation mechanisms, forcing functions, and multiple fuel rod and coolant channel interactions.

Within the initial conditions subcategory, four entries were judged as being of high importance by the panel. They are: pellet and cladding dimensions, burnup distribution, power distribution, and thickness of oxide layer and surface condition. One of the subcategory entries, thickness of oxide layer and surface condition, had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the mechanical loading to cladding subcategory pellet thermal expansion, pellet-cladding contact (gap closure), and fission gas induced swelling were judged as being of high importance by the panel. Each of the three phenomena had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the fuel and cladding temperature changes subcategory, heat resistances in the fuel, gap, and cladding; transient cladding-to-coolant heat transfer coefficient; heat capacities of fuel and cladding; and transient oxidation and energy source were judged as being of high importance by the panel. With the exception of the heat capacities of fuel and cladding, each of the remaining subcategory entries had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the cladding deformation subcategory, stress versus strain response and cladding temperature were judged as being of high importance by the panel. Cladding temperature was also judged by the panel to have a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the pellet deformation mechanisms subcategory, the single entry of fracture stress, yield stress in compression, plastic deformation, grain boundary decohesion, pellet cracking, and evolution of pellet stress state was judged as being of high importance by the panel. It was also judged by the panel to have a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the forcing functions subcategory, both entries, transient power distribution and coolant conditions were judged to be highly important by the panel. They were also judged by the panel to have knowledge ratios that were sufficiently low to flag them as candidates for additional consideration.

Within the multiple fuel rod and coolant channel interactions subcategory, rod-to-channel interactions and rod and spacer grid interactions were judged by the panel to be of high importance. Rod-to-channel interactions was also judged by the panel as having a sufficiently low knowledge level to flag it for additional consideration.

### 3.4.4. Category D: Separate Effect Testing

This category includes phenomena related to testing for the mechanical properties of high burnup BWR cladding. It is important to have these tests to understand the results from the integral tests and to help explore the possible variations in parameters. The panel 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.

This category is divided into two subcategories, "Specimen selection" and "Test conditions." The first subcategory focuses on pretest characteristics of the test specimen. The second subcategory focuses on test design and operating conditions.

For the specimen selection subcategory, the extent of oxide spalling and related hydride blisters were judged by the panel as being of high importance if present, although they are unlikely to occur in BWRs. Hydride orientation was also found to be important.

For the test conditions subcategory, five test condition parameters were judged by the panel as being of high importance. They are: cladding integrity, stress state imposed on specimen, cycling conditions, tensile test specimen design, and burst specimen design.

## 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 Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel," US Nuclear Regulatory Commission document NUREG/CR-6744 (September 2001).

## Table 3-1. Category A. Plant Transient Analysis PIRT

| | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | H | M | L | IR | F | C | R | B | K | PK | UK | KR |
| Calculation of power history during event | Moderator feedback | 8 | 0 | 0 | 100 | N | N | N | N | 8 | 0 | 0 | 100 |
| | Fuel temperature feedback | 8 | 0 | 0 | 100 | N | N | N | N | 8 | 0 | 0 | 100 |
| | Delayed-neutron fraction | 2 | 4 | 0 | 67 | N | N | N | N | 7 | 0 | 0 | 100 |
| | Fuel cycle design | 6 | 0 | 0 | 100 | N | N | N | N | 7 | 0 | 0 | 100 |
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Heat resistances in high-burnup fuel, gap, and cladding (including oxide layer) | 8 | 0 | 0 | 100 | N | N | N | N | 8 | 0 | 0 | 100 |
| | Heat capacities of fuel and cladding | 8 | 0 | 0 | 100 | N | N | N | N | 8 | 0 | 0 | 100 |
| | Fractional energy deposition in pellet | 2 | 1 | 3 | 42 | N | N | N | N | 7 | 0 | 0 | 100 |
| | Pellet radial power distribution | 2 | 4 | 0 | 50 | N | N | N | Y | 5 | 1 | 0 | 92 |
| | Pin peaking factors | 6 | 1 | 0 | 93 | N | N | N | N | 6 | 1 | 0 | 93 |
| | Metal water reaction heat addition | 2 | 4 | 1 | 57 | N | N | N | N | 6 | 0 | 0 | 100 |
| Calculation of fuel to coolant heat transfer | Single-phase convection | 0 | 5 | 1 | 42 | N | N | N | N | 7 | 0 | 0 | 100 |
| | **Subcooled boiling** | 6 | 0 | 0 | 100 | N | N | N | N | 0 | 5 | 0 | 50 |
| | Nucleate boiling, bulk boiling, and forced convection vaporization | 4 | 1 | 0 | 90 | N | N | N | N | 4 | 1 | 0 | 90 |
| | **Dryout** | 6 | 0 | 0 | 100 | N | N | N | Y | 0 | 6 | 1 | 43 |
| | **Film boiling over a wide void fraction range** | 6 | 1 | 0 | 93 | N | N | N | N | 0 | 6 | 0 | 50 |
| | **Rewet** | 7 | 0 | 0 | 100 | N | N | N | N | 0 | 7 | 0 | 50 |

*Table continued on next page*

## Table 3-1. Category A. Plant Transient Analysis PIRT (continued)

| | | | Importance[**] | | | | Applicability[†,††] | | | | Uncertainty[§,§§] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | | **H** | **M** | **L** | **IR** | **F** | **C** | **R** | **B** | **K** | **PK** | **UK** | **KR** |
| Calculation of core and system hydraulics | Bypass: | Flow fraction | 2 | 3 | 3 | 44 | N | N | N | N | 4 | 3 | 0 | 79 |
| | | **Void fraction due to direct moderator heating** | **5** | **2** | **0** | **86** | **N** | **N** | **N** | **N** | **2** | **5** | **0** | **64** |
| | Core: | Void distribution including subcooled boiling | 7 | 2 | 0 | 89 | N | N | N | N | 5 | 2 | 0 | 86 |
| | | Frictional pressure drop | 6 | 2 | 0 | 88 | N | N | N | N | 7 | 0 | 0 | 100 |
| | | Form pressure drop | 7 | 0 | 0 | 100 | N | N | N | N | 4 | 3 | 0 | 79 |
| | | Acceleration pressure drop | 0 | 6 | 1 | 43 | N | N | N | N | 7 | 0 | 0 | 100 |
| | | Direct moderator heating | 3 | 3 | 1 | 64 | N | N | N | N | 7 | 0 | 0 | 100 |
| | | Counter current flow limitation | 1 | 4 | 0 | 60 | N | N | N | N | 3 | 1 | 0 | 88 |
| | | **Flow blockage** | **5** | **3** | **0** | **81** | **N** | **N** | **N** | **N** | **0** | **1** | **7** | **6** |
| | Downcomer: | Void distribution | 0 | 0 | 7 | 0 | N | N | N | N | 6 | 0 | 0 | 100 |
| | | Condensation heat transfer | 4 | 3 | 0 | 79 | N | N | N | N | 3 | 1 | 0 | 88 |
| | | Mixing and thermal stratification | 2 | 1 | 3 | 42 | N | N | N | N | 0 | 5 | 0 | 50 |
| | | Jet pump or internal pump loss | 6 | 0 | 0 | 100 | N | N | N | N | 6 | 0 | 0 | 100 |
| | | Friction and form loss | 0 | 0 | 7 | 0 | N | N | N | N | 6 | 1 | 0 | 93 |

*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; 9x9, or 10x10 rods in a fuel assembly..
C = Cladding types from various vendors, e.g., GE and Siemens.
R = Reactor type, e.g., 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 0.0%–25% of full knowledge and understanding.

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

## Table 3-2. Category B. Integral Testing PIRT – Low Temperature Phase

| | | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | | **H** | **M** | **L** | **IR** | **F** | **C** | **R** | **B** | **K** | **PK** | **UK** | **KR** |
| Fuel rod selection | Fuel condition | Burnup | 4 | 2 | 0 | 83 | N | N | N | N | NA | NA | NA | NA |
| | | Enrichment (initial) | 0 | 1 | 5 | 8 | N | N | N | N | NA | NA | NA | NA |
| | | Base irradiation conditions | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Rim size | 0 | 0 | 5 | 0 | N | N | N | N | NA | NA | NA | NA |
| | | Fission gas distribution | 0 | 1 | 5 | 8 | N | N | N | N | NA | NA | NA | NA |
| | | Grain size | 0 | 0 | 5 | 0 | N | N | N | N | NA | NA | NA | NA |
| | | Pellet type | 0 | 3 | 3 | 25 | N | N | N | N | NA | NA | NA | NA |
| | Cladding: | Amount of oxide | 3 | 2 | 1 | 67 | N | N | N | N | NA | NA | NA | NA |
| | | Type of oxidation | 3 | 3 | 0 | 75 | N | N | N | N | NA | NA | NA | NA |
| | | Extent of oxide spalling and hydride blisters | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Extent of oxide delamination | 0 | 2 | 2 | 25 | N | N | N | N | NA | NA | NA | NA |
| | | Type (liner/non-liner) | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Amount of Hydrogen | 4 | 2 | 0 | 83 | N | N | N | N | NA | NA | NA | NA |
| | | Hydrogen distribution | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Hydride orientation | 1 | 2 | 1 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Dimensions | 0 | 4 | 2 | 33 | N | N | N | N | NA | NA | NA | NA |
| | | Fluence | 0 | 0 | 6 | 0 | N | N | N | N | NA | NA | NA | NA |
| | | Integrity | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |

*Table continued on next page*

## Table 3-2. Category B. Integral Testing PIRT – Low Temperature Phase (continued)

| | | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | | **H** | **M** | **L** | **IR** | **F** | **C** | **R** | **B** | **K** | **PK** | **UK** | **KR** |
| Conduct of test | Specimen design: | Plenum volume | 0 | 4 | 1 | 40 | N | N | N | N | NA | NA | NA | NA |
| | | Internal pressure | 0 | 4 | 1 | 40 | N | N | N | N | NA | NA | NA | NA |
| | | Gas composition | 0 | 3 | 2 | 30 | N | N | N | N | NA | NA | NA | NA |
| | | Length | 2 | 3 | 0 | 70 | N | N | N | N | NA | NA | NA | NA |
| | | Attachments | 2 | 3 | 0 | 70 | N | N | N | N | NA | NA | NA | NA |
| | | Constraints | 2 | 3 | 0 | 70 | N | N | N | N | NA | NA | NA | NA |
| | | Single rod versus bundle | 0 | 1 | 4 | 10 | N | N | N | N | NA | NA | NA | NA |
| | During the test: | Pulse shape | 0 | 2 | 4 | 17 | N | N | N | N | NA | NA | NA | NA |
| | | Fuel enthalpy increase | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Pulse width | 0 | 5 | 1 | 42 | N | N | N | N | NA | NA | NA | NA |
| | | Pulse period | 0 | 1 | 4 | 10 | N | N | N | N | NA | NA | NA | NA |
| | | Total number of pulses | 5 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Pulse height variation | 2 | 2 | 2 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Power drop (baseline power for pulses) | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Initial precondition power level | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Axial power profile | 0 | 3 | 3 | 25 | N | N | N | N | NA | NA | NA | NA |
| | | Coolant heat transfer conditions (design) | 2 | 5 | 0 | 64 | N | N | N | N | NA | NA | NA | NA |
| | | Fuel dispersal measurement on-line | 1 | 4 | 1 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Pressure pulse measurement on-line | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Fission product measurement on-line | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Cladding deformation measurement on-line | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |

*Table continued on next page*

## Table 3-2. Category B. Integral Testing PIRT – Low Temperature Phase (continued)

| | | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subcategory | Phenomenon* | | H | M | L | IR | F | C | R | B | K | PK | UK | KR |
| Conduct of test (continued) | During the test: | Time and location of failure | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Temperature of coolant | 0 | 0 | 7 | 0 | N | N | N | N | NA | NA | NA | NA |
| | | Cladding temperature | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Fuel stack elongation | 0 | 7 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Cladding elongation | 4 | 3 | 0 | 79 | N | N | N | N | NA | NA | NA | NA |
| | | Fuel rod internal pressure | 0 | 4 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |

*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; 9x9, or 10x10 rods in a fuel assembly..
C= Cladding types from various vendors, e.g., GE and Siemens.
R= Reactor type, e.g., 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 0.0%–25% of full knowledge and understanding.

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

## Table 3-3. Category B. Integral Testing PIRT – High Temperature Phase

| | | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | | **H** | **M** | **L** | **IR** | **F** | **C** | **R** | **B** | **K** | **PK** | **UK** | **KR** |
| Fuel rod selection | Fuel: | Thermal inertia | 3 | 3 | 0 | 75 | N | N | N | N | NA | NA | NA | NA |
| | Cladding: | Amount of oxide | 0 | 2 | 2 | 25 | N | N | N | N | NA | NA | NA | NA |
| | | Surface conditions | 1 | 1 | 1 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Dimensions | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Gap size | 4 | 2 | 1 | 71 | N | N | N | N | NA | NA | NA | NA |
| Conduct of test | Specimen design: | Thermal conductance of gap | 0 | 6 | 1 | 43 | N | N | N | N | NA | NA | NA | NA |
| | | Length | 3 | 2 | 0 | 80 | N | N | N | N | NA | NA | NA | NA |
| | | Grid and constraints | 4 | 1 | 0 | 90 | N | N | N | N | NA | NA | NA | NA |
| | | Attachments | 4 | 2 | 0 | 83 | N | N | N | N | NA | NA | NA | NA |
| | | Single rod versus bundle | 4 | 2 | 0 | 83 | N | N | N | N | NA | NA | NA | NA |
| | | Channel boundary conditions | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | During the test: | Power pulse characteristics | 0 | 5 | 1 | 42 | N | N | N | N | NA | NA | NA | NA |
| | | Flow oscillation characteristics | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Average power level | 6 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Axial power profile | 2 | 4 | 0 | 67 | N | N | N | N | NA | NA | NA | NA |
| | | Coolant heat transfer | 4 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Steam quality | 5 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Steam quality measurement | 5 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Vapor temperature | 4 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Measure vapor temperature | 1 | 1 | 0 | 75 | N | N | N | N | NA | NA | NA | NA |
| | | Temperature of cladding | 5 | 2 | 0 | 86 | N | N | N | N | NA | NA | NA | NA |
| | | DNB and rewet detection | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |

*Table continued on next page*

## Table 3-3. Category B. Integral Testing PIRT – High Temperature Phase (continued)

| | | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subcategory | Phenomenon* | | H | M | L | IR | F | C | R | B | K | PK | UK | KR |
| Conduct of test | During the test: | Fuel centerline temperature | 0 | 5 | 1 | 42 | N | N | N | N | NA | NA | NA | NA |
| (continued) | | Mass flow rate | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | | Pressure | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | | Interior cladding temperature | 0 | 2 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |

*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; 9x9, or 10x10 rods in a fuel assembly..
C= Cladding types from various vendors, e.g., GE and Siemens.
R= Reactor type, e.g., 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.

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

## Table 3-4. 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 | 0 | 0 | 6 | 0 | N | N | N | N | 3 | 1 | 0 | 88 |
|  | Gas pressure | 0 | 0 | 7 | 0 | N | N | N | N | 7 | 0 | 0 | 100 |
|  | Gas composition | 0 | 0 | 7 | 0 | N | N | N | N | 6 | 1 | 0 | 93 |
|  | Gas distribution | 0 | 0 | 7 | 0 | N | N | N | N | 1 | 5 | 0 | 58 |
|  | Pellet and cladding dimensions | 4 | 3 | 0 | 79 | N | N | N | N | 7 | 0 | 0 | 100 |
|  | Burnup distribution | 5 | 0 | 0 | 100 | N | N | N | N | 6 | 0 | 0 | 100 |
|  | Hydrogen concentration | 0 | 0 | 7 | 0 | N | N | N | N | 1 | 6 | 0 | 57 |
|  | Hydrogen distribution | 0 | 0 | 7 | 0 | N | N | N | N | 1 | 6 | 0 | 57 |
|  | Fast fluence | 0 | 0 | 5 | 0 | N | N | N | N | 6 | 0 | 0 | 100 |
|  | Porosity distribution | 0 | 5 | 0 | 50 | N | N | N | N | 0 | 6 | 0 | 50 |
|  | Rim size | 0 | 4 | 2 | 33 | Y | N | N | N | 0 | 5 | 0 | 50 |
|  | Power distribution | 7 | 0 | 0 | 100 | N | N | N | N | 6 | 0 | 0 | 100 |
|  | Fuel-clad gap friction coefficient | 0 | 0 | 6 | 0 | N | N | N | N | 1 | 1 | 0 | 75 |
|  | **Thickness of oxide layer and surface condition (rewet)** | **6** | **0** | **0** | **100** | **N** | **N** | **N** | **N** | **0** | **6** | **0** | **50** |
|  | Rod free volume | 0 | 0 | 7 | 0 | N | N | N | N | 6 | 0 | 0 | 100 |
| Mechanical loading to cladding | **Pellet thermal expansion, including expansion due to fuel melting** | **6** | **1** | **0** | **93** | **N** | **N** | **N** | **N** | **0** | **6** | **0** | **50** |
|  | Direct gas pressure loading | 1 | 5 | 0 | 58 | N | N | N | N | 0 | 6 | 0 | 50 |
|  | **Pellet-cladding contact (gap closure)** | **6** | **1** | **0** | **93** | **N** | **N** | **N** | **N** | **0** | **6** | **0** | **50** |
|  | **Fission gas induced pellet swelling** | **4** | **4** | **0** | **75** | **N** | **N** | **N** | **N** | **0** | **7** | **0** | **50** |
|  | Fission gas release | 1 | 5 | 0 | 58 | N | N | N | N | 0 | 6 | 0 | 50 |

*Table continued on next page*

## Table 3-4. Category C. Transient Fuel Rod Analysis PIRT (continued)

| | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Subcategory** | **Phenomenon*** | **H** | **M** | **L** | **IR** | **F** | **C** | **R** | **B** | **K** | **PK** | **UK** | **KR** |
| Fuel and cladding temperature changes | **Heat resistances in fuel, gap, and cladding** | 8 | 0 | 0 | 100 | N | N | N | N | 1 | 7 | 0 | 56 |
| | **Transient cladding-to-coolant heat transfer coefficient (oxidized cladding)** | 8 | 0 | 0 | 100 | N | N | N | N | 0 | 8 | 0 | 50 |
| | Heat capacities of fuel and cladding | 8 | 0 | 0 | 100 | N | N | N | N | 8 | 0 | 0 | 100 |
| | **Transient oxidation and energy source** | 5 | 3 | 0 | 81 | Y | Y | N | Y | 0 | 7 | 0 | 50 |
| Cladding deformation | Stress versus strain response | 5 | 0 | 0 | 100 | N | N | N | N | 6 | 0 | 0 | 100 |
| | Strain rate effects | 0 | 0 | 6 | 0 | N | N | N | N | 6 | 0 | 0 | 100 |
| | Anisotropy | 0 | 0 | 6 | 0 | N | N | N | N | 6 | 0 | 0 | 100 |
| | Pellet shape | 0 | 0 | 8 | 0 | N | N | N | N | 0 | 6 | 0 | 50 |
| | **Cladding temperature** | 6 | 0 | 0 | 100 | N | N | N | N | 0 | 6 | 0 | 50 |
| | Localized effects | 0 | 0 | 8 | 0 | N | N | N | N | 0 | 6 | 0 | 50 |
| | Biaxiality | 0 | 0 | 8 | 0 | N | N | N | N | 8 | 0 | 0 | 100 |
| Pellet deformation mechanisms | **Fracture stress, yield stress in compression, plastic deformation, grain boundary decohesion, pellet cracking, and evolution of pellet stress state** | 4 | 1 | 0 | 90 | N | N | N | N | 1 | 6 | 0 | 57 |
| Forcing functions | **Transient power distribution** | 8 | 0 | 0 | 100 | N | N | N | N | 0 | 8 | 0 | 50 |
| | **Coolant conditions** | 8 | 0 | 0 | 100 | N | N | N | N | 0 | 8 | 0 | 50 |
| Multiple fuel rod and coolant channel interactions | Rod-to-rod interactions | 3 | 4 | 1 | 63 | Y | N | N | N | 0 | 1 | 6 | 7 |
| | **Rod-to-channel interactions** | 4 | 4 | 0 | 75 | Y | N | N | N | 0 | 1 | 6 | 7 |
| | Rod and spacer grid interactions | 7 | 0 | 0 | 100 | N | N | N | N | 5 | 0 | 0 | 100 |

[*] 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; 9x9, or 10x10 rods in a fuel assembly..
C= Cladding types from various vendors, e.g., GE and Siemens.
R= Reactor type, e.g., 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 C.

[§] 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 0.0%–25% of full knowledge and understanding.

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

## Table 3-5. Category D. Separate Effect Testing PIRT

| | | Importance** | | | | Applicability†,†† | | | | Uncertainty§,§§ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Subcategory | Phenomenon* | H | M | L | IR | F | C | R | B | K | PK | UK | KR |
| Specimen selection | Amount of oxide | 0 | 7 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | Type of oxidation | 2 | 5 | 0 | 64 | N | N | N | N | NA | NA | NA | NA |
| | Cladding dimensions | 0 | 0 | 6 | 0 | N | N | N | N | NA | NA | NA | NA |
| | Extent of oxide spalling and hydride blisters | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | Extent of oxide delamination | 0 | 2 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | Presence of barrier layer | 0 | 1 | 4 | 10 | N | N | N | N | NA | NA | NA | NA |
| | Amount of hydrogen | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | Hydrogen distribution | 0 | 6 | 0 | 50 | N | N | N | N | NA | NA | NA | NA |
| | Hydride orientation | 4 | 2 | 0 | 83 | N | N | N | N | NA | NA | NA | NA |
| Test conditions | Fluence | 0 | 4 | 2 | 33 | N | N | N | N | NA | NA | NA | NA |
| | Cladding integrity | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | Test temperature | 0 | 0 | 6 | 0 | N | N | N | N | NA | NA | NA | NA |
| | Strain rate | 0 | 0 | 6 | 0 | N | N | N | N | NA | NA | NA | NA |
| | Stress state imposed on specimen | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | Cycling conditions | 4 | 3 | 0 | 79 | N | N | N | N | NA | NA | NA | NA |
| | Tensile test specimen design | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |
| | Burst specimen design | 7 | 0 | 0 | 100 | N | N | N | N | NA | NA | NA | NA |

[*] 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; 9x9, or 10x10 rods in a fuel assembly..
C= Cladding types from various vendors, e.g., GE and Siemens.
R= Reactor type, e.g., 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 0.0%–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 BWR power oscillation 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. A limited amount of additional data applicable to BWR fuel and cladding has been developed.

### 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 BWR power oscillation PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

Cladding Mechanical Property Tests (Japan)

Ductility reduction due to hydrogen absorption and neutron irradiation was investigated for BWR cladding using the uniaxial tensile test many years ago, though both the hydrogen concentration and neutron fluence were much lower than the level currently of interest for high burnup fuels. Except for the general post-irradiation examination, BWR cladding has not been tested in recent years. Less significant corrosion and hydrogen pick-up than occurs in high burnup PWR fuel are important factors is this situation. However, ductility reduction in BWR cladding is possible in the expected high-burnup range. Thus, mechanical property tests are planned. JAERI is interested in the morphology and the distribution of hydrides that are specific to BWR cladding. Tube burst tests for hydrided claddings are planned.

### 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 BWR power oscillation PIRT panel are provided. References to Appendix E, where additional summary information is found, are also provided.

NSRR Pulse-Irradiation Experiments with BWR Fuels (Japan)

The JAERI Nuclear Safety Research Reactor (NSRR) is a modified Training, Research, Isotopes, General Atomics-Annular-Core Pulse Reactor (TRIGA-ACPR) (Annular Core Pulse Reactor) featuring a large pulsing power capability and large dry irradiation space located in the center of the reactor core. The experimental capsule used in the pulse irradiation is a double-container system for the irradiated fuel rod test. The capsule contains an instrumented test fuel rod with stagnant water at atmospheric pressure and ambient temperature. The data obtained during the pulse irradiation includes cladding surface temperature, water coolant temperature, pellet stack and cladding tube axial elongations, fuel rod internal pressure, and capsule internal pressure. A water column velocity sensor is installed in some experiments for measurement of mechanical energy generation. This sensor replaces the axial elongation sensors when it is used. A new capsule for high-temperature and high-pressure conditions is under development. Additional information on the NSRR pulse-irradiation experiments with BWR fuels is provided in Appendix E-2. The experiments were for pulse conditions. Although the fuel was BWR specific, the extension of results to BWR power oscillations should be undertaken with care.

SPERT Test Reactor Data (United States)

BWR-type fuel rods have been tested in the Special Power Excursion Reactor Test (SPERT) program and the Power Burst Facility (PBF). These were also pulse tests and results should be used with caution for power oscillations. The SPERT tests of interest were performed in 1969-1970. Additional information SPERT test reactor data obtained for BWR-type fuel rods is provided in Appendix E-2.

Transient Critical Heat Flux Experiments and Rewet Data

The power oscillations 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 transient critical heat flux experiments and rewet data are provided in Appendix E.

Dryout Effects on High Burnup Fuel (OECD 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 rods 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 power oscillations without scram. 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 incorporate 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 power oscillations.

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 F, Table F-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 F, Table F-1.

The SCANAIR code is a French Institute for Protection and Nuclear Safety (IPSN; France)-sponsored 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 F, Table F-3.

## 4.3 Additional Information

Additional information describing the thermal-hydraulic and neutronic processes and phenomena expected to occur in a BWR during a period of power oscillations without scram was presented to the panel during the PIRT process. The information presented to the panel is found in Appendix G.

## 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).

# 5. ADDITIONAL PANEL INSIGHTS

Through the course of the BWR oscillation without scram 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. In addition, 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.

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 form 62 to 75 GWd/t. This information is provided in Ref. 5-1, Appendix H.

## 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 the following: 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 as to 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 effort 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 G.

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 review is enhanced if it is 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 different for other fuel arrays or fuel types, 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. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of power history during event | Moderator feedback | Reactivity feedback from moderator temperature and density changes in active channels, bypass region, and water channels. These changes are a result of direct deposition to the coolant and heat transfer from the cladding.<br>H(8) Void feedback is the dominant phenomenon affecting the power oscillations. The 3-dimensional distribution of the void reactivity feedback controls the spatial power distribution.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(8): Can calculate within 25%.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of power history during event | Fuel temperature feedback | Reactivity feedback from fuel temperature changes. This effect results from the heating of the fuel and the associated neutronic effects, in particular the Doppler effect, and heat transfer from the fuel rod cladding.<br>H(8) Fuel temperature reactivity feedback terminates the power increase for large reactivity excursions; it is approximately equal to prompt criticality.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(8): Can calculate with a high degree of certainty.<br>PK(0): No votes.<br>UK(0): No votes. |

### Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of power history during event | Delayed-neutron fraction | The fraction of fission neutrons that are not emitted instantaneously designated beta (β). Prompt criticality occurs when the reactivity exceeds the effective delayed neutron fraction.<br>H(2) Same rationale as below but weighted as more important.<br>M(4) Controls when prompt criticality is reached and how fast the power increases.<br>L(0) No votes.<br>Fuel: Baseline PIRT importance rank applicable.<br>Clad: Baseline PIRT importance rank applicable.<br>Reactor: Baseline PIRT importance rank applicable.<br>Burnup: Baseline PIRT importance rank applicable.<br>K(7): Has been well known from the inception of nuclear reactor theory.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of power history during event | Fuel cycle design | Includes those important design elements that determine the neutronic and hydraulic properties of the core at event initiation, such as the loading pattern, axial and radial power shapes, control history (control rod, spectral shift), burnup, and exposure. By loading pattern is meant knowledge of the design of the assemblies, their placement, and burnup at the time of the accident.<br>H(6) Controls the power shape and distribution in the core at the start of the event.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Calculation technologies have progressed to where the core initial state can be predicted for a given fuel cycle design.<br>PK(0): No votes.<br>UK(0): No votes. |

**Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Heat resistances in the fuel, gap, and cladding (including oxide layer) | 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 clad).<br>H(8) The resistance controls the heat transfer to the fluid. The damping and delay and phase shift is important for the instabilities. The thermal resistance also determines the fuel temperature and Doppler feedbacks.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(8): These phenomena can be predicted to within 25%. Also measurements confirm theory.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Heat capacities of fuel and cladding | The respective quantities of heat required to raise the fuel and cladding one degree in temperature at constant pressure.<br>H(8) The heat capacities affect the thermal time constant for the fuel. The heat capacity determines the temperature rise and the Doppler feedback. The temperature rise is important for rewet following a dryout.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(8): These are material properties that are firmly established.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Fractional energy deposition in pellet | The fraction of total fission energy that is deposited directly in the pellet.<br>H(2) It is important to have the correct amount of energy deposited in the fuel.<br>M(1) The code outcome is not sensitive to this parameter.<br>L(3) The fraction of energy in the fuel is very high (approximately 97%) and the uncertainty are very low.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Well understood, small effect.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Pellet radial power distribution | The radial distribution of the power produced in the fuel rod.<br>H(2) Will affect the thermal time constant in the fuel and the stored energy.<br>M(4) It is a secondary effect. For fast power excursions, it will have a small effect on the average fuel temperature increase.<br>L(0) No votes.<br>Fuel: Baseline PIRT importance rank applicable.<br>Clad: Baseline PIRT importance rank applicable.<br>Reactor: Baseline PIRT importance rank applicable.<br>Burnup: Burnup causes the radial power distribution to shift towards the outer pellet surface. This could increase the importance of this phenomenon.<br>K(5): Evolution of power distribution is well understood.<br>PK(1): Condition of fuel is not so well known, so radial power distribution is not readily predicted.<br>UK(0): No votes. |
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Pin peaking factors | Pin power distribution within an assembly during the transient.<br>H(6) The pin to pin peaking determines which rod and how many rods will potentially go into boiling transition.<br>M(1) It is less important than the enrichment distribution.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(6): Can be calculated to within 25%.<br>PK(1): Not a trivial determination with void and other uncertainties.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of pin fuel enthalpy increase during event (includes cladding temperature) | Metal-water reaction heat addition | The additional heat generated in the cladding due to metal-water reactions.<br>H(2) It can be a significant heat addition for high cladding temperatures.<br>M(4) It is small compared to the fission power level.<br>L(1) It is very small fraction compared to the total heat output.<br>All: Baseline PIRT importance rank applicable.<br>K(6): This phenomenon has been studied in several NRC programs and is well understood.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of fuel to coolant heat transfer | Single phase convection | Convection heat transfer to single-phase fluid (liquid or steam).<br>H(0) No votes.<br>M(5) Partially determines when boiling will begin.<br>L(1) It is a small fraction of the active fuel length.<br>All: Baseline PIRT importance rank applicable.<br>K(7): This has been well understood for many years; also product line data is available and supports correlations.<br>PK(0): No votes.<br>UK(0): No votes. |

### Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of fuel to coolant heat transfer | Subcooled boiling | The fluid temperature is less than the saturation temperature at the coolant temperature (includes nucleate boiling).<br>H(6) Subcooling boiling range is from the point of net vapor generation until the bulk liquid reaches saturation (approximately 40% void). This is a significant fraction of the active fuel length. The subcooled boiling region significantly affects the transit time.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(0): No votes.<br>PK(5): More uncertainty introduced by the transient nature of this phenomenon.<br>UK(0): No votes. |
| Calculation of fuel to coolant heat transfer | Nucleate boiling, bulk boiling and forced convection vaporization | Heat transfer and evaporation from the thin liquid film on the heated surface.<br>H(4) Heat transfer regime is the precursor to dryout. It is the heat transfer mode for the major portion of the fuel bundle.<br>M(1) The heat transfer coefficient is so large that it is not the dominant resistance.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(4): Full-scale data available.<br>PK(1): Transient conditions introduce uncertainty.<br>UK(0): No votes. |

**Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of fuel to coolant heat transfer | Dryout | The absence of liquid on a heated surface results in a temperature excursion (increase) of the heated surface.<br>H(6) Determines when heatup will occur.<br>M(0) No votes.<br>L(0) No votes.<br>Fuel: Baseline PIRT importance rank applicable.<br>Clad: Baseline PIRT importance rank applicable.<br>Reactor: Baseline PIRT importance rank applicable.<br>Burnup: May become less important for high burnup fuel because the power is lower.<br>K(0): No votes.<br>PK(6): Cannot be calculated well for transient behavior using steady-state dryout correlations. Also, reverse flow cannot be predicted with confidence.<br>UK(1): Cannot be calculated well for transient behavior with possible flow reversal. |
| Calculation of fuel to coolant heat transfer | Film boiling over a wide void fraction range | Includes low void fraction, inverted annular, and high void fraction dispersed film boiling.<br>H(6) Determines rate of temperature increase after boiling transition.<br>M(1) Not as important as when boiling transition occurs.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(0): No votes.<br>PK(6): Transient behavior and surface conditions make it difficult to predict accurately.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of fuel to coolant heat transfer | Rewet | A surface that has previously experienced dryout once again comes into contact with liquid when the surface temperature decreases to the minimum film boiling point.<br>H(7) Rewetting terminates temperature excursion and prevents fuel failure.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(0): No votes.<br>PK(7): Although data are available, they do not cover all surface conditions expected.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Bypass:<br>Flow fraction | Fraction of vessel flow in bypass region.<br>H(2) Low bypass flow fraction and potential voiding will affect the power shape and the oscillations.<br>M(3) Flow variations less important than other effects because of the low value of the leakage flow.<br>L(3) Flow variations much less important than other effects because of the low value of the leakage flow.<br>All: Baseline PIRT importance rank applicable.<br>K(4): Extensive database available.<br>PK(3): The data does not directly apply to the transient.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Bypass:<br>Void fraction due to direct moderator heating | Void fraction distribution.<br>H(5) Void will affect the power shape and nature of the oscillations due to void reactivity feedback.<br>M(2) The void fraction is relatively low.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(2): If heat addition is known, calculation predicts voids, whether flow is up or down.<br>PK(5): Some uncertainty about where energy is deposited due to 3D effects.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Core:<br>Void fraction distribution including subcooled boiling | Void fraction distribution.<br>H(7) Determines the power shape and the void reactivity feedback as well as the heat transfer mode.<br>M(2) Existing test data may not be applicable for natural circulation conditions.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(5): Can calculate within 25% and both steady state and transient data to support calculations.<br>PK(2): Well understood for steady state but not so well understood for transients.<br>UK(0): No votes. |

**Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Core:<br>Frictional pressure drop | The difference in pressure between two points in a single- or two-phase flow system, caused by frictional resistance to the fluid flowing through a system.<br>H(6) Natural circulation is a balance between buoyancy and friction.<br>M(2) Influences power shape and void reactivity feedback as well as the heat transfer mode.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Has been known and understood and validated by experiments.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Core:<br>Form pressure drop | Single- and two-phase pressure drop resulting from the flow around or through a body of a particular shape.<br>H(7) Natural circulation is a balance between buoyancy and friction. Also determines the balance between single-phase and two-phase pressure drop.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(4): Data has been obtained and can calculate transients using steady-state pressure drop results.<br>PK(3): Flow reversal may have less well-known effects.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Core:<br>Acceleration pressure drop | The pressure drop associated with the acceleration of a fluid.<br>H(0) No votes.<br>M(6) Has little to no impact on onset of instability, but will affect the oscillations for large limit cycle oscillations.<br>L(1) Small compared to other effects.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Phenomenon is well understood and has been benchmarked.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Core:<br>Direct moderator heating | Energy deposited directly into the moderator.<br>H(3) Void feedback due to direct moderator heating is instantaneous while the surface heat flux oscillation is delayed and damped.<br>M(3) It is not the dominant feedback.<br>L(1) It is not the dominant feedback.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Because void distribution can be calculated, it is possible to accurately predict direct moderator heating.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Core:<br>Counter-current flow limitation | Condition in liquid-vapor counter flow in which the rate of vapor rise is insufficient to prevent liquid downflow.<br>H(1) Important for getting flow into the channel.<br>M(4) Top of bundle tends to be in counter-current flow.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(3): General Electric has extensively studied the phenomenon.<br>PK(1): Phenomenon is not known with a high degree of certainty for the conditions of concern.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Core:<br>Flow blockage | Reduction in flow area due to geometry changes arising from clad ballooning and fuel-rod deformation.<br>H(5) Severe flow blockage will lead to an uncoolable geometry.<br>M(3) Sufficient to have capability to monitor flow blockage. If it is demonstrated that blockage does not occur, it is only sufficient to calculate when blockage will occur, not the effect if it was to occur.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(0): No votes.<br>PK(1): Blockage configurations can be identified and described.<br>UK(7): Blockage is a function of all other thermal-hydraulics and materials inputs, which collectively, are not sufficiently well known. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Downcomer:<br>Void distribution | Void fraction distribution.<br>H(0) No votes.<br>M(0) No votes.<br>L(7) During natural circulation the downward velocity in the downcomer is insufficient to entrain vapor.<br>All: Baseline PIRT importance rank applicable.<br>K(6): We know how bubbles move in liquid in steady state, and since bubbles have very little inertia, prediction in transients is comparable.<br>PK(0): No votes.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Downcomer:<br>Condensation heat transfer | Condensation on feedwater flow coming out of a sparger after the liquid level drops below the sparger outlets.<br>H(4) Condensation heat transfer when the water level is below the feedwater sparger will remove the core inlet subcooling and reduce the magnitude of the oscillations.<br>M(3) Not as important as other phenomena such as core void fraction.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(3): Has been thoroughly studied, and models have been validated by specific tests.<br>PK(1): There is a lot of data but it is difficult to predict and is sensitive to geometry.<br>UK(0): No votes. |

**Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Downcomer:<br>Mixing and thermal stratification | Mixing of cold feedwater with feedwater flow in downcomer when sparger is still covered.<br>H(2) Analysis and magnitude of oscillations depend on core inlet subcooling.<br>M(1) Medium importance compared to other phenomena.<br>L(3) Stratification is not significant in downcomer; it is more enthalpy propagation with downward flow velocity.<br>All: Baseline PIRT importance rank applicable.<br>K(0):<br>PK(5): Can predict reasonably with computational fluid dynamics codes, but very geometry dependent, and selection of mixing properties ( e.g., k, ε ) have a range of uncertainty.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Downcomer:<br>Jet pump or internal pump loss | Friction pressure drop in jet pump suction.<br>H(6) Jet pump or internal pump is the only significant place with a pressure drop in the downcomer region. It affects the natural circulation rate.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(6): Both scaled and full-scale data are available and the associated models are verified.<br>PK(0): No votes.<br>UK(0): No votes. |

### Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Downcomer:<br>Friction and form loss | Friction and form loss in downcomer flow path outside jet pump.<br>H(0) No votes.<br>M(0) No votes.<br>L(7) These regions have large hydraulic diameter, low velocities, and friction is very small.<br>All: Baseline PIRT importance rank applicable.<br>K(6): Tests and data are available (low flow situation). Scaling can be off and not strongly affect the result.<br>PK(1): Form losses are not well understood for this complex geometry.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Lower plenum:<br>Mixing or thermal stratification | Mixing due to core flow reversals.<br>H(7) Cold water, with and without boron, can stratify at the bottom of the lower plenum. Hot water from the core region will mix with the colder water in the lower plenum. The stratification and mixing will control the core inlet subcooling.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(0): No votes.<br>PK(7): Data are available. Predictions are relatively acceptable, but complicated by geometry.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Lower plenum:<br>Friction and form loss | Friction and form loss in lower plenum.<br>H(0) No votes.<br>M(0) No votes.<br>L(7) These regions have large hydraulic diameter, low velocities, and friction is very small.<br>All: Baseline PIRT importance rank applicable.<br>K(6): Tests and data are available (low flow situation). Scaling can be off and not strongly affect the result.<br>PK(1): The form loss coefficient may not be well known for this complex geometry.<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Upper plenum:<br>Void distribution | Spatial distribution of voids in the upper plenum.<br>H(3) The balance between buoyancy and friction controls natural circulation. The upper plenum is an important contributor to the buoyancy.<br>M(1) Less important contributor than described above.<br>L(1) Insignificant contributor as described above.<br>All: Baseline PIRT importance rank applicable.<br>K(1): Test data are available for water injection in full-size segment tests (for LOCA).<br>PK(6): Difficult to predict temperature effects in driving downflow; also a high-pressure environment.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Upper plenum: Condensation heat transfer | Condensation heat transfer due to high-pressure coolant system.<br>H(6) High pressure cooling system is a source of cold water. Incomplete condensation and downflow into the peripheral bundles would be a source of cold water to the core regions.<br>M(0) No votes.<br>L(0) No votes.<br>Fuel: Baseline PIRT importance rank applicable.<br>Clad: Baseline PIRT importance rank applicable.<br>Reactor: The ranking will be less important for reactors that do not have the high-pressure core spray system to inject subcooled water into the core.<br>Burnup: Baseline PIRT importance rank applicable.<br>K(1): Test data are available for water injection in full-size segment tests (for LOCA).<br>PK(6): Difficult to predict temperature effects in driving downflow; also a high-pressure environment.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Upper plenum:<br>Friction and form loss | Friction and form loss in upper plenum.<br>H(0) No votes.<br>M(0) No votes.<br>L(7) These regions have large hydraulic diameter, low velocities, and friction is very small.<br>All: Baseline PIRT importance rank applicable.<br>K(6): Tests and data are available (low flow situation). Scaling can be off and not strongly affect the result.<br>PK(1): ?????<br>UK(0): No votes. |
| Calculation of core and system hydraulics | Separator:<br>Carry under | Steam carried downward by the liquid to the downcomer.<br>H(0) No votes.<br>M(0) No votes.<br>L(6) Carry under from the separators will increase for these conditions, but the low downward velocities in the mixing and downcomer regions will cause the vapor to separate in the mixing regions.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Separators have been tested over a wide range of performance.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Calculation of core and system hydraulics | Total pressure loss | The combination of frictional, form, and acceleration pressures losses as previously defined.<br>H(4) This is an important contributor to the losses that affect the natural circulation and stability.<br>M(3) This phenomenon is a less important than the losses in the core region.<br>L(0) No votes.<br>Fuel: Baseline PIRT importance rank applicable.<br>Clad: Baseline PIRT importance rank applicable.<br>Reactor: The ranking will increase for reactor systems (e.g., Asea Brown Boveri) that have an increased (higher) pressure loss across the steam separators.<br>Burnup: Baseline PIRT importance rank applicable.<br>K(7): Extensive data are available, both steady state and transient.<br>PK(0): No votes.<br>UK(0): No votes. |
| Boundary conditions for reactor vessel | Feedwater flow rate and subcooling | Title is the definition.<br>H(7) Controls the power level and inlet subcooling to the core region.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(7): This is a known boundary condition.<br>PK(0): No votes.<br>UK(0): No votes. |

## Table A-1. BWR Power Oscillations without Scram. Category A – Plant Transient Analysis PIRT (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Boundary conditions for reactor vessel | Steamline pressure and flow | Title is the definition.<br>H(1) It is important to get the boundary conditions correct.<br>M(5) Less important than feedwater flow and subcooling.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable.<br>K(7): Calculated from an energy balance by well-established methods.<br>PK(0): No votes.<br>UK(0): No votes. |

# APPENDIX B

## CATEGORY B
## INTEGRAL TESTING
## (Low-Temperature Phase and High Temperature Phase)

## 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 – Low Temperature Phase and Table 3-3, Integral Testing PIRT – High Temperature Phase. Entries in the Table B-1, columns 1 and 2, follow the same order as in Tables 3-2 and 3-3. Tables B-1 (low temperature phase) and B-2 (high temperature phase), column 3, also document 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 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 panel determined that this area did not warrant further consideration (please see Section 3.4.2 of this report for the panel's reasons for this approach).

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

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Fuel condition:<br>Burnup | Amount of nuclear fuel that has been consumed in fuel pellets used in the test article in, for instance, Gwd/t.<br>H(4) The gap needs to close and bonding take place before serious fuel damage can occur.<br>M(2) The rate of change of the cladding condition with burnup after gap closure is small and all subsequent burnup produces little additional change.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Fuel condition:<br>Enrichment (initial) | The fraction of U-235 (for MOX the equivalent enrichment considering Pu) in the fuel sample at the time it was manufactured prior to burnup in a power reactor. Helps define the amount of energy deposition available.<br>H(0) No votes.<br>M(1) The enrichment affects the residual fissions and that controls the power distribution at the pulse<br>L(5) The variation of fuel condition with differing enrichment is not strong. Longer pulse widths diminish the effect of residual fissions.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Fuel condition:<br>Base irradiation conditions | The power history, axial burnup profile, and temperature to which the fuel rod was exposed prior to testing.<br>H(0) No votes.<br>M(6) No rationale recorded<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Fuel condition:<br>Rim size | Width of radial zone at outer periphery of pellet characterized by high porosity, high local burnup and plutonium content, and small grain structure incorporating fission gases in tiny closed pores.<br>H (0) No votes.<br>M(0) No votes.<br>L(5): Questionable during rod ejection accident if important, but during this transient there is much less peaking and at a lower average value.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Fuel condition:<br>Fission gas distribution | The radial distribution of fission gas in the pellet (inter-granular, grain boundaries, porosity), including the rim zone.<br>H(0) No votes.<br>M(1) If PCMI exists it would arise from fission gas distribution<br>L(5) Given longer times of transient, it is less important where the fission gas was located initially.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Fuel condition:<br>Grain size | The fuel pellet consists of compacted grains of $UO_2$ that, upon undergoing burnup, change in size resulting in a variation of grain size through the pellet.<br>H(0) No votes.<br>M(0) No votes.<br>L(5): Correlation between grain size and dispersal in an power oscillation without scram accident is not strongly correlated.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Fuel condition:<br>Pellet type | The essential characteristics of a pellet such as length and diameter that identify the pellet. as well as the presence of dish or chamfers.<br>H(0) No votes.<br>M(3) There is a difference between dished and undished and longer L/Ds and there is an impact on ridging with more ridging with bigger L/Ds and dishing<br>L(3) GE fuel should be used so there is no choice.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Amount of oxide | The amount of zirconium oxide on both the inside and outside cladding surfaces. The oxygen source on the inner surface is $UO_2$ and the source on the outer surface is $H_2O$.<br>H(3) To investigate PCMI, oxide layer is primary. Want to select test specimen with the proper oxide layer to reflect the possible degradation.<br>M(2) Impact of oxide thickness on mechanical properties of medium importance for PCMI phenomenon because the wall thinning is of little importance.<br>L(1) Impact of oxide thickness on mechanical properties of low importance for PCMI phenomenon because the wall thinning is of negligible importance.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Type of oxidation[a] | Whether the clad oxidation prior to testing was uniform, nodular or both.<br>H(3) If there is extensive nodular corrosion, the size is such that the strength of the corrosion is significantly impaired.<br>M(3) Will have only a moderate impact on the outcome of the test.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Extent of oxide spalling and hydride blisters[a] | 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<br>H(7) If oxide spalling is present it can lead to high local hydrogen distributions and reduce the overall ductility of the cladding.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

[a] Discriminating factor: Rods that exhibit these characteristics should not be selected unless they occur to a significant extent in the population of rods to be investigated.

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Extent of oxide delamination | Separation of an outer oxide layer from the underlying oxide or base metal. Can lead to increased temperature and enhanced localized corrosion.<br>H(0) No votes.<br>M(2) To the extent that it exists, it should be included although the consequences are not expected to be high.<br>L(2) If it existed, the consequences would be minor.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Type | Related to the presence or absence of a barrier (liner) in the cladding. Barrier produced by co-extrusion process so bond between the layers is of high quality.<br>H(6) For PCMI, the presence or non-presence of the barrier can make a significant impact relative to stress corrosion cracking (SCC). Barrier was added to prevent this mechanism.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

**Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Amount of Hydrogen | Total amount of hydrogen in the cladding.<br>H(4) Hydrogen affects the behavior of the cladding under low temperature PCMI conditions.<br>M(2) Hydrogen at low levels so the impact is only moderate.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Hydrogen distribution[a] | Spatial distribution of the hydrogen, including local hydride formations in the cladding (hydride rim) but excluding hydride blisters.<br>H(0) No votes.<br>M(6) Hydride rim could have a moderate impact on the outcome of the experiment. There is little choice regarding the hydride rim; the phenomenon comes with the specimen.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

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[a] Discriminating factor: Rods that exhibit these characteristics should not be selected unless they occur to a significant extent in the population of rods to be investigated.

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Hydride orientation[a] | The orientation of the hydrides, either axial or radial.<br>H(1) The existence of a radially oriented hydrides, if it exists, is important.<br>M(2) Although important, hydride orientation will not be a primary discriminating factor in selecting the test rod.<br>L(1) Hydride orientation will not be a significant discriminating factor in selecting the test rod.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Dimensions | The thickness and diameter of the fuel cladding.<br>H(0) No votes.<br>M(4) Dimensions to the extent they vary across various designs will only have a moderate effect on hydrides and oxide concentrations.<br>L(2) Change in hydride and oxide concentration is small given the range of dimensional variations.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

[a] Discriminating factor: Rods that exhibit these characteristics should not be selected unless they occur to a significant extent in the population of rods to be investigated.

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Fluence | Time-integrated particle flux to which the cladding is exposed (Energy > 1.0 Mev, i.e., fast fluence)<br>H(0) No votes.<br>M(0) No votes.<br>L(6) Small effect on mechanical properties over the time scale of the event. Effects saturate in a short time.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Fuel rod selection | Cladding:<br>Integrity[a] | Whether the cladding is leak-proof, and whether it has any non-representative defects.<br>H(7) Defects are bad; they are to be avoided in test specimens.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

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[a] Discriminating factor: Rods that exhibit these characteristics should not be selected unless they occur to a significant extent in the population of rods to be investigated.

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | Specimen design:<br>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.<br>H(0) No votes.<br>M(4) Design should ensure that there is enough plenum volume available to accommodate any fuel expansion and avoid inducing an unwanted end effect. Gas communication and axial end effects are of moderate importance for high burnup fuel rods.<br>L(1) There is little gas communication in the rod.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | Specimen design:<br>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.<br>H(0) No votes.<br>M(4) Fission gas does not play a large role in loading the cladding. Important to design and run the experiment with the appropriate pressure difference.<br>L(1) Factors other than the delta-P across the cladding dominate. PCMI stresses are going to be much higher than stresses induced by internal pressure.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | Specimen design:<br>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.<br>H(0) No votes.<br>M(3) Heat transfer is important. Gas composition affects the heat transfer of the gap.<br>L(2) In high burnup fuel, the gap is already closed, so gas composition has less effect on heat transfer.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | Specimen design:<br>Length | The appropriate length of the test article such that the data delivered from the test is useable.<br>H(2) Important because it is essential that the length of the specimen is such that useable data must be delivered.<br>M(3) Axial interactions can be important and these can be simulated for a wide range of test specimens<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

### Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | Specimen design:<br>Attachments | Any item, e.g., instrumentation, affixed to the test article.<br>H(2) If not properly designed, attachments may have a large and deleterious effect on the sample (for example acting as a failure site) and thereby alter the test results and mask the real behavior.<br>M(3) Possible to provide reasonable instrumentation.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | Specimen design:<br>Constraints | The mechanical setup used to hold the test article in place.<br>H(2) The manner in which the test article is held is important. Mechanical axial interaction due to constraints could cause bending, leading to premature failure. Improperly designed radial constraints could affect cladding deformation and local cooling.<br>M(3) Constraints are of relatively less importance than other highly ranked phenomena.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | Specimen design:<br>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.<br>H(0) No votes.<br>M(1) Most of the needed understanding can be obtained in a single fuel rod tests by focusing on fuel rod failure but well-founded insights as to the impact on the bundle are desirable.<br>L(4) Bundle not needed to resolve PCMI phenomena in the low temperature phase of the test.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Pulse shape | Shape of the pulse to which the test article is exposed, e.g., square vs triangular but with same integrated energy.<br>H(0) No votes.<br>M(2) Reasonably accurate amount of time for prototypical relaxation to take place.<br>L(4) Will set up the test to get the correct thermal response so the pulse shape itself will have only a minor impact.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Fuel enthalpy increase | Calculated increase radially averaged fuel enthalpy of the fuel pellets in the test article as a result of power deposited during the test. This parameter determines the fuel temperature.<br>H(7) The fuel enthalpy increase governs the loading of the cladding, which causes failure.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Pulse width | The duration of a single pulse (e.g. full-width, half-maximum or FWHM) imposed on the test article, and which defines the energy deposition rate.<br>H(0) No votes.<br>M(5) The pulse width is sufficiently wide that reasonable differences in the pulse shape will have only a modest impact on the cladding.<br>L(1) More benign rise in temperature and repeated pulses.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Pulse period | The time for one complete pulse cycle.<br>Note: analytical results defining of the thermal response of the cladding are needed, otherwise, the ranking of this phenomenon carries a high uncertainty.<br>H(0) No votes.<br>M(1) Important to simulate relaxation and thermal response of the cladding through several cycles<br>L(4) The appropriate thermal history of the cladding can be established without rigorously simulating the pulse period.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Total number of pulses | Number of pulses that the fuel rod will be exposed to during the test.<br>H(5) Need to characterize the temperature history which is a combination of the pulse shape and number of pulses.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Pulse height variation | Variation in the time of pulse height (regular or chaotic)<br>H(2) No rationale recorded.<br>M(2) No rationale recorded.<br>L(2) No rationale recorded.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Power drop (baseline power for pulses) | Difference between the initial pre condition power and the power level at the start of the oscillations.<br>H(6) The drop causes an opening of the gap which represents a credit because the gap can accommodate the additional expansion that occurs during the oscillations. It is also important to hit the average power representative of the transient, which, for the low temperature phase, is a reduction in power to a lower level (40% of full power) at which the oscillations begin.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Initial precondition power level | Power level at the initiation of the event.<br>H(0) No votes.<br>M(6) The level at which the initial power level is set is not too important relative to the power drop but one does want a value representative of the initial level.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Axial power profile | The axial variation over a test article length equivalent to the axial variation over the fuel assemblies in a power reactor, taken at the axial location in the power reactor for which testing is specified.<br>H(0) No votes.<br>M(3) Moderately important to model the axial power profile expected in reactor conditions.<br>L(3) The axial power profile must be known but once known, the results can be interpreted and extended to the actual power profile.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Coolant heat transfer conditions (design) | The specified coolant environment to which the test article is to be exposed, e.g., coolant type, velocity, temperature, pressure, steam quality, etc., to achieve the desired cladding temperature.<br>H(2) This is a constraint of the experiment and must be attained with high accuracy.<br>M(5) Must get the coolant heat transfer conditions correct but very tight accuracy is not required.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Fuel dispersal measurement on-line | Measurement of the movement of fuel particles out of the cladding and into the coolant and the increase in pressure due to subsequent interaction of the fuel particles with the coolant.<br>H(1) Fuel dispersal is a controversial issue and this information is always sought and it is important if it occurs.<br>M(4) Would be important if fuel dispersal occurs but it is unlikely that it will occur.<br>L(1) Not important in initial experiment so a gross measurement is acceptable but provision should be made to include more refined measurements later.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Pressure pulse measurement on-line | Measurement during the test of a rapid pressure transient in the coolant caused by the interaction of fuel dispersed into the coolant and the coolant.<br>H(7) Easy experiment to make and it provides an indication of cladding failure and fuel dispersal.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Fission product measurement on-line | Detection of the time at which fission gases escape from the fuel rod into the test channel.<br>H(6) Wealth of information provided by this measurement about what is happening and when and the measurement is relatively inexpensive.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Cladding deformation measurement on-line | Measurement of the time-dependent variation of clad hoop strain during the test.<br>H(6) One of the best indicators or what is happening to the fuel rod up to the point of fuel failure.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Time and location of failure | The time resolution (which pulse) of failure occurrence and its axial location in the test rod.<br>H(7) This is the primary outcome of the test and it is important to know when the failure occurs during the complex history to aid in the interpretation.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Temperature of coolant | Measurement during the test of the coolant temperature variation.<br>H(0) No votes.<br>M(0) No votes.<br>L(7) Experiment will be at saturation conditions and will know, therefore, the temperature. The departure from saturation conditions will be captured by other measurements.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Cladding temperature | Cladding temperature response.<br>H(7) The primary measurement for qualification of the appropriateness of the test. Also, cladding temperature measurement is the primary means of determining the departure from nucleate boiling.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

**Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)**

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Fuel stack elongation | Measurement during the test of the fuel stack elongation.<br>H(0) No votes.<br>M(7) A useful measurement in that it shows the fuel thermal response but less important than the cladding elongation.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |
| Conduct of test | During the test:<br>Cladding elongation | Measurement during the test of the cladding axial elongation.<br>H(4) Provides information about the onset of gap closure, failure, and possibly the departure from nucleate boiling.<br>M(3) Other online measurements provide better information, e.g., radial deformation. This information is redundant.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-1. BWR Power Oscillations without Scram. Category B – Integral Testing - Low Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance, Applicability, and Uncertainty) |
|---|---|---|
| Conduct of test | During the test:<br>Fuel rod internal pressure | Pressure of the fuel-rod plenum volume during the transient.<br>H(0) No votes.<br>M(4) Useful measurement that provides information that can be obtained no other way.<br>L(0) No votes.<br>All: Baseline importance rank applicable.<br>K: Not applicable.<br>PK: Not applicable.<br>UK: Not applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Fuel rod selection | Fuel:<br>Thermal inertia | Diffusivity: Physical property of fuel rod; thermal conductivity divided by heat capacity and density. Thermal mass inside of electrically heated fuel-rod simulator.<br>H(3) The Rebecca tests have shown the occurrence of quench fronts on the cladding is highly dependent upon the existence of a thermal mass in the fuel-rod simulator and the gap.<br>M(3) Thermal inertia is required but the outcome is not sensitive to the insert as a representative input is provided.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Fuel rod selection | Cladding:<br>Amount of oxide | The amount of zirconium oxide on both the inside and outside cladding surfaces. The oxygen source on the inner surface is $UO_2$ and the source on the outer surface is $H_2O$.<br>H(0) No votes.<br>M(2) It offers an extra resistance for heat flow and it should be typical and representation is of moderate importance.<br>L(2) Surface condition will not have much of an impact on the listed phenomena. The temperature decrease across modest oxide layers is small.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Surface conditions | The presence of nodular corrosion, delamination, crud, scratches, and other irregularities that would affect bubble nucleation.<br>H(1) The surface conditions are the parameter that differentiate high and low burnup cladding conditions the most and thus this parameter is of high importance.<br>M(1) The presence of surface imperfections can lead to easier nucleation of bubbles and change the critical heat flux.<br>L(1) The presence of surface imperfections can lead to easier nucleation of bubbles and change the critical heat flux but less so than for moderate. May affect rewet a little.<br>All: Baseline PIRT importance rank applicable. |
| Fuel rod selection | Cladding:<br>Dimensions | The thickness and diameter of the fuel cladding.<br>H(0) No votes.<br>M(6) There are a number of effects associated with dimensions such as surface area, heat flux and thermal mass but the impact is moderate.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Fuel rod selection | Cladding:<br>Gap size | Gap size (opening between the fuel and cladding) existing in the test specimen prior to the test.<br>Spacing between the internal heater and cladding in an electrical heater element.<br>H(4) The Rebecca tests have shown the occurrence of quench fronts on the cladding is highly dependent upon the existence of a thermal mass in the fuel-rod simulator and the gap.<br>M(2) The thermal inertia from the inner clad surface inward, controls heat transfer and it will have a moderate impact similar to that of the thermal inertia.<br>L(1) This is a part of the overall time constant and the time constant effect is small to start.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | Specimen design:<br>Thermal conductance of gas | The amount of heat conducted by the gap gas divided by the temperature difference across the gap.<br>H(0) No votes.<br>M(6) The gap brings in the thermal inertia of the fuel. Gap size and thermal conductivity of the gas influence gap conductance.<br>L(1) The time constant is of medium importance and the thermal conductance of the gas is just a portion of the time constant.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | Specimen design:<br>Length | The appropriate length of the test article such that the data delivered from the test is useable.<br>H(3) Flow conditioning is needed on the flow inlet, whether the flow is from one direction only or if the flow comes , from both ends, i.e., if reversal occurs.<br>M(2) Length needs to accommodate one grid-spacer span but it doesn't need to be very exact beyond that.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | Specimen design:<br>Grid and constraints | Grid: geometry of the shaped fixture that retains the top and the bottom of the test rod; spacing should be representative of the geometry and grid spacing in a reactor. Constraints: The mechanical setup used to hold the test article in place.<br>H(4) Flow conditioning is needed on the flow inlet, whether the flow is from one direction only or if the flow comes , from both ends, i.e., if reversal occurs. Also, the conditions in the subchannel need to be simulated.<br>M(1) Difficult to fully represent the grid and constraints and there are other parameters that we should more closely focus our attention on.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | Specimen design:<br>Attachments | Attachments: Any item, e.g., instrumentation, affixed to the test article. Importance of location and method.<br>H(4) Attachments must be carefully considered because they have the potential to influence the results, e.g., the presence of external thermocouples can create a cold spot and influence wetting.<br>M(2) Attachments can be designed such that the influence is minimized.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | Specimen design:<br>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? A high vote means that a bundle test is needed while low vote means single rod tests will suffice.<br>H(4) The empirical nature of the correlation drives you to using prototypical lengths, geometries, and grids because the fundamental understanding of the phenomena is weak.<br>M(2) Single tube and single bundle tests provide useful insights into the key processes and phenomena, even if one does not perform bundle tests.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | Specimen design:<br>Channel boundary conditions | Shape and temperature of test shroud.<br>H(6) If you can do a good job of the boundary conditions one can run with a smaller bundle.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Power pulse characteristics | Pulse shape, full-width half maximum, period, height variation, and total number of pulses.<br>H(0) No votes.<br>M(5) The heat flux is the key parameter and the damping represented by the fuel-time constant is smoothing much of the instantaneous behavior.<br>L(1) Same as above but even less emphasis on the accurate modeling of the power pulse characteristics.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Flow oscillation characteristics | Fluctuating characteristics of the flow, e.g., shape, width, period, and total number of flow oscillations.<br>H(6) Flow characteristics have an immediate impact on the cladding behavior and have a major effect on the capability of rewet.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Average power level | Time averaged power during oscillations<br>H(6) Important to develop the conditions to initiate rewet and critical heat flux so that this vital information can be used for code validation. The average power sets the base condition from which the margin associated the oscillatory behavior can be determined.<br>M(0) No votes.<br>L(0 No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Axial power profile | The axial variation over a test article length (long or full-length test article) equivalent to the axial variation over the fuel assemblies in a power reactor, taken at the axial location in the power reactor for which testing is specified.<br>H(2) The phenomena to be studied are the integral of the test conditions and must be captured accurately in a full-length test fixture. There will be significant differences in results between shaped and average power shapes.<br>M(4) The average power level is the most important power factor and any peaking above that is only of moderate impact.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Coolant heat transfer | The coolant environment to which the test article is exposed, including, for example, turbulence, flow rate, flow regimes, twist, droplet diameter and population, etc.<br>H(4) Highly non-equilibrium flow field and coolant heat transfer will be important relative to the rewet characteristics of the test.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Steam quality | Specification and setting of the mass percentage of steam in the two-phase flow.<br>H(5) Highly non-equilibrium flow field and coolant heat transfer will be important relative to the rewet characteristics of the test.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Steam quality measurement | Measurement of the mass percentage of steam in the two-phase flow.<br>H(5) Need to know this parameter and its variation if the test is to be convincing and return the needed data.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Vapor temperature | Specification and setting of the vapor temperature, including superheat, that occurs in the bundle during the test.<br>H(4) Highly non-equilibrium flow field and coolant heat transfer will be important relative to the rewet characteristics of the test.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Measure vapor temperature | Measurement of vapor temperature, including superheat, that occurs in the bundle during the test.<br>H(1) Measurement of the vapor temperature is important to qualify the test and make it useful and also if you wish to do correlation development.<br>M(1) Important variable to measure but difficult parameter to measure accurately.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Temperature of cladding | Measurement during the test of the cladding temperature variation.<br>H(5) Cladding temperature is the key output that determines whether the test will proceed to the high temperature regime or stay in the low temperature regime.<br>M(2) The most important issue is whether the test progresses through the low temperature regime and into the high temperature regime. As there are several means to do this, e.g., cladding elongation, a moderate ranking is appropriate because other measurements are less intrusive.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>DNB and rewet detection | Measurement during the test of the time and location of any departure from nucleate boiling and subsequent rewetting. Candidate techniques include cladding temperature or cladding elongation measurement or acoustic measurement.<br>H(7) DNB detection is a primary purpose of the test<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Fuel centerline temperature | Measurement of the fuel temperature at the centerline of the fuel in an integral (in-reactor) test.<br>H(0) No votes.<br>M(5) Provides useful but not essential information. This is a mature technique<br>L(1) The procedure is intrusive in that the pellets are drilled and this affects the outcome.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Mass flow rate | Specification of the experimental flow rate, including both forward and reverse flows.<br>H(7) One of the primary parameters for creating the specified test conditions.<br>M(0) No votes.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |
| Conduct of test | During the test:<br>Pressure | Specification and measurement of the pressure in the test section.<br>H(0) No votes.<br>M(6) Critical heat fluxes vary with pressure so it is moderately important to be in the correct pressure range.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

## Table B-2. BWR Power Oscillations without Scram. Category B – Integral Testing - High Temperature (continued)

| Subcategory | Phenomena | Definition and Rationale (Importance and Applicability) |
|---|---|---|
| Conduct of test | During the test:<br>Interior cladding temperature | Independent measurement during the test of the inner radius cladding temperature variation with the objective of permitting the calculation of the cladding heat flux.<br>H(0) No votes.<br>M(2) A desirable measurement to develop the heat flux, although this information is not absolutely necessary.<br>L(0) No votes.<br>All: Baseline PIRT importance rank applicable. |

[a] Discriminating factor: Rods that exhibit these characteristics should not be selected unless they occur to a significant extent in the population of rods to be investigated.