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Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel

Los Alamos National Laboratory

U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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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 thought to occur 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 a rod ejection accident in pressurized water reactors containing high burnup fuel.

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EXECUTIVE SUMMARY

In the United States, two types of regulatory criteria have been used in safety analyses to address reactivity-initiated accidents. One criterion is a limit of 280-cal/g fuel on peak fuel-rod enthalpy. This limit was intended 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 occur at 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 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 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 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 (PWRs) 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 twenty-one 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 a rod ejection accident in a PWR containing high-burnup fuel. The plant selected for the PWR rod ejection accident PIRT is TMI-1, a Babcock & Wilcox Company-designed reactor containing uranium dioxide fuel and Zircaloy-4 cladding at a burnup of 62 GWd/t. 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.

The panel recognized that it is necessary to use a combination of experimental data (both from integral tests and from separate effects tests) and analyses (including

plant transient analysis and fuel rod analysis) to resolve issues related to fuel burnup. Integral tests refer to the testing of fueled rods in a reactor when subjected to a sudden reactivity increase, in facilities such as Cabri (France), Nuclear Safety Research Reactor (NSRR, Japan), and BIGR (Russia). Although these are the tests that most closely approximate the actual rod ejection accident event, they are extremely expensive, so that it is financially impractical to devise a research program based solely on integral tests. Because of this, the effects of various parameters must be studied in separate-effects tests that can investigate the relevant parameters in detail. In addition, it is necessary to perform fuel rod analysis to translate the results of the integral testing to the power plants and to be able to extract data from the experimental results. Such analysis can factor in any inherent differences between the integral tests and real power plants (such as the presence of a sodium loop instead of water or low reactor temperatures). It is also necessary to perform analyses of plant transients that give the boundary conditions for the rod ejection accident, as well as assessing its likelihood.

The panel came to recognize that the unfavorable consequences of a rod ejection accident could be divided into two scenarios, low temperature failures occurring early in the transient and high temperature failures that would occur later in the transient. The panel discussion and phenomena evaluation efforts for the rod ejection accident focused on the low temperature scenario. The panel determined that the high temperature phenomena would be evaluated as part of the loss-of-coolant accident (LOCA) PIRT (NUREG/CR-6744).

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

The PIRT phenomena identified by the panel were grouped into four categories: (A) Plant Transient Analysis, (B) Integral Testing, (C) Transient Fuel Rod Analysis, and (D) Separate Effects Testing. 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 according to a set of well-defined questions, which are listed for each subcategory in Section 2.5; (3) ranked their importance to the primary evaluation criterion as high, medium, or low; (4) documented the rationales for the importance votes; (5) evaluated the current uncertainty in the knowledge of these phenomena as "known," "partially known," 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 rod ejection 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 that are near to, but not meeting, the screening criteria. Those applying these PIRT results should carefully examine and consider both the PIRT votes and the documented rationales.

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

Plant Transient Analysis (Category A)

This 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. In this category, the panel considered the calculations of power history and energy deposition in the fuel during the transient. Of the list shown in Table 3-1, six phenomena* in this category were identified as being of high importance: (1) ejected control rod worth, (2) fuel temperature feedback, (3) delayed-neutron fraction, (4) fuel cycle design, (5) heat capacities for fuel and cladding, and (6) pin peaking factors. However, no highly important phenomenon had a corresponding knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. The combined result implies that the six phenomena passing the importance ratio screen are important but well known.

Integral Testing (Category B)

The integral testing category includes the phenomena related to the integral testing of fuel rods, such as performed at Cabri, NSRR, and BIGR. This category was divided into two subcategories: fuel rod selection and conduct of the test. Fuel rod selection includes the initial conditions that are considered to be of importance in selecting fuel rods for use in integral tests, both in terms of capturing the important physical characteristics and in terms of assuring prototypicality of the testing. The

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* Definitions of each phenomenon listed are found in Appendices A–D of this report. The rationales for importance and uncertainty rankings are found in the same appendices.

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.

Within the fuel rod selection subcategory, seven phenomena satisfied both the importance and the knowledge screening criteria, three associated with the fuel and four with the cladding. The fuel-related characteristics were (1) rim size, (2) fission gas distribution, and (3) plutonium-rich agglomerates (for mixed-oxide [MOX] fuel). The development of a rim structure near the edge of the fuel pellet caused by increased plutonium concentration can affect the power deposition, the loading on the cladding, the fission gas release during the transient and possibly the fuel dispersal in the case of failure. The fission gas distribution in the fuel pellet when the rod ejection accident occurs affects fission gas release and possibly the cladding loading. The presence of plutonium-rich agglomerates causes an uneven distribution of power during the transient, which may affect fuel and cladding response.

The cladding-related phenomena were the (4) amount of hydrogen, (5) hydrogen distribution, (6) hydride orientation, and (7) cladding integrity. The panel identified the effect of hydrogen (amount of hydrogen, hydride distribution, and hydride orientation) as being the predominant factor in influencing cladding failure. It is also important to ensure that no pre-existing or fabrication defects are present in the specimen to be tested.

Within the conduct of test subcategory, five phenomena satisfied both the importance and the knowledge screening criteria. These five phenomena were (1) on-line measurements of fuel dispersal, (2) pressure pulse, (3) fission product release, (4) rod deformation, and (5) the time and location of failure. These are phenomena that need to be monitored during an integral test.

The on-line measurement of fuel dispersal is directly related to the primary evaluation criterion (cladding failure with significant fuel dispersal), as is the presence of a pressure pulse. The detection of fission gases aids in the determination of fuel dispersal and also permits assessment of the extent of gas loading. The measurement of rod strain supports calibration of predictive models of fuel rod mechanical behavior. Finally, the detection of failure time and location is essential to understand how the failure started and propagated, i.e., the failure mechanism.

Having met the dual screening criteria, each of the above listed phenomena in the fuel rod selection and conduct of test subcategories has been flagged by the panel as a candidate for additional consideration.

Transient Fuel Rod Analysis (Category C)

The Transient Fuel Rod Analysis category includes the phenomena and outcomes of calculations of transient fuel rod behavior predicting the fuel behavior in reactor integral tests and in separate effect tests. These calculations are performed with codes such as FRAPTRAN, FALCON, and SCANAIR. This category is divided into five subcategories that may require modeling in the codes. The first (initial conditions) captures the characteristics of the fuel and cladding before the transient.

The remaining four subcategories (mechanical loading to the cladding, fuel and cladding temperature changes, cladding deformation, and pellet deformation) 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 the event.

Within the initial conditions subcategory, five characteristics satisfied both the importance and the knowledge screening criteria. They are (1) gas distribution, (2) hydrogen distribution, (3) fuel-clad gap friction coefficient, (4) condition of oxidation (spalling), and (5) bubble size and bubble distribution. These are all phenomena that influence the loading on the cladding or its ability to withstand the rod ejection accident event.

The gas distribution (as well as bubble size and bubble distribution) affects the cladding loading and can drive fuel fragmentation. Hydrogen distribution can affect the ductility of the cladding, due to the presence of localized hydrides; this is also the reason for the high importance of condition of oxidation (spalling) as that can cause hydride blisters. The friction coefficient between the pellet and the cladding during the transient determines the stress state of the cladding and may impact failure.

Within the mechanical loading subcategory, one characteristic, pellet-cladding contact (gap closure) satisfied both the importance and the knowledge screening criteria.

Three characteristics in the fuel and cladding temperature changes subcategory were identified as being of high importance: (1) heat resistances in fuel, gap, and cladding; (2) heat capacities of fuel and cladding; and (3) coolant conditions. However, none of these three had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration. Thus, the panel believes these factors are important but well known.

Within the cladding deformation subcategory, two characteristics satisfied both the importance and the knowledge screening criteria. They are (1) stress versus strain response and (2) localized effects. The stress-strain response is used by the codes to determine the mechanical response of the cladding.

Within the pellet deformation subcategory, two characteristics satisfied both the importance and the knowledge screening criteria. They are (1) grain boundary decohesion and (2) evolution of pellet stress state. Grain boundary decohesion can lead to fuel fragmentation and dispersal and may influence the loading to the cladding. The evolution of the pellet stress state is a result of the complex interaction of other important phenomena during the transient; and, as such, it was considered to be of high importance.

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)

The Separate Effect Testing category includes the important phenomena relevant to mechanical testing designed to measure the properties relevant to extending the integral testing database and providing mechanistic understanding of failure. This category was divided into two subcategories: specimen selection and test conditions.

Within the specimen selection subcategory, six selection characteristics satisfied both the importance and the knowledge screening criteria. They are (1) extent of oxide spalling, (2) extent of oxide delamination, (3) amount of hydrogen, (4) hydrogen distribution, (5) hydride orientation, and (6) cladding integrity. Similar phenomena were emphasized in Category B, indicating the importance the panel puts on the role of hydrogen in degrading cladding ductility. It was also clear that the panel recognizes the importance of stress state in performing mechanical tests that are relevant to rod ejection accidents.

Within the test conditions subcategory, three parameters satisfied both the importance and the knowledge screening criteria. They are (1) stress state imposed on specimen, (2) tensile test specimen design, and (3) burst specimen design.

Having met the dual screening criteria, each of the above has been flagged by the panel as a candidate for additional consideration.

In addition to developing and analyzing the phenomena identification and ranking tables (PIRTs), panel members responded individually with written comments on the "Availability and Applicability of a Bounding Approach for High Burnup Fuel" and "Panel Perspectives on Approaches to Increasing the Burnup Limit from 62 to 75 GWd/t." Panel member responses for these two topics are found in Appendices G and H, respectively. 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 power oscillations without scram in BWRs containing high burnup fuel (NUREG/CR-6743) 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.

Thomas L. King, Director
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In Memory of
Franz K. Schmitz

In November of 1993, a test was run in the Cabri test reactor in France that raised questions about the regulatory criteria that are used around the world in the analysis of reactivity accidents for cases with high-burnup fuel. This indication was confirmed in later tests in Cabri and in the Nuclear Safety Research Reactor in Japan and led to current activities to resolve related issues. As leader of the reactivity accident research program in France, it was Franz Schmitz's insights and deep understanding of transient fuel behavior that led to these developments and to plans for more prototypical testing in a water loop in Cabri. He was born in Cologne in 1935 and received a Ph.D. degree in physics from the University of Braunschweig (Germany) in 1965. As a Euratom employee, Dr. Schmitz was detached to the Atomic Energy Commission (CEA) in France, where he lived permanently thereafter. From 1976 to 1998, he was in charge of safety-related aspects of fuel behavior at the Cadarache Research Center within the framework of international programs in the Cabri and Scarabée test reactors. Because the focus of his recent work was on PWR rod-ejection accidents, Dr. Schmitz was, of course, selected for the PIRT panel, whose work is the subject of this report; and he would have been the defacto dean of the group of experts. Failing health, however, prevented his attendance at the PIRT panel meetings, although he was able to send comments by e-mail. He died on November 16, 1999, before the work of this panel was finished. The authors and sponsors of the work would like to dedicate this report to his memory.

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 and C focused on analytical issues and was chaired by Kenneth Peddicord. The working group for Categories B and D focused on experimental issues and was chaired by Arthur Motta. The working group chairpersons were responsible for planning and facilitating discussions and documenting the identification and ranking outcomes of the working group.
- David Diamond of Brookhaven National Laboratory, Philip MacDonald of the Idaho National Engineering and Environmental Laboratory, and Carl Beyer of Pacific Northwest National Laboratory served as technical elicitors and, as such, were instrumental in assisting the panel with its phenomena identification and ranking efforts. In addition, David Diamond prepared the following working document: D. J. Diamond, "A Review Prepared for the Working Group to Develop a PWR RIA PIRT for High Burnup Fuel," Brookhaven National Laboratory (1999). This document formed the basis for the information presented in Section 2.2 and is presented in its entirety in Appendix J. Michael Billone of Argonne National Laboratory participated in several PIRT panel meetings and provided technical insights.
- Arthur Motta is a member of the PIRT panel. In addition, however, he was instrumental in preparing a description of high burnup fuel initial conditions as well as the response of the fuel to the rod ejection accident. Much of the text in Section 2.3.2, as well as in Figs. 2-1 and 2-5, was provided by Arthur Motta. Joe Rashid, whose participation in the PIRT effort was sponsored by the Electric Power Research Institute (EPRI), reviewed and commented on this document; and his suggestions were incorporated. Carl Beyer performed a similar service.
- Robert Montgomery of Anatech, Inc., also sponsored by EPRI, participated in the second panel meeting in the absence of Joe Rashid; and his participation and contributions are gratefully acknowledged.

- The Electric Power Research Institute suggested industry participants for panel membership. These individuals represented a cross section of the nuclear power industry. 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

ANL	Argonne National Laboratory
ACPR	Annular Core Pulse Reactor
ATWS	Anticipated Transient Without Scram
B&W	Babcock & Wilcox
BWR	Boiling water reactor
CE	Combustion Engineering
CEA	Commissariat à l'Energie Atomique (France)
DNB	Departure from nucleate boiling
EDF	Electricité de France
EOL	End of Life
EPRI	Electric Power Research Institute
FEM	finite element model
FGR	fission gas release during transient
GDC	General design criterion
GRS	Gesellschaft fuer Anlagen- und Reaktorsicherheit
IGR	Impulse Graphite Reactor
IPSN	Institute for Protection and Nuclear Safety
IR	Importance ratio
JAERI	Japan Atomic Energy Research Institute
JMTR	Japan Materials Testing Reactor
KR	Knowledge ratio
LOCA	Loss-of-coolant accident
LWR	Light-water reactor
MOX	Mixed oxide
NRC	United States Nuclear Regulatory Commission
NSRR	Nuclear Safety Research Reactor
PBF	Power Burst Facility
PCMI	pellet-cladding mechanical interaction
PIRT	Phenomena Identification and Ranking Table
PSU	Pennsylvania State University
PWR	Pressurized water reactor
RCS	Reactor coolant system
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 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) a PWR rod ejection accident, (2) BWR power oscillations without scram, and (3) PWR and BWR loss-of-coolant accidents (LOCAs). In the remainder of this report, the authors document the findings of the High Burnup Fuel PIRT panel for the PWR rod ejection accident. Additional reports have been issued for the remaining plant scenarios.[1-1, 1-2]

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

- Section 1, Introduction, summarizes the issues associated with high burnup fuel, provides an overview of the PIRT process, identifies the members of 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, PWR Rod Ejection Accident 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 rationales for Category B, Integral Testing.
- Appendix C contains the phenomena descriptions and ranking rationales for Category C, Transient Fuel Rod Analysis.
- Appendix D contains the phenomena descriptions and ranking rationales for Category D, Separate Effect Testing.

- Appendix E describes the experimental programs whose data comprise the majority of the experimental database used by the panel in preparing the PWR rod ejection accident PIRT.

- Appendix F contains a tabulated summary comparing features of three transient fuel rod analysis codes (FRAPTRAN, FALCON, and SCANAIR).

- Appendix G provides panel member insights regarding the availability and applicability of a bounding approach for high burnup fuel.

- Appendix H summarizes the perspectives of various panel members on approaches to supporting an increase in the burnup limit from 62 to 75 GWd/t.

- Brief experience summaries for each panel member are provided in Appendix I.

- Finally, a review of the control rod ejection accident presented to the PIRT panel is provided in Appendix J.

1.1. Background

Only a small number of design-basis accidents are postulated for licensing of light-water reactors (LWRs) in the United States and one class of these events includes reactivity accidents.[1-3] In PWRs, it is assumed that in the most severe of such accidents a control-rod housing in the pressure-vessel head breaks and the control-rod assembly is ejected from the core as a result of a pressure differential. The worst such potential accident would occur from zero-power conditions, and the minimum coolant temperature for one such plant is, for example, 271°C (520°F) as set by technical specifications.

As expressed in the General Design Criterion (GDC) 28,[1-4] NRC regulations contain a two-fold regulatory criterion for reactivity accidents: avoid reactivity accidents that result in (1) damage greater than limited local yielding of the pressure boundary or (2) significant impairment of the capability to cool the core.

In the United States, two types of regulatory criteria have been used in safety analyses to address these reactivity-related accidents.[1-5] One is a limit of 280-cal/g fuel on peak fuel-rod enthalpy.[1-6] 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 regulatory 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. This criterion is used in calculating radiological releases for comparison with other limits. For PWRs, a critical heat flux value related to departure from nucleate boiling (DNB) is used. For BWRs, a similar value is used for high-power accidents; but for low-power and zero-power accidents, a peak fuel-rod enthalpy of 170-cal/g fuel is used.

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

In late 1993, a test 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 and the 170 cal/g fuel failure criterion that the NRC initiated an investigation into this situation and issued an Information Notice to licensees.[1-7] 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. It was decided that a revision of Regulatory Guide 1.77 is needed 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 a new criterion to replace the 280 cal/g coolability limit and the cladding failure criterion of Regulatory Guide 1.77.

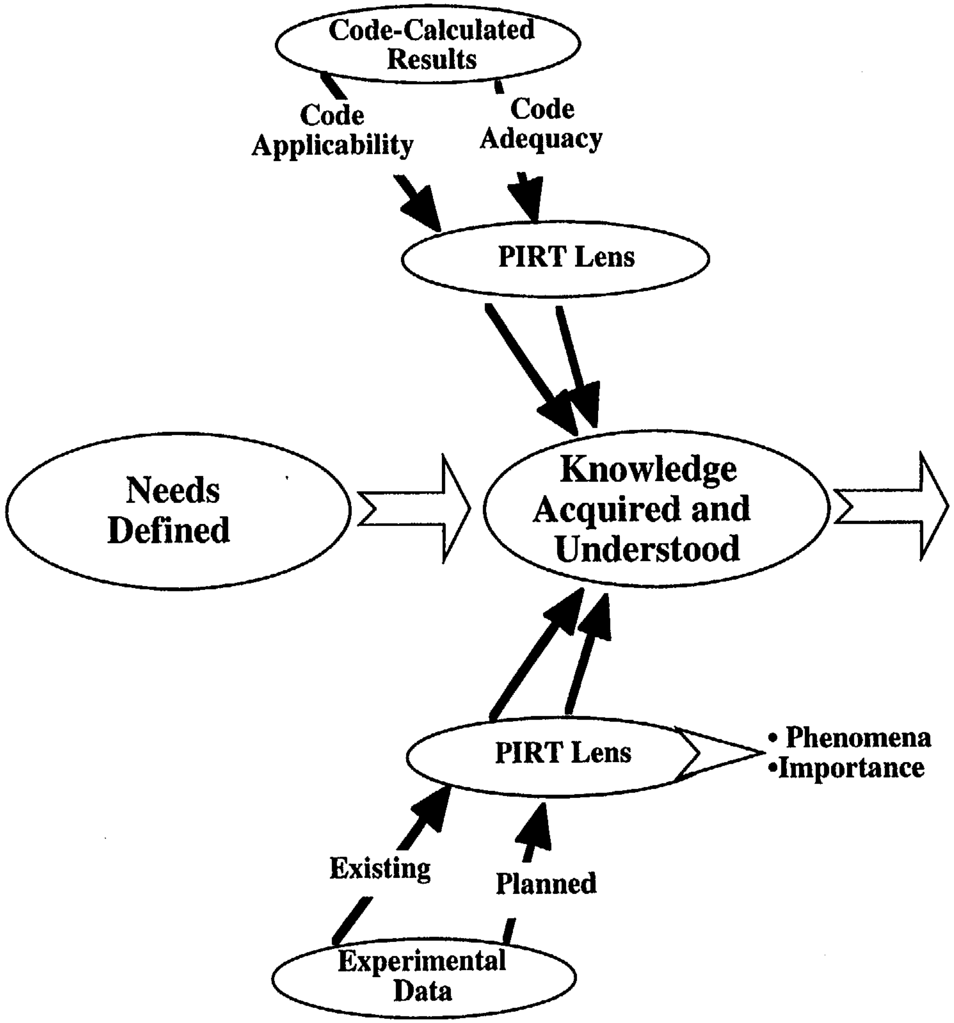
The PIRT documented in this report is a tool that will be used by the NRC in addressing these two needs. The PIRT presented in this report can be visualized as a lens through which existing experimental data and planned experiments can be examined. Because the PIRT both identifies and ranks phenomena 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 identified needs is illustrated in Fig. 1-1. In reality, the acquisition of knowledge and understanding is not a once-through process. Rather, the process is inevitably iterative in nature, e.g., improved modeling leads to improved code-calculated results and refined experiments contribute to an improved experimental database.

There are many specific questions that must be answered while addressing the NRC's needs. As answers are collected and issues resolved, the knowledge and understanding required to satisfy NRC's needs will be obtained. Figure 1-1 identifies several of the questions, which, once answered, will demonstrate that the database needed to develop a new criteria for Regulatory Guide 1.77 has been developed. 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



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.

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 PWR rod ejection PIRT were as follows:

- Carl A. Alexander, Battelle Memorial Institute;
- Richard Deveney, Framatome Cogema Fuels;
- Bert Dunn, Framatome Technologies, Inc.;
- Toyoshi Fuketa, Japan Atomic Energy Research Institute;
- Keith Higar, Northern States Power Company;
- Lawrence Hochreiter, The Pennsylvania State University;
- Gene Jensen, Siemens Power Corporation;
- Siegfried Langenbuch, Gesellschaft fuer Anlagen- und Reaktorsicherheit (GRS) mbH;
- Fred Moody, Consultant;
- Arthur Motta, The Pennsylvania State University;
- Mitchell Nissley, Westinghouse Electric Corporation;
- Jöelle Papin, Institute for Protection and Nuclear Safety;
- Kenneth Peddicord, Texas A&M University;
- Gerald Potts, Global Nuclear Fuel, Inc.;
- Doug Pruitt, Siemens Power Corporation;
- Joe Rashid, Anatech Corporation;
- Daniel Risher, Westinghouse Electric Corporation;
- Richard Rohrer, Northern States Power Company;
- James S. Tulenko, University of Florida;
- Keijo Valtonen, Finnish Center Radiation and Nuclear Safety;
- Nicolas Waeckel, Electric Power Research Institute; and
- Wolfgang Wiesenack, Halden Reactor Project.

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

1.3. PIRT Overview

The PIRT process has evolved from its initial development and application[1-8, 1-9, 1-10] to its description as a generalized process.[1-11] A PIRT can be used to support several important decision-making processes. For example, the information can be used to support either the definition of requirements for related experiments and analytical tools or the adequacy and applicability of existing experiments and analytical tools.

This information is important because it is neither cost effective or required to assess each feature of an experiment or analytical tool in a uniform fashion. The PIRT methodology brings into focus 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 PWR PIRT for high burnup fuel, is illustrated in Fig. 1-2 and described as follows.

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

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

3. Define the hardware and equipment scenario for which the PIRT is to be prepared. Generally, a specific hardware configuration and specific scenario are specified. Experience gained from previous PIRT efforts indicates that any consideration of multiple hardware configurations or scenarios impedes PIRT development. After the baseline PIRT is completed for the specified hardware and scenario, the applicability of the PIRT to related hardware configurations and scenarios can be assessed as illustrated in Fig. 1-2.

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

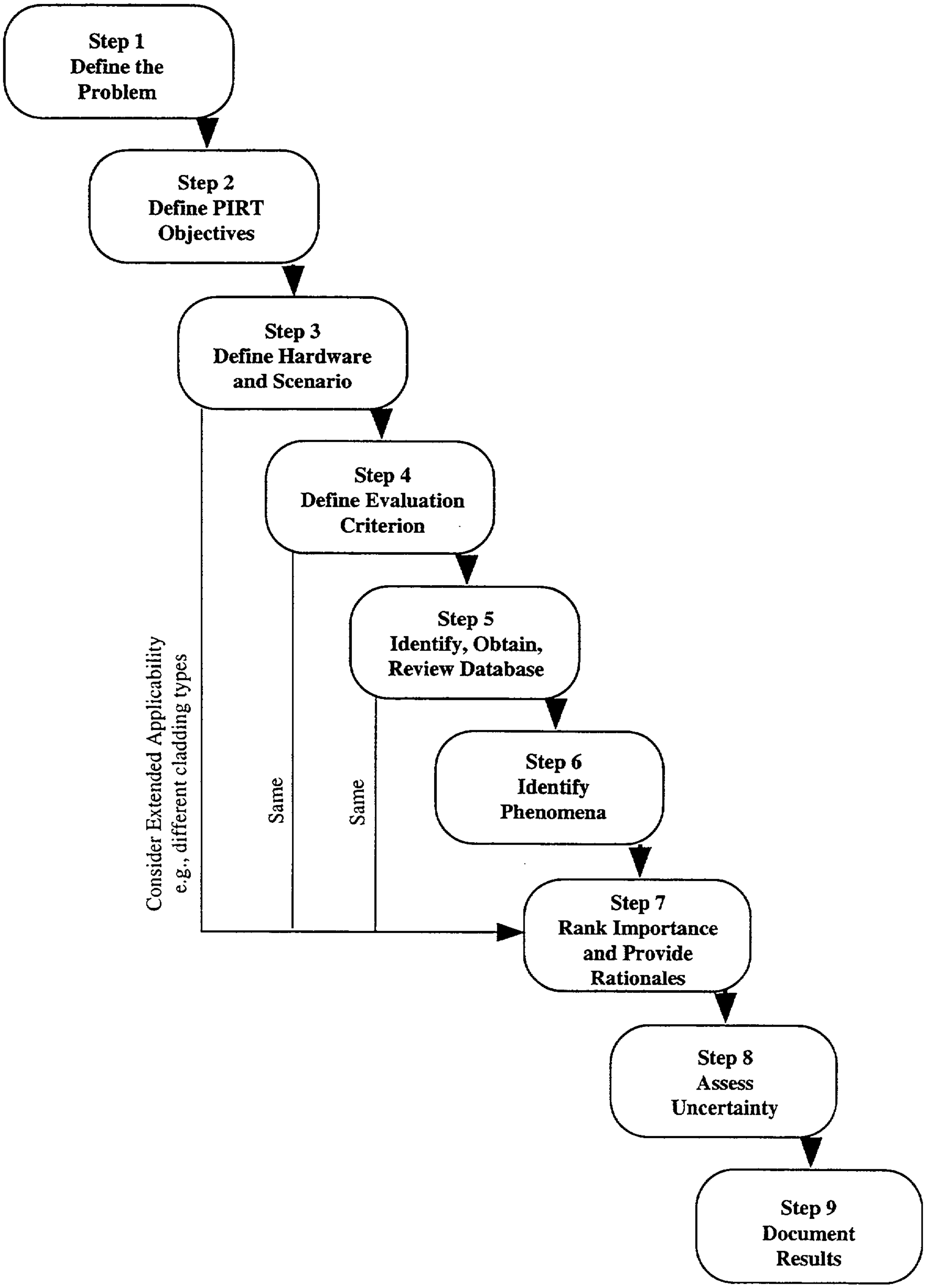


Fig. 1-2. Illustration of PWR rod ejection accident PIRT process.

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 those for the PWR rod ejection accident (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 to the primary evaluation criterion when voting. The degree of knowledge or understanding of an individual 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.[1-11] By explicitly addressing uncertainty, an observed defect of earlier PIRT efforts has been addressed, namely, the tendency of PIRT panel members to assign high importance to a phenomenon for which it is concluded that there is significantly less than full knowledge and understanding.

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

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

1.4. PIRT Objectives

The PIRT panel was organized to develop a PIRT for a PWR containing high burnup fuel and experiencing a rod ejection accident. The PIRT was developed and documented so that it could be used to help guide future NRC-sponsored analytical, experimental, and modeling efforts conducted as part of its program to develop a new criterion to replace the 280 cal/g criterion of Regulatory Guide 1.77. An NRC staff report that strives to utilize these PIRT results has also been issued.[1-12]

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1-4. Code of Federal Regulations, Title 10 (January 1, 1990).

1-5. US Nuclear Regulatory Commission Standard Review Plan, Section 4.2, "Fuel System Design," NUREG-0800, Rev. 2 (July 1981).

1-6. US Nuclear Regulatory Commission, "Assumptions Used for Evaluating a Control Rod Ejection Accident for Pressurized Water Reactors," Regulatory Guide 1.77 (May 1974).

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1-9. 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.

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1-11. 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).

1-12. 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 the rod ejection PIRT development are discussed in Section 2.1. Because the phenomena of interest during a rod ejection accident occur within several seconds of accident initiation, greater emphasis is placed on the fuel design for this PIRT effort. Descriptions of the selected fuel type for this PIRT and its state at high burnup prior to the event are described in Section 2.2.

The accident scenario selected for the PWR PIRT is discussed in Section 2.3. Fuel and cladding behavior during a rod ejection accident 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 plant selected for this PIRT is the Three Mile Island unit one (TMI-1). TMI-1 is a Babcock & Wilcox Company (B&W)-designed facility rated at 786 MWe. Its coolant piping is arranged in a 2 x 4 configuration consisting of two hot legs, two steam generators, four coolant pumps and four cold legs. The unit contains 177 fuel assemblies with fuel rods arranged in a 15 x 15 configuration. The fuel is uranium dioxide (UO_2) and the cladding is Zircaloy-4.

With the exception of beginning 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 (Westinghouse [W] and Combustion Engineering [CE]), fuel types (mixed-oxide [MOX] fuel utilizing fissile plutonium), cladding types introducing niobium (Nb) or having reduced tin (Sn) content (ZIRLO, Duplex, M5, etc.), and burnup to 75 GWd/t.

2.2. Description of Fuel and Cladding State at High Burnup

The extended operational exposure that accompanies high burnup causes changes to the fuel and cladding that may affect the fuel rod's ability to withstand the accident without losing its integrity (Fig. 2-1). These changes, which occur gradually over the life of the fuel rod, can be considered as initial conditions for the accident.

There are many changes that occur to the fuel and cladding as a result of prolonged exposure to the irradiation field present in a reactor core and to the corroding environment and high temperature. The combination of high temperature, radiation damage, transmutation, mechanical stresses, and chemical reactions causes the microstructure of cladding and fuel to evolve considerably during reactor exposure. These changes in microstructure, microchemistry, and macroscopic characteristics of pellet and cladding are responsible for the changes in material behavior observed at high burnup. These changes are very complex and difficult to predict in mechanistic fashion. Of the many changes to the fuel and cladding, it is important to discern which are of greatest importance to determining fuel rod behavior during a rod ejection accident. We list some of the more important material degradation phenomena, recognizing that the list may not be inclusive. The changes to the fuel and cladding are important to both pressurized water reactor (PWR) and boiling water reactor (BWR) fuel types. However, the discussions will primarily be for PWR fuel because it leads the BWR fuel in terms of both fuel burnup and waterside corrosion.

2.2.1. Cladding Changes

The main degradation mechanisms to Zircaloy-4 cladding, such as are present in TMI, include uniform waterside corrosion, hydriding, and radiation damage.

Uniform waterside corrosion occurs throughout the reactor exposure. The corrosion rates depend on many factors including alloy chemistry and thermomechanical treatment, coolant chemistry, radiation-induced changes to cladding microchemistry, and irradiation temperature. For cladding with burnups in excess of 50 GWd/t, the oxide thickness can exceed 100 μm depending on fuel duty, i.e., power and temperature versus time and burnup. The burnup level at which any given oxide thickness is reached for a given alloy is dependent on the fuel duty. The more modern alloys such as ZIRLO and M5, can have lower corrosion rates than standard Zr-4 and low-Sn Zr-4 at similar burnup. All of the zirconium alloys examined to date show a change in corrosion rate when the oxide exceeds a certain thickness (20–30 μm in thickness), which indicates a change in corrosion regime, termed **breakaway corrosion.** Therefore, it is likely that even the new modern alloys, such as ZIRLO, will eventually experience breakaway corrosion. The question with the new modern alloys is the burnup level at which breakaway corrosion will be observed.

For example, fuel that experiences a high fuel duty will experience breakaway corrosion at a lower burnup level than fuel with a lower fuel duty. One of the concerns with large oxide thicknesses is the higher probability of **oxide delamination**, whereby portions of the oxide layer are detached from the adherent oxide creating an oxide region with worse heat conduction characteristics. Ultimately the detached oxide can break off (**oxide spalling**), creating a thinner oxide. The associated temperature gradients created by spalling have been shown to influence hydride blister formation in the spalled region.[2-1] The hydride blister is brittle, and its presence has been shown to affect overall cladding ductility.

The main concerns associated with the uniform corrosion process are the potential for oxide spalling resulting in hydride blisters, which affect the overall cladding ductility; loss of thermal conductivity; non-uniform wall thinning (non-uniform oxide); and overall wall thinning.

Hydriding occurs as hydrogen is absorbed into the cladding as a result of the cladding uniform corrosion. (Roughly 15%–20% of the hydrogen generated by the corrosion reaction is absorbed into the alloy.) This hydrogen precipitates as hydrides throughout the cladding thickness at corrosion thicknesses greater than 50 μm. When the overall hydrogen level is high enough (>1000 parts per million [ppm]), the cladding is brittle when tested at reactor temperature. It is possible that lower levels of hydrogen (600–800 ppm) can affect cladding ductility, especially at lower temperature.

However, lower levels of hydrogen, can also degrade the overall cladding ductility depending on the hydride distribution. Hydrogen has high mobility but low solubility in Zircaloy, so hydrogen will tend to precipitate out in any cold spot formed in the material. For example, there is a much greater hydride concentration near the surface of the cladding creating a **hydride rim** with local hydrogen levels higher than 1000 ppm. In addition to being radially localized, the axial distribution of hydrogen is also non-homogeneous, with greater concentration in the region in-between the fuel pellets due to the slightly lower heat fluxes and lower temperatures at pellet interfaces.

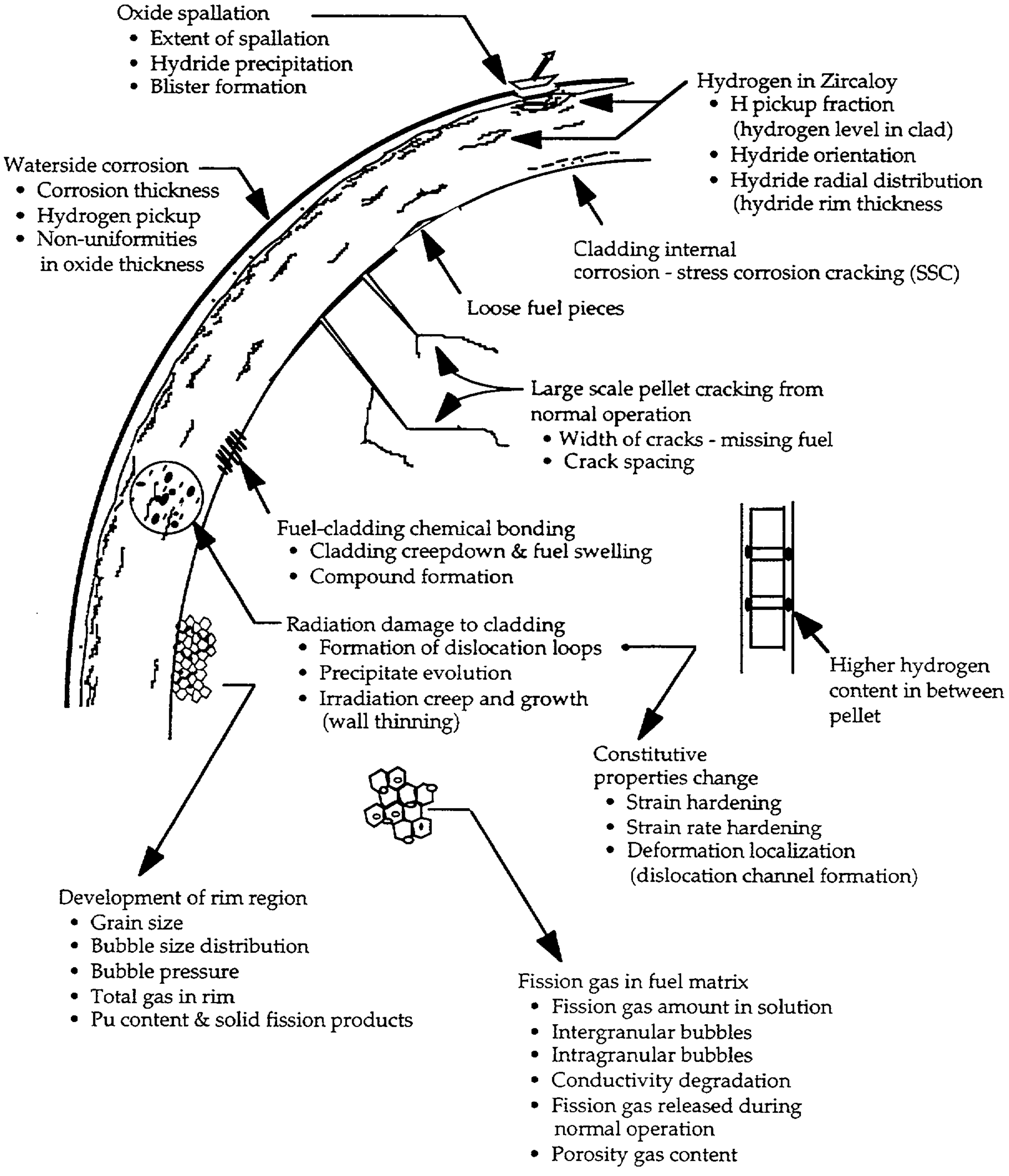

Fig. 2-1. Fuel state at high burnup.

The main concerns associated with hydriding are (a) lower ductility and/or embrittlement resulting from an overall change in constitutive properties and (b) creation of weak spots in cladding resulting from the formation of a hydride rim and/or hydride blisters.

Radiation damage. When irradiated to 30 GWd/t (corresponding to a fast fluence of ~ 10^{22} n/cm^2, E>1 MeV), the cladding suffers an amount of damage calculated at about 20 dpa (displacements per atom).[2-2] The dpa level is roughly proportional to the fluence or burnup, so that 60 GWd/t corresponds to about 40 dpa and 75 GWd/t to 50 dpa. This very high level of displacements is translated mostly into radiation-induced dislocation loops, both <a> and <c> type that form from the agglomeration of point defects. Although the overall <a> dislocation density saturates after about one month of reactor irradiation at a level comparable to that found in cold-worked, stress-relieved cladding, the <c> type dislocations evolve over a more extended period of time. In addition, there are microchemical changes in the alloy related to irradiation-induced intermetallic precipitate amorphization and dissolution, which can **change corrosion resistance** and hydrogen pickup.

The **constitutive response** of the cladding is also affected by the radiation damage, in particular the dislocation loop microstructure formed under irradiation. The yield stress increases and the uniform strain decreases; i.e., the material undergoes **hardening** and ductility decrease. The increase in dislocation loop density decreases the strain hardening coefficient of the material. At the microscopic level, these loops can also influence deformation localization at the microscopic level (dislocation channeling); the effects of these microscopic processes on macroscopic deformation and failure are not clear at the moment. There is also **cladding creep down**, which can cause the gap to be closed, creating the conditions for fuel-clad chemical bonding to develop.

The main concerns relating to radiation damage are radiation hardening and possible embrittlement, change of corrosion resistance through microchemical changes, mechanical property changes, and deformation localization (e.g., dislocation channeling, possibly leading to easier axial crack propagation).

2.2.2. Fuel Changes

During normal operation, fission gas is formed inside the UO_2 fuel, and distributes itself largely into five 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 rod void volume, and (5) gas in fuel porosity.

The amount of gas dissolved in the UO_2 matrix is small, as the solubility of fission gases in UO_2 is low. Contributions *(ii)* and *(iii)* result in fuel swelling with consequent pellet-cladding mechanical interaction (PCMI) and contribution *(iv)* is the result of fission gas release (FGR), which increases the internal rod pressure and results in hoop stress on the cladding. The exact partitioning of these gases among the three inventories are dependent on the power history, temperature, fuel microstructure, etc.

Rim Formation. Because of Uranium-238 resonance neutron capture at the UO_2 pellet surface, the amount of plutonium formed in the fuel is greater at the edge of the pellet than in the center. This causes the fission rate at the pellet surface to slowly increase with burnup, while the fission rate in the bulk of the pellet decreases. The ratio of fission at the edge of the pellet to the center may be as high as 3 at high burnups. Such a region is called the **rim region** and its thickness is approximately 100–300 μm. The rim region is formed when the local burnup at the rim exceeds ~ 60 GWd/t (40-45 GWd/t radial averaged). The **rim region** has a characteristic microstructure that consists of sub-micron-size grains with bubbles under high gas pressures and has high porosity (10%–20%). Some of these bubbles may be in non-equilibrium with the matrix because there are large strain fields around the smaller bubbles and there is further evidence that they exist within the interior of the pellet as well as on the rim if the irradiation temperatures are low.

The main concerns with the formation of the rim region relate to its effects on (a) the amount of fission gas loading and (b) the lubrication (By shearing during deformation, the rim could reduce the friction coefficient between cladding and fuel.).

Fuel restructuring and large cracking. These phenomena occur at low burnups when a significant fuel-cladding gap exists. The fuel-cladding gap is either very small or non-existent (as evidenced by chemical bonding) in high burnup fuel even when the fuel is at hot zero power (reactor coolant is still hot). Therefore, these phenomena are not likely to occur in high burnup fuel.

Micro-cracking. The mechanical stresses and thermal stresses present in the fuel during the rod ejection accident can cause **microcracking** to occur at the grain boundaries weakened by gas bubbles. The microcracking and its extent can affect both fission gas swelling and deformation.

Pellet-cladding Interface. As burnup increases, a metallurgical or chemical bond starts to form between the cladding and the fuel, so that **fuel-cladding bonding** occurs. Clearly the development of this bond depends on the establishment of clad-fuel contact resulting from creep down and fuel swelling. At intermediate stages, the friction coefficient will increase but without perfect bonding. It is important to determine the friction coefficient so that we can determine the stress state and failure mode of the cladding during pellet-cladding mechanical interaction.

2.3. Accident Scenario

The transient selected as the basis for the reactivity-related PWR PIRT is a control rod ejection accident. At the time the rod ejection accident occurs, the plant is assumed to be at hot zero power. Under such conditions, the reactor pressure is 14.86 MPa or 2155 psig; and the temperature is 278°C (532°F). The rod ejection accident is defined as the mechanical failure of a control rod mechanism housing such that the reactor coolant system (RCS) pressure ejects a control rod assembly and drive shaft to a fully withdrawn position. This would require a complete (or almost complete) instantaneous circumferential rupture of the control element drive mechanism. The ejection and corresponding addition of reactivity to the reactor core occurs within approximately 100 ms; the actual time being determined by the reactor pressure and the break size.

In Section 2.3.1, a description of the plant behavior after rod injection accident initiation 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 rod ejection accident that focuses on the fuel and cladding behavior is presented in Section 2.3.2.

2.3.1. Plant Behavior

Upon ejection of the control rod and if the reactivity insertion is sufficient, the reactor will become prompt-critical and power will rise rapidly until the negative fuel temperature reactivity feedback (primarily due to the Doppler effect) terminates the power rise within another few hundred milliseconds. After the power pulse is terminated, the power level is still significant with respect to energy deposition. Eventually more negative reactivity is added by moderator feedback and by the insertion of control rods due to the reactor being tripped. Although the reactor is quickly shut down, the concern is the potential for fuel damage due to the localized energy deposition around the position of the ejected control rod.

The general behavior of the rod ejection accident can be seen in the graph of relative reactor power versus time given in Figs. 2-2 and 2-3. The initial power is 10^{-6} times the nominal 100% power, i.e., hot zero power condition. Figure 2-2 shows the short-term behavior and the almost symmetric power pulse that occurs immediately after the reactivity insertion. For this example, the ejected control rod worth was \$1.2 and it was assumed that tripping the reactor was delayed so that no effect is seen during the 5-s period shown Fig. 2. The corresponding pellet average fuel temperatures near the top of the core for three assemblies near the ejected rod are given in Fig. 2-4. At 2.5 s the maximum value corresponds to an energy deposition of approximately 50 cal/g.

Although the code-calculated results presented in Figs. 2-2 through 2-4 assume no reactor trip, one would occur and effectively terminate the transient at that time. Because of the rate at which the power increase and subsequent power decrease occur, core thermal-hydraulic processes have little impact on the outcome of the accident if the energy deposition is sufficiently low to avoid a departure from nucleate boiling (DNB).

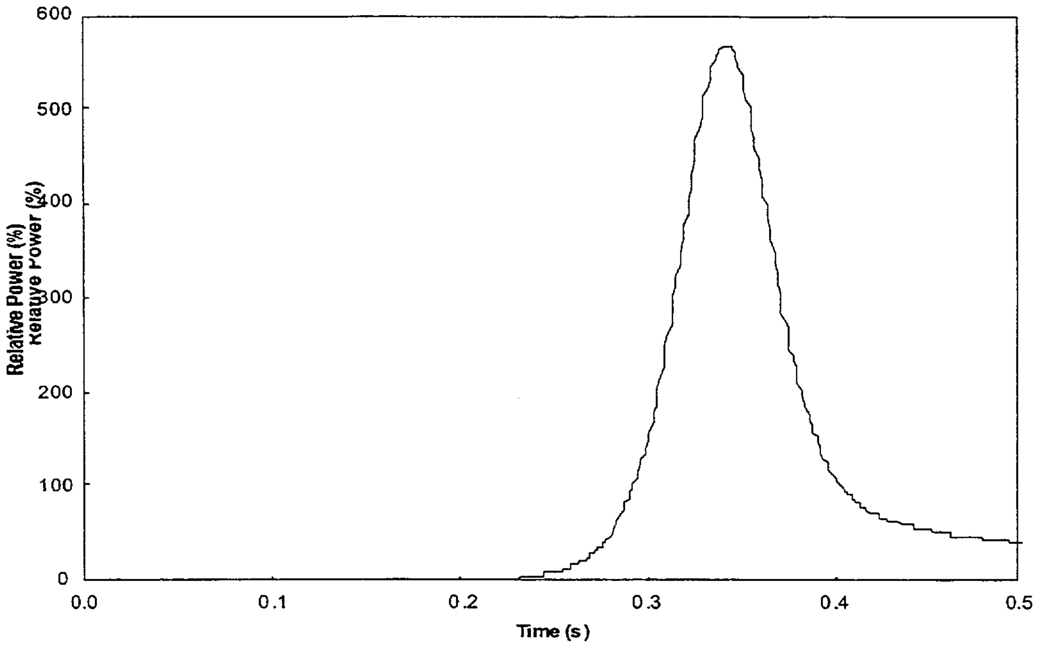

Fig. 2-2. Reactor power during a rod ejection accident (0–0.5 s).

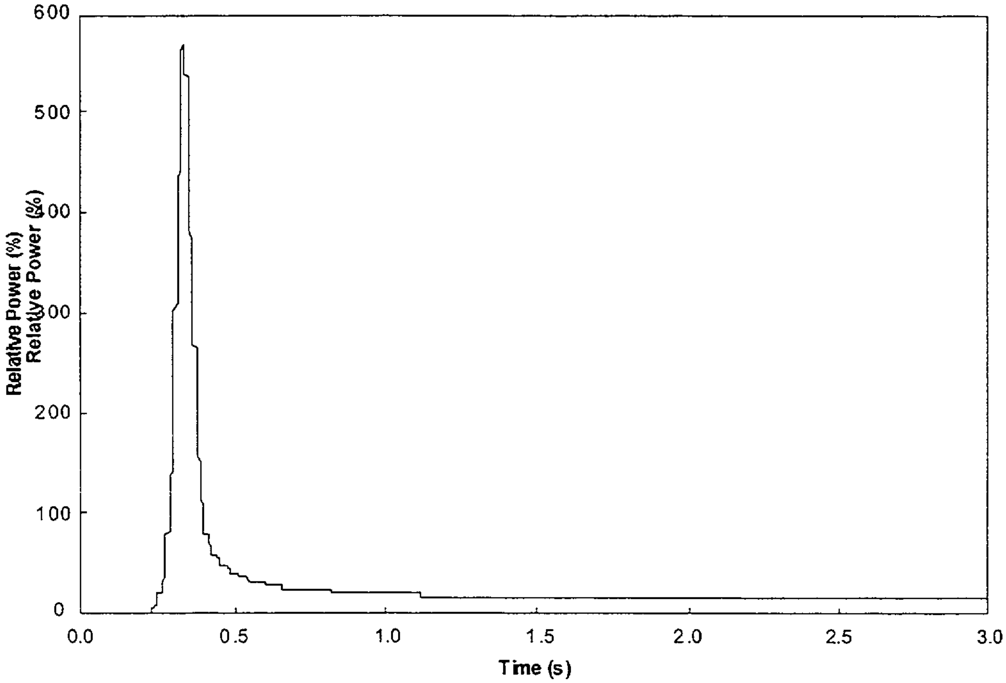

Fig. 2-3. Reactor power during an rod ejection accident (0–3.0 s).

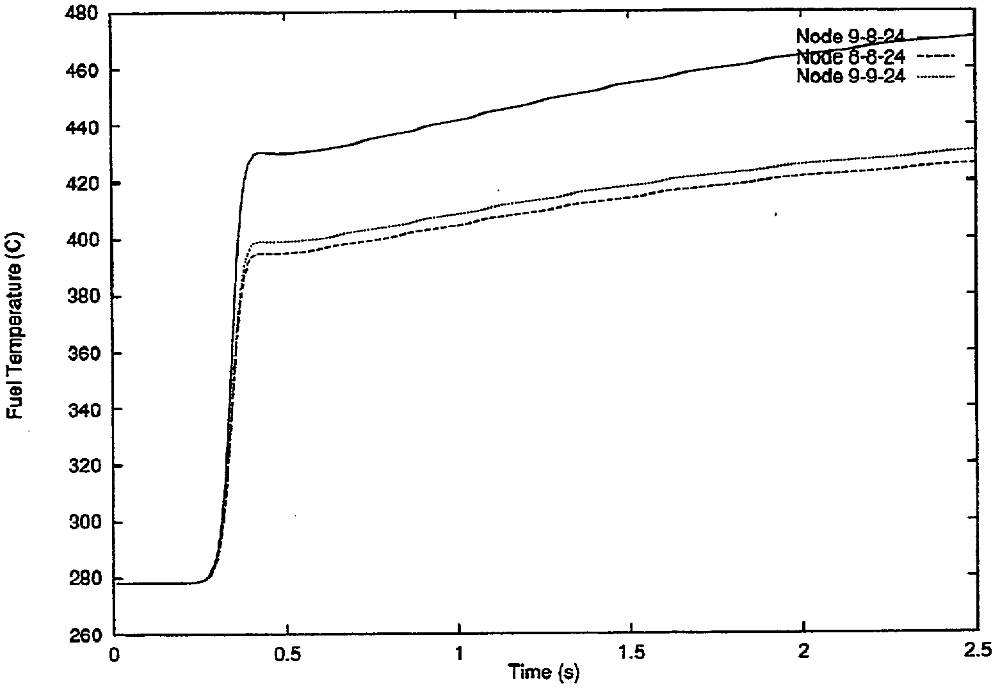

Fig. 2-4. Average pellet temperatures for three nodes.

2.3.2. Fuel and Cladding Behavior during a Rod Ejection Accident

The processes that occur during a rod ejection accident and which may result in cladding failure are illustrated in Fig. 2-5. Phenomena discussed in this section and appearing in Fig. 2-5 appear in **bold type**. Reference is also made in this section to some phenomena that occur during operation to high burnup as illustrated in Fig. 2-1.

As discussed in the previous section, the rod ejection event consists of a large insertion of reactivity due to a control rod ejection, which deposits a considerable amount of energy in the fuel in a brief period (tens of milliseconds). The energy deposition causes the fuel temperature to rise and the fuel to thermally expand rapidly against the cladding. Because of the higher concentration of plutonium near the outer rim (See Section 2.2.), the energy deposition is proportionally higher in that region. The resulting **pellet-cladding mechanical interaction** (PCMI) results in cladding loading. Another contribution to **PCMI** loading may be the result of **gaseous swelling** (due to dynamic bubble expansion) on the grain boundaries and from intragranular bubbles in the case of high energy deposition (>500 J/g). Another possible contribution to cladding loading the rise in internal pressure caused by **fission gas release**. Such **gaseous swelling** or **fission gas release** may not occur homogeneously through the fuel because the rim region has a significantly higher concentration of bubbles than that in the bulk and also exhibits higher temperatures

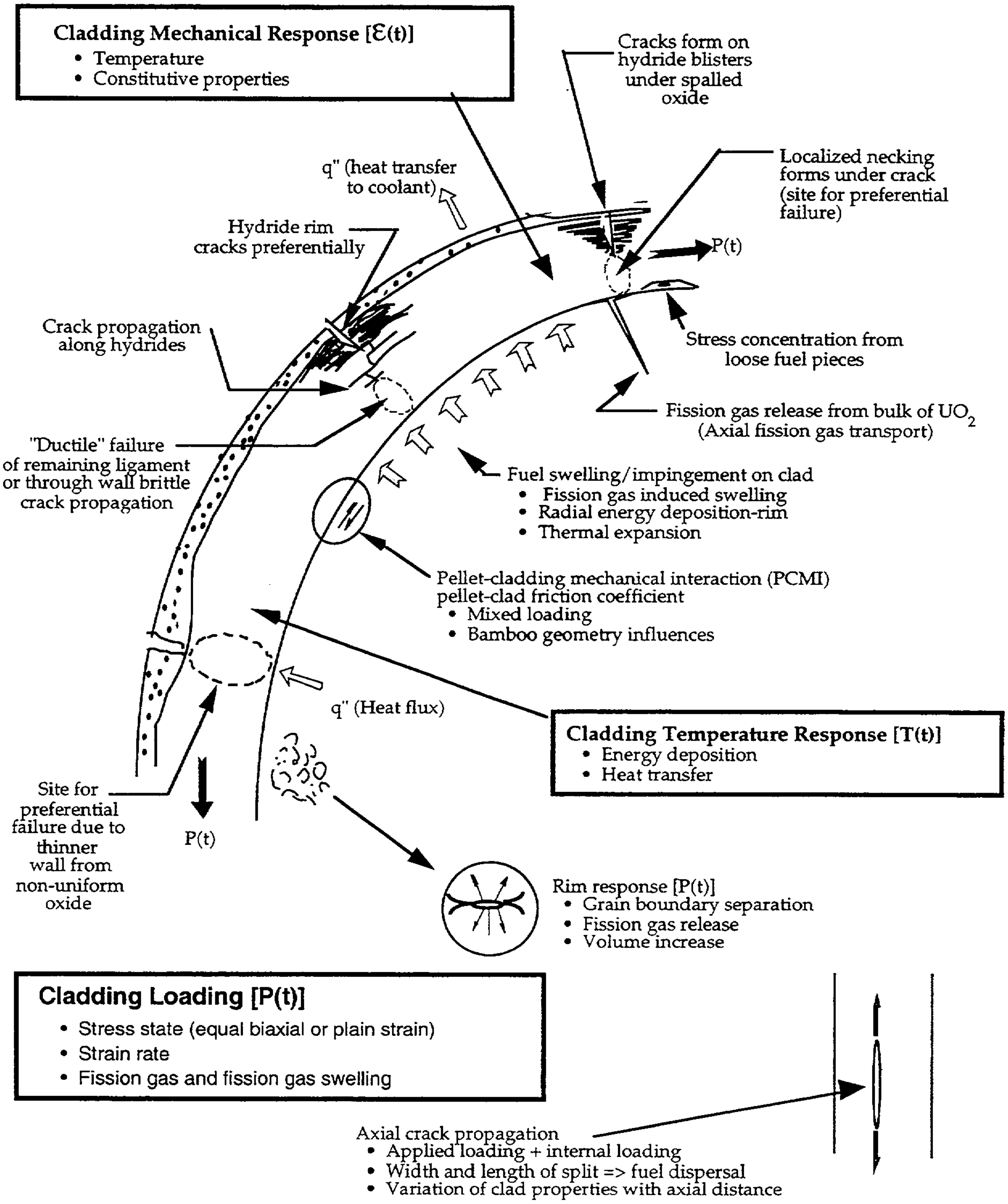

Fig. 2-5. Phenomena during a rod ejection accident leading to cladding failure.

during a rod ejection accident. Fission gas release and gaseous swelling may also occur from the bulk of the UO_2 fuel pellet as well as from the bubbles in the rim region. These mechanisms (thermal expansion, gaseous swelling, and **fission gas release**) have been proposed to provide the cladding loading P(t) during the reactivity transient.

Cladding failure during a rod ejection accident is determined by the interplay of the mechanical loading P(t), the cladding mechanical response $\varepsilon(t)$, and the temperature response T(t). The relationships between physical location within the fuel pellet, pellet-cladding interface, or cladding and the physical phenomena arising in these locations and P(t), ε**(t)**, and T(t) is further illustrated in Table 2-1.

The loading elicits a mechanical strain response from the cladding [$\varepsilon(t)$], which is governed by the loading characteristics, the constitutive properties of the cladding, and the cladding thermal response T(t). As the transient proceeds, the exact time dependence and characteristics of **P(t),** ε**(t), and T(t)** in combination with the cladding initial conditions, determine whether failure occurs. For example, one of the crucial aspects of cladding failure during a rod ejection accident is the temperature at which the maximum load occurs. If the maximum load happens near the beginning of the transient, the cold cladding may not have enough ductility to survive the accident; if it happens later, the greater ductility afforded by the higher temperature may help the cladding survive. Several failure mechanisms are possible, each with its own failure criterion, and overall cladding failure occurs if one of these criteria is satisfied.

Cladding Loading P(t). The cladding loading occurs very rapidly (at strain rates on the order of 1 to 10 s^{-1}), as a result of a combination of fuel impingement on the cladding and fission gas overpressure. The exact proportion of these contributions is still undetermined. The cladding loading from fission gas pressure results in multiaxial loading and, frequently, near plane strain loading. The **stress state** imposed on the cladding as the result of PCMI could be either **equal biaxial** (in the case where the fuel is attached to the cladding) or **plane strain** (in the case where the fuel-to-clad friction coefficient is zero) or more likely, a mixture of the two in the case of a non-zero fuel-cladding friction coefficient. The mechanical response of the cladding and the failure mechanisms available depends strongly on the stress state, thus **the fuel-to-cladding friction coefficient** is an important parameter for the transient. Thus, it is important to determine the amount of grain boundary gas available in the rim and its vicinity and how much of it affects cladding behavior in the initial part of the transient. A final characteristic of the loading is whether load transfer occurs along the cladding perimeter, as in fission gas loading or if friction effects constrain loading to a local section of the clad. The failure criteria for these two modes of loading differ. Specifically, the onset of localized necking will dictate failure when load transfer occurs while local failure strain is critical if friction constraints dominate.

Table 2-1
Effects of Fuel Rod Initial Conditions on Cladding Failure During Rod Ejection Events

Location	Effects and Consequences during the event	Parameter Affected
Fuel Pellet Initial Conditions		
Burnup		
Available fissionable material	Reactivity/deposited energy	$P(t)$
Plutonium profile	Energy deposition radial distribution	$P(t)$
Microstructural evolution of fuel		
Porous rim and grain structure	Fission gas loading, fuel/cladding contact	$P(t)$*
Large-scale cracking	Fission gas loading, fuel/cladding contact	$P(t)$, $\varepsilon(t)$,† $T(t)$‡
Fuel thermal conductivity degradation	Temperature distribution	$T(t)$
Mechanical compliance and thermal expansion	PCMI loading	$\varepsilon(t)$
Fission gas distribution	Contribution to cladding loading	$P(t)$
Fuel swelling	PCMI loading in steady state operation	$P(t)$, $T(t)$
Fuel Cladding Interface Initial Conditions		
Gap (size, composition, contact pressure)	Heat transfer to cladding	$T(t)$
Fuel cladding chemical bonding	Loading biaxiality	$P(t)$, $\varepsilon(t)$, FC§
Fuel-cladding friction	Load transfer, friction coefficient (displacement or force loading) = > stress state	$P(t)$, $\varepsilon(t)$, FC
Cladding bambooing	Friction coefficient, axial fission gas transport	$P(t)$, $T(t)$
Cladding Initial Conditions		
Oxidation		
Oxide thickness	Clad wall thinning: loss of load carrying capacity	$\varepsilon(t)$, FC
Oxide non-uniformity	Preferential failure site	FC, $\varepsilon(t)$
Oxide delamination	Thermal insulation	$T(t)$
Oxide spallation	Localized cooling/hydride precipitation and blister formation/loss of ductility	$\varepsilon(t)$, FC

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*$P(t)$ cladding loading during rod ejection accident

†$\varepsilon(t)$ mechanical response of the cladding during rod ejection accident

‡ $T(t)$ temperature response of the cladding during rod ejection accident

§ FC cladding failure criterion

Table continued on next page

Table 2-1. Effects of Fuel Rod Initial Conditions on Cladding Failure during Rod Ejection Events (continued)

Location	Effects/Consequences during the Event	Parameter Affected
Hydriding		
Hydrogen content	Increase yield stress and ultimate tensile strength (UTS), decrease uniform and total elongation	$\varepsilon(t)$,[*] FC[†]
Hydride distribution		
Hydride rim	Preferential failure site, loss of ductility	$\varepsilon(t)$, FC
Axial hydride localization	Preferential failure site, crack initiation	$\varepsilon(t)$, FC
Hydride orientation	Higher loss of ductility if radial hydrides present (rare)	FC
Fast fluence and radiation damage		
High dislocation loop density	Increase yield stress and UTS, decrease uniform and total elongation	$\varepsilon(t)$, FC
Constitutive properties	Strain hardening exponent decrease	$\varepsilon(t)$
	Strain rate exponent	$\varepsilon(t)$, FC
	Anisotropy decrease	$\varepsilon(t)$
Irradiation-Induced cladding deformation (creep and growth)	Clad wall thinning: loss of load carrying capacity	$\varepsilon(t)$, FC
Macroscopic cladding defects		
Fabrication defects	Clad wall thinning: loss of load carrying capacity	$\varepsilon(t)$, FC
Fretting	Preferential failure sites	FC
Other steady-state operation cladding failure mechanisms	Preferential failure sites	FC

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[*] $\varepsilon(t)$ mechanical response of the cladding during rod ejection accident

[†] FC cladding failure criterion

Cladding Temperature Response T(t). The temperature increase of the cladding during the rod ejection accident will, to a large extent, determine the cladding's mechanical response and the occurrence of failure. The total energy deposited and the energy deposition rate, associated with the increase in fission rate, can be calculated from the reactivity insertion kinetics. This is one of the crucial aspects of the transient and depends on the rate of temperature increase in the fuel, as well as the heat transfer coefficient between the fuel and the cladding that is largely determined by the fuel-clad contact and the coolant heat transfer. If the power in the pulse is big enough, fuel rods will experience DNB and cladding temperatures may reach very high levels. A qualitative plot of cladding temperature response to this transient is shown in Fig. 2-6.

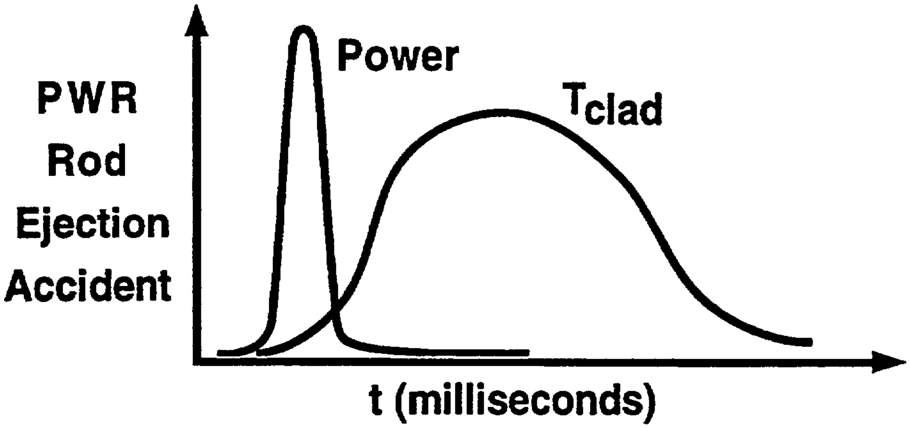

Fig. 2-6. Cladding temperature response to PWR rod ejection accident power.

Cladding Mechanical Response: ε(t). Although it is important to determine the mechanical response of the cladding, the critical step in assessing the rod ejection accident risk is cladding failure. At one extreme, cladding failure could occur during **homogeneous deformation** because the overall ability of the cladding to resist deformation is impaired by reactor exposure (burnup). In this type of failure, reactor exposure causes the cladding properties to change such that there is insufficient overall cladding ductility to withstand the loading from a rod ejection accident. Several tests have indicated that hydrogen can play a key role in cladding failure. At very high levels of hydrogen (1,000–2,000 ppm) separate effects tests show that the cladding fails in a brittle manner by crack propagation along hydrides.

At the other extreme, cladding fails as a result of **localized deformation**. In such cases where the deformation is localized, the overall ductility of the cladding may have little bearing on the cladding failure. This situation occurs because the localized nature of the deformation and necking cause failure at strains much smaller than the uniform strain. The most likely scenario is a localized failure in a highly hydrided spot of the cladding. This can occur in the case of oxide spalling, which creates a local cold spot during in-reactor operation, where hydrogen can precipitate and form **hydride blisters**. Such blisters have much less ductility than the alloy and can fail early in the transient, creating a site for preferential cladding failure. Consequently, part of the failure is brittle and part ductile (as evidenced by the 45°-shear angle observed in some of the test rod failures with high oxide spalling). The deformation is localized, because of the local brittle hydride spot and the overall cladding strain is small, resulting in significantly reduced ductility.

Such deformation localization could also occur because of other inhomogenities that can exist in the hydride rim. For example, the hydrogen absorbed into the cladding normally collects toward the cooler outer side of the wall, forming a **hydride rim**. All hydrides referred to in this write-up are circumferentially orientated hydrides; radial hydrides have a much more severe effect on ductility but are much rarer. Such a hydride rim could also cause early in the transient a brittle crack resulting in "ductile" failure of the underlying metal. Inhomogeneities in oxide thickness can also cause such deformation localization and loss of ductility to occur. Research has shown[2-3, 2-4] that under plane strain loading, small thickness inhomogenities, (~ 3%) can severely limit cladding ductility. This ductility is further limited when the strain hardening coefficient decreases under irradiation.

For the rod ejection accident to have significant consequences in terms of fuel dispersal, the initial cladding failure has to propagate axially; and, thus, axial crack propagation and the variation of all these properties with axial distance are also important. Axial crack propagation is facilitated by stress concentration at the crack trip. Another important point is that the dislocation channeling that is possible in radiation-damaged material may favor axial crack propagation.

Some cladding alloys, like the Russian alloy E-110 used in the Russian-designed Vodo-Vodyannoy Energeticheskiy Reactors (VVERs) and perhaps the M5 alloy being introduced in France and the United States, have very low corrosion rates and retain significant ductility even at high fuel burnups. These cladding types may not fail by mechanical interaction as described above. However, if such fuel rods experience DNB, they could balloon and burst as seen in the Russian Research Institute – Kurchatov Institute's Impulse Graphite Reactor (IGR) tests. Ballooning is likely, although the system is not fully depressurized, because at high burnup and high temperature the rod pressure would exceed the system pressure.

2.4. Primary Evaluation Criterion

The main concern in the case of reactivity accidents is that they might lead to the loss of core coolability and damaging pressure pulses. There are two main scenarios whereby this could happen:

1. Low-Temperature Failures. In this scenario, the cladding has low ductility and fails by the pellet-cladding mechanical interaction. The through-wall crack could propagate, producing a long axial split. If energies are high enough and the pulse is narrow enough, grain-sized fuel particles could be dispersed by expanding gas and entrainment. The particles could interact with the coolant in a manner similar to a steam explosion. The resulting

pressure pulse might threaten the integrity of adjacent fuel rods, core structures, and the reactor vessel. The dispersed fuel particles themselves could block flow channels and result directly in loss of coolable geometry.

2. High-Temperature Failures. In this scenario, the cladding has enough ductility to survive the mechanical interaction with the pellet. Departure from nucleate boiling (DN could occur later in the power pulse, and the cladding temperature could continue to rise. The fuel rods could balloon, rupture, oxidize, and melt, depending on the energy available in the pulse. When cooling occurs, the cladding might fragment and release hot grain-sized fuel particles into the coolant. Threatening pressure pulses could develop and loss of coolable geometry could occur as in the low-temperature scenario. The panel determined that the high-temperature phenomena would be evaluated as part of the loss-of-coolant (LOCA) accident PIRT.

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

- Cladding failure,
- Fuel dispersal,
- Channel blockage,
- Pressure pulse generation.

The panel concluded that core coolability can be ensured by either (a) accepting cladding failure as a possibility and ensuring that the fuel dispersal that occurs does not lead to significant (or limiting) channel blockage and disruptive pressure pulses or (b) ensuring that the cladding does not fail in such a manner that significant fuel dispersal would occur.

Approach (a) would require knowledge of the failure type, 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 significant channel blockage. Conducting the needed experiments and developing and certifying analytical tools for approach (a) was thought to be an extremely challenging undertaking. Although there were differing opinions among the panel members (See appendices G and H.), 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 panel recognizes that cladding failure can occur without deleterious consequences, and indeed, without fuel dispersal. However, it is clear that if there is no cladding failure with fuel dispersal, there is no loss of core coolability or large pressure pulses. Because of this, the primary evaluation criterion was chosen to be "cladding failure with significant fuel dispersal."

2.5. Categories of Phenomena

The panel recognized that it is necessary to use a combination of experimental data (both from integral tests and from separate effects tests) and analysis (including plant transient analysis and fuel rod analysis) to resolve issues related to fuel burnup. 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).

Integral tests refer to the testing of fueled rods in a reactor when subjected to a sudden reactivity increase, in facilities such as Cabri (France), NSRR (Japan), and BIGR (Russia). Although these are the tests that most closely approximate the actual rod ejection accident event, they are extremely expensive, so that it is financially impractical to devise a research program based solely on integral tests. Because of this, the effects of various parameters must be studied in separate-effects tests that can investigate the relevant parameters in detail.

Fuel rod analysis are performed to translate the results of the integral testing to the power plants and to be able to extract data from the experimental results. Such analysis can factor in any inherent differences between the integral tests and real power plants (such as the presence of a sodium loop instead of water or as low reactor temperatures).

It is also necessary to perform power plant transient analyses that give the boundary conditions for the rod ejection accident, as well as assessing its likelihood. 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 power-plant-specific reactor kinetics and reactivity response for the power 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 Cabri 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 focuses on 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

Is the result of the test sensitive to this fuel initial condition or to this feature of the test? If the answer is "yes," rank this item "high."

or

Is it important to the understanding derived from this test that this experimental quantity be measured? If the answer is "yes," rank this item "high."

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 Testing

Is the result of the test sensitive to this fuel or cladding initial condition or to this feature of the test? If the answer is "yes," rank this item "high."

or

Is it important to the understanding derived from this test that this experimental quantity be measured? If the answer is "yes," rank this item "high."

The panel notes that these broad questions were not consistently applied throughout the PIRT process for the PWR rod ejection accident. Rather, the criteria (and the questions) evolved during the course of the panel discussions. Also, a degree of consistency was lost because a common understanding of either definitions or process was lacking in some areas. For example, if a series of events were all necessary to bring about a given outcome and one of the events was very improbable, some panel members assumed the improbable was true so they could evaluate the impact of the rest, while others assumed the other events were of low importance since they were highly unlikely as they occurred after an extremely unlikely event. Clearly the two approaches can and did lead on occasion to inconsistencies in the ranking effort.

The panel also recognized that, even if the panel's judgment was that a particular initial condition was not important, it might still be desirable to have that initial condition represent actual fuel rods as closely as possible, because such an approach could preclude criticism about whether the test was prototypical.

Finally, continuing and evolving discussion about the primary evaluation criterion influenced some of the voting. During the PIRT exercise, the following were at different times considered by panel members as the primary evaluation criterion: the "cladding failure," "severe fuel failure with fuel dispersal," and "flow blockage." Because failure does not always lead to dispersal and blockage, panel members occasionally voted a phenomenon as having "low" importance because of their assessment about the ultimate likelihood of unfavorable consequences (e.g., cladding failures unlikely to lead to fuel dispersal). Conversely, arguments about the influence of subsequent phenomena were occasionally used to justify voting a phenomenon as important (e.g., fission gas does not have a significant influence on cladding loading, but it could be an important factor in fuel dispersal).

Because of this necessary evolution of the process, the panel revisited the voting and identified and corrected discrepancies.

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 a dominant influence on the primary evaluation criterion, i.e., cladding failure with significant fuel dispersal, 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 a moderate impact on the primary evaluation criterion. The phenomenon should be well modeled, but accuracy may be somewhat compromised in code development and assessment efforts. The phenomenon should also be considered in any experimental programs.

- Low. The phenomenon or process has small effect on the primary evaluation criterion. The phenomenon should be represented in the code, but almost any model will be sufficient. The phenomenon should be considered in any experimental programs to the extent possible.

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

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

Panel members were asked to vote on only those phenomena for which they have a firm opinion about importance. Generally, 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, and cladding types was assessed, the panel has considered and evaluated the applicability of the reactor- and fuel-specific PIRT to other reactor, fuel, and cladding types. The evaluation consisted of asking whether the importance ranks recorded for a given phenomenon would change for a different fuel type, specifically MOX, designated (F) in Tables 3-1 to 3-4; a different cladding alloy, e.g., ZIRLO, M5, Duplex, etc., designated (C); a different reactor type, specifically CE and W, designated (R); and extended burnup to 75 GWd/t, designated (B). If the answer was "yes," an entry was made and the rationale reported. The outcome of the extended PIRT applicability assessment is reported as part of the PIRT tabulation.

2.8. Uncertainty Evaluation

The NRC requested that the panel consider the uncertainty relative to the panel's understanding of the phenomena. The panel did so for each phenomenon by assigning uncertainty for the phenomenon 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. A. M. Garde, G. P. Smith, and R. C. Pirek, "Effects of Hydride Precipitate Localization and Neutron Fluence on the Ductility of Irradiated Zircaloy-4," in *11th International Symposium on Zr in the Nuclear Industry,* Volume STP 1295. Garmisch-Partenkirchen: ASTM (1996), p. 407.

2-2. "Standard Practice for Neutron Radiation Damage Simulation by Charged-Particle Irradiation," American Society for Testing and Materials Standard Practice E521-96 (1996).

2-3. T. M. Link, D. A. Koss, and A. T. Motta, "Failure of Zircaloy cladding under transverse plane-strain deformation," *Nuclear Engineering and Design* **186,** 379–394 (1998).

2-4. T. M. Link, D. A. Koss, and A. T. Motta, "Strain Localization in Sheets Containing a Geometric Defect," *Metallurgical Transactions A Letters,* **31A,** 1883–1886 (2000).

3. PWR ROD EJECTION ACCIDENT 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 control rod ejection scenario in TMI-1 assuming the core contains high burnup, Zircaloy-clad, UO_2 fuel. The plant and fuel, description of fuel and cladding state at high burnup, and accident scenario are described in Sections 2.1, 2.2, and 2.3, respectively. The selection of the four PIRT categories, as well as the phenomena definitions, differ somewhat from those appearing in previously published PIRTs. The reader is referred to Section 2.4 for further information, including the primary evaluation criterion used by the panel to assess importance.

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 criterion presented in Section 2.4, namely, cladding failure with significant fuel dispersal caused by a rod ejection accident. 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" is 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 C and D. From further discussions, the prevailing opinion of the panel members was that fuel behavior for a high-temperature scenario for a rod ejection accident 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 this NUREG report on LOCA (i.e., Vol. III).

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 and the transient thermal analysis of the fuel rod that are deemed relevant for understanding and predicting fuel behavior during a rod ejection accident. 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 rod ejection event and the calculation of fuel enthalpy increase during the event.

3.1.2. Category B: Integral Testing

The Integral Testing category includes the phenomena related to the integral testing of fuel rods, such as performed at Cabri, NSRR, and BIGR. This category is 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 PIRT for Integral Testing is provided in Table 3-2. This PIRT examines the phenomena that impact fuel rod selection and specimen preparation, energy deposition, coolant heat transfer conditions, fuel dispersal and pressure pulse, and single rod versus bundle.

3.1.3. Category C: Fuel Rod Transient Analysis

The Transient Fuel Rod Analysis category includes the phenomena and outcomes of 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. This category is divided into five 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 four subcategories (mechanical loading to the cladding, fuel and cladding temperature changes, cladding deformation, and pellet deformation) 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 the event. The PIRT for Transient Fuel Rod Analysis is provided in Table 3-3. Phenomena specifically related to high-temperature ballooning, bursting, and oxidation are discussed and ranked in the LOCA PIRT, Vol. III.

3.1.4. Category D: Separate Effect Testing

The Separate Effect Testing category includes the important phenomena relevant to mechanical testing designed to measure the properties relevant to extending the integral testing database and providing mechanistic understanding of failure. The category is divided into two subcategories, specimen selection, and test conditions. The specimen selection subcategory 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 3-4. This PIRT examines the phenomena that impact the selection and testing of specimens for measurement of mechanical properties. Separate effect tests and phenomena specifically related to high-temperature ballooning, bursting, and oxidation are discussed and ranked in the LOCA PIRT, Vol. III.

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 (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. 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 rod ejection accidents.

The panel notes that our approach to the PWR rod ejection PIRT evolved during the course of its development. 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?" 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 was being addressed by the panel 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 IR by considering any phenomenon with an IR greater than 75 to be highly important.

We applied the 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

The Plant Transient Analysis category consists of two subcategories: (1) calculation of power history during the pulse and (2) calculation of pin fuel enthalpy increase during the pulse.

Within the "Calculation of power history during the pulse" subcategory, ejected control rod worth, fuel temperature feedback, delayed-neutron fraction, and fuel cycle design were judged as being of high importance by the panel; i.e., each has an IR greater than 75. Within the "Calculation of pin fuel enthalpy increase during the pulse" subcategory, heat capacities of fuel and cladding and pin-peaking factors were judged as being of high importance by the panel. However, no highly important Category A phenomenon had a corresponding knowledge ratio that was sufficiently low, i.e., KR less than 75, to flag it as a candidate for additional consideration.

With respect to the knowledge factor, it is clear from the recorded rationales that the panel was addressing the question, "How well do we (specialists in the field) know or how well can we calculate the *value of the parameter?"* as contrasted to, "How well do we know the *impact of this parameter* on the evaluation criterion?" Given the question addressed, the six items receiving a high importance rating also received high knowledge ratios. This combined result implies that the six phenomena passing the importance ratio screen are important but well known.

3.4.2 Category B: Integral Testing

This category collects the phenomena related to integral testing in facilities such as Cabri, NSRR, and BIGR. 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.

The category was divided into two subcategories, fuel rod selection and conduct of the test. The fuel-rod-selection category includes the initial conditions that are considered to be of importance in selecting fuel rods for use in integral tests, both in terms of capturing the important physical characteristics and in terms of assuring that the test was prototypical. 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.

For the fuel-rod-selection subcategory, five fuel-selection characteristics were judged by the panel as being of high importance. They are: burnup, test reactor irradiation condition, rim size, fission gas distribution, and agglomerates (MOX only).

Four cladding-related characteristics were also judged by the panel as being of high importance. They are: amount of hydrogen, hydrogen distribution, hydride orientation, and integrity.

Three of the five high-importance fuel-related characteristics (rim size, fission gas distribution, and plutonium-rich agglomerates [MOX only]) had knowledge ratios that were sufficiently low, i.e., KR less than 75, to flag them as candidates for additional consideration. The development of a rim structure near the edge of the fuel pellet caused by increased plutonium concentration can affect power deposition, loading on the cladding, fission gas release during the transient, and possibly fuel dispersal in the case of failure. The fission gas distribution in the fuel pellet when the rod ejection accident occurs affects fission gas release and possibly the cladding loading. The presence of plutonium-rich agglomerates causes an uneven distribution of power during the transient, which may affect fuel and cladding response.

Each of the four high-importance cladding-related characteristics had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. The panel identified the effect of hydrogen (amount of hydrogen, hydride distribution, and hydride orientation) as being the predominant factor in influencing cladding failure. It is also important to ensure that no pre-existing or fabrication defects are present in the specimen to be tested.

For the conduct-of-the-test subcategory, two specimen-design characteristics (length and attachments) were judged by the panel as being of high importance. Ten phenomena in the during-the-test subcategory were judged by the panel as being of high importance. They are: fuel enthalpy increase, pulse width, coolant heat transfer conditions, fuel dispersal measurements on-line, pressure pulse measurement on-line, fission product measurement on-line, rod-deformation measurement on-line, time and location of failure, temperature of cladding and coolant, and fuel stack and cladding elongation.

Neither of the high-importance specimen design characteristics had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration.

Five of the high-importance phenomena occurring during the test had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. They are: on-line measurements of fuel dispersal, pressure pulse, fission product release, rod deformation, and time and location of failure.

The on-line measurement of fuel dispersal is directly related to the primary evaluation criterion (cladding failure with significant fuel dispersal), as is the presence of a pressure pulse. The detection of fission gases aids in the determination of fuel dispersal and also permits assessment of the extent of gas loading. The measurement of rod strain supports calibration of predictive models of fuel rod mechanical behavior. Finally, the detection of failure time and location is essential to understand how the failure started and propagated, i.e., the failure mechanism.

With respect to the first subcategory, fuel-rod selection, the recorded uncertainty rationales indicate that the panel was addressing the question, "How well do we know or how well can we characterize each phenomenon?" For example, several such questions were, "How well can we characterize the amount of oxide spalling and delamination?" or, "What is the fission gas distribution for a given chosen rod?"

In the second conduct-of-the-test subcategory, i.e., "during the test", the panel focused on specimen design features that needed to be correctly implemented or data which, if it was feasible to acquire, were highly desirable. The panel explicitly excluded from consideration the difficulty of obtaining the data. In this regard, then, a number of the items listed were acknowledged by the panel to be of the "wish list" type.

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.

3.4.3. Category C: Transient Fuel Rod Analysis

The Transient Fuel Rod Analysis category includes the phenomena and outcomes of calculations of transient fuel rod behavior 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. This category is divided into five sub-categories that may require modeling in the codes. The first category (initial conditions) captures the characteristics of the fuel and cladding before the transient. The remaining four subcategories (mechanical loading to the cladding, fuel and cladding temperature changes, cladding deformation, and pellet deformation) simulate the loading and the thermal and mechanical responses of the fuel and cladding that need to be modeled by the code to assess fuel failure during the event.

Within the initial conditions subcategory, ten characteristics were judged as being of high importance by the panel. They are: gap size, gas distribution, pellet and cladding dimensions, hydrogen distribution, power distribution, fuel-clad gap friction coefficient, condition of oxidation (spalling), coolant conditions, bubble size and bubble distribution, and transient power specification.

Five of these subcategory entries had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. They are: gas distribution, hydrogen distribution, fuel-clad gap friction coefficient, condition of oxidation (spalling), and bubble size and bubble distribution.

These are all phenomena that influence the loading on the cladding or its ability to withstand the rod ejection accident event. The gas distribution (as well as bubble size and bubble distribution) affects the cladding loading and can drive fuel fragmentation. Hydrogen distribution can affect the ductility of the cladding, due to the presence of localized hydrides; this is also the reason for the high importance of the condition of oxidation (spalling), as spalling can cause hydride blisters. The friction coefficient between the pellet and the cladding during the transient determines the stress state of the cladding and may impact failure.

Upon further evaluation, the panel also felt that rim size was a phenomenon that deserves further consideration, even though the phenomenon did not satisfy the IR screening criterion.

Within the mechanical-loading-to-cladding subcategory, pellet thermal expansion and pellet-cladding contact (gap closure) were judged as being of high importance by the panel. Pellet-cladding contact (gap closure) 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, three phenomena were judged as being of high importance by the panel. They are: heat resistances in the fuel, gap, and cladding; heat capacities of fuel and cladding; and coolant conditions. None of these three subcategory entries had a knowledge ratio that was sufficiently low to flag it as a candidate for additional consideration.

Within the cladding-deformation subcategory, three phenomena were judged as being of high importance by the panel. They are: stress-versus-strain response, cladding temperature, and localized effects. Two of them, stress-versus-strain response and localized effects, had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. However, it is noted that the stress-versus-strain phenomenon does not show a high degree of uncertainty.

Within the pellet-deformation subcategory, four phenomena were judged as being of high importance by the panel. They are: yield stress in compression, plastic deformation, grain boundary decohesion, and evolution of pellet stress state. Two of them, grain boundary decohesion and evolution of pellet stress state, had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. Grain boundary decohesion can lead to fuel fragmentation and dispersal and may influence the loading to the cladding. The evolution of the pellet stress state is a result of the complex interaction of other important phenomena during the transient and, as such, it was considered to be of high importance.

3.4.4. Category D: Separate Effect Testing

This category collects the phenomena related to separate effect testing. It is important to have these tests to translate 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: (1) specimen selection and (2) 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, six selection characteristics were judged by the panel as being of high importance. They are: extent of oxide spalling, extent of oxide delamination, amount of hydrogen, hydrogen distribution, hydride orientation, and cladding integrity. Each of the six parameters had knowledge ratios that were sufficiently low to flag them as candidates for additional consideration. Similar phenomena were emphasized in Category B, indicating the importance the panel puts on the role of hydrogen in degrading cladding ductility. It was also clear that the panel recognizes the importance of stress state in performing mechanical tests that are relevant to rod ejection accidents.

For the test conditions category, five test condition parameters were judged by the panel as being of high importance. They are: heating rate, temperature range, stress state imposed on the specimen, tensile test specimen design, and burst specimen design. Of these, three parameters had knowledge ratios sufficiently low to flag them as candidates for additional consideration. They are: stress state imposed on the specimen, tensile test specimen design, and burst specimen design. The importance of not having major flaws in the test specimen was also emphasized.

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 pulse (includes pulse width)	Ejected control rod worth	12	0	0	100	N	N	N	N	13	0	0	100
	Rate of reactivity insertion	3	5	1	61	N	N	N	N	10	3	0	88
	Moderator feedback	0	6	2	38	Y	N	N	N	12	2	0	93
	Fuel temperature feedback	12	0	0	100	N	N	N	N	12	1	0	96
	Delayed-neutron fraction	10	1	0	95	N	N	N	N	13	1	0	96
	Reactor trip reactivity	0	0	10	0	N	N	N	N	13	1	0	96
	Fuel cycle design	11	2	0	92	N	N	N	1	12	0	0	100
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Heat resistances in high burnup fuel, gap, and cladding (including oxide layer)	3	15	0	58	N	Y	N	1	5	10	0	67
	Transient cladding-to-coolant heat transfer coefficient	2	15	0	56	N	N	N	1	4	10	0	64
	Heat capacities of fuel and cladding	15	2	0	94	N	N	N	N	12	3	0	90
	Fractional energy deposition in pellet	0	1	13	4	N	N	N	1	12	2	0	93
	Pellet radial power distribution	4	12	0	63	N	N	N	3	10	3	0	88
	Pin-peaking factors	15	1	0	97	N	N	N	N	12	0	0	100

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

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

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

F = Fuel type, e.g., mixed oxide fuel (MOX);
C = Cladding alloy, e.g., ZIRLO, M5, Duplex;
R = Reactor type, e.g., B&W, CE, W;
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

			Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	**Phenomenon***		**H**	**M**	**L**	**IR**	**F**	**C**	**R**	**B**	**K**	**PK**	**UK**	**KR**
Fuel rod selection	Fuel condition:	Burnup	16	0	0	100	N	N	N	1	11	1	0	96
		Enrichment (initial)	0	6	1	43	N	N	N	2	12	0	0	100
		Test reactor irradiation condition	14	0	0	100	N	N	N	N	7	3	0	85
		Power history (normal power reactors)	1	13	0	54	N	N	N	2	11	1	0	96
		Rim size	6	5	0	77	N	N	N	2	1	8	0	56
		Fission gas distribution	10	1	0	95	N	N	N	1	0	10	0	50
		Grain size	3	6	1	60	Y	N	N	1	5	3	0	81
		Pellet type	3	6	0	67	N	N	N	1	12	0	0	100
		Agglomerates (MOX only)	13	1	0	96	N	N	N	N	4	5	0	72
	Cladding:	Amount of oxide	6	7	0	73	N	N	N	1	5	5	0	75
		Extent of oxide spalling	4	5	0	72	N	N	N	1	1	8	3	42
		Extent of oxide delamination	3	4	0	71	N	N	N	1	1	8	3	42
		Alloy	3	4	3	50	N	N	N	1	12	0	0	100
		Amount of Hydrogen	9	4	0	85	N	N	N	1	3	7	0	65
		Hydrogen distribution	13	0	0	100	N	N	N	1	0	7	3	35
		Hydride orientation	6	2	0	88	N	N	N	1	5	3	1	72
		Fluence	1	2	6	22	N	N	N	1	11	0	0	100
		Integrity	12	0	0	100	N	N	N	1	3	7	0	65
Conduct of the test	Specimen design:	Plenum volume	0	7	4	32	N	N	N	1	10	1	0	95
		Internal pressure	2	4	4	40	N	N	N	1	9	1	0	95
		Gas composition	0	3	6	17	N	N	N	N	11	0	0	100
		Length	8	3	0	86	N	N	N	N	11	0	0	100
		Attachments	6	3	0	83	N	N	N	N	8	2	0	90
		Constraints	6	4	3	62	N	N	N	N	9	1	0	95
		Single rod versus bundle	5	6	2	62	N	N	N	N	1	10	0	55

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Table 3-2. Category B. Integral Testing PIRT (continued)

		Importance**				Applicability†,††				Uncertainty§,§§			
Subcategory	Phenomenon*	H	M	L	IR	F	C	R	B	K	PK	UK	KR
Conduct of the test (continued)	During the test: pulse shape	0	12	0	50	N	N	N	N	10	1	0	95
	Fuel enthalpy increase	17	0	0	100	N	N	N	N	10	0	0	100
	Pulse width	12	3	0	90	N	N	N	N	10	1	0	95
	Axial power profile	1	8	1	50	N	N	N	N	11	0	0	100
	Coolant heat transfer conditions	15	0	0	100	N	N	N	N	8	2	0	90
	Fuel dispersal measurement on-line	**9**	**1**	**0**	**95**	**N**	**N**	**N**	**1**	**0**	**5**	**2**	**36**
	Pressure pulse measurement on-line	**8**	**2**	**0**	**90**	**N**	**N**	**N**	**1**	**0**	**5**	**2**	**36**
	Fission product measurement on-line	**6**	**2**	**0**	**88**	**N**	**N**	**N**	**N**	**2**	**2**	**0**	**75**
	Rod deformation measurement on-line	**9**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**0**	**4**	**0**	**50**
	Time and location of failure	**11**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**2**	**2**	**0**	**75**
	Temperature of cladding and coolant	7	2	0	89	N	N	N	N	4	0	0	100
	Fuel stack and cladding elongation	6	3	0	83	N	N	N	N	3	1	0	88
	DNB detection	5	2	2	67	N	N	N	N	2	2	0	75

*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 type, e.g., mixed-oxide fuel (MOX);
C = Cladding alloy, e.g., ZIRLO, M5, Duplex;
R = Reactor type, e.g., B&W, CE, W;
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 3-5 are documented in Appendix B.

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

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

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

Table 3-3. 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	13	1	0	96	N	N	N	1	9	5	0	82
	Gas pressure	1	10	2	46	N	N	N	3	7	7	0	75
	Gas composition	0	1	10	5	N	N	N	N	11	2	0	92
	Gas distribution	**7**	**5**	**0**	**79**	**Y**	**N**	**N**	**1**	**1**	**10**	**1**	**50**
	Pellet and cladding dimensions	13	3	0	91	N	N	N	1	13	1	0	96
	Burnup distribution	1	9	0	55	N	N	N	1	11	3	0	89
	Cladding oxidation	1	10	2	46	N	N	N	2	6	7	0	73
	Hydrogen concentration	3	9	0	63	N	N	N	3	5	6	0	73
	Hydrogen distribution	**13**	**0**	**0**	**100**	**N**	**N**	**N**	**1**	**2**	**7**	**2**	**50**
	Fast fluence	1	1	7	17	N	N	N	1	13	0	0	100
	Porosity distribution	1	7	4	38	Y	N	N	1	2	5	2	50
	Rim size	4	7	0	68	N	N	N	4	1	8	1	50
	Power distribution	14	0	0	100	N	N	N	N	11	3	0	89
	Fuel-clad gap friction coefficient	**5**	**5**	**0**	**75**	**N**	**N**	**N**	**N**	**0**	**6**	**4**	**30**
	Condition of oxidation (spalling)	**15**	**0**	**0**	**100**	**N**	**N**	**N**	**1**	**1**	**9**	**2**	**46**
	Coolant conditions	12	2	0	93	N	N	N	N	12	1	0	96
	Bubble size and bubble distribution	**8**	**4**	**0**	**83**	**Y**	**N**	**N**	**N**	**0**	**4**	**6**	**20**
	Rod free volume	0	9	1	45	N	N	N	1	6	5	0	77
	Transient power specification	15	0	0	100	N	N	N	N	7	1	0	94
Mechanical loading to cladding	Pellet thermal expansion	15	0	0	100	N	N	N	N	10	4	0	86
	Direct gas pressure loading	1	7	3	41	Y	N	N	3	0	8	3	36
	Pellet-cladding contact (gap closure)	**13**	**0**	**0**	**100**	**N**	**N**	**N**	**1**	**5**	**6**	**0**	**73**
	Fission gas induced pellet swelling	6	6	2	64	Y	N	N	7	1	7	3	41
	Fission gas release	4	6	2	58	Y	N	N	7	0	8	2	40
Fuel and cladding temperature changes	Heat resistances in fuel, gap, and cladding	9	6	1	75	N	N	N	1	7	6	0	77

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Table 3-3. 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 (continued)	Transient cladding-to-coolant heat transfer coefficient (oxidized cladding)	0	16	0	50	N	N	N	1	3	9	1	58
	Heat capacities of fuel and cladding	13	2	1	88	N	N	N	N	12	2	0	93
	Coolant conditions	9	4	0	85	N	N	N	N	10	3	0	88
	Transient spalling effect	2	6	1	56	N	N	N	2	0	3	4	21
Cladding deformation	**Stress versus strain response**	**10**	**3**	**1**	**82**	**N**	**N**	**N**	**1**	**5**	**5**	**2**	**63**
	Strain rate effects	0	0	7	0	N	N	N	1	4	5	1	65
	Anisotropy	1	2	5	25	N	N	N	N	1	7	2	45
	Pellet shape	0	5	2	36	N	N	N	N	6	3	1	75
	Cladding temperature	12	1	0	96	N	N	N	N	7	5	0	79
	Localized effects	**1**	**1**	**0**	**75**	**N**	**N**	**N**	**N**	**0**	**8**	**1**	**44**
	Biaxiality	1	6	0	57	N	N	N	N	0	7	2	39
Pellet deformation	Fracture stress	2	3	0	70	N	N	N	N	4	2	0	83
	Yield stress in compression	4	2	0	83	N	N	N	N	6	0	0	100
	Plastic deformation	2	2	0	75	N	N	N	N	3	2	0	80
	Grain boundary decohesion	**6**	**1**	**0**	**93**	**N**	**N**	**N**	**N**	**0**	**3**	**3**	**25**
	Evolution of pellet stress state	**6**	**0**	**0**	**100**	**N**	**N**	**N**	**N**	**1**	**3**	**0**	**63**

*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 type, e.g., mixed-oxide fuel (MOX);
C = Cladding alloy, e.g., ZIRLO, M5, Duplex;
R = Reactor type, e.g., B&W, CE, W;
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 3-4. 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	6	7	0	73	N	N	N	1	5	4	0	78
	Extent of oxide spalling	14	0	0	100	N	N	N	N	2	6	2	50
	Extent of oxide delamination	14	0	0	100	N	N	N	N	2	6	2	50
	Alloy	3	4	3	50	N	N	N	1	9	0	1	90
	Amount of hydrogen	9	4	0	85	N	N	N	N	3	7	0	65
	Hydrogen distribution	13	0	0	100	N	N	N	N	2	4	3	44
	Hydride orientation	6	2	0	88	N	N	N	N	5	2	2	67
	Fluence	1	2	6	22	N	N	N	N	9	0	0	100
	Cladding integrity	12	0	0	100	N	N	N	N	3	5	1	61
Test conditions	Heating rate: (>550° C)	4	2	0	83	N	N	N	N	3	1	0	88
	Temperature range (test)	6	0	0	100	N	N	N	N	5	1	0	92
	Strain rate	5	3	2	65	N	N	N	N	1	2	0	50
	Stress state imposed on specimen	6	0	0	100	N	N	N	N	1	2	0	67
	Tensile test specimen design	8	0	0	100	N	N	N	N	3	3	0	75
	Burst specimen design	8	0	0	100	N	N	N	N	1	4	0	60

*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 type, e.g., mixed-oxide fuel (MOX);
C = Cladding alloy, e.g., ZIRLO, M5, Duplex;
R = Reactor type, e.g., B&W, CE, W;
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 PWR rod ejection PIRT panel are documented in Section 4.1. The analytical databases used by the panel are documented in Section 4.2. 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. Members of the PIRT panel have provided brief summaries of these experimental programs, and this information is presented in Appendix E.

4.1.1. Separate Effect Tests

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

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

Cladding Mechanical Properties Tests (United States). Argonne National Laboratory (ANL) and the Pennsylvania State University (PSU) are working together on a NRC-funded program to investigate cladding properties at high burnups. Mechanical-properties testing is being done under both LOCA conditions and reactivity accident conditions. The objectives of the tests at relatively low temperatures and high strain rates appropriate for reactivity accident conditions are two-fold: to understand the degradation in cladding failure behavior at high burnup and to obtain stress-strain relationships that will serve as inputs to codes. A ring tensile specimen design has been developed and tested at ANL to generate tensile properties in the hoop direction. A related ring specimen design was developed and tested at PSU to provide a near plane-strain stress state that approximates the stress state produced by expanding fuel pellets during a reactivity accident. Similar testing will be done on axial tensile specimens electromachined from de-fueled portions of irradiated fuel rods and from nonirradiated tubing specimens. These tests will be performed over the same temperature range and strain-rate range as the ring-stretch tests. Biaxial tube burst tests will be done in a more limited 300 °C–400 °C temperature range, but they will explore the effects on deformation and failure of stress biaxiality ratios from 1:1 to 2:1 at high strain rate.

The PROMETRA Program (France). The Cabri REP-Na reactivity accident program has been carried out jointly by Electricité de France (EDF) and the Institute for Protection and Nuclear Safety (IPSN) to determine a criterion which will guarantee no fuel dispersal during a rod ejection event for cores containing high-burnup fuel. To transpose the Cabri REP-Na test results to PWR conditions will require computer simulations using thermomechanical codes. An accurate cladding mechanical behavior model is needed to reproduce the stress-strain state of the cladding, during an event, when strong and fast pellet cladding mechanical interaction (PCMI) occurs. A large experimental mechanical properties database is needed to calibrate such a model. The PROMETRA (derived from "PROpriétés MEcaniques en TRAnsitoire" or "Transient Mechanical Properties") program has been conducted by EDF, IPSN, and Commissariat à l'Energie Atomique (CEA) in order to provide experimental data on highly irradiated cladding materials. Additional information on the PROMETRA experimental program is provided in Appendix E-1.

***Fission Gas Transient Behavior* (France).** Fission gas transient behavior testing is planned to begin in the SILENE reactor in the second half of 2001. The test fixture will consist of a double-wall capsule with two independent cells and various on-line instrumentation. Pre- and post-test measurements will be performed on several thin-slice samples as well as fuel pieces. Presently, the test matrix includes 20 tests using high burnup UO_2 fuel and MOX fuel. Additional information on these tests are provided in Appendix E-1.

Cladding Mechanical Property Tests (Japan). Mechanical property tests for fuel cladding have been carried out at Japan Atomic Energy Research Institute (JAERI), applying various testing methods and specimen configurations according to the purpose. Ring tensile test and burst tests are useful for examining mechanical property in the circumferential direction. The uniaxial tensile test is also used to examine the representative mechanical property of the cladding, since the relation between strain and stress is easily obtained in this testing configuration. Additional information on these Cladding Mechanical Properties Tests is provided in Appendix E-1.

4.1.2. Integral Tests

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

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

Cabri REP-Na Experimental Program (France). The first part of the Cabri REP-Na experimental program (tests 1 to 10) has been performed by the IPSN in collaboration with EDF and with the support of the NRC. The program began in 1992. The Cabri REP-Na experimental program investigates the effect of high burnup on UO_2 and MOX fuel behavior. It also provides data that can be used to verify the safety criteria for reactivity transients in plants containing high burnup fuel. Finally, data have also been obtained to support licensing of irradiated MOX fuel. Additional information on the Cabri REP-Na experimental program is provided in Appendix E-2.

NSRR Pulse-Irradiation Experiments with PWR Fuels (Japan). The JAERI Nuclear Safety Research Reactor (NSRR) is a modified Training, Research, Isotopes, General Atomics-Annular-Core Pulse Reactor (TRIGA-ACPR) featuring a large pulsing power capability and large dry irradiation space located in the center of the reactor core. The experiment 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 include 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 PWR fuels is provided in Appendix E-2.

PBF Test Reactor Data (United States). The earliest PWR tests on irradiated fuel rods under the transient conditions of a reactivity accident were performed in the Power Burst Facility (PBF). PBF tests of interest were performed in 1978 to 1980. Additional information on the PBF test reactor data is provided in Appendix E-2.

IGR and BIGR Test Reactor Data (Russia). During the 1980s and early 1990s, a large series of reactivity tests was carried out in the Impulse Graphite Reactor (IGR) by the Russian Research Center Kurchatov Institute. The IGR is a uranium-graphite pulse reactor with a central experimental channel. Tests were performed with specimens in capsules under ambient conditions. As a rule, an experimental capsule contained two fuel rods: one high-burnup fuel rod and one fresh fuel rod. For safety reasons, instrument penetrations were not used when irradiated specimens were being tested, so the tests with high-burnup fuel were not instrumented. The natural pulse width for this reactor is about 700 ms, which is much broader than pulses expected in power reactors (~ 30 ms). Later testing with a narrow pulse (~ 3 ms) was performed in the BIGR test reactor. Additional information on the IGR and BIGR test reactor data is provided in Appendix E-2.

4.2. Analytical Databases

The experimental data derived from the programs described in the previous section are valuable in their own right because they provide insights into the basic physical processes occurring in a reactor should high burnup fuel undergo a rod ejection accident. 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, they are incorporated into an integrated computer model. The models are then validated. The resulting code can then be used to predict the behavior of high burnup fuel in a reactor undergoing a reactivity transient.

The modeling features of three representative computer codes currently being developed, validated, and used to predict the behavior of high burnup fuel undergoing a rod ejection accident are described in Appendix F. Each of the codes simulates the following phenomena as well as the coupling between the following phenomena: (1) fuel and clad mechanical behavior, (2) fission gas transient behavior, and (3) the thermal behavior of the system (fuel, gap, cladding, and coolant).

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 Appendix F, Table F-1.

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 Appendix F, Table F-2.

The SCANAIR code is an ISPN (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 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 PWR during a rod ejection accident was presented to the panel early in the PIRT process. The information presented to the panel is found in Appendix J. The objective of the review paper was to provide a description of the control rod ejection accident in a pressurized water reactor.

5. ADDITIONAL PANEL INSIGHTS

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

5.1. Technical Insights

1. At the first PIRT panel meeting, descriptions were provided of three transient fuel rod analysis codes—FRAPTRAN, FALCON, and SCANAIR. 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 Appendix F.
2. The panel was asked to provide its perspectives on bounding analyses, specifically whether there is a bounding approach that can be used and whether such bounding analyses would mask fuel or plant behavior that might be risk significant. Panel member perspectives on these matters are discussed in Appendix G.
3. Very little data exist about the state of fuel at burnups approaching 75 GWd/t. Consequently, the PIRT applies most directly to burnups of 62 GWd/t. The panel did assess the applicability of its phenomenon importance rankings at 75 GWd/t and this information is tabulated in each of the PIRT tables in Section 3. In addition, the panel also addressed the question of what additional information is needed to justify increasing the burnup limit from 62 to 75 GWd/t. This information is provided in Appendix H.
4. Within Category C, subcategory for fuel and cladding temperature changes, the phenomena "transient cladding-to-coolant heat transfer coefficient (oxidized cladding)" was ranked as having medium importance. The implication of this ranking is that water loop tests may not be needed since the importance of the phenomena was not ranked as high.

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. Review 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, an expert tutorial was presented to the panel and this tutorial is provided in Appendix J.

7. Review 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.

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.

APPENDIX A

CATEGORY A
PLANT TRANSIENT ANALYSIS

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

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

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

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

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

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

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Ejected control rod worth	The reactivity worth of the control rod assumed to be ejected during the REA. H(12) Determines the amount of reactivity insertion. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(13): Parameter is measured for integral differential works every cycle; this is accurately predicted in order for the reactor to start up. PK(0): No votes. UK(0): No votes. Note: for reactivity ejection accidents, the transient is so rapid that it is insensitive to rate.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Rate of reactivity insertion	The rate at which reactivity is inserted into the core as a result of the ejection of the control rod. H(3) The adverse effects of a rod ejection accident are directly related to the rate of reactivity insertion. M(5) Within limits, the outcome is insensitive to the rate of reactivity insertion. This outcome was supported by calculations performed by panel members L(1) When you insert reactivity from a subcritical condition, the rate is not important. It is when you reach prompt critical that is important. Fuel: N Clad: N Reactor: N Burnup: N K(10): Calculation can be made with a high degree of confidence. The overall accident was relatively insensitive to this rate. PK(3): No rationale recorded. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Moderator feedback	Reactivity feedback from moderator temperature and density changes in the active channels, by-pass, and water channels. These changes are a result of direct deposition to the coolant and heat transfer from the cladding. H(0) No votes. M(6) While the moderator coefficient can be up to 30 times larger than the Doppler temperature coefficient, the moderator temperature rise is small. The moderator can make a contribution even at the time of the peak power. While it is small compared to the Doppler, it is not negligible. L(2) The transient is very short relative to the time constant of the rod in order to get energy out to effectively change the moderator. Fuel: The moderator coefficient is so much larger that it might promote the lows up to medium on the moderator feedback. Clad: N Reactor: N Burnup: N K(12): This is a measured and known parameter. There is a specification in the tech specs for both beginning and end of cycle. This parameter can be accurately predicted with a reasonable amount of confidence. PK(2): No rationale recorded. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Fuel temperature feedback	Reactivity feedback from fuel temperature changes. This results from the heating of the fuel and the associated neutronic effects, in particular the Doppler effect. H(12) The fuel temperature feedback causes the power excursion to turn around and essentially limits the energy deposition. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(12): This parameter can be calculated with reasonable accuracy from the existing methods. PK(1): The fuel temperature feedback is very well known for in-reactor condition. When the pellet radial temperature distribution is parabolic, there is less certainty. During the transient phase, the temperature is higher in the periphery of the pellet. It is totally reversed compared with the parabolic temperature, radial temperature distribution. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Delayed-neutron fraction	The fraction of fission neutrons [designated beta (β)] that are not emitted instantaneously. Prompt criticality occurs when the reactivity exceeds the effective delayed neutron fraction. H(10) Parameter determines when prompt criticality is reached. M(1) Parameter determines the timing schedule. By going to lower beta values, the power increases faster, but the peak is determined when the temperature is sufficiently high. Therefore, the power release is not so strongly dependent on beta, because reactivity insertion and the Doppler feedback determine this. There is a shifting in the time, but not so much effect on the pellets. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(13): This parameter can be calculated with reasonable accuracy from the existing methods. PK(1): There is some uncertainty for high burnup fuel with regard to delayed neutron fraction. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Reactor trip reactivity	Negative reactivity associated with insertion of control rods after receipt of a reactor trip signal. H(0) No votes. M(0) No votes. L(10) It's important to have the rods trip to terminate the event but the effect is minor relative to the pulse. Fuel: N Clad: N Reactor: N Burnup: N K(13): Calculations have been compared with measurements and been found to be in reasonable agreement. PK(1): No rationale recorded. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of power history during pulse (includes pulse width)	Fuel cycle design	Includes those important design elements that determine the neutronic properties of the core at event initiation, such as the loading pattern, 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. H(11) The fuel cycle design determines the total control rod worth, and it may also affect the high burnup fuel assemblies adjacent to fresh fuel assemblies. M(2) There may not be enough variation in a core design containing both normal and high burnup fuel to propagate an event that is driven by a high-powered assembly into a low-powered assembly. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: At higher burnups, different approaches might be used as the fuel loading patterns control rod strategies. Optimum fuel cycle designs for very high burnup fuel must be developed. K(12): This parameter is specified for the cycle design. After the cycle is designed, and the reactor is started, the power distribution is measured and this confirms the cycle design itself. PK(0): No votes. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Heat resistances in high-burnup 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). H(3) Resistance to heat transfer causes the energy to be retained in the fuel which directly impacts the fuel temperature neutronic feedback and also maximizes the fuel expansion which loads the cladding. M(15) Per several analyses discussed, at maximum, 25 percent of the deposited energy is conducted out and does not contribute to the fuel enthalpy. L(0) No votes. Fuel: N Clad: "Yes" but rationale not recorded. Reactor: N Burnup: The heat resistance will increase due to microstructure changes and increased fission gas concentration. Importance may vary from the base PIRT ranking. K(5): This is a standard calculation in fuel rods and fuel pin models; it has routinely been checked against measurements and found to be in reasonable agreement. This transient is very rapid and nearly adiabatic, and consequently, some of these uncertainties aren't so important in terms of peak enthalpy, PK(10): Gap heat transfer can change over time and is not accurately known, i.e., it's going to depend upon the pellet loading, gas loading; what's in the gap; whether the pellet gap contact has closed, etc. With high burnup fuel, and the collection of different phenomena in this single category, e.g., cladding hydriding, oxide layer, and spallation, and the state of collective knowledge about these phenomena is only partial. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Transient cladding-to-coolant heat transfer coefficient	The correlation that determines transport of energy at the interface by one or more of the following modes: forced convection-liquid, nucleate boiling, transition boiling, film boiling, or forced convection-vapor. H(2) Resistance to heat transfer means the energy is retained in the fuel which directly impacts the fuel temperature neutronic feedback and also maximizes the fuel expansion which loads the cladding. M(15) Per several analyses discussed, at maximum, 25 percent of the deposited energy is conducted out and does not contribute to the fuel enthalpy. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: The heat transfer will change due to microstructure changes and increased fission gas concentration. This event can lead to a departure from nucleate boiling, a significant change. K(4): Accurate models exist for predicting whether the flow is single phase or whether DNB occurs and these models show reasonable agreement with data. PK(10): This is a rapid transient that is being predicted with steady-state models. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (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 H(15) Enthalpy is the integral of heat capacity and temperature. Enthalpy and enthalpy increases are both highly important. M(2) The energy input into the pellet is known. Therefore, the heat capacity as a factor influencing the energy that is getting the heat out of the pellet. Thus, it is of equal importance to the previous two items. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(12): This is a well-known parameter; it is a measured parameter. PK(3): No rationale recorded. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Fractional energy deposition in pellet	The fraction of total fission energy that is deposited directly in the pellet. The fractional energy deposited in the moderator is one minus the fractional energy deposited in the fuel. H(0) No votes. M(1) The fraction of the total power deposited in the coolant, although small, is sufficiently large (on the order of 2-3%) to have a moderate influence. L(13) The fraction of the total power deposited in the coolant is small. Fuel: N Clad: N Reactor: N Burnup: The rim effect and power peaking will presumably be even sharper at 75 GWd/t. K(12): Available calculational techniques permit us to predict this parameter with good accuracy (within the 25% figure used here in the definition of known). PK(2): No rationale recorded. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Pellet radial power distribution	The radial distribution of the power produced in the fuel rod. H(4) Because most of the energy is deposited in the outer part of the pellet, the heat transfer path is shorter and, therefore, the peak enthalpy is reduced. M(12) The total heat transfer is rated high; this element is rated lower because it's only one part of the overall heat transfer audit. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: The rim effect and power peaking will presumably be even sharper at 75 GWd/t. K(10): Available calculational techniques permit us to predict this parameter with good accuracy (within the 25% figure used here in the definition of known). PK(3): At very high burnups, phenomena are uncertain and the importance of phenomena may be changing. The uncertainty is sufficiently high to categorize this as partially known. UK(0): No votes.

Table A-1. PWR Rod Ejection Accident. Category A – Plant Transient Analysis PIRT (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Calculation of pin fuel enthalpy increase during pulse (includes cladding temperature)	Pin peaking factors	Pin power distribution within an assembly during the transient. H(15) The peaking factor is a very important parameter in this event, of similar importance to ejected rod worth and beta, because it determines how much energy is directed to the peak location. M(1) The peaking factor is an important parameter in this event but not of the greatest importance. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(12): The pin peaking factor is an integrated value; for this integrated value we have very good accuracy. PK(0): No votes. UK(0): No votes.

APPENDIX B

CATEGORY B
INTEGRAL TESTING

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

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

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

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

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

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

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fuel condition: Burnup	The behavior of high burnup fuel is determined by the condition of both the fuel and the cladding. Although some processes occurring in fuel may saturate at a moderate burnup, others may not saturate but continue to grow with burnup. The database for high burnup fuel is significantly smaller than for low and moderate burnups. Therefore, it is important to select fuel rod specimens that have burnups levels representative of the levels that will occur in plants. H(16) Burnup must be prototypical because burnup is the issue for which a revised criterion is to be developed. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: By definition. K(11): The burnup and also the history of the burnup; the power history experienced by fuel within the range of variation of the normal power plants is well known. Burnup is typically known within 5 percent. PK(1): No rationale recorded. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	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. H(0) No votes. M(6) The variation of enrichment gives a different power density within the power profile. Lower enrichments have a higher plutonium power fraction, so it has a much higher rim effect. L(1) For the variability in enrichments to be encountered, the effect is small. Fuel: N Clad: N Reactor: N Burnup: It is more important at higher burnups to test fuel rods with the appropriate initial enrichment. K(12): This is a specified parameter and fuel is selected which meets the specification. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Test reactor irradiation condition	Irradiation conditions (e.g. flux, chemistry, and temperature) in test reactor as compared to power reactor. H(14) If rods irradiated in a test reactor are used it is very important that they be fully characterized to develop the understanding as to whether they are prototypic M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(7): The conditions under which these tests would be carried out are quite well known. PK(3): The irradiation conditions within a test reactor are never completely known. Given this situation, the rod may not be prototypical and that causes further problems in data interpretation and extrapolation to plant conditions. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Power history (normal power reactors)	The power history experienced by fuel (e.g. whether baseload or load following, end-of-life power level etc.) within the range of variation of the normal power plants up to 60 GWd/t. H(1) It is important to select and test specimens that are prototypic of the environment (e.g. fuel management in which high burnup fuel will have its lifetime to high burnup. M(13) Although non-prototypical power histories (e.g. due to low power irradiation in lead test assemblies) can cause lower oxidation and/or lower fission gas release, which can affect fuel rod behavior, it is not believed to be a major effect. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: The test rods must be representative in terms of fuel rod irradiation conditions. The higher the burnup, the more important that the irradiation campaign be prototypical. If the test rods come from lead test assemblies, it is important to check that the power history is representative of the future commercial reload. K(2): The burnup and also the history of the burnup; the power history experienced by fuel within the range of variation of the normal power plants is well known. PK(11): No rationale recorded. UK(1): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	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. H(6) The amount of fission gas likely to contribute to cladding loading during the transient is related to rim size. It will also affect the cladding to pellet contact. The rim size is related to the Pu distribution, which determines the radial power distribution. The size will likely determine how much fuel is injected into the coolant if there's a failure. M(5) The rim plays a part in the response of the fuel pellet, but it is not a strongly important part of that response. The rim is softer than the pellet and can have a beneficial effect on the loading of the cladding. The impact of the rim on the behavior of the rods is speculation. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: A step change of +20% on burnup is likely to cause changes in phenomena related to size, power peaking, fission product generation and redistribution, interaction with the clad, bonding, etc. K(1): No rationale recorded. PK(8): Rim size seems to be highly variable. In addition, rim size can be determined only by destructive testing of the rod. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fission gas distribution	The radial distribution of fission gas in the pellet (inter-granular, grain boundaries, porosity), including the rim zone. H(10) If the gas is actually in solution in the fuel pellet, then it's not going to come out because diffusion processes are slow. If there are bubbles running along grain boundaries and in the cladding porosity, then the gas moves easier and a lot of gas could be released. Thus, the distribution is very important. Radial distribution of the fission gas and also the fission gas inventory in the grain boundaries will have a strong effect on the expansion of the pellet and also on the PCMI loading. Intragranular bubbles can contribute at high energy deposition (high temperature). M(1) The importance of gaseous swelling is not fully understood and so ranked as having medium importance. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: A step change of +20% on burnup is likely to cause changes in phenomena related to size, power peaking, fission product generation and redistribution, interaction with the clad, bonding, etc. K(0): No votes. PK(10): Fission gas distribution can be determined only by destructive testing of the rod. If one predicted the fission gas distribution via calculation and then did a destructive analysis of a test rod for data, the uncertainty would remain larger than 25 percent. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	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. H(3) Grain size has a strong impact on how much of the fission gas accumulates in the grain boundary, the grain boundary inventory of fission gas, and also, the fission gas release. Grain size may affect the size distribution of the ejected fuel particles in the case of fuel dispersal. M(6) The more important factors are more directly captured in phenomena such as the fission gas distribution so the grain size is less important. L(1) For the grain sizes of interest, the differences are not large. Fuel: Grain size might become more important. Distributed through the fuel matrix are some agglomerates of high plutonium content and U2 content, and porosity changes close to the little agglomerates. Local burnup in the area of the plutonium spot is very high, producing a very fine microstructure in the vicinity of the plutonium spot. The fission gas inventory in that position is very high because of very high local burnup. There is comparatively less damage in the rest of the matrix than the normal fuel. Clad: N Reactor: N Burnup: A step change of +20% on burnup is likely to cause changes in phenomena related to size, power peaking, fission product generation and redistribution, interaction with the clad, bonding, etc. K(5): The as-fabricated grain size can be determined by pre-examination with little uncertainty. A sufficient database exists such that reasonable predictions can be made. PK(3): Although the as-fabricated grain size is known, the changes with burnup are not known within 25 percent. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	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. H(3) It is important to characterize the fuel pellet geometry in order to see how it's going to impact the cladding. The pellet type should be prototypic. The existence of chamfering can lead to higher inter-pellet hydrogen concentration. M(6) Some non-prototypicalities can be allowed in testing and still lead to significant insights about fuel performance. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: No rationale recorded. K(12): The physical characteristics of the pellets are known. Only specimens for which well-known characteristics with fabrication records exist will be selected. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Agglomerates (MOX only)	Agglomerates are $(U,Pu)O_2$ particles embedded in the fuel matrix; they change with burnup. Different fabrication pro- cedures result in different agglomerate size and distribution. H(13) Important to characterize the performance of MOX fuel if it is to be used in plants. MOX fuel will display some differences as compared to UO_2 (see Appendix D). Local burnup, temperature, fission gas release can be very high and can affect the transient behavior. M(1) Same as above but differences are only believed to be moderate. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(4): The MIMAS process is sufficiently well developed that the MOX fuel that's being produced with respect to agglomerates and agglomerate size distribution is well-known and can be actually part of the fuel specification. PK(5): The agglomerates change with burnup and their size and distribution within the pellet can be statistically all over the map and the uncertainty is greater than 25%. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding: 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. H(6) Oxide affects the structural strength of the cladding by reducing the metallic cladding thickness. The greater the oxide thickness, the higher the probability of some non-uniformity in the oxide. There is also a second order effect regarding the temperature distribution, but the main effect is on the structural strength of the cladding. M(7) We have not observed high temperature failures in oxidized fuel rods (up to 85 microns) in the absence of spallation. The amount of wall thinning associated with expected cladding oxidation has a small impact on structural integrity. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(5): The amount of cladding oxide can be measured before testing. PK(5): There's some variability in the amount of oxide; therefore, there is some uncertainty in selecting the particular specimen such that it is characteristic of the amount of oxide. It may be necessary to have a complete map of the pin to fully understand the oxide all over the pin before testing. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Extent of oxide spalling	Peeling of the oxide layer from the cladding during in-reactor operation, leaving the underlying material exposed to the coolant. Can lead to a local cold spot and hydride blister formation. This item considers the extent (surface area involved) of spallation. H(4) Spalling is important because it leads to high localized concentrations of hydrides (blisters), and the formation of a preferential failure spot. M(5) The total number of spalled spots is of less importance than the existence of some spallation with associated hydride blisters. The hydride blisters are themselves considered individually. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(1): No rationale recorded. PK(8): Lacking a full understanding about how spallation occurs in a reactor, it's difficult to make the link between test rod and how to select the rod to bound reactor rods. UK(3): Spallation occurs at very high oxide thicknesses, and there isn't as much experience with the new alloys at these higher oxide thicknesses. This is a local phenomenon that may or may not occur. It could depend upon such abstract things like vibration of the rod within the reactor or a shock wave during a transient.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	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 during reactor operation. H(3) Delamination may enhance transient spalling. It is important because of its effect on heat transfer characteristics and the resulting temperature of the cladding during loading. M(4) In-reactor oxide delamination does not impact the cladding ductility. It may enhance transient spallation of oxide during the rod ejection accident. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(1): No rationale recorded. PK(8): Lacking a full understanding about how delamination occurs in a reactor, it's difficult to make the link between test rod and how to select the rod to bound reactor rods. UK(3): Delamination occurs at very high oxide thicknesses, and there isn't as much experience with the new alloys at these higher oxide thicknesses.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Alloy	Cladding utilized (e.g., Zr-4, ZIRLO, M5,) including thermo-mechanical processing. H(3) It is important that testing be done on prototypic cladding materials because mechanical properties may differ. Test results on one cladding may not be directly applicable to another cladding material. M(4) The changes in cladding alloy content are not large and thus limited testing should address differences from the primary cladding database. L(3) There will be a full characterization of mechanical properties will allow extrapolation of the behavior under accident conditions from alloy to alloy. Fuel: N Clad: N Reactor: N Burnup: Only a limited number of alloys will be able to go up to 75 GWd/t. It is important to pick the right one to test. K(12): The alloy is a specified element in the test specification and there is no uncertainty. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Amount of Hydrogen	Total amount of hydrogen in the cladding. H(9) Hydrogen, even if it's evenly distributed, will still affect the mechanical properties and may affect the failure criteria of zirconium alloys. There is clear correlation between how much hydrogen exists in the cladding and whether fuel fails or will not fail. M(4) Separate effect tests indicate that the amount of hydrogen has a weak impact on the mechanical properties of the cladding, up to 700 PPM. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(3): For the regular fuel rod at high burnup is pretty constant. It's always around 600 to 700. PK(7): The accuracy requirements have a degree of uncertainty. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Hydrogen distribution	Spatial distribution of the hydrogen, including local hydride formations in the cladding. H(13) Hydrogen concentration, either in a blister or a hydride rim can create a preferential failure spot, and limit cladding ductility. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(0): No votes. PK(7): The hydrides are very much dependent on the temperature distribution, the stress state, the prior history. If there is any hidden delamination or spallation, various distributions of hydrides that are not easily visible could be formed. UK(3): The distribution of hydrogen cannot be determined with a mechanistic evaluation. Hydrogen is one of the hardest things to find, probably the hardest single element to deal with that there is, because it's so light that there's just almost no techniques whatever to really find out where it is.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Hydride orientation	The orientation of the hydrides, either axial or radial. H(6) Radial hydrides or the radial component of primarily circumferential hydrides can affect cladding mechanical properties. A high vote assumes that they might exist and must be characterized. M(2) Radial hydrides do not typically arise in real applications but a measure of uncertainty leads to a vote of medium importance. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(5): Hydride orientation is known and understood within the 25 percent confidence limit. PK(3): The location and orientation of the hydrides are uncertain at a level commensurate with partially known. UK(1): The location and orientation of the hydrides are uncertain at a level commensurate with unknown.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Fluence	Time-integrated particle flux to which the cladding is exposed. H(1) No rationale recorded. M(2) Radiation damage saturates at a low value, but our knowledge about cladding alloys is incomplete; we don't know if there are processes that are accelerated at higher fluence and change how the cladding behaves. A medium vote represents uncertainty about its importance. Also, prototypicality is important. L(6) There is a saturation effect after one or two cycles. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(11): Because the reactor power history can be calculated with reasonable accuracy, it is possible to also determine what occurred in the fuel rod. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Fuel rod selection	Cladding integrity	Whether the cladding is leak-proof, and whether it has any non-representative defects. H(12) Non-representative defects can strongly affect the test results (including cladding failure). M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(3): The integrity of the rod and the specimen preparation is controlled. PK(7): There is some uncertainty because there are inconsistencies relative to visual examinations and more elaborate or electronic examinations, i.e., partial failures detected by ultrasonic testing cannot be seen visually. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Specimen design: Plenum volume	A volume incorporated into the test article to be representative of internal pressure, amount of gases available, accommodate fuel expansion, and avoid end-effect. H(0) No votes. M(7) 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. L(4) There is little gas communication in the rod. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(10): The plenum volume is a design parameter. PK(1): No rationale recorded UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Internal pressure	The total pressure in the test specimen gap at the start of in-reactor testing resulting from the introduction of the fill gas at the time the test specimen was prepared. H(2) Pressure loading on the cladding is important.. 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. L(4) Factors other than the delta-P across the cladding dominate. PCMI stresses are going to be much higher than stresses induced by internal pressure. Fuel: N Clad: N Reactor: N Burnup: Phenomenon becomes more important as burnup increases. K(9): It is possible to produce a sample with a backfill pressure that is fairly well known. There is little uncertainty in the initial pressure resulting from the fill gas. PK(1): No rationale recorded. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Gas composition	The composition of the gas in the gap and the plenum resulting from the introduction of the fill gas at the time the test specimen was prepared. H(0) No votes. M(3) Heat transfer is important. Gas composition affects the heat transfer of the gap. L(6) In high burnup PWR fuel, the gap is already closed, so gas composition has less effect on heat transfer. Fuel: N Clad: N Reactor: N Burnup: N K(11): A known parameter at the time the test article is prepared. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Length	The appropriate length of the test article such that the data delivered from the test is useable. H(8) It is important that test specimens be of sufficient length that the processes and phenomena occurring in the test article are representative of those that would occur in the full fuel rod. M(3) Length issues are of relatively less importance than other highly ranked phenomena. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(11): Length is a measured parameter. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Attachments	Any item, e.g., instrumentation, affixed to the test article. H(6) 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. M(3) Attachment design is of relatively less importance than other highly ranked phenomena. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(8): The mechanical and joining features are known. PK(2): Before designing the test rig, it is not known if some attachment will have an unforeseen impact on the test results. Shortcomings in the attachment design have been detected relative to some tests that have been conducted. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Constraints	The mechanical setup used to hold the test article in place. H(6) 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. M(4) Constraints are of relatively less importance than other highly ranked phenomena. L(3) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(9): The features of the constraints are known at the time the test is conducted. PK(1): Before designing the test rig, it is not known if the constraints will have an unforeseen impact on the test results. Such an impact has been observed on some MOX tests with large cladding strain. The strain grown was impaired at the location of the holding spring. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
Conduct of test	Single rod versus bundle	The phenomenon is best expressed as a question, namely, is it possible to characterize the needed phenomena in a single rod test article or is it necessary to conduct some testing in a bundle? H(5) It is important to understand the rod ejection accident from beginning to end and to understand whether failure in a single fuel rod propagates and engages all or apart of a bundle. M(6) 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. L(2) Most of the needed understanding can be obtained in single fuel rod tests and there is little need to conduct bundle tests. Fuel: N Clad: N Reactor: N Burnup: N K(1): Rationale not recorded. PK(10): Some data exist (Power Burst Facility and perhaps some Japanese data) on bundles versus rods. The same failure mechanism and a similar power level were observed, so there is some indication that single rod data is adequate. Some uncertainty remains. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Pulse shape	Shape of the pulse to which the test article is exposed, e.g., single or double hump. H(0) No votes. M(12) As long as the integrated curves for various pulse shapes are similar and have similar durations the impact of pulse shape is only moderate, similar behavior of the fuel rod arises. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(10): The conditions under which testing occurred would be well-known, particularly with respect to a power history during a pulse PK(1): No rationale recorded. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	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. H(17) The fuel enthalpy increase governs the loading of the cladding, which causes failure. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(10): The fuel enthalpy increased is obtained through a calculation given the power trace and the uncertainty in this process is sufficiently low to warrant the designation of known. Calculations have been performed with several codes for the same tests and the scatter amongst calculated results was small. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Pulse width	The duration of the pulse (e.g., full-width, median-height) imposed on the test article, and which defines the energy deposition rate. H(12) Energy deposition rate determines the loading and heating rates. Testing in CABRI with several pulse rates has shown a significant impact on the outcome. M(3) The impact of pulse width has not been demonstrated for prototypic fuel. The CABRI tests Rep-Na1, RepNa8 and Rep-Na10 were conducted with very brittle cladding. Pulse width is less important in more prototypic cladding. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(10): The parameter is measured with the requisite degree of accuracy to be qualified as known. PK(1): The pulse width is a function of the energy deposition. In a rod ejection accident, the higher the reactivity insertion, the narrower the width. It's not clear the needed corrections are being made in experiments. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Axial power profile (during the test)	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. H(1) Important to have a prototypic axial power profile. M(8) The ejection time of the rod is so quick that you're going from one axially fixed setup to another axially fixed setup, which doesn't change. The change in axial distribution of material is only over a very insignificant amount of time. L(1) The axial power profile must be known but once known, the results can be interpreted and extended to the actual power profile. Fuel: N Clad: N Reactor: N Burnup: N K(11): This parameter is the outcome of measurement and calculation and its value is known within the requisite accuracy for this uncertainty category. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Coolant heat transfer conditions	The coolant environment to which the test article is exposed, e.g., coolant type, velocity, temperature, pressure, etc. H(15) By extending the primary evaluation criterion to examine conditions beyond failure and including dispersal and pressure pulse generation, coolant conditions become very important. Also, as much as 25% of the total deposited energy can be conducted out to the coolant, again leading to the conclusion that coolant conditions are important. M(0) No votes. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: N K(8): The necessary parameters can be measured (pressure, temperature, and flow rates) and the remaining conditions can be accurately calculated. PK(2): In a test reactor, the coolant heat transfer conditions are not well known for conditions in which boiling crisis occurs. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	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. H(9) The basic criterion is the expulsion of large, uncontrollable amounts of fission products into the coolant. It is important to measure directly fuel dispersal into the coolant. M(1) This information can be obtained more precisely and a lot more cheaply from pressure measurements. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: If the conditions of a larger rim and fine-grain, highly burned fuel next to the clad exist, and these conditions contribute to fuel dispersal, this phenomenon could be more important. K(0): No votes. PK(5): This is a difficult phenomenon to simulate. UK(2): Dispersal data in hot, pressurized water is not available.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	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. H(8) The pressure pulse measurement is complementary to fission product and fuel particle data. It facilitates the separation of effects. The absence of substantial pressure pulses indicates that there was little or no fuel dispersal. M(2) These data are of less importance than the other on-line data listed. L(0) No votes. Fuel: N Clad: N Reactor: N Burnup: If the conditions of a larger rim and fine-grain, highly burned fuel next to the clad exist, and these conditions contribute to fuel dispersal, this phenomenon could be more important. K(0): No votes. PK(5): No rationale recorded. UK(2): No rationale recorded.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Fission product measurement on-line	Detection of the time at which fission gases escape from the fuel rod into the test channel. H(6) Knowledge of fission gas release during the transient is important in that it will provide the basis for better understanding the gas expansion loading phenomenon. Also, if fuel dispersion occurs, it will be facilitated by the gas that serves as a propellant to cause dispersion. M(2) No rationale recorded. L(0) No votes. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(2): No rationale recorded. PK(2): No rationale recorded. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Rod deformation measurement on-line	Measurement of the time-dependent variation of clad hoop strain during the test. H(9) This measurement will provide the basis to calibrate predictive models and, as a result, will permit us to understand how the fuel rod behaves during the transient. M(0) No votes. L(0) No votes. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(0): No votes. PK(4): Design of such a sensor has been completed; the sensor is in the development stage. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Time and location of failure	The detection of failure occurrence and its axial location in the test rod. H(11) It's important to know when and where the failure started and how it propagated. Combined with the integrated energy deposition, this begins to lay the basis for acceptance criteria. M(0) No votes. L(0) No votes. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(2): No rationale recorded. PK(2): Time of failure can be precisely determined with a rod internal pressure sensor, but the location of the failure is difficult to measure. Acoustic measurement is not applicable. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Temperature of cladding and coolant	Measurement of the time-dependent variation of the cladding and coolant temperature during the test. H(7) The temperature of the cladding will, to a large extent, determine its thermal response, and it's important to know what the variation of it is with time during the transient. Mechanical properties are related to temperature. M(2) The temperature profile doesn't actually strongly reach the exterior of the cladding. There will be asymmetries in the azimuthal as well as the axial dimensions. The temperature measurement is not as important as the timing of the rupture or the strain. L(0) No votes. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(4): This is a mature technique. PK(0): No votes. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	Fuel stack and cladding elongation	Measurement during the test of the increase in the length of the stack and clad axial elongation. H(6) This is one of the few opportunities to get direct experimental information during the experiment on the fuel. The fuel stack elongation is one measure of axial swelling and fuel swelling in general. M(3) This parameter is of lesser importance than the other measurements for use by the code analyst; this ranking reflects a prioritization with respect to resource allocation. L(0) No votes. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(3): This is a mature technique. PK(1): No rationale recorded. UK(0): No votes.

Table B-1. PWR Rod Ejection Accident. Category B – Integral Testing (continued)

Subcategory	Phenomena	Definition and Rationale (Importance, Applicability, and Uncertainty)
During the test	DNB detection	Measurement during the test of the time and location of any departure from nucleate boiling. H(5) It's important to know whether, during the test, DNB has occurred somewhere in the fuel rod, because it impacts on the fuel rod behavior afterwards. M(2) There are other means to detect DNB from other measurements. This is an important factor because the standard DNB measurement might not be effective in this application. This parameter is of lesser importance than the other measurements for use by the code analyst; this ranking reflects a prioritization with respect to resource allocation. L(2) The transient DNB-R effect is best tested in some other type of clean facility if it's an issue. Fuel: Applicability not assessed by panel. Clad: Applicability not assessed by panel. Reactor: Applicability not assessed by panel. Burnup: Applicability not assessed by panel. K(2): No votes. PK(2): No rationale recorded. UK(0): No rationale recorded.