U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7307

Phenomena Identification and Ranking Tables on High Burnup Fuel Fragmentation, Relocation, Dispersal, and Its Consequences for Design-Basis Accidents in Pressurized- and Boiling-Water Reactors

Office of Nuclear Regulatory Research

AVAILABILITY OF REFERENCE MATERIALS IN NRC PUBLICATIONS

NRC Reference Material

As of November 1999, you may electronically access NUREG-series publications and other NRC records at the NRC's Library at www.nrc.gov/reading-rm.html. Publicly released records include, to name a few, NUREG-series publications; *Federal Register* notices; applicant, licensee, and vendor documents and correspondence; NRC correspondence and internal memoranda; bulletins and information notices; inspection and investigative reports; licensee event reports; and Commission papers and their attachments.

NRC publications in the NUREG series, NRC regulations, and Title 10, "Energy," in the *Code of Federal Regulations* may also be purchased from one of these two sources:

1. **The Superintendent of Documents**
   U.S. Government Publishing Office
   Washington, DC 20402-0001
   Internet: https://bookstore.gpo.gov/
   Telephone: (202) 512-1800
   Fax: (202) 512-2104

2. **The National Technical Information Service**
   5301 Shawnee Road
   Alexandria, VA 22312-0002
   Internet: https://www.ntis.gov/
   1-800-553-6847 or, locally, (703) 605-6000

A single copy of each NRC draft report for comment is available free, to the extent of supply, upon written request as follows:

Address: **U.S. Nuclear Regulatory Commission**
Office of Administration
Digital Communications and Administrative
Services Branch
Washington, DC 20555-0001
E-mail: Reproduction.Resource@nrc.gov
Facsimile: (301) 415-2289

Some publications in the NUREG series that are posted at the NRC's Web site address www.nrc.gov/reading-rm/doc-collections/nuregs are updated periodically and may differ from the last printed version. Although references to material found on a Web site bear the date the material was accessed, the material available on the date cited may subsequently be removed from the site.

Non-NRC Reference Material

Documents available from public and special technical libraries include all open literature items, such as books, journal articles, transactions, *Federal Register* notices, Federal and State legislation, and congressional reports. Such documents as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings may be purchased from their sponsoring organization.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at—

The NRC Technical Library
Two White Flint North
11545 Rockville Pike
Rockville, MD 20852-2738

These standards are available in the library for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from—

American National Standards Institute
11 West 42nd Street
New York, NY 10036-8002
Internet: www.ansi.org
(212) 642-4900

Legally binding regulatory requirements are stated only in laws; NRC regulations; licenses, including technical specifications; or orders, not in NUREG-series publications. The views expressed in contractor prepared publications in this series are not necessarily those of the NRC.

The NUREG series comprises (1) technical and administrative reports and books prepared by the staff (NUREG–XXXX) or agency contractors (NUREG/CR–XXXX), (2) proceedings of conferences (NUREG/CP–XXXX), (3) reports resulting from international agreements (NUREG/IA–XXXX),(4) brochures (NUREG/BR–XXXX), and (5) compilations of legal decisions and orders of the Commission and the Atomic and Safety Licensing Boards and of Directors' decisions under Section 2.206 of the NRC's regulations (NUREG-0750), (6) Knowledge Management prepared by NRC staff or agency contractors (NUREG/KM-XXXX).

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG/CR-7307

Phenomena Identification and Ranking Tables on High Burnup Fuel Fragmentation, Relocation, Dispersal, and Its Consequences for Design-Basis Accidents in Pressurized- and Boiling-Water Reactors

Manuscript Completed: March 2024
Date Published: May 2024

Prepared by:
Vesselin Palazov[1], Francis Bolger[2], Nathan Capps[3], David Kropaczek[4],
Wade Marcum[5], Kurshad Muftuoglu[2], Gretar Tryggvason[6], and
Wolfgang Wiesenack[7]

[1]Information Systems Laboratories, Inc.
Tysons Corner, VA 22182

[2]Electric Power Research Institute
Palo Alto, CA 94304

[3]Oak Ridge National Laboratory
Oak Ridge, TN 37830

[4]Veracity Nuclear
Lenoir City, TN 37771

[5]Oregon State University
Corvallis, OR 97331

[6]Johns Hopkins University
Baltimore, MD 21218

[7]Halden Reactor Project (retired)
Halden, Norway

James Corson and Shawn Campbell, NRC Project Managers

Office of Nuclear Regulatory Research

ABSTRACT

This report presents the results from the U.S. Nuclear Regulatory Commission's expert elicitation effort to develop phenomena identification and ranking tables (PIRTs) in support of addressing technical issues related to fuel fragmentation, relocation, and dispersal (FFRD) and its consequences during design-basis accidents related to the use of extended enrichment (EE) and high burnup (HBU) fuel in domestically operated pressurized- and boiling-water reactors. The developed PIRTs identify phenomena seen as relevant to EE/HBU FFRD and its consequences from a safety viewpoint and assess the importance, level of knowledge, and related uncertainty for the considered phenomena. The PIRTs enhance the agency's knowledge base related to FFRD and its potential consequences for EE/HBU fuel use.

TABLE OF CONTENTS

LIST OF TABLES

ABBREVIATIONS AND ACRONYMS

3D	three dimensional
ADAMS	Agencywide Documents Access and Management System
ATF	accident tolerant fuel
BWR	boiling-water reactor
C	Celsius
cal/g	calorie/gram
CCFL	counter-current flow limitation
CFR	*Code of Federal Regulations*
CHF	critical heat flux
CRDA	control rod drop accident
CREA	control rod ejection accident
DBA	design-basis accident
ECCS	emergency core cooling system
ECR	equivalent cladding reacted
EE	extended enrichment
EPRI	Electric Power Research Institute
FF	fuel fragmentation
FFRD	fuel fragmentation, relocation, and dispersal
FGR	fission gas release
FHA	fuel handling accident
FOM	figure of merit
FP	fission product
GSI	generic safety issue
GWd/MTU	gigawatt days per metric ton of uranium
GWd/tHM	gigawatt days per ton of heavy metal
H	high (ranking)
HBU	high burnup
IFBA	integral fuel burnable absorber
Imp.	importance
ISL	Information Systems Laboratories, Inc.
L	low (ranking)
LOCA	loss-of-coolant accident
LWR	light-water reactor
M	medium (ranking)
MWd/kgU	megawatt days per kilogram of uranium
NEA	Nuclear Energy Agency of the OECD
NRC	U.S. Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory

OSU	Oregon State University
PCMI	pellet-cladding mechanical interaction
PCT	peak cladding temperature
PIRT	phenomena identification and ranking table
PWR	pressurized-water reactor
RCS	reactor coolant system
RG	regulatory guide
RIA	reactivity-initiated accident
SoK	state of knowledge
TFGR	transient fission gas release
U	uncertainty
UO_2	uranium dioxide
WABA	wet annular burnable absorber

1 INTRODUCTION

1.1 Background

The U.S. nuclear industry is currently applying for licensing approvals from the U.S. Nuclear Regulatory Commission (NRC) to increase fuel burnup limits for commercial light-water reactors (LWRs) up to 75 or 80 gigawatt days per metric ton of uranium (GWd/MTU), which would be beyond the currently licensed rod average burnup limit of 62 GWd/MTU. In addition, commercial utilities and fuel vendors have expressed interest in increasing fuel enrichment beyond 5 weight percent uranium-235.

In SRM-SECY-21-0109, “Staff Requirements—SECY-21-0109—Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors,” dated March 16, 2022 [1], the NRC initiated a rulemaking to amend requirements for the use of LWR fuel containing uranium enriched above 5.0 weight percent uranium-235. Importantly, the Commission asked the NRC staff to appropriately address and analyze fuel fragmentation, relocation, and dispersal (FFRD) issues relevant to fuels of increased enrichment and burnup levels in the regulatory basis for this rulemaking. On September 8, 2023, the NRC requested public comments on a regulatory basis titled “Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors” in support of this rulemaking process.

Evidence from extensive experimental research and produced data supported by the NRC and other domestic and international entities led to the general agreement that fuel becomes increasingly susceptible to FFRD once burnup exceeds about 55 GWd/MTU and cladding hoop strain increases above approximately 3 percent. The NRC is concerned with the degree to which FFRD and its consequences from the introduction of extended enrichment (EE) and high burnup (HBU) fuel in the operating fleet of pressurized-water reactors (PWRs) and boiling-water reactors (BWRs) could potentially challenge the existing regulatory framework for design-basis accidents (DBAs). Thus, the existing loss-of-coolant-accident (LOCA) regulations, put in place to ensure that the core remains in a coolable geometry by keeping fuel and its cladding in a structured coolable array, involve fuel behavior. As burnup has a strong effect on fuel behavior, issues related to FFRD and its consequences require adequate consideration and resolution. Furthermore, FFRD phenomena and the resulting consequences for EE/HBU fuel may have implications for other non-LOCA DBAs, such as fuel failure from cladding ballooning and burst due to heatup or direct pellet-cladding mechanical interaction (PCMI) in reactivity-initiated accidents (RIAs). Fuel failures from mechanical damage that breaches the fuel cladding in ex-reactor nonthermal events like fuel handling accidents (FHAs) can also lead to dispersal of fragmented HBU fuel.

1.2 Objectives

To help address technical issues related to FFRD and its consequences during DBAs involving the use of EE/HBU fuel in domestically operated PWRs and BWRs, the NRC undertook the expert elicitation effort documented in this report. The effort was aimed at contributing to and enhancing the NRC’s knowledge base related to FFRD and its potential consequences for EE/HBU fuel. The elicitation process involved establishment of the FFRD Expert Panel that contributed to the development of the phenomena identification and ranking tables (PIRTs) on FFRD and its consequences for EE/HBU fuel documented in this report. These PIRTs were developed to identify phenomena seen as relevant to EE/HBU FFRD and its consequences from a safety viewpoint and to assess their importance, level of knowledge about them, and related uncertainty.

It is emphasized that, in developing the documented PIRTs, the FFRD Expert Panel effort was focused on expected fuel behavior at burnup levels beyond the currently licensed rod average burnup limit of 62 GWd/MTU, at which burnup levels FFRD and its consequence may become relevant to ensuring reactor safety. In this important regard, the currently developed PIRTs differ from the PIRTs on HBU fuel that the NRC developed more than two decades ago as part of establishing the currently approved burnup limit. These previous PIRTs, published by the NRC in 2001, were developed for LOCAs in PWRs and BWRs (NUREG/CR-6744, Agencywide Documents Access and Management System Accession No. ML013540584) [2], rod ejection accidents in PWRs (NUREG/CR-6742, ML012890477)[1] [3], and power oscillation events without scram in BWRs (NUREG/CR-6743, ML012850300, ML012850315) [4], and none of them considered phenomena related to FFRD.

---

[1] Although the reactivity-initiated rod ejection accident PIRT for PWRs, documented in NUREG/CR-6742, “Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel,” issued September 2001 [3], did address fuel dispersal, it was more focused on a violent expulsion of fuel due to very high peak enthalpies, rather than on dispersal of fragmented HBU fuel due to ballooning and burst.

2 PHENOMENA IDENTIFICATION AND RANKING METHODOLOGY

2.1 Technological Scope and Licensing Events Outline

As already mentioned, the PIRT effort documented in this report is concerned with the possible future use of EE/HBU fuel in LWRs of both PWR and BWR designs that are currently in operation in the United States. Only standard fuel designs with uranium dioxide (UO_2) fuel and traditional zirconium-based cladding alloys, such as Zircaloy, were considered in this PIRT effort. It is noted that accident tolerant fuel (ATF) designs were outside its scope.

DBAs considered in this PIRT effort included both LOCA and non-LOCA transients leading to thermal events engaging the entire core fuel load or a local part of the core, as in the case of RIAs. In addition, the DBAs considered ex-reactor nonthermal events involving fuel failures from mechanical damage that breaches the fuel cladding, such as occurs in FHAs. In general, the DBA events considered in this PIRT effort were grouped into the following three main categories:

(1) whole-core thermal events
(2) local core events
(3) ex-reactor nonthermal events

Category 1 of whole-core thermal events includes DBAs that could expose the entire core to heatup transients, increasing the fuel temperatures by a few hundred degrees above in-reactor normal operating fuel temperature levels, particularly at fuel pellet mid-radius and in the outer rim region. For such transients, core-wide FFRD of HBU fuel becomes possible. A large-break LOCA is viewed as the limiting transient within this category of DBAs.

Category 2 of local core events includes transients such as RIAs caused by a control rod ejection accident (CREA) in a PWR or by a control rod drop accident (CRDA) in a BWR. Although such RIAs produce a highly localized impact on the core, fuel temperatures in the limited number of affected fuel pins, located in the vicinity of the ejected or dropped control rod, can increase more than a thousand degrees above normal operating temperatures. In addition to elevated fuel and cladding temperatures potentially leading to fuel failure due to clad ballooning and burst, fuel expansion can result in fuel failure from a PCMI. These fuel failures can potentially result in strong HBU fuel dispersal. In general, RIAs are expected to result in less fuel dispersal and lower dose consequences compared to LOCAs.

Category 3 of ex-reactor nonthermal events includes accidents such as FHAs involving dropping or otherwise impacting mechanically (e.g., hitting) a fuel assembly, thus causing mechanical damage that breaches the cladding of the fuel rods, leading to the release of gap activity. In the case of HBU fuel, fragmented fuel particulates can be also ejected due to the high pin internal pressure from normal fuel operation. These accidents are postulated to occur inside the containment or in the fuel building from fuel handling operations such as those taking place during reactor refueling outages. Bounding nonmechanistic assumptions involving an instantaneous shearing off of the fuel pins upon impacting the fuel assembly and subsequent release of fission gas from the damaged fuel rods are usually considered in analyzing FHA consequences. As discussed later in this report, experimental data are available from tests involving the rupture of pressurized-fuel specimens caused by mechanical loads that resulted in small amounts of released fine fuel fragments at various burnup levels. As for Category 2 events, FHAs are expected to produce much less fuel dispersal and lower dose consequences compared to LOCAs.

2.2 PIRT Elicitation Process Outline

As mentioned above, the elicitation process, implemented in this effort to develop the described PIRTs on EE and HBU FFRD and their consequences, involved the selection, establishment, and work of an expert panel. The FFRD Expert Panel consisted of seven nationally and internationally recognized distinguished professionals carefully selected and approved by the NRC. The agency considered each expert's technical background, experience, and recognized contributions in specialty areas related to analytical, experimental, and licensing methods and aspects pertinent to fuel performance evaluation during DBAs in commercial power reactors, with a particular focus on processes related to EE/HBU FFRD and its consequences. APPENDIX A to this report summarizes the professional credentials of the Panel members.

A major step in the PIRT development process was the review by the FFRD Expert Panel of a draft report on the review of literature sources related to HBU FFRD and its consequences [5]. The report, prepared by Information Systems Laboratories, Inc. (ISL), as part of this PIRT development effort, was provided to the members of the FFRD Expert Panel on November 21, 2023, well in advance of the initiation of the Panel's deliberation efforts. The report synthesized findings from the evaluation of publicly available information on FFRD phenomena, including HBU fuel dispersal and transport in the reactor coolant system (RCS) and potential impacts from DBAs. The goal of the report was to inform the FFRD Expert Panel and facilitate its elicitation efforts.

The NRC organized, scheduled, and supported the PIRT deliberation sessions of the FFRD Expert Panel, which took place as open public meetings officially announced by the NRC. These meetings included an initial 4-day, in-person meeting in Rockville, Maryland, on December 4–7, 2023. This first meeting was followed by four virtual meetings on January 19, February 26, February 27, and March 21, 2024. The meetings were attended by the members of the FFRD Expert Panel, NRC technical and management staff, ISL support personnel, and interested participants from the public. During these sessions, the panelists discussed and elaborated on specific phenomena, applicable conditions, and parameters and ranked each identified item with regard to figures of merit (FOMs) deemed of relevance for the considered DBA categories as described below.

2.3 PIRT Generation Approach

Based on the categorization of DBA events described above, this report develops and documents three separate PIRTs that each covers one of three event categories:

(1) PIRT on High Burnup FFRD and Its Consequences for Whole-Core Thermal Events
(2) PIRT on High Burnup FFRD and Its Consequences for Local Core Events
(3) PIRT on High Burnup FFRD and Its Consequences for Ex-Reactor Nonthermal Events

As noted previously, the Panel reviewed a large-break LOCA as the limiting transient in terms of FFRD and its consequences within Category 1 DBAs on whole-core thermal events. Therefore, this report refers to the corresponding PIRT as a LOCA PIRT. Similarly, the FFRD Expert Panel envisioned RIAs to be transients of primary importance within Category 2 DBAs on local core events. Accordingly, this report refers to the PIRT for Category 2 events as an RIA PIRT. The

FFRD Panel developed the third PIRT for ex-reactor nonthermal events with an FHA in mind. As such, the third PIRT is considered an FHA PIRT in essence and is referred to accordingly in this report.

For each of the above PIRTs, the FFRD Expert Panel discussed the formulation of each identified phenomenon, applicable condition, or parameter, along with its relevance when considering potential consequences related to FFRD. The corresponding formulations for each considered item were provided in the documented PIRTs in two separate columns identified with the headings “Description” and “Relevance,” respectively.

The FFRD Expert Panel identified and ranked FOMs on a PIRT-specific basis. Each individual FOM was determined to be related to an area of concern viewed as relevant to FFRD and its potential consequences for EE/HBU fuel. For the LOCA PIRT, the two ranked FOMs were selected as related to the areas of coolability and, for some items, criticality, respectively. The existing regulatory requirements regarding the cooling performance of emergency core cooling systems (ECCSs) provided in Title 10 of the *Code of Federal Regulations* (10 CFR) 50.46, “Acceptance criteria for emergency core cooling systems for light-water nuclear power reactors,” and Appendix K, “ECCS Evaluation Models,” to 10 CFR Part 50, “Domestic Licensing of Production and Utilization Facilities,” involve fuel behavior, which can be strongly affected by FFRD at HBUs, due to the use of EE fuel and longer fuel cycles.

Assuring coolability requires consideration of additional effects that may be caused by or associated with dispersed fuel fragments from fuel rod failures expected to occur during a LOCA. FFRD-associated phenomena that carry the potential of adversely impacting reactor coolability can include processes such as the formation of debris beds on spacer grids within the core or elsewhere within the RCS, if dispersed particulates get transported by the coolant flow; coolability of such debris beds, depending on the mass and properties of dispersed and agglomerated fuel particulates; bed impact on coolability of adjacent fuel rods; core flow blockage by debris beds; and clogging of coolable permeable fuel debris beds by circulating coolant precipitants during long-term cooling, thus impacting bed coolability. For the RIA PIRT, the two applied FOMs were identified as related to the areas of fuel failure modes and radiological release, accordingly. One FOM, related to the area of radiological release, was identified and ranked for the FHA PIRT. Finally, the FFRD Expert Panel ranked each identified FOM in separate areas, with the panelists providing their qualitative rankings (measures) reflecting the perceived degree of significance. The following areas of FOM ranking were selected:

- Importance (Imp.)
- State of Knowledge (SoK)
- Uncertainty (U)

For each of the above FOM areas, the panelists ranked each considered individual phenomenon, applicable condition, or parameter using three the following qualitative rankings (measures) reflecting their subjective opinions as to the degree of significance (importance):.

- High (H)
- Medium (M)
- Low (L)

These rankings (votes) by each panelist were recorded in the corresponding PIRT for each considered phenomenon, applicable condition, or parameter. APPENDIX B, APPENDIX C, and APPENDIX D to this report contain the full FFRD PIRTs documenting the ranking votes by the panelists:

- APPENDIX B Tables B-1 through B-9 contain the ranking votes for the LOCA PIRT.
- APPENDIX C Table C-1 contains the ranking votes for the RIA PIRT.
- APPENDIX D Table D-1 contains the ranking votes for the FHA PIRT.

3 PHENOMENA IDENTIFICATION AND RANKING TABLES

3.1 PIRT on High Burnup FFRD and Its Consequences for Whole-Core Thermal Events

3.1.1 High Burnup FFRD PIRT for Whole-Core Thermal Events (Loss-of-Coolant Accidents)

The FFRD PIRT Panel developed the PIRT on HBU FFRD and its consequences for whole-core thermal events considering the large-break LOCA as the bounding scenario for operating PWR and BWR systems in this DBA category. As part of the LOCA PIRT development, a preliminary list of phenomena, conditions, and parameters was prepared, along with corresponding formulations for the relevance of each identified item to HBU FFRD and its consequences. The FFRD PIRT Panel elaborated on the proposed preliminary list to finalize the formulation and relevance description for the phenomena that were included in the developed FFRD LOCA PIRT. During these deliberations, the Panel also ranked each phenomenon in terms of “Importance” (Imp.), “State of Knowledge” (SoK), and “Uncertainty” (U) for the applicable FOM(s). The Panel used the three qualitative grades of “High” (H), “Medium” (M), and “Low” (L), described in section 2.3 , in weighing the significance of the phenomena in each of the above three ranking areas of importance, state of knowledge, and uncertainty. It is emphasized here that the rankings provided by the FFRD PIRT Panel reflect the incremental effect of going to HBU with FFRD (beyond the currently existing limits). In this regard, it is important to note that a low ranking does not mean that a phenomenon is not important to LOCA modeling in general when assessing the accident consequences. Rather, such a low ranking implies that going beyond 62 GWd/MTU is expected to have a low impact on coolability.

The phenomena included in the FFRD LOCA PIRT were grouped in the following nine categories:

(1) Fuel Initial Conditions

(2) Transient Power Distribution

(3) Transient/Steady-State Heat Transfer from Cladding (Blowdown, Refill, Reflood, Core Spray)

(4) Transient Core Coolant Conditions

(5) Fuel Rod Transient Response

(6) Fuel Dispersal

(7) Multiple Rod Effects—Mechanical

(8) Multiple Rod Effects—Thermal

(9) Dispersed Fuel Transport and Its Consequences

The rankings for each of the phenomena included in these nine categories were summarized and documented separately for each category in Table 3-1 through Table 3-9 at the end of this subsection. Tables B-1 through B-9 in APPENDIX B to this report document the complete FFRD

LOCA PIRT containing the full record of ranking votes by each Panel member individually for each phenomenological category.

The panelists deliberated on and ranked the majority of the phenomena in the FFRD LOCA PIRT during the December 2023 meeting. A relatively small group of items that were not covered at this meeting due to insufficient time was considered during the follow-up virtual Panel meeting on January 19, 2024. This group of phenomena included items 6.3a through 6.5 in Category 6 documented in Table 3-6, as well as all items in Categories 7 and 8 included in Table 3-7 and Table 3-8, respectively. Item 1.22 in Table 3-1 was ranked for both FOM-1, “Coolability,” and FOM-2, “Criticality”; items 9.18 and 9.19 in Table 3-9 were ranked only for FOM-2, “Criticality”; and item 9.21 in Table 3-9 was ranked for FOM-3, “Radiological Release.” All remaining phenomena in the FFRD LOCA PIRT were ranked for FOM-1, “Coolability” only, reflected in Table 3-1 through Table 3-9.

Finally, the items documented in some of the above-identified LOCA PIRT tables do not appear numbered in a strictly sequential order. Thus, Table 3-1 and Table B-1 do not include item 13, Table 3-3 and Table B-3 include item 3.7a but no item 3.7b, and, finally, Table 3-5 and Table B-5 do not include items 5.2, 5.12, 5.21, and 5.25. This numbering is not in error, as it reflects the history of the PIRT development. During the PIRT deliberation process, the Panel removed some preliminary items from the tables while reformulating or splitting certain other phenomena into two or more individual items .

Table 3-1 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 1, “Fuel Initial Conditions”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
1. Fuel initial conditions	1.1	Fuel cycle design, including rod power history (power uprated cores), transitional vs. equilibrium cycle	Determines rod failures, gap released, initial oxidation, and most likely FFRD amount	**M(5)**	**H(7)**	**L(7)-PWR** **M(7)-BWR**
				H(2)	-	-
	1.2	Core axial power distribution	Impacts fuel thermal response	**H(6)**	**H(7)**	**L(7)**
				M(1)	-	-
	1.3	Fuel assembly peaking factor	Determines rod failures, gap releases, initial oxidation, and most likely FFRD amount	**H(7)**	**H(7)**	**L(7)**
	1.4	Pin peaking factor	Rod failure location, local oxidation, and most likely FFRD amount, including importance of flatness of pin peaking	**H(6)**	**H(7)**	**L(7)**
				M(1)	-	-
	1.5	Pellet radial power distribution	Burnup profile / high burnup rim thickness	**H(7)**	**M(7)**	**M(7)**

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
	1.6	Initial stored energy in fuel	Rod failure	**M(6)**	**H(7)**	**M(5)**
				L(1)	-	L(2)
	1.7	Initial stored energy in structures	Impacts RCS and core thermal hydraulic response (e.g., downcomer boiling)	**L(7)**	**H(7)**	**L(7)**
	1.8a	Fuel assembly spacer grid	Locations where debris, dispersed fuel can be trapped	**H(7)**	**L(7)**	**H(7)**
	1.8b	Fuel assembly inlet nozzle design	Locations where debris, dispersed fuel can be trapped	**L(6)**	**L(5)**	**M(7)**
				M(1)	M(2)	-
	1.9	Hydrogen pickup in cladding material	Impact on cladding high-temperature mechanical performance (balloon and rupture size)	**M(5)**	**H(5)**	**M(6)**
				H(1)	M(2)	L(1)
				L(1)	-	-
	1.10	Cladding oxidation—inner	Pre-transient cladding oxidation due to fuel clad bonding	**L(7)**	**H(5)**	**L(7)**
				-	M(2)	-
	1.11	Cladding crud deposits	Initial cladding temperatures	**L(7)**	**H(7)**	**L(7)**
	1.12	Pre-transient reactor coolant conditions	Higher exit temperature results in higher corrosion/crud	**L(7)**	**H(7)**	**L(7)**
	1.14	Core-wide 3D spatial burnup distribution—pin-to-pin in the core	Most important factor for determining when performing FFRD analysis	**H(7)**	**H(7)**	**L(7)**
	1.15	Rod gas pressure	Rod failure/dispersal	**H(7)**	**H(4)**	**M(7)**
				-	M(3)	-
	1.16	Rod gap size	Gap most likely closed at initial rod powers and moderate burnups	**L(7)**	**H(7)**	**L(7)**
	1.17	Rod gas composition	Gap conductance	**L(7)**	**H(7)**	**L(7)**
	1.18	Rod free volume	Possible FFRD effect	**M(5)**	**H(7)**	**L(7)**
				H(1)	-	-
				L(1)	-	-
	1.19	Rod gas volume communication	Number of burst locations and FFRD	**H(7)**	**M(6)**	**M(6)**
				-	L(1)	H(1)
	1.20	Fuel thermal properties	Initial stored energy	**H(7)**	**H(7)**	**L(7)**

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
	1.21	Burnable absorber (IFBA/WABA/ Gadolinia)	Generally at lower burnups than fuel rods but can operate at moderate to higher powers at moderate/high burnups (conductivity, rod internal pressure, high-burnup structure, and fragmentation behavior)	**M(7)** -	**H(4)** M(3)	**M(5)** H(2)
	1.22	Fissile material composition	Radioactive isotope inventory, recriticality: **FOM-1**	**L(7)**	**H(7)**	**L(7)**
			Radioactive isotope inventory, recriticality: **FOM-2**	**M(6)** L(1)	**H(7)** -	**L(7)** -
	1.23	Fuel pellet cracking/relocation—normal operation	Impact on conductivity, stored energy	**H(4)** M(3)	**H(6)** M(1)	**L(6)** M(1)
	1.24	Fission gas release	Radiological and initial pressure	**H(7)** - -	**H(7)** - -	**M(5)** H(1) L(1)

Table 3-2 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 2, "Transient Power Distribution"

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
2. Transient power distribution	2.1	Moderator reactivity feedback	Impact on fission power	**L(7)**	**H(7)**	**L(7)**
	2.2	Fuel temperature reactivity feedback	Impact on fission power	**L(7)**	**H(7)**	**L(7)**
	2.3	Decay heat	Decay heat of actinides and FPs (deposited mainly in fuel) impacts temperature	**M(5)** H(1) L(1)	**H(7)** - -	**L(7)** - -
	2.4	Delayed neutron fraction	Impact on fission power	**L(7)**	**H(7)**	**L(7)**
	2.5	Energy deposition in fuel and outside	Impact on fuel thermal response	**L(6)** M(1)	**H(7)** -	**L(7)** -

Table 3-3 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 3, “Transient/Steady-State Heat Transfer from Cladding (Blowdown, Refill, Reflood, Core Spray)”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
3. Transient/steady-state heat transfer from cladding (blowdown, refill, reflood, core spray)	3.1	Single-phase convection	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.2	Boiling (subcooled, nucleate, bulk)	Impact on cladding temperature, mixture level	**L(7)**	**H(7)**	**L(7)**
	3.3	Liquid droplet entrainment	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.4a	Liquid droplet vaporization	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.4b	Critical heat flux	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.5	Film boiling (inverted annular, dispersed flow)	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.6	Fuel rewet	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.7a	Rod-grid interaction (thermal)	Limits ballooning, results in cooler spot	**H(5)**	**H(4)**	**L(4)**
				M(2)	M(3)	M(3)
	3.8	Spacer grid rewetting, droplet breakup	Impact on cladding temperature	**L(7)**	**H(7)**	**L(7)**
	3.9	Coplanar rod ballooning and packing fraction at more than one location impact on heat transfer	Rod failure of adjacent rods and coolability	**M(6)**	**M(6)**	**H(7)**
				H(1)	L(1)	-

Table 3-4 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 4, "Transient Core Coolant Conditions"

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
4. Transient core coolant conditions	4.1	Pressure	Contributes to differential pressure and cladding stresses	**M(5)**	**H(7)**	**L(7)**
				L(2)	-	-
	4.2	Temperature (fluid outside cladding)	Impact on coolability	**L(6)**	**H(7)**	**L(7)**
				M(1)	-	-
	4.3	Void fraction	Impact on core mixture level, fuel uncovery	**L(7)**	**H(7)**	**L(7)**
	4.4	Flow quality	Impact on coolability	**L(7)**	**H(7)**	**L(7)**
	4.5a	Mass flux, direction (CCFL)	Impact on coolability	**L(7)**	**H(7)**	**L(7)**
	4.5b	Coolant mass flux	Impact on coolability	**M(4)**	**H(7)**	**L(7)**
				L(3)	-	-
	4.5c	Coolant mass flux	Impact on particle mobility	**H(5)**	**L(7)**	**H(7)**
				M(2)	-	-
	4.6	Formation, transport, and deposition of coagulants in the core	Clogging of debris beds formed by dispersed fuel and/or containment debris	**H(4)**	**L(6)**	**H(6)**
				M(3)	M(1)	M(1)
	4.7	Boron precipitation from boiling in the core	Flow blockage	**L(7)**	**H(7)**	**L(7)**
	4.8a	Effects of flow blockage—inlet nozzle	Impact on core coolability	**L(6)**	**M(7)**	**M(7)**
				M(1)	-	-
	4.8b	Effects of flow blockage—grid spacers	Impact on core coolability	**H(4)**	**L(4)**	**H(4)**
				M(3)	M(3)	M(3)
	4.9	Coplanar rod ballooning	Impact on core coolability	**L(5)**	**H(7)**	**L(7)**
				M(2)	-	-

Table 3-5 High Burnup FFRD PIRT on Whole-Core Thermal DBAs (LOCAs) for Phenomena Category 5, “Fuel Rod Transient Response”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
5. Fuel rod transient response	5.1a	Clad plastic deformation (thinning, ballooning, burst)	ECR, cladding failure, fuel relocation	**H(7)**	**M(7)**	**M(6)** H(1)
	5.1b	Extent of axial ballooning	Impact on fuel relocation and extent of fuel fragmentation	**H(7)**	**M(7)**	**H(7)**
	5.1c	Rod-grid interaction (mechanical)	Mechanically impacts ballooning and amount of dispersal	**H(7)** - -	**M(6)** H(1) -	**H(3)** M(3) L(1)
	5.3	Clad differential pressure load	Rod failure and dispersal	**H(7)** -	**M(4)** H(3)	**M(5)** H(2)
	5.4	Clad loading during quench	Rod failure	**L(7)**	**H(7)**	**L(7)**
	5.5	Clad thermal deformation	Clad azimuthal thermal bending deformation	**L(6)** M(1)	**M(7)** -	**M(7)** -
	5.6	Clad elastic deformation	Contributes to rod dimensional changes	**L(7)**	**H(7)**	**L(7)**
	5.7	Pellet thermal deformation	Enhances fragmentation	**L(7)**	**H(7)**	**L(7)**
	5.8	Pellet swelling	No immediate correlation to FFRD	**L(7)**	**H(7)**	**L(7)**
	5.9	Transient fission gas release	Contributes to cladding rupture, dispersal, and radiological release	**H(6)** M(1)	**L(5)** M(2)	**H(6)** M(1)
	5.10	Fuel temperature distribution—pellet radial	Fuel fragmentation, transient fission gas release	**M(7)**	**H(7)**	**L(7)**
	5.11a	Clad temperature distribution—axial	Ballooning and burst location	**H(7)**	**H(7)**	**L(7)**
	5.11b	Clad temperature distribution—azimuthal	Ballooning and burst location	**L(7)**	**M(7)**	**M(7)**

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
	5.13	Clad thermal resistance—radial, axial	Cladding oxidation/hydriding	**L(7)**	**H(7)**	**L(7)**
	5.14	Clad oxide layer thermal resistance—radial	Transient oxidation/hydriding and ECR	**L(7)**	**H(7)**	**L(7)**
	5.15	Clad oxidation—inner, outer surface	Transient oxidation/hydriding and ECR	**L(6)** M(1)	**H(7)** -	**L(7)** -
	5.16	Metal-water oxidation heat release	Transient oxidation/hydriding and ECR	**L(7)**	**H(7)**	**L(7)**
	5.17	Fuel fragmentation mass during heatup	Mass source term for dispersal	**H(7)** -	**M(7)** -	**M(5)** H(2)
	5.18	Fragmented fuel size distribution	Radiological, coolability, and criticality	**M(5)** H(2)	**H(4)** M(3)	**M(4)** L(3)
	5.19	Fuel relocation and packing fraction in ballooning regions	Coolability	**H(5)** M(2)	**M(7)** -	**M(7)** -
	5.20a	Fuel relocation (in between grid spacers)	Limits dispersed mass	**H(7)**	**M(7)**	**M(7)**
	5.20b	Effect of grid spacer on relocation	Limits dispersed mass	**H(7)** -	**M(4)** H(3)	**M(4)** L(3)
	5.22	Cladding phase changes	Cladding ductility/burst	**L(6)** H(1)	**H(6)** M(1)	**L(6)** M(1)
	5.23	Fuel properties—thermal, mechanical	Fuel temperature response	**M(5)** L(2)	**H(7)** -	**L(6)** M(1)
	5.24a	Clad rupture—criteria	Rod failure and burst size	**H(6)** M(1)	**H(7)** -	**L(6)** M(1)
	5.24b	Clad rupture geometry (width, length, shape)	Rod failure, dispersal	**M(6)** H(1) -	**M(5)** L(1) H(1)	**H(7)** - -
	5.26	Gap transient behavior—size, heat resistance	Fuel/cladding temperature vs. time	**L(6)** M(1)	**M(4)** H(3)	**L(6)** M(1)
	5.27	Clad burst—size, shape, single, multiple	Dispersal mass	**H(5)** M(2) -	**M(6)** H(1) -	**H(3)** M(3) L(1)

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
	5.28a	Core axial location of burst	Dispersal (burnup axial distribution)	**M(7)**	**M(7)**	**M(7)**
	5.28b	Grid span axial location	Dispersal	**M(7)**	**M(7)**	**M(7)**
	5.28c	Burst azimuthal orientation	Dispersal	**M(4)**	**M(7)**	**H(5)**
				L(3)	-	M(2)
	5.29	Time of burst	Dispersal	**M(5)**	**H(6)**	**M(5)**
				L(2)	M(1)	H(1)
				-	-	L(1)
	5.30	Axial gas communication in the fuel rod	Rod ballooning, burst, and dispersal	**H(7)**	**M(6)**	**H(6)**
				-	L(1)	M(1)

Table 3-6 High Burnup FFRD Summary PIRT on Whole-Core Thermal Events for Phenomena Category 6, “Fuel Dispersal”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp.	SoK	U
6. Fuel dispersal	6.1	Rod internal pressure differential	Rod burst and dispersal	**M(6)**	**L(6)**	**H(6)**
				H(1)	M(1)	M(1)
	6.2a	Particle size-to-opening width ratio	Dispersal mass	**H(7)**	**L(4)**	**H(6)**
				-	M(3)	M(1)
	6.2b	Burst opening—size, shape	Dispersal mass	**H(7)**	**M(4)**	**M(4)**
				-	H(1)	H(3)
				-	L(2)	-
	6.3a	Rod opening axial location—single	Dispersal mass; axial location of dispersed mass	**L(5)**	**M(5)**	**M(6)**
				M(2)	H(2)	L(1)
	6.3b	Rod opening axial location—multiple	Dispersal mass; axial location of dispersed mass	**L(4)**	**M(3)**	**M(3)**
				M(3)	L(3)	L(2)
				-	H(1)	H(2)
	6.4	Surrounding coolant conditions—vapor, liquid	Transportability of dispersed mass	**M(4)**	**H(4)**	**M(5)**
				H(3)	M(3)	L(2)
	6.5	Effect of fragmented fuel size distribution and characteristics on dispersal	Coolability and criticality	**H(6)**	**M(5)**	**H(5)**
				M(1)	H(1)	M(2)
				-	L(1)	-

Table 3-7 High Burnup FFRD Summary PIRT on Whole-Core Thermal Events for Phenomena Category 7, “Multiple Rod Effects–Mechanical”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp.	SoK	U
7. Multiple rod effects—mechanical	7.1	Rod-to-rod interactions	Rod burst and coolability	**L(4)** M(3)	**M(6)** H(1)	**M(6)** L(1)
	7.2	Rod bowing between spacer grids	Rod burst and coolability	**L(5)** M(2)	**M(5)** H(2)	**M(6)** L(1)
	7.3	Surrounding rod impact on fuel dispersal	Rod burst propagation and dispersal consequences	M(6) L(1)	M(4) L(3)	H(4) M(3)
	7.4	Flow constraining/blockage from coplanar ballooning/burst of multiple rods and locations	Coolability	**L(4)** M(3)	**M(6)** H(1)	**M(6)** L(1)

Table 3-8 High Burnup FFRD Summary PIRT on Whole-Core Thermal Events for Phenomena Category 8, “Multiple Rod Effects–Thermal”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp.	SoK	U
8. Multiple rod effects—thermal	8.1	Heat transfer between rods and fuel debris bed	Cladding failure	**M(5)** H(1) L(1)	**L(5)** H(2) -	**H(4)** M(2) L(1)
	8.2	Heat transfer between bundle structure elements and fuel debris bed	Coolable geometry	**L(4)** M(3) -	**L(4)** H(2) M(1)	**M(5)** H(2) -
	8.3	Rod-to-channel box radiative heat transfer (BWR)	Clad temperature	**L(7)** -	**H(4)** M(3)	**L(4)** M(3)
	8.4	Rod-to-water rod radiative heat transfer (BWR)	Clad temperature	**L(7)** -	**M(3)** H(3) L(1)	**L(4)** M(3) -
	8.5	Rod-to-spacer grid local heat transfer	Clad temperature	**L(5)** H(1) M(1)	**H(4)** M(3) -	**L(4)** M(3) -

Table 3-9 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 9, “Dispersed Fuel Transport and Its Consequences”

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
9. Dispersed fuel transport and its consequences	9.1a	Fuel particle sedimentation and porous bed formations at spacer grids	Flow blockage, debris bed coolability	**M(4)** H(3)	**M(7)** -	**H(7)** -
	9.1b	Fuel particle sedimentation and porous bed formations at inlet nozzle grids	Flow blockage, debris bed coolability	**L(7)**	**M(7)**	**H(7)**
	9.2	Fuel particle sedimentation in lower plenum	Impact on distribution of dispersed fuel	**L(4)** M(3)	**M(5)** H(2)	**M(5)** H(2)
	9.3	Fuel particle fluidization in porous beds residing within the core	Coolability of debris beds (CHF)	**L(7)**	**M(7)**	**H(7)**
	9.4	Fuel particle entrainment and transport by coolant flow in the RCS	Dispersed fuel distribution	**L(7)** -	**M(5)** H(2)	**M(5)** H(2)
	9.5	Fuel particle ejection into the containment by break flow (LOCA)	Radioactive release	**L(7)**	**M(7)**	**L(7)**
	9.6	Fuel particle sedimentation/trapping in upper plenum and other RCS locations	Dispersed fuel distribution, coolability	**L(7)** -	**L(6)** M(1)	**M(7)** -
	9.7	Fuel particle trapping/filtration at fibrous beds in the core	Coolability	**L(7)**	**L(7)**	**M(7)**
	9.8	Fuel particle sedimentation/trapping at various locations in the containment	Radioactive release, coolability	**L(7)**	**L(7)**	**M(7)**
	9.9	Fuel particle filtration by fibrous beds on containment sump strainer surfaces	Coolability	**L(7)** -	**M(5)** H(2)	**M(5)** L(2)
	9.10	Suspension of fine fuel particles in coolant fluid resulting in coolant-particle mixtures	Impact on temperature, recriticality	**L(7)**	**H(7)**	**L(7)**
	9.11	Heat transfer from porous fuel debris beds to coolant	Coolability	**M(6)** L(1)	**M(6)** L(1)	**L(6)** M(1)
	9.12	Heat transfer from porous fuel debris beds to protruding fuel rods and structural elements	Structural integrity	**L(6)** M(1)	**M(6)** L(1)	**L(6)** M(1)

Phenomena				Rankings		
				FOM-1 (Coolability)		
Cat.	No.	Phenomena Description	Relevance	Imp	SoK	U
	9.13	Heat transfer from fuel debris beds to supporting structures (e.g., spacer grids, other RCS structures, sump strainer)	Coolability, structural integrity	**L(7)**	**M(7)**	**L(7)**
	9.14	Flow blockage by porous fuel debris beds in the core	Core coolability	**L(6)** M(1)	**H(4)** M(3)	**M(7)**
	9.15	Porous fuel debris bed clogging by chemical precipitants and/or containment debris (particulates, fiber)	Bed coolability	**L(7)**	**M(5)** L(2)	**M(5)** H(2)
	9.16	Heat transfer from debris beds with clogged pores to coolant, fuel rods, and other structures	Structural integrity	**L(7)**	**M(7)**	**M(7)**
	9.17	Flow blockage by clogged fuel debris beds in the core	Impact on core coolability	**L(5)** M(2)	**M(7)** -	**M(7)** -
	9.18	Recriticality of core containing EE fuel	Recriticality: **FOM-2**	**L(6)** M(1)	**H(6)** M(1)	**L(6)** M(1)
	9.19	Recriticality of coolant-fuel homogeneous mixtures	Recriticality: **FOM-2**	**L(7)**	**H(5)** M(2)	**L(6)** M(1)
	9.20	Impact on reactor core coolable geometry	Coolability	**M(4)** L(3)	**M(7)** -	**M(7)** -
	9.21	Radioactivity release fraction due to fragment-coolant interaction (chemical reactions, dissolution)	Radiological release: **FOM-3**	**L(5)** M(2)	**H(5)** M(2)	**M(7)** -
	9.22	Radioactivity release fraction due to fragment propagation into the containment	Radiological release	-	-	-

3.1.2 Summary of Panel Discussions

This section summarizes key insights from the LOCA PIRT elicitation discussions that took place during the in-person FFRD PIRT Panel meeting in Rockville, Maryland, on December 4-7, 2023, as well as during the follow-up virtual Panel meeting on January 19, 2024. These insights summarize the panelists' views and perspectives on the impacts of FFRD and related consequences on whole-core thermal DBAs (LOCAs) in operating PWRs and BWRs from the potential use of EE/HBU fuel above the currently licensed limits. Given the significant number of items included in the developed FFRD LOCA PIRT documented in Table 3-1 through

Table 3-9 in the previous section and in tables B-1 through B-9 in APPENDIX B to this report, the discussion below focuses on items that were ranked predominantly as “H” for importance, “L” for state of knowledge, and “H” for uncertainty. In addition, it includes newly recognized; unexpected; or, to a certain degree, counterintuitive phenomena.

Elaborating on the phenomena in Category 1, “Fuel Initial Conditions,” documented in Table 3-1, the FFRD PIRT Panel unanimously recognized the importance of item 1.8a by providing 7 “H” votes for importance, 7 “L” votes for state of knowledge, and 7 “H” votes for uncertainty. Item 1.8a relates to the effect of fuel assembly spacer grids with relevance to locations where debris and fuel dispersal can be trapped and, ultimately, impact coolability (FOM-1). The following text summarizes the noteworthy phenomenological insights shared by the FFRD PIRT Panel during the discussion on item 1.8a.

The Panel deliberated on the impact fuel assembly designs, specifically spacer grids and inlet nozzles, have on trapping dispersed fuel. The discussion initially addressed whether specific design features would be more prone to trapping dispersed fuel than others. It was noted that inlet nozzle debris filters could be a source of additional concentration or collection of dispersed fuel. A panelist acknowledged that specific design features are proprietary, and the Panel should not focus on specific vendor designs.

A panelist indicated that, during a LOCA, the assembly refloods from the bottom. As it refloods, steam is generated in the fuel, which ends up cooling the upper portion of the fuel. While it is unknown if the assembly inlet can become completely clogged with dispersed fuel, it is expected that fluid will still fill that region of the rods above the filter location and cool the fuel in a PWR and that top cooling with core sprays in a BWR can help mitigate clogged inlet nozzles. From a coolable geometry perspective, the inlet nozzle is suggested to have low importance for both PWRs and BWRs, although for different reasons. But the spacer grid is a little different because it can collect, potentially on the underside, as particles flow up or as they drop down from the top. From a coolable geometry perspective, the spacer grid is suggested to have high importance.

After further discussion, it was agreed that the impact of assembly spacer grids (item 1.8a) and inlet nozzles (item 1.8b) should be evaluated separately. It was also suggested that pinning of the balloon is an important factor and should be evaluated separately. The Panel asked for additional clarification on whether the trapping nature, or the potential for the trapping behavior, was being evaluated. It was explained that the evaluation was related to the consequences of fuel dispersal following initial fuel ejection. The concern was that dispersed fuel could be trapped at certain locations within the core so that the formation of a debris bed of a certain thickness could become a challenge to coolability of the heat-generating debris bed and impacted rods. A related concern was that the initially porous bed could become impermeable during the long-term phase due to clogging by chemical precipitants carried in the recirculating coolant, thus impacting bed coolability. From an incremental perspective, the Panel deliberated whether the dispersal of HBU fuel resulting in the trapping of materials on spacer grids should remain a high-importance phenomenon for coolability during a LOCA. It was indicated that relocation had been accounted for in prior LOCA analyses, whereas trapping of particulates from fuel dispersal had not. The Panel noted that, in the realm of Generic Safety Issue (GSI)-191, extensive research and experiments have been done to study the formation of beds consisting of fibrous containment debris, latent containment debris, and chemical precipitants. With fibrous debris being highly susceptible to trapping, the debris bed formation phenomenon could occur during the coolant recirculation phase of long-term cooling, which had not been part of the evaluation considered under GSI-191. The panelists generally agreed that the state of knowledge is low and the uncertainty is high, especially considering the information in the public domain. This appeared to be a consensus throughout. Furthermore, the low state of knowledge and high degree of uncertainty would suggest that a high importance ranking was conservative, at least until proven otherwise.

The panelists discussed a thought exercise that considered a scenario without spacer grids. The addition of any grid spacer would create a nonrecoverable loss and a flow restriction within the fuel bundle, thus inherently creating a location for potential restitution of fuel debris. If the spacer grids were not there, then debris would ultimately fall to the bottom or be swept upwards and would not conglomerate at some axial location. One panelist offered an opinion regarding possible parameters of primary importance when considering uncertainties related to grid clogging. In this regard, the panelist identified these parameters as those that would determine whether particles would fall down or get trapped, such as particle size (large or small) and the amount of particles (small or large). From experimental observations, most of the fragmented fuel particles were large (more than 4 millimeters in size), and most of them would have no chance of escaping the fuel rods or the local grid span if dispersed. Additionally, the quantity of smaller particles was much less and accounted for only a few percent of the fuel mass at most "(at least up to a pellet-average burnup of about 75 GWd/MTU)." These smaller particles would probably not be enough to clog the spacer grids and would either fall through the grid or be carried away by the coolant flow. The panelists noted that the evaluations were focused on fuel trapping considerations and not on specific grid designs. The Panel ultimately concluded that the impact of the fuel assembly spacer grid on coolability was of high importance, a low state of knowledge, and high uncertainty.

Elaborating on the phenomena in Category 4, "Transient Core Coolant Conditions," documented in Table 3-4, the FFRD PIRT Panel discussions on items 4.5c, 4.6, and 4.8b resulted in most of the rankings being "H" for importance," L" for state of knowledge," and "H" for uncertainty. The following text summarizes the noteworthy phenomenological insights shared by the Panel during the discussions of these three items.

During the its discussion on item 4.5c on coolant mass flux, the FFRD Panel recognized almost unanimously the item's significance by providing 5 "H" votes for importance, 7 "L" votes for state of knowledge, and 7 "H" votes for uncertainty. Item 4.5c relates to the effect of the coolant mass flux on particle mobility and, ultimately, coolability (FOM-1). One panelist noted that the mass flux of the coolant during the transient would have the most significant impact on dispersal and transport of particles within the core region and the RCS. Another panelist noted that, aside from fuel transport by the coolant, many models had been built within the current thermal-hydraulic codes featuring validation support with respect to mass flux under different conditions. If one would take the perspective of the coolant solely, the models were accurate and the uncertainty low. However, concerning transport of particles, the uncertainty would be high because of the lack of data representative of the influence of mass flux on the transport of particles throughout the core region and the RCS. The Panel's general consensus was that the impact on particle mobility was of high importance, low state of knowledge, and high uncertainty. One panelist ranked the importance "M," based on the understanding that, with regard to particle mobility, parameters related to particle size, shape, and characteristics were more important than coolant mass flux.

An inquiry was posed to the NRC staff regarding the perspective on mass flux as it related to the relocation of particles. The response was that the behavior of the dispersed fuel following its ejection out of the rods was not analyzed in the most recent NRC paper presented at the 20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-20) [6].

The staff also explained that, in prior studies around 2015, the NRC performed some simple calculations to analyze whether a particle would go up or drift downwards based on calculated mass flux or velocity using the TRAC/RELAP Advanced Computational Engine (TRACE) code [7]. The results showed that some of the particles would be transported out of the core, depending on the particle size distribution, exact time of burst, and many other parameters.

The Panel further discussed when the particles would be ejected from the rod, considering whether this would occur very quickly or if the particles would work their way out over a period of a few minutes. The understanding was that, once the differential pressure across the burst opening had been reduced to zero, no further dispersion of particles would take place. The reason why such considerations could be important was that the mass flux changes as a function of time during the LOCA scenario. If the time frame of interest was about 10 seconds after the burst, the fluid conditions would be better known; however, with the accident progression in time, it could become more difficult to understand the impact of the mass flux. A panelist indicated that there were simply not enough data to answer such questions and, therefore, the uncertainty was ranked high.

Another panelist elaborated on ongoing academic studies and on why the state of knowledge was considered low. The imposed rod internal pressure was a perceived boundary condition representing a best guess based on nominal failure pressure ranges that could not be representative of actual conditions. The panelist believed that the bulk quantity of fuel material would be ejected by the initial blowdown and, depending upon the mass flux of the gas carrier, particles could be entrained from within the rodlet during a period of time with the possibility of some particles getting stuck or bridged at the burst opening, thus preventing additional dispersal through the rupture opening. Accordingly, the panelist was certain that the related level of knowledge was low.

During its discussion on item 4.6, the FFRD PIRT Panel recognized almost unanimously the importance of this item by providing 4 “H” votes for importance, 6 “L” votes for state of knowledge, and 6 “H” votes for uncertainty. Item 4.6 relates to the formation, transport, and deposition of coagulants in the core and the relevance on clogging of debris beds formed by dispersed fuel or containment debris, or both, and ultimately on coolability (FOM-1). It was explained that the fuel bed conglomerate would initially be porous, thus allowing for coolability up to a certain thickness of the fuel debris bed. The concern was that bed coolability could be lost due to coagulants that could clog the porosity and change the heat extraction mechanism from the heat-generating conglomerate of fuel particles. In this regard, the coagulants were not considered from the viewpoint of possible core flow blockage as part of downstream effects of GSI-191 debris, or containment debris, that would create a different type of phenomena. Rather, the evaluation for HBU FFRD and its consequences was focused on the coolability of agglomerations of dispersed fuel particles forming fuel debris beds in the core that could become impervious due to clogging by chemical precipitants carried in the recirculating coolant.

In response to a panelist suggesting that two items require further defining, the burnup being considered and the amount of fuel mass dispersed, the NRC staff indicated that the burnup would probably be on the order of 75–80 GWd/MTU rod average. Given these burnup levels, a panelist ranked item 4.6 as being medium for importance, state of knowledge, and coolability. Another panelist pointed out the significant body of work on core flow blockage by containment debris and related consequences as part of GSI-191, providing useful information on the state of knowledge relative to the considered HBU FFRD phenomenon. Regarding flow downstream effects by the fuel debris bed, the conditions above the blockage would not be different from what was considered in GSI-191, with related information showing that, above an area of blockage, the fuel rods would be cooled. In the panelist's opinion, what was unknown concerned the possibility of dispersed fuel material being in contact with rods impacted by the fuel bed and whether these rods would remain coolable in that region. This phenomenological condition was deemed a little different from the GSI-191 situation. Ultimately, the panelist ranked the phenomena as high importance, low state of knowledge, and high uncertainty. From the viewpoint of the item's incremental aspect, another panelist ranked its importance medium, state of knowledge low, and uncertainty high. The general consensus by the FFRD PIRT Panel on coolability for item 4.6 was high (4 votes) to medium (3 votes) for importance, low state of knowledge, and high uncertainty.

During the discussion on item 4.8b, the FFRD Panel recognized the importance of this item by providing 4 "H" votes for importance, 4 "L" votes for state of knowledge, and 4 "H" votes for uncertainty. Item 4.8b relates to the effects of spacer grid flow blockage and the impact on core coolability (FOM-1). The Panel deliberated on the effects of flow blockage from inlet nozzles, grid spacers, and coplanar rod ballooning, and the resulting impact on core coolability. The following captures Panel discussions that ultimately ranked the flow blockage effects related to the inlet nozzle (item 4.8a) and coplanar ballooning (item 4.9) as less important than the flow blockage effects by grid spacers (item 4.8b). The elaboration bore similarities to the Panel discussion on item 1.8, which evaluated the impact of fuel assembly spacer grids (item 1.8a) and inlet nozzle designs (item 1.8b) on trapping dispersed fuel and impacting core coolability. As an introduction, the Panel was asked about the effects of flow blockage at various locations by dispersed fuel, formation of the burst cladding, and multiple coplanar burst occurrences such that the resulting flow blockage would become of concern with regard to cooling the core structure. The Panel generally thought this topic was deliberated previously, with the exception of coplanar rod ballooning. A panelist indicated that rod ballooning was not considered to be a concern and had been demonstrated, as part of fuel licensing, to not impact core coolability. Accordingly, rod ballooning was considered to have a low importance, high state of knowledge, and low uncertainty impact on core coolability. It was further emphasized that this evaluation should focus on the posttransient period and not steady state (i.e., item 1.8 in Table 3-1). A panelist noted that work done by the PWR Owners Group and the BWR Owners Group showed that, even with blockage during the transient, the effect on a LOCA was negligible.

The Panel was asked if ballooning and burst could become more pronounced for HBU fuel assemblies. A panelist referenced NUREG-0630, "Cladding Swelling and Rupture Models for LOCA Analysis," issued April 1980 [8], which indicated that, as the rupture temperature decreased, which was aligned with higher rod internal pressure, the balloon size actually became smaller. Furthermore, NUREG-0630 looked at coplanar blockages, and the panelist recalled that the conclusion was that even maximum flow blockages did not prevent cooling. Thus, considering possibly lower balloons at higher pressures consistent with higher burnup conditions, along with the results from historical documentation on coplanar ballooning, the fuel behavior would be improved for HBU fuel.

Another panelist indicated that modeling showed that the flow, for example in a PWR with an open lattice core, would go around the blockage and thus maintain coolability. Thus, this phenomenon had been covered previously, except that the fuel packing fraction in the balloon region was not included. When looking at coplanar rod ballooning only, it had been shown that there would be no coolability issue, based on past experimental results and analysis. It would become more complicated when considering the fuel packing fraction in the rod balloon region. This would complicate considerations quite a bit because the packing fraction would be a source of high uncertainty.

The panelists proposed that the effects of flow blockage by the inlet nozzle and grid spacers be separated from coplanar rod ballooning (item 4.9). The general consensus by the panelists on flow blockage effects by coplanar rod ballooning was that it was of low importance, high state of knowledge, and low uncertainty. It was also proposed that the effects of flow blockage related to the inlet nozzle (item 4.8a) and grid spacer (item 4.8b) be evaluated separately, due to the inlet nozzle being at the bottom of the core and the rupture location typically assumed to be above the midplane of the core. It was expected that large particles would be trapped in the fuel segment within the grid span where the rupture occurred. Accordingly, the concern was the fine particulates being, or probably being, mobile beyond the grid spacers. Regarding the effect of flow blockage at the spacer grid, the general consensus was split between high importance, low state of knowledge, and high uncertainty versus medium importance, medium state of knowledge, and medium uncertainty. It was argued that the grid spacer had a higher probability of trapping dispersed material that could block flow in this localized region than other areas in the core. The FFRD PIRT Panel also considered the rankings to be consistent with the evaluation of item 4.6.

Elaborating on the phenomena in Category 5, “Fuel Rod Transient Response,” documented in Table 3-5, the FFRD PIRT Panel recognized almost unanimously the importance of item 5.9 by providing 6 “H” votes for importance, 5 “L” votes for state of knowledge, and 6 “H” votes for uncertainty. Item 5.9 relates to the effect of transient fission gas release and its contribution to cladding rupture and dispersal and, eventually, to radiological release. The item was evaluated as FOM-1 on coolability. The following text discusses the noteworthy phenomenological insights shared by the Panel.

When questioned whether the phenomenon was related to fuel fragmentation, a panelist providing the following clarification. Mentioning that there was not enough certainty in terms of knowledge, it was explained that microscopy observations had revealed microstructural changes in observed dark zone regions and in regions where fuel pulverized, as in the rim, specifically associated with increased porosity shown to be caused by fission gas bubbles. The prevailing theory was fission gas bubble overpressurization was driving microcracking and, as the microcracking continued, it evolved into full-blown pulverization of these localized regions, although this was only a prevailing theory and not a consensus among all experts in the industry. The gas pressure in a single bubble in the bulk material could be on the order of gigapascals and well over the fracture stress of UO_2. However, the enormous mass amount of bulk material surrounding the bubble would prevent fracturing. As the temperature of that bubble would increase with the gas volume unaffected, the only way for the gas to expand would be by physically cracking the material. A single crack could affect a neighboring bubble, propagating the crack further and causing a domino effect. Since the microstructure is changing for HBU fuel, the impact of transient fission gas would be at least important for understanding the fracture fuel mechanism. With increasing burnup, which would also depend somewhat on prior power history, the density of the bubbles would increase, becoming an important contributor when transitioning to higher burnups.

Another panelist pointed to the possibility of using sensitivity studies with some gross conservative assumptions regarding fission gas release (FGR) timing, rate, and amount that could perhaps avoid the need to perform detailed transient fission gas release (TFGR) analyses. Given the uncertainties were so high and with a lack of data, one would need to bound this analysis in terms of fragmentation and FGR. The panelist generally agreed that the TFGR phenomenon was of high importance, low state of knowledge, and high uncertainty, while suggesting that relying on bounding sensitivity studies could avoid excessive experimental testing.

A slightly different opinion focused on the temperature also being a factor affecting TFGR. It was pointed out that, as the temperature distribution inside the cladding would flatten, the rim region temperature would increase but not to the temperatures at which the data indicated substantial TFGR. Accordingly, the contribution from TFGR to the rod pressure was viewed by the panelist as relatively small, ranking its importance as medium, state of knowledge low, and uncertainty high.

Another panelist referred to extensive work dating back to the 2000s that started in Japan. The major concern was that the immense amount of fission gas stored in the rim region could have an enormous impact on the FGR. The panelist suggested that a large fraction of the fission gas would be expected to come from the periphery of the fuel where most of the gas would be stored. While the temperature in the fuel center region would generally decrease during the transient, the rim temperature would be expected to increase and would do so rather quickly. Accordingly, by doing an exhaustive sensitivity study to show how rate, amount, and timing of the TFGR would impact clad burst behavior, it would be possible to develop a bounding threshold to ensure acceptable outcomes as long as conditions remained beneath the threshold.

A panelist presented two figures indicating that FGR was a significant contributor during a LOCA. One figure was related to test measurements using a segment with a small plenum (1.5 cubic centimeters (cm^3)) that represented a rod section between two adjacent spacers that did not have access to the rod plenum, so that the released gas was confined to that segment. The onset of FGR was reflected by a change in the linear trend of the rod pressure development to a parabolic trend occurring at approximately 430 degrees Celsius (°C). As thermal diffusion would require much higher temperatures on the order of close to about 1,000°C, the observed results were caused by a different effect that could possibly be attributed to the release of fission gas stored in the rim, and maybe some other parts of the fuel, given that the rim is the part subjected to temperature changes not experienced before, has significant fission gas accumulation, and undergoes disintegration. The second figure showed similar results for a segment with a plenum 10 times as large (16 cm^3), in which case, the pressure increase exhibited a lower gradient. Although the amount of FGR would be close in both cases, its fraction compared to what was already present in the rod was much smaller, thus leading to a smaller contribution in the second experiment. In the panelist's view, as long as HBU fuel reached such temperatures with the axial gas flow restricted, there would be enough driving force from local FGR to the gap leading to ballooning. Based on the above understanding, the panelist ranked importance high, state of knowledge medium, and uncertainty medium, while mentioning the existence of models attempting to simulate these processes. The overall consensus from the Panel was high importance, low state of knowledge, and high uncertainty for TFGR and its contribution to cladding rupture, dispersal, and radiological release.

Elaborating on the phenomena in Category 6, "Fuel Dispersal," documented in Table 3-6, the FFRD PIRT Panel discussions on items 6.2a and 6.5 each resulted in majority rankings of "H" for importance, "L" and "M" votes for state of knowledge, and "H" votes for uncertainty. The following text summarizes the noteworthy phenomenological insights shared by the Panel during the discussions of these two items.

The FFRD Panel recognized the importance of item 6.2a almost unanimously by providing 7 "H" votes for importance, 4 "L" votes for state of knowledge, and 6 "H" votes for uncertainty. Item 6.2a relates to the ratio of particle size to opening width and relevance to dispersal mass and ultimately coolability (FOM-1). The phenomenon was originally titled "burst opening (size, shape, location)" as it related to dispersal mass. The Panel proposed reformulating the phenomenon description and removing the location from the description, as the burst location had already been discussed. A panelist mentioned observable differences in burst shape and the vertical and lateral dimensions, specifically. It was explained that it was possible to perform experiments with a very large cross-sectional area and a narrow shape of the burst opening that would produce no dispersal. At the same time, an opening of a smaller area size with a nominally circular shape could disperse quite a bit of fuel surrogate mass. The panelist noted possible variations in the opening shape being represented by a slit, a cat eye, a diamond, or a fishbone, all associated with key geometric parameters describing the shape. Based on the experiments performed at Oregon State University (OSU) [9], this factor was found to be the most influential parameter impacting the quantity of dispersed material. In this regard, the two confounding factors were the ratio of nominal dimensions (particle size to opening width) and then the opening geometry in and of itself. Experiments at OSU that tested three different opening shapes (a circle, an oval, and a diamond), all having the same minimum cord length and using the same surrogate particle sizes, dispersed very different quantities.

In response to proposing a bounding analysis to capture the high uncertainty in predicting the fuel dispersal amount, the panelist noted that, while it could be possible to get to a point where the length and width of the rupture opening could be determined with some certainty, the opening shape remained a major unknown. It was therefore recommended to separate the initially combined item 6.2 into two separate items, one related to the ratio of particle size to breach opening size (item 6.2a), and the other related to the burst opening size and shape (item 6.2b). The general consensus for the particle size-to-opening width ratio (item 6.2a) regarding dispersal mass was high importance, low to medium state of knowledge, and high uncertainty. A panelist noted that there was more uncertainty related to item 6.2a than to item 6.2b. The general consensus for burst opening size and shape (item 6.2b) regarding dispersal mass was high importance, medium to high state of knowledge, and medium to high uncertainty. A panelist indicated that, while there was an important body of information on burst opening, there was a significant degree of scatter observed in the burst opening size and shape; hence, the high uncertainty ranking.

Elaborating on the phenomena in Category 6, “Fuel Dispersal,” documented in Table 3-6, the FFRD Panel recognized almost unanimously the high importance of item 6.5 on the effects of fragmented HBU fuel size distribution and other relevant characteristics. In ranking item 6.5 relative to FOM-1, “Coolability,” the Panel provided 6 “H” votes for importance, 5 “M” votes for state of knowledge,” and 5 “H” votes for uncertainty. It was emphasized during the Panel deliberation that the appearance of small fragments and their quantity depended on fuel burnup and were the factors that one would need to worry most about in terms of related consequences. At the same time, it was noted that large fuel pieces, already existing from base irradiation, were of no concern. As fine fuel fragments would first develop in the pellet rim region, they would exist only if a rim region were to develop as observed under high-enough burnup levels in the Halden tests, which have shown that, for pellet burnup below 75 megawatt-days per kilogram of uranium (MWd/kgU), the fine fragments come from the rim and, for pellet burnup above 80 MWd/kgU, central parts of the fuel can disintegrate into fine fragments as well, although not as fine as most of the rim fragments. The Panel pointed out key experimental observations from fuel testing under LOCA-related conditions that revealed that most of the fuel retained in the rods following cladding burst was in the form of large pieces that accounted for approximately 95 percent of the total fuel mass. The remaining few percent of the fuel mass accounted for mostly small fuel fragments lost during the burst. Although large variations in the amount of these small fragments were observed in the experiments, the dispersed mass fraction had always been below a few percent and appeared dependent on the burst opening size, among other factors. While a clear correlation with burnup had been observed for the dispersed mass of such small fragments, the related overall state of knowledge was evaluated as “M” (5 votes) and the level of uncertainty was evaluated as “H” (5 votes). The Panel also recognized that the fuel fragment size distribution was an important parameter playing a role in other FFRD phenomena considered in the FFRD LOCA PIRT.

Discussing the phenomena in Category 8, “Multiple Rod Effects—Thermal,” documented in Table 3-8, the FFRD PIRT Panel elaborations on item 8.1 and item 8.5 resulted in each item receiving 1 “H” vote in terms of importance. The following text summarizes the noteworthy phenomenological insights shared by the Panel during the discussions of these two items.

During the discussion of item 8.1 related to heat transfer between rods and a fuel debris bed, one panelist described the formation of a fuel debris bed within the core region as representing the most limiting condition with regard to coolability concerns and the need to maintain adequate structural integrity and coolable geometry. The panelist recognized that processes triggered by such debris beds could result in cladding failures, melting of the fuel, and possibly loss of coolable geometry. Accordingly, the panelist suggested that it would be more appropriate to change the item’s relevance description in Table 3-8 from “Cladding failure” to “Coolable geometry.” The panelist further explained that his major concern was related to whether the fuel rods adjacent to and impacted by the fuel debris bed would maintain their coolability, noting that the debris bed would transfer heat to the affected fuel rods. In the panelist’s opinion, the thermal behavior of such a rather localized region within the core could result in the region getting as hot as, or hotter than, other regions, even within the same affected bundle. The panelist viewed this phenomenological condition as being directly related to the central question of defining adequately the meaning of coolable geometry when considering such possible HBU FFRD consequences. With respect to state of knowledge and uncertainty, the Panel considered the large possible variabilities related to important contributing parameters, such as mass of collected dispersed fuel, size of the fuel particles, thickness of the debris bed, possible geometry of the fuel bed, and decay heat generation rate, in ranking item 8.1 as predominantly “L” with 5 votes for state of knowledge and predominantly “H” with 4 votes for uncertainty.

During the discussion of item 8.1, another panelist shared the opinion that most of the fragments that would be dispersed by failed fuel rods would be very tiny in size. Such fragments would come from the rim and would not need large burst openings to escape from the failed rods. These fragments would not represent a large amount and, because of their small size, would probably either be carried away upwards and out of the core or fall through the grids and possibly accumulate at the bottom of the fuel assembly, depending on the flow conditions in the core. If larger fuel fragments were to be dispersed, they would result from large burst openings. In the panelist’s opinion, the number of such rod failures was not expected to be significant, which would again limit the mass of large, dispersed fuel fragments. If these larger fragments were to form a debris bed, it would not be very compact and thus would have large porosity. For the outlined reasons, the panelist believed that, if a fuel debris bed were to form, it would be very thin and cooled by the surrounding liquid. Accordingly, the panelist suggested that it was more appropriate to talk about debris bed thinness, rather than debris bed thickness if the bed were to exist altogether, in case some small quantity of larger fragments accumulated on a spacer grid. While recognizing that, due to the decay heat, there could be some higher temperatures, the panelist considered it unlikely that this would endanger the cladding of the impacted rods or result in high temperatures of 1,200 degrees or so, causing fuel volatility. Overall, the FFRD Panel recognized the importance of item 8.1 as being predominantly medium by providing 5 “M” votes for its importance relative to FOM-1, “Coolability.”

During the discussion of item 8.5 concerning rod-to-spacer grid local heat transfer, as well as other recognized effects attributed to spacer grids, one panelist highlighted pertinent observations from a test in the Halden IFA-650 test series involving BWR fuel rods. Whereas all remaining BWR test specimens were cut between two adjacent grid spacers, the specimen in the IFA-650.14 test was a rod segment within the span of which a spacer grid was located during the rod irradiation and later removed when preparing the specimen. While areas adjacent to the spacer position experienced ballooning, the location where the spacer was positioned during the rod irradiation did not balloon during the test. The panelist described this observed clad ballooning behavior as completely unexpected. It was attributed to spacer-related effects that possibly impacted the local clad material properties during the normal fuel irradiation and later manifested themselves during the test when the spacer was not present. Although described as not entirely understood by the panelist, the mechanisms believed to cause the observed cladding behavior were attributed to heat transfer enhancement by the spacer, thus lowering local cladding temperatures and clad corrosion rates, as well as to local reduction in the neutron flux due to spacer absorption that would reduce cladding fluence exposure and local burnup.

Furthermore, in the panelist's opinion, this observed phenomenon could also cause a restriction of axial gas communication that could be beneficial for limiting clad ballooning. The observed spacer effect resulting in reduced clad propensity for ballooning within the vicinity of or under the spacer grid, thus possibly causing the axial restriction of fission gas communication, was also hypothesized by the panelist as possibly playing an important role for other phenomena, including multiple balloons and bursts. Under such conditions, ballooning within a segment between adjacent spacer grids would be driven by the fission gases residing in this segment without a contribution from fission gases accumulated elsewhere in the fuel rod, including the plenum and gap regions. Such an effect, if taking place at the bottom and top spacer grid locations, could also isolate significant fractions of the fission gases trapped within these two end regions of the rod where burnup would be axially decreasing. This phenomenon would reduce the likelihood of clad ballooning and bursting elsewhere in the rod where burnup could be higher. The panelist also argued that the described clad behavior and spacer-grid effects were indicative of the fact that increased burnup would make a difference with regard to clad ballooning and burst, thus underscoring the importance of considering HBU FFRD and its consequences. Based on the above-described experimental observations and understanding, the panelist ranked item 8.5 as being "H" for importance. At the same time, the prevalent opinion shared by the Panel members and reflected by 5 "L" votes for importance, was that the spacer grid would not affect the peak cladding temperature that was expected to occur at approximately the midspan location between adjacent spacers, thus rendering this location as most vulnerable to heatup and eventually to clad ballooning and burst.

3.1.3 Key LOCA PIRT Panel Considerations

(1) During its deliberations on item 1.8a, "Effect of fuel assembly spacer grids and relevance to locations where debris and fuel dispersal can be trapped," the FFRD Panel indicated that inlet nozzles are expected to have low importance while spacer grids are expected to have high importance with regard to trapping dispersed fuel and maintaining core coolability. The Panel noted that, during a LOCA, the assembly refloods from the bottom. As it refloods, steam is generated in the fuel and ends up cooling the upper portion of the fuel. While it is unknown whether the assembly inlet can become completely clogged with dispersed fuel, it is expected that fluid will fill the region of the rods above the filter location and cool the fuel.

(2) During its deliberations on item 4.8b, “Effect of spacer grid flow blockage and the impact on core coolability,” the FFRD Panel discussed the effects of flow blockage from inlet nozzles, grid spacers, and coplanar rod ballooning, and the resulting impact on core coolability. It was expected that large particles would be trapped in the fuel segment within the grid span where the rupture occurred. Accordingly, the concern was the fine particulates being, or probably being, mobile beyond the grid spacers. Regarding the effect of flow blockage at the spacer grid, the general consensus was split between high importance, low state of knowledge, and high uncertainty versus medium importance, medium state of knowledge, and medium uncertainty. It was argued that the grid spacer had a higher probability of trapping dispersed material that could block flow in this localized region than other areas in the core.

(3) During its discussion on item 4.5c, “Effect of the coolant mass flux on particle mobility, and ultimately coolability,” the FFRD Panel noted that the mass flux of the coolant during the transient was considered the most significant impact of dispersal and transport of particles within the core region and the RCS. It was further noted that, aside from fuel transport by the coolant, there were many models that had been built within the current thermal-hydraulic codes featuring validation support with respect to mass flux under different conditions. If one would take the perspective of the coolant solely, the models were accurate and the uncertainty low. However, concerning transport of particles, the uncertainty would be high because of the lack of data representative of the influence of mass flux on the transport of particles throughout the core region and the RCS. The Panel’s general consensus was that the impact on particle mobility was of high importance, low state of knowledge, and high uncertainty.

(4) During its discussion on item 4.6, “The formation, transport, and deposition of coagulants in the core and the relevance on clogging of debris beds formed by dispersed fuel and/or containment debris,” the FFRD Panel noted that the significant body of work on core flow blockage by containment debris and related consequences as part of GSI-191 can provide useful information to the state of knowledge relative to the considered HBU FFRD phenomenon. Regarding flow downstream effects by the fuel debris bed, the conditions above the blockage would not be different from those considered in GSI-191, with related information showing that, above an area of blockage, the fuel rods would be cooled. In the panelist’s opinion, what was unknown concerned the possibility of dispersed fuel material being in contact with rods impacted by the fuel bed and whether these rods would remain coolable in that region, a phenomenological condition that was deemed different from the GSI-191 situation. The general consensus by the Panel on coolability for item 4.6 was high (4 votes) to medium (3 votes) for importance, low state of knowledge, and high uncertainty.

(5) During its discussion on item 5.9, “Effect of transient fission gas release and its contribution to cladding rupture and dispersal and, eventually, radiological release,” the FFRD Panel noted that TFGR was considered a significant contributor to cladding rupture, dispersal, and radiological release, based on extensive industry experiments and analysis. However, the Panel generally agreed there is a low to medium state of knowledge and high uncertainty. Accordingly, by doing an exhaustive sensitivity study to show how rate, amount, and timing of the TFGR would impact clad burst behavior, it would be possible to develop a bounding threshold to ensure acceptable outcomes, as long as conditions would remain beneath the threshold.

(6) During its discussion on item 6.2a, “Effect of particle size-to-opening width ratio and relevance to dispersal mass,” the FFRD Panel explained that it was possible to perform experiments with a very large cross-sectional area and a narrow shape of the burst opening that would produce no dispersal. At the same time, an opening of a smaller area size with a nominally circular shape could disperse quite a bit of fuel surrogate mass. In this regard, two confounding factors were identified—the ratio of nominal dimensions (particle size to opening width) and then the opening geometry in and of itself. Experiments at OSU that tested three different opening shapes (a circle, an oval, and a diamond), all with the same minimum cord length and using the same surrogate particle sizes, dispersed very different quantities. In response to proposing a bounding analysis to capture the high uncertainty in predicting the fuel dispersal amount, the panelist noted that, while it could be possible to determine the length and width of the rupture opening with some certainty, the opening shape remained a major unknown. The general consensus for the ratio of particle size to opening width regarding dispersal mass was high importance, low to medium state of knowledge, and high uncertainty.

(7) An unexpected new phenomenon regarding the cladding behavior, observed in the IFA-650.14 test, was recognized during the Panel deliberations on item 8.5, “Rod-to-spacer grid local heat transfer.” The identified test involved a segment cut from an irradiated BWR rod so that the specimen included a location where a spacer grid was positioned during the rod irradiation and later removed when preparing the specimen. While areas adjacent to the spacer location ballooned in the test, the region where the spacer was positioned during rod irradiation did not balloon. Although not entirely understood, the mechanisms believed to cause this cladding behavior were attributed to spacer heat transfer enhancement lowering local cladding temperatures and clad corrosion and to local neutron flux reduction due to spacer absorption reducing clad fluence exposure and local fuel burnup.

(8) The reduced clad propensity for ballooning within the vicinity of or under the spacer grid, observed in the IFA-650.14 test and possibly caused by the above-described spacer-related effects on cladding material properties and fuel burnup, was also identified as a possible mechanism for axial restriction of fission gas communication. In the presence of such a mechanism, ballooning within a segment between adjacent spacer grids would be driven by the fission gases residing in this segment without contribution from fission gases accumulated elsewhere in the fuel rod, including the plenum and gap regions. Such an effect could also play an important role for other phenomena, including multiple rod balloons and bursts. On the other hand, if such an effect is taking place at the bottom and top spacer grid locations, significant portions of the fuel could be isolated from the plenum due to restricted axial gas communication and, in this way, limit the ballooning propensity.

(9) Regarding item 6.5, “Effect of fragmented fuel size distribution and characteristics on dispersal,” the FFRD Panel emphasized that the appearance of small fragments and their quantity were the factors about which one would need to worry most when considering burnup effects on fuel behavior. Fine fuel fragments had been observed in the pellet rim present only under high-enough burnup levels. Key experimental observations under LOCA-related conditions had revealed that most of the fuel retained in the rods following cladding burst was in the form of large pieces accounting for approximately 95 percent of the fuel mass. The remaining few percent of the fuel was represented by mostly small fuel fragments lost during burst. Although large variations in

the mass of small fragments had been observed, the dispersed mass fraction had always been below a few percent and appeared dependent on the burst opening size.

(10) During its deliberations on item 8.1, “Heat transfer between rods and fuel debris bed,” a panelist described the possible formation of a debris bed containing dispersed HBU fuel particulates in the core as potentially representing the most limiting condition with regard to the need to maintain coolable geometry. Processes caused by such debris beds could possibly result in cladding failures, fuel melting, and eventually loss of coolable geometry. The major expressed concern was whether the fuel rods would maintain their coolability when heated externally by the bed. This condition was viewed as directly related to the central question of defining adequately the meaning of coolable geometry in consideration of such possible HBU FFRD effects.

3.2 PIRT on High Burnup FFRD and Its Consequences for Local Core Events

3.2.1 High Burnup FFRD PIRT for Local Core Events (RIAs)

The FFRD Panel developed its PIRT on HBU FFRD and its consequences for local core thermal events having in mind DBA scenarios typically viewed as being bounded by RIAs, such as those caused by a CREA in a PWR or a CRDA in a BWR. Accordingly, the expert elicitation process for this PIRT was focused on FFRD considerations related to RIAs in operating PWR and BWR systems.

A preliminary PIRT comprising phenomena, conditions, and parameters grouped in items, along with corresponding relevance descriptions with regard to FFRD, was developed and distributed to the Panel members on January 22, 2024, asking them to elaborate on the proposed phenomena and provide rankings on three characteristics defined as “Importance” (Imp.), “State of Knowledge” (SoK), and “Uncertainty” (U) for two FOMs defined as “Fuel Rod Failure” (FOM-1) and “Radiological Release” (FOM-3). The panelists provided their initial input independently from each other, which included FOM rankings and written discussion notes by panelists on ranked phenomena. An integral draft PIRT that included the initial input from all panelists was made available to the Panel members on February 1, 2024, to present them with the opportunity to affirm and, if deemed appropriate, modify their initial input based on the holistic PIRT outcome and the discussion notes. The affirmation process resulted in some panelists updating some of the initial rankings or providing additional rankings for an FOM that was not initially ranked. The Panel discussed the preliminary FFRD RIA PIRT in its virtual meetings held February 26–27, 2024. During the deliberations, specific preliminary rankings for certain individual phenomena included in the RIA PIRT were updated as a result of the collaborative exchange of opinions among panelists. The phenomena in the FFRD RIA PIRT were ranked with regard to FOM-1, “Fuel Rod Failure,” and FOM-3, “Radiological Release.”

The final rankings for each of the 14 phenomena included in the FFRD PIRT for Category 2 local core DBA events (RIAs) is provided in Table 3-10, which identifies the individual phenomena, their relevance to HBU FFRD and its consequences, and rankings for FOM-1 and FOM-3. The PIRT documents the previously described ranking scale based on three qualitative grades of “High” (H), “Medium” (M), and “Low” (L), as measures of significance in weighing the above-described three individual characteristics for each of the FOMs. Table C-1 in APPENDIX C to this report documents the complete FFRD RIA PIRT containing the full record of ranking votes provided by each member of the FFRD PIRT Panel.

Table 3-10 PIRT on High Burnup FFRD and Its Consequences for Local Core Events (RIAs)

Phenomena			Rankings					
No.	Phenomena Description	Relevance	FOM-1 (Fuel Rod Failure)			FOM-3 (Release)		
			Imp.	SoK	U	Imp.	SoK	U
1.1	Fuel cycle design, including HBU placement initial condition	Determines the number of fuel rods susceptible to RIA failure	**H (6)**	**H (6)**	**L (6)**	**M (5)**	**M (5)**	**M (5)**
			L (1)	M (1)	M (1)	H (3)	H (2)	L (2)
1.2	Core-wide pin-by-pin spatial power distribution initial condition	Determines maximum uncontrolled rod worth and the adjacent HBU fuel rods susceptible to failure	**H (5)**	**H (6)**	**L (6)**	**M (4)**	**M (4)**	**M (5)**
			L (2)	M (1)	M (1)	H (2)	H (3)	L (2)
			-	-	-	L (1)	-	-
1.3	Pellet radial power distribution initial condition	Determines fuel temperature profile and its impact on melting	**H (4)**	**M (4)**	**M (5)**	**M (4)**	**M (5)**	**M (4)**
			L (2)	H (3)	L (2)	L (2)	H (2)	L (2)
			M (1)	-	-	H (1)	-	H (1)
1.4	Pellet radial burnup distribution initial condition	High-temperature cladding failure mechanisms including FF	**H (4)**	**M (5)**	**M (6)**	**H (3)**	**M (7)**	**M (6)**
			L (2)	H (2)	L (1)	M (3)		H (1)
			M (1)	-	-	L (1)	-	-
1.5	Clad excess hydrogen initial condition	PCMI cladding failure as a function of enthalpy, including geometry for FFRD	**H (6)**	**H (4)**	**M (5)**	**M (6)**	**M (5)**	**M (5)**
			L(1)	M (3)	L (2)	L (1)	H (2)	L (2)
			-	-	-	-	-	-
1.6	Fuel pellet cracking/relocation initial condition	Impact on RIA enthalpy and fuel conductivity	**L(7)**	**H (7)**	**L (7)**	**L (7)**	**H (7)**	**L (7)**
1.7	Fuel temperature reactivity feedback	Impact on peak enthalpy (cal/g)	**L (4)**	**H (7)**	**L (7)**	**L (7)**	**H (5)**	**L (7)**
			M (3)	-	-		M (2)	-
			-	-	-	-	-	-
1.8	Delayed neutron fraction(2)	Impact on peak enthalpy (cal/g)	**L (6)**	**H (7)**	**L (7)**	**L (7)**	**H (5)**	**L (7)**
			M (1)	-	-	-	M (2)	-
1.9	Fissile material composition	Source term for radiological release	**L (6)**	**H (7)**	**L (7)**	**M (4)**	**H (6)**	**L (7)**
			M (1)	-	-	L (2)	M (1)	-
			-	-	-	H (1)	-	-
1.10	Fuel thermal properties	Transient peak fuel temperature and clad temperature gradient (heat flux)	**H (4)**	**H (7)**	**L (5)**	**L (7)**	**H (7)**	**L (7)**
			M (3)	-	M (2)	-	-	-

Phenomena			Rankings					
No.	Phenomena Description	Relevance	FOM-1 (Fuel Rod Failure)			FOM-3 (Release)		
			Imp.	SoK	U	Imp.	SoK	U
1.11	Single and two-phase heat transfer	Critical heat flux and peak cladding temperature; also, RCS system pressure	**M (5)**	**M (4)**	**M (4)**	**L (4)**	**H (4)**	**M (4)**
			L (2)	H (3)	L (3)	M (3)	M (3)	L (3)
			-	-	-	-	-	-
1.12	Transient clad differential pressure	High-temperature cladding failure threshold (brittle and ductile failure) as a function of peak enthalpy (cal/g)	**H (3)**	**H (4)**	**M (5)**	**L (5)**	**M (5)**	**M (4)**
			M (3)	M (3)	L (2)	M (2)	H (2)	L (2)
			L (1)	-	-	-	-	H (1)
1.13	Transient fission gas release	Impacts clad differential pressure and source term for radiological release	**H (4)**	**L (4)**	**H (5)**	**M (7)**	**M (6)**	**M (5)**
			M (2)	M (3)	M (1)		L (1)	H (1)
			L (1)	-	L (1)	-	-	L (1)
1.14	Fuel fragmentation release to coolant	Impacts coolability of fuel and source term	**M (5)**	**M (5)**	**H (4)**	**M (5)**	**L (4)**	**H (5)**
			H (2)	L (2)	M (3)	H (2)	M (3)	M (2)

3.2.2 Summary of Panel Discussions

This section summarizes key insights from the elicitation discussions on the FFRD RIA PIRT held during the virtual Panel meetings on February 26–27, 2024. The Panel discussed items 1.1 through 1.12 in Table 3-10 during the meeting on February 26, 2024, and the remaining items 1.13 and 1.14 during the meeting on February 27, 2024. The insights summarize the panelists’ views and perspectives on impacts of FFRD and related consequences associated with the potential use of EE and HBU fuel above the currently licensed limits during local core thermal DBA events (RIAs) in operating PWRs and BWRs. The discussion below focuses on items that the Panel ranked predominantly as “H” for importance.

Elaborating on the phenomena in Table 3-10, the FFRD PIRT Panel recognized almost unanimously the importance of item 1.1 related to the fuel cycle design, including the HBU placement initial condition relative to FOM-1, “Fuel Rod Failure.” The item received 6 “H” votes for importance, 6 “H” votes for state of knowledge, and 6 “L” votes for uncertainty for FOM-1. The prevalent high importance ranking attributed to this item reflected the view that the reuse of HBU fuel rods and bundles after two or even three cycles of operation in possible future core designs and loading patterns could involve placement of HBU fuel in very high-powered core regions accommodating once- and twice-burnt or even once-burnt and fresh fuel. Possible power uprates and extended 24-month core fuel cycles with HBU fuel were viewed as having a significant impact on equilibrium core cycle conditions and core design parameters, driving the values of various core characteristics requiring consideration in determining the worst RIA scenario. In this context, the Panel ultimately recognized the proximity of the HBU fuel to the ejected rod or dropped control element as the main factor driving the consequences from the considered RIAs. A panelist expressed the hypothesis that the presence of very fine fragments on the very edge of the pellet coming in contact with the cladding during fuel expansion, resulting in PCMI and eventual fuel failure, could actually spread out the stress, thus mitigating the severity of the PCMI impact in such a scenario. In a more generalized sense, the panelist questioned whether the presence of fine fragments in HBU fuel would altogether lead to any mechanisms that could worsen the consequences already expected for lower burnup fuel during an RIA. This understanding served as the panelist's rationale for giving an "L" ranking for the importance of item 1.1, as well as for the importance of several other phenomena in the FFRD RIA PIRT that were otherwise found of high importance by the majority of the panelists. It is noted that, with regard to FOM-3, "Radiological Release," item 1.1 was ranked as predominantly medium for importance, state of knowledge, and uncertainty, with 5 "M" votes in each of the ranking areas.

Item 1.2, which relates to the core-wide pin-by-pin spatial power distribution initial condition, was ranked similarly by the FFRD PIRT Panel during the elaboration. The item was given 5 "H" votes for importance while receiving 5 "H" votes for state of knowledge, and 5 "L" votes for uncertainty for FOM-1, "Fuel Rod Failure." During the discussion, burnup-related considerations shared by a Panel member pointed out the importance of pin-by-pin distributions within each bundle and local variations that could reach approximately 8 percent or so, driven by localized spatial gradients associated with the bundle location or orientation, or both, that could be particularly exacerbated if an HBU fuel bundle were to be relocated from the core periphery to the central core region. On the other hand, another panelist expressed the view that burnup would lead to diminishing local variabilities and the flattening out of fuel properties, resulting in almost uniform peaking factors that would differ by only a few percent or so. Based on this incremental viewpoint focused on recognizing the outlined effects associated with HBU fuel, the panelist considered this item as being of low importance. Regarding FOM-3, "Radiological Release," item 1.2 was ranked as predominantly medium with 4 "M" votes for importance and state of knowledge and 5 "M" votes for uncertainty.

Another item that was ranked predominantly high in importance for FOM-1, "Fuel Rod Failure," was item 1.3, related to the pellet radial power distribution initial condition. The item received 4 "H," 2 "M," and 1 "L" votes for importance, while being ranked as predominantly medium for both state of knowledge" and uncertainty for FOM-1. One panelist pointed out the importance of initial fuel enrichment when considering burnup associated effects. The panelist's main point was related to the importance of initial fuel enrichment and fuel irradiation during operation as being key factors that would require consideration for HBU fuel and its related consequences. It was pointed out that the fuel properties at the same pellet average burnup level of 60 GWd/MTU, as an example, would be rather different for fuel with an initial enrichment of 2.4 percent to 4 or 5 percent, and for fuel with an initial enrichment of 6 percent. Extended fuel enrichment would result in higher power and more burnup from fission of uranium-235, whereas, for low-enriched fuel, the additional burnup would be produced more or less by generation and fission of plutonium-239, which would have an impact on the HBU fuel and its rim properties, like structure, fission gas generation, and FGR. The panelist considered the change in initial uranium-238 concentration due to different fuel enrichment as a secondary factor with negligible effects. Pushing burnup higher through irradiating lower enriched fuel by surrounding it with high-powered bundles would be either impossible, beyond a certain burnup level, due to either criticality requirements or to unacceptable fuel behavior under accident conditions. Accordingly, a point was made that increasing fuel burnup to pellet average levels of 75 GWd/MTU or so in a "good" way would need to go hand in hand with increasing initial fuel enrichment (i.e., considering the use of EE fuel). Another panelist expressed the view that the amount of energy deposition during an RIA would dominate over possible radial variabilities in parameters such as power distribution within the pellet. Overall, the prevalent high importance ranking attributed to this item relative to FOM-1 was in recognition of the importance of the initial fuel conditions pertinent to item 1.3. It was ranked as predominantly medium with 4 "M" votes for importance, state of knowledge, and uncertainty regarding FOM-3, "Radiological Release."

As with the above-discussed items 1.1 through 1.3, the FFRD PIRT Panel ranked item 1.4 as predominantly high in importance for FOM-1, “Fuel Rod Failure.” Item 1.4, which relates to the pellet radial burnup distribution initial condition, received 4 “H,” 2 “L,” and 1 “M” votes for importance, while being ranked as predominantly medium for both state of knowledge and uncertainty for FOM-1. During the discussion on this item, the Panel recognized the importance of burnup effects on key fuel properties, such as fuel melting temperature and thermal conductivity, in the context of a potential burnup increase to 75–80 GWd/MTU. In addition, the Panel identified other burnup effects pertinent to pellet rim structure, fuel particle size, and fuel pulverization. The discussion also recognized the need to consider these effects in conjunction with additional effects from energy deposition caused by the reactivity insertion pulse. Also, the panelist pointed out that the radial burnup distribution was not expected to change the RIA consequences as much as the overall burnup level and available source terms. Item 1.4 was ranked with 3 “H” and 3 “M” votes for importance, while it was almost unanimously ranked as medium for state of knowledge and uncertainty regarding FOM-3, “Radiological Release.”

Another item in the FFRD RIA PIRT that the majority of the FFRD PIRT Panel ranked as high in importance for FOM-1, “Fuel Rod Failure,” was item 1.5, related to the clad excess hydrogen initial condition. The item received 6 “H” votes and 1 “L” vote for importance, while being ranked moderately high for state of knowledge and predominantly medium for uncertainty for FOM-1. Key highlights from the elicitation discussion reflected the understanding that hydrogen would drive the propensity for fuel failure due to PCMI, compared to fuel failure from clad ballooning, since hydrogen would make the cladding more brittle. Higher burnup would be associated with increased oxidation and hydrogen pickup, which would ultimately result in more brittle fuel cladding. Elaborating on the subject, a panelist stressed the importance of this item and the potential uncertainties associated with it. The panelist pointed out that the cladding becoming more brittle as a result of hydrogen pickup due to clad oxidation could actually be beneficial from an RIA viewpoint, since the cladding would fail from PCMI very early in time with a small split opening. Such an outcome would be beneficial compared to a potentially much larger opening from clad ballooning occurring later in the transient, if the clad ductility had been preserved due to low hydrogen content, as in the case of low burnup fuel.

Related to the considered embrittlement phenomenon, the same panelist recognized the importance of the question of whether hydrides, when already present in the cladding, would dissolve during the short duration of the transient. While the panelist alluded to significant uncertainties related to the discussed phenomena with regard to the ongoing efforts by the industry to develop and employ low-corroding cladding materials, it was stated that this was not the case for current zirconium-based cladding materials, in which the panelist ranked the state of knowledge as high with the uncertainty being medium at best. Regarding FOM-3, “Radiological Release,” item 1.5 was ranked as predominantly medium, with 6 “M” votes for importance, 5 “M” votes for state of knowledge, and 5 “M” votes for uncertainty. In relation to FOM-3, a panelist noted that, while the PCMI failure threshold could change as a function of hydrogen pickup, the item was viewed by the panelist as having no impact on radiological release (i.e., FOM-3). In the panelist’s view, item 1.5 concerned only the failure mechanism that would just become a trigger for a subsequent radiological release and dose consequence analysis; hence, his rankings of low for importance, high for state of knowledge, and low for uncertainty on FOM-3.

3.2.3 Key RIA PIRT Panel Considerations

(1) The Panel recognized phenomenological areas deemed as main contributors to uncertainties related to FFRD of EE and HBU fuel and its consequences during RIAs as

related mainly to the influence of the pellet and particularly the HBU rim expansion and axial gas communication (or lack thereof) on pellet expansion and cladding failure, and as possibly further affecting the rupture geometry and amount of fuel fragments available for dispersal in extreme cases. The possibility of extended in-core residence times affecting unfavorably the cladding properties in the case of HBU fuel was identified as an additional such area.

(2) Overall, the Panel deemed it reasonable to judge additional consequences from FFRD phenomena associated with HBU fuel behavior in an RIA as being limited, compared to the behavior already observed in experiments, such as the REPNa test series in the CABRI experimental reactor.

(3) FFRD phenomena and related consequences should be judged based on detailed modeling and, eventually, experiments with HBU fuel aimed at an understanding of and accounting for the combined effect of two opposing factors specific to HBU fuel: (1) fuel possibly responding less severely to reactivity insertion, and (2) heatup of the overpressurized pores in the rim exerting an extra load on the cladding, thus producing more failures. Specifically, sufficient understanding and detailed modeling of the rim fragmentation phenomenon was identified as needing additional consideration.

(4) Addressing uncertainties related to the extent of axial and radial fuel relocation as part of considering FFRD of HBU fuel during an RIA, it was recognized that axial and radial relocation of HBU fuel would require a minimum cladding distension of a few percent to open a gap between the pellets and the cladding. In an RIA, this required condition would be affected by the RCS primary pressure (pressurized or depressurized) and possibly by the duration of the RIA pulse (a short duration would limit cladding creep).

(5) The Panel found it hard to judge the consequences of possibly the entire pellet cross-section being fragmented into medium and small pieces for burnups exceeding 80 MWd/kgU. The counteracting force of the cladding being in contact with the pellets, should the RCS be pressurized, would play a major role requiring consideration.

(6) The Panel envisioned the geometry of the burst opening in an RIA as being more of an axial split than a large opening, as observed in LOCA tests. It is believed that the described condition was in recognition of the fact that HBU fuel is more likely to fail due to PCMI during an RIA, which tends to result in an axial split. The Panel recognized a smaller burst opening, combined with more limited fine fragmentation (or even not present for an RIA with no rod overpressure to a still-pressurized RCS, except for extreme cases), as factors eventually limiting the dispersal of fine fragments on a burst of the cladding and any consequence associated with FFRD of HBU fuel for RIAs. It remains unclear how other clad failure modes related to high-temperature cladding and molten fuel thresholds pertaining to RIAs would impact the burst opening shape and size and thus the potential for HBU fuel relocation and dispersal, and these would compare to the burst opening and dispersal observed for HBU fuel during a LOCA.

(7) As an overarching observation by the Panel, with dispersal being limited to a very local region in the core, the RIA consequences would be less significant than the LOCA evaluation. Furthermore, the Panel identified no specific additional coolability concerns arising from fuel dispersal, considering its rather limited amount.

(8) The need to further improve models for rim formation and fragmentation in fuel rod thermal-mechanical performance codes was identified as being of importance for gaining an improved understanding in support of well-founded safety analyses of FFRD and its consequences for EE/HBU fuel performance during RIAs. In addition, the Panel identified a definitive need to determine the capabilities of such codes to account for axial gas communication, including possible lack thereof, and for the effect of released and locally stored fission gas in calculations using such codes.

(9) The Panel recognized that the correctness of RIA modeling and underlying assumptions for related safety criteria could only be assured through data obtained from prototypical experiments. In this regard, the panelists emphasized the importance of using test specimens, obtained from lead test assemblies, where the HBU is achieved in a natural way using EE fuels, while noting that relevant test fuels seemed to be lacking presently.

(10) The FFRD PIRT Panel considered the PCMI failure mode as the dominant mechanism causing fuel failure during an RIA for currently employed zirconium-based claddings when it comes to EE and HBU fuel. Higher burnup, associated with increased oxidation and hydrogen pickup in the cladding material, would result in more brittle fuel cladding that could be beneficial, since the cladding would fail due to PCMI very early in time with a small split opening. Such an outcome would be beneficial compared to a potentially much larger opening from clad ballooning occurring later in the transient should clad ductility have been preserved in the case of cladding with low hydrogen content for low burnup fuel. The important question of whether hydrides already present in the cladding would dissolve during the short duration of the transient was also recognized as relevant. Whereas it was suggested that significant uncertainties related to the discussed phenomena could arise as part of the ongoing industry efforts to develop low-corroding cladding materials, the relevant state of knowledge for current zirconium-based cladding materials was considered high and the uncertainty judged as medium at best.

3.3 PIRT on High Burnup FFRD and Its Consequences for Fuel Handling Accidents

3.3.1 High Burnup FFRD PIRT for Fuel Handling Accidents

The FFRD PIRT Panel deliberated on the PIRT for FHAs during its virtual second meeting, which took place on January 19, 2024, with all Panel members in attendance. Leading to the meeting, the panelists received a preliminary PIRT that included a draft list of phenomena, their relevance description, and three candidate FOMs on coolability, criticality, and radiological release. The panelists provided their initial input independently from each other through email. The initial input included rankings on one or more FOMs, as found appropriate by each panelist. In addition, some panelists provided written discussion notes on some of the ranked phenomena. Before the January 19, 2024, meeting, panelists received an integral draft PIRT, which included the initial input from all panelists. Before discussing the individual FHA phenomena included in the PIRT, the panelists agreed unanimously to include and rank only a single FOM on radiological release. During the deliberations, some panelists found it appropriate to update some of the initial rankings.

The FFRD PIRT for FHAs in Table 3-11 identifies the phenomena, their relevance to HBU fuel and FFRD consequences, and the rankings for FOM-3, “Radiological Release,” in terms of Importance (Imp.), State of Knowledge (SoK), and Uncertainty (U). The phenomena were grouped in two categories: Category 1, “Fuel Initial Conditions” (item 1.1 through item 1.3), and Category 2, “Mechanical Impact” (items 2.1 and 2.2). Table D-1 in APPENDIX D to this report documents the complete FFRD FHA PIRT containing the full record of ranking votes provided by each member of the FFRD PIRT Panel.

Table 3-11 PIRT on High Burnup FFRD and Its Consequences for FHAs

Phenomena				FOM (Release)		
Cat.	**No.**	**Phenomena**	**Relevance**	**Imp.**	**SoK**	**U**
1. Fuel initial conditions	1.1	Rod powers and burnups that bound operating release	Regulations state that radiological consequences should not be underestimated	**L(4)**	**H(7)**	**L(6)**
				M(3)	-	M(1)
	1.2	Gap volatile radioactive release	Radiological	**M(4)**	**M(4)**	**M(5)**
				L(3)	H(2)	H(1)
				-	L(1)	L(1)
	1.3	Fuel bundle structural design characteristics	Fewer rods per bundle generally result in higher release (e.g., PWR 14x14 vs. 17X17)	**L(4)**	**M(4)**	**L(6)**
				M(3)	H(3)	M(1)
2. Mechanical impact	2.1	Additional fuel fragmentation from mechanical shock	Increases radiological release	**L(4)**	**M(5)**	**H(3)**
				M(3)	H(1)	M(2)
				-	L(1)	L(2)
	2.2	Additional gas release from mechanical shock	Increases radiological release	**L(7)**	**M(3)**	**H(3)**
				-	H(2)	M(2)
				-	L(2)	L(2)

3.3.2 Summary of Panel Notes

As mentioned, some panelists provided notes on specific items included in both Category 1, “Fuel Initial Conditions,” and Category 2, “Mechanical Impact.” Concerning Category 1 phenomena, a note on item 1.1 (bounding rod powers and burnups) emphasized that the impact of rod burnup and bounding operating conditions is the significant driver for almost all safety-related outcomes detailed within the PIRT, noting that “the uncertainty is well-quantified with characterized confidence.” Furthermore, it was noted that EE will change how fuel is used within the core of operating reactors with fuel preconditioning being dependent on the linear power density and burnup histories, which will impact locally the fission gas, isotopic distribution, stored energy (decay heat), and fuel fragment distribution. It was also noted that “rod powers, burnups, and isotopics can be calculated to high accuracy with low uncertainty.” Regarding item 1.2 (gap volatile radioactive release), panelists noted that, while Regulatory Guide (RG) 1.183, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,” [12] specifies the gap release, the question is whether fuel fragmentation (FF) could occur during an FHA and whether any additional gap source term could be added initially or after fuel is wetted. It was also noted that, although total fission product inventory is known, the amount and distribution of fission gas throughout the rod has higher uncertainty, which may impact the gas release under an FHA. In its notes on item 1.3 (fuel bundle structural design characteristics), the Panel recognized that there is sufficient information to provide the rod initial conditions and that gas generation change from extending fuel burnup can be determined to calculate the gas content in the fuel. Additional data and analysis will determine the gap gas content.

Regarding Category 2, “Mechanical Impact,” items, a panelist noted, on item 2.1 (additional FF from mechanical shock), that, while Studsvik Cladding Integrity Project (SCIP) IV has some data, the extent of fuel fragmentation during an FHA would be near negligible compared to what had been observed under LOCA conditions.[2] In a note on the same item 2.1, another panelist noted that item 2.1 includes consideration of the potential impact on Iodine release in the event that fission fragments come in contact with water. A third panelist noted that mechanical shock could potentially break the clad-fuel bonding and lead to additional breakup of the fuel into smaller fragments that would need to be further evaluated for release. An opinion that radiological releases would be most dominantly governed by FGR was also expressed. In a note on item 2.2 (additional release from mechanical shock), while recognizing the possibility of FGR during mechanical shock, it was stated that FGR is typically driven by fission gas bubble overpressurization. Accordingly, an external force could cause local FGR but global FGR is not possible under FHA conditions. Similarly, another panelist noted that FGR is driven by the fuel temperature, and the mechanical effects on FGR are low. In a note on the same item, a panelist

---

[2] Past studies have looked at releases during an FHA with the experimental work by Vlassopoulos et al. presented at the 2021 TopFuel conference being such an example [10]. The work reported results from tests in which fuel rod specimens were subjected to loads from quasistatic bending and dynamic gravitational impact to induce rod rupture and measure the released fuel mass by weighing the specimen before and after the test. Rupturing nondefueled rod segments taken from a light-water reactor UO_2 fuel rod with a burnup of 58.6 GWd/tHM [gigawatt days per ton of heavy metal], repressurized to the fuel rod internal pressure measured after discharge, yielded 1.18 grams of released fuel for the bending test and 2.09 grams of predominantly fuel mass (some cladding fragments mostly from the clad oxide layer were also observed) for the gravitational impact test. In the latter case, up to 99.5 percent of the released mass consisted of fragments collected at the bottom of the test chamber. The missing small fraction of 0.5 percent (or about 0.01 gram) accounted for aerosol and fine particulates seen on high-speed camera videos floating before eventually depositing on the chamber walls or being filtered out by the test chamber aspiration system, indicating negligibly small releases in the form of fine aerosols particles (an equivalent circle diameter of 6.3 micrometers was determined from scanning electron microscopy imagery).

recognized that fuel breakup due to mechanical shock would release additional fission gas, resulting in greater potential for release. A Panel member also suggested that the gas release considered in item 2.2 is of a lesser importance than the potential impact of fission fragments recognized in item 2.1.

3.3.3 Summary of Panel Deliberation Insights

Upon opening the deliberation session of the Panel for HBU FFRD and its consequences, one panelist expressed the opinion that, while higher burnup could result in higher consequences from an FHA due to, for example, higher fission product release and gap content, such effects from higher fuel burnup are not driven by new phenomena. The panelist also referred to his note on item 2.2 that FGR is driven by the fuel temperature while mechanical effects on FGR are low. This was the panelist’s overarching rationale to rank all phenomena in the FHA PIRT as “L” for importance, “H” for state of knowledge, and “L” for uncertainty. This view was supported by another panelist who also stated that there is a gap in the panelist’s own knowledge when it comes to this PIRT, mentioning specifically release impact on control room habitability. Another panelist also commented on his limited professional knowledge on gap volatile radioactive release of relevance to the PIRT.

Deliberating on the items in Category 1, “Fuel Initial Conditions,” a panelist commented that it is guaranteed that the activities underway right now to move to HBU and high enrichment fuel will become an enabler for various rather new and innovative core loading patterns. This was the panelist’s rationale for ranking the three items included in PIRT Category 1 as “M” for importance. To underscore the significance of the PIRT, the same panelist commented on past experience with utility-specific core calculations and the need to implement limits on fuel burnup as a function of linear heat generation rate, with such core design constraints being driven by radiological releases from an FHA.

In considering possible impacts associated with FHA-related phenomena, two panelists shared the opinion that forces triggered by such an accident are expected to be small compared to what fuel experiences during a LOCA heatup. One of the panelists expressed the view that such forces causing total disintegration of the fuel rim region, as seen in heatup, are inconceivable. Gas bubbles containing fission products within the fuel are very small, with their sizes on the order from a couple micrometers to nanometers. Whether the fuel bundle is being dropped or hit, the mechanical impact could result in some extra cracks with such very localized effects impacting only a very tiny fraction of all gas bubbles in the fuel, since the number of bubbles that can propagate through a newly formed crack will be very small. In addition, the panelist mentioned that, in an FHA, such as dropping an assembly, structural features of the assembly would relieve the fuel from some of the mechanical impact.

During the deliberations, the Panel acknowledged the lack of applicable experimental data, while suggesting that some lessons learned from spent fuel handling and cask drop analysis could help glean some understanding. Discussing item 1.3 (fuel bundle structural design characteristics), the Panel recognized that, with HBU and EE fuel, the fuel product designs will change, with eventual improvements involving possible modifications related to the fuel pellet diameter and the cladding thickness viewed as most consequential. Panelists expressed the opinion that such changes will need to be analyzed in terms of determining the impact on the source term when assessing the consequence from an FHA. Overall, the PIRT results reflect an approximately equal split between “M” and “L” for the rankings on importance for this, as well as the remaining phenomena in Category 1.

Elaborating on the rationale for ranking some of the phenomena in the FHA PIRT as “M” for importance, “L” for state of knowledge, and “H” for uncertainty, a panelist pointed out a lack of understanding about how HBU fuel and its potential fragmentation could impact source terms and how this relates to the limits in RG 1.183. Specifically, the panelist explained that the high degree of uncertainty and low level of knowledge rankings accounted for an additional potential source term when considering what might happen with the gas bubbles as well as for another possible source term as a result of small fuel particles that could be released in an FHA and further interact with water. Related to this view, the panelists shared additional uncertainties as to the source term associated with more fissile material; more fission products, particularly more fission gas; and the potential release of fragmented fuel as a result of HBU fuel. Related to this, the panelists also recognized the need to confirm the adequacy of the source term limits found in the recently revised RG 1.183 (Revision 1, issued October 2023) and underlying supporting assumptions, such as a bounding power profile and others, for HBU fuel in excess of the maximum rod-average applicability limit of 68 GWd/MTU provided in RG 1.183.

3.3.4 Key FHA PIRT Panel Considerations

(1) The Panel is of the overall opinion that fuel dispersal and TFGR from an FHA involving HBU fuel are expected to be small compared to what fuel experiences during a LOCA heatup. This is reflected in an approximately equal overall split between “M” and “L” for the rankings on importance for all phenomena in the FHA PIRT except for item 2.2, unanimously ranked “L” in importance.

(2) The Panel recognized additional uncertainties in the source term associated with more fissile material; more fission products, particularly more fission gas; and the potential of fragmented fuel release as a result of HBU fuel that would need consideration. In this relevance, it is noted that, based on Section B.4, “Noble Gases and Particulates,” of RG 1.183, Revision 1, particulate radionuclide releases following an FHA are assumed to be retained by the water in the reactor spent fuel pool or reactor cavity. While this is meant to include the alkali metals residing in the fuel rod plenum and gap as specified in tables 3 and 4 in RG 1.183, it equally applies to any fuel fragments that would be released in an FHA.

4 SUMMARY AND CONCLUSIONS

This section summarizes the main elicitation insights, observations, and findings from the FFRD PIRT Panel gleaned during the development of the three PIRTs, with the Panel's focus on potential incremental effects from expected future use of EE and HBU fuel in the U.S. operating fleet of PWRs and BWRs with standard zirconium-based cladding materials. Section 4.1 outlines the Panel's major outcomes, and section 4.2 offers the main implications foreseen with regard to the possible use of EE and HBU fuel.

4.1 Major Outcomes from the FFRD PIRT Panel Effort

The Panel discussed several unique DBA scenarios as they relate to FFRD. In considering these scenarios, panelists maintained close agreement across many of the phenomena considered as a part of the discussion. The RIA scenario resulted in a relatively lower significance or importance level but higher variance in the ranking among members. The LOCA transient was generally found to be the scenario that led to the largest and most significant implications for safety matters with regard to FFRD and its consequence under HBU conditions. Specific to the LOCA event, the discussion tended to center thematically on questions related to fuel release and those related to the impact of geometric sensitivities, including, but not limited to, breach size and shape, ratio of ballooning size to rod pitch, and the relative location of breach compared to grid spacer and grid-spacer geometry.

For HBU, the Panel identified the primary phenomena of concern for FFRD and found they related to fuel particle size, clad burst opening size and shape, and fuel rod pre-transient power and burnup distribution. In addition, the role of spacer grids is extremely important, as grids affect axial fuel relocation; axial gas communication; balloon burst; fuel release and dispersal; the potential formation of debris beds; and, ultimately, coolability. The following items identify some main outcomes and observations from the Panel during the PIRT development efforts as they related to evaluating FFRD and its consequences for EE and HBU fuel:

(1) For HBU fuel, particle size distribution is critical to the amount of material released (ratio of particle size to opening). Experiments on HBU have shown a propensity for smaller particle sizes to disperse through the cladding rupture. It is the amount of fine fragments in this smaller particle size distribution that, when released, may create the local accumulation of debris within the system. Therefore, particle size distribution is important to determine the dispersal mass released into the primary system during a LOCA and its potential for accumulation within debris beds, particularly at spacers. This is a concern for coolability but not for criticality.

(2) Within the LOCA category, particle release is impacted by the balloon burst opening size and the proximity of the burst location to neighboring rods. The extent of particle release depends not only on the particle size distribution but also on the geometry of the burst opening. Adjacent fuel rods can limit the dispersal of particles from a burst location and may localize the particle release. Experimental data exist that confirm this observation.

(3) Spacer grids are a primary trapping mechanism of concern for HBU. The creation of larger debris beds with HBU versus non-HBU fuel behavior is identified as a key consideration for a LOCA. Burst locations relative to fuel grids and the release of material will impact debris bed formation, particularly in the vicinity of the upper grid spans where rod failures are typically expected to occur. It is noted that other trapping

mechanisms, such as inlet debris filters and lower grid spans, were deemed inconsequential for coolability because of conduction and single-phase convective cooling.

(4) Spacer grids impact axial fuel relocation and gas communication within the fuel rods. This will impact the location(s) of ballooning and the potential for rod failure. Burst locations below a grid and the release of material will impact debris bed formation in the vicinity of the grid.

(5) The initial fuel rod axial power and axial burnup distribution as a precondition to fuel rod failure during a LOCA are important parameters. Fuel rods with top-peaked axial power profiles at higher burnup are more likely to fail at higher elevations due to high heat flux and clad temperature when the steam-only flow is the dominant cooling mechanism and the upper grid spans have yet to reach reflood conditions.

(6) HBU fuel assemblies reloaded in interior core locations due to increased burnup limits have the potential for increased fuel rod failures in a LOCA. HBU is an enabler for new fuel management strategies that differ from the current practice of loading the highest burned fuel in low-power locations on the core periphery. The fuel rods susceptible to failure depend on the fuel rod history and placement.

(7) Transient fission gas has a low to medium state of knowledge and high uncertainty, which will continue to be the case with HBU fuel. The primary drivers of clad rupture are the TFGR and differential pressure with the RCS. Potentially higher fission gas with HBU, combined with clad embrittlement and degradation of thermal properties, may drive additional ballooning events during a LOCA.

(8) The impact of HBU on PCMI, the primary failure for an RIA, was deemed to have a minimal impact on the worsening of coolability and criticality. For an RIA, HBU fuel increases clad embrittlement; however, the fragmentation of the pellet rim was viewed as a positive for accommodating clad stresses from fuel expansion. In addition, PCMI-initiated clad failure openings differ from those observed in LOCA tests in that they are not a broad breach. RIA failures are localized small holes or narrow axial splits that make particulate release minimal. The larger concern for an RIA is FGR, which could be larger with HBU. As noted in item (7), FGR for HBU has a low to medium state of knowledge and high uncertainty for HBU fuel.

As recognized by the FFRD Panel, predicting the effect of fuel fragmentation release and distribution requires knowledge of the state of the fuel (fragment size, distribution, and relocation in the rod), as well as the rupture of the rod and the shape of the break. Those require detailed knowledge of the material properties of the fuel and the cladding and their response to the various environmental factors that cause their degradation and failure. While it is critical to know whether, when, and where a rupture takes place, and the state of the fuel, the following summary observations focus specifically on what happens after the fuel burst.

Once a rupture happens, determining the ejection of fragments from the rod, their dispersal, and their deposition relies on an understanding of the interaction of particles with fluid. The initial dispersal depends strongly on the conditions in the rod, including the pressure, how much the rod has ballooned, the fragmentation of the fuel and how it is distributed, the shape of the rupture, and the ambient fluid flow and pressure. Small fragments, initially located close to the rupture and ejected into quiescent steam, are likely to be dispersed differently than fragments ejected into liquid or into rapidly moving steam. Fragments with sharp corners are also more likely to get stuck in the opening, blocking further release, particularly as their size increases. The initial particle ejection is likely to take a relatively short time but how far the particles are ejected will significantly impact their subsequent dispersal. What happens next depends on the fragment size and shapes and the flow conditions. Rapidly moving steam or liquid may entrain fragments, but fragments of comparable size in quiescent steam may fall down. For particles in a single-phase flow, particularly for particle shapes that are relatively simple, such as spheroids, the motion is relatively well understood and can be modeled reasonably accurately. Indeed, several numerical codes exist that provide models for the flow of dispersed particles in turbulent single-phase flow. However, if the flow is a multiphase vapor-liquid mixture, very little is known, and for complex particle shapes, even less is known. The fragments are also likely to be of different sizes and shapes, thus moving differently. In general, we expect the fragments to encounter spacer grids as they fall down, or are carried with the flow, while how the particles interact with and possibly accumulate on the grids is poorly understood, particularly for complex particle shapes. Differently designed spacer grids only add to the complexity and the uncertainty. Accumulation resulting in the formation of a solid bed is likely to affect the structure of the flow, the heat transfer, and thus the cooling of the fuel rods. While porous beds of large particles may result in relatively little effect on the flow, that will change if consolidation takes place with time.

While the dispersal of fuel fragments after a rupture of a fuel rod remains poorly understood, the question of how much material is released is an even more important one. There are indications that, in some cases, it may be very limited, such as if the fuel fragments mostly into large particles that remain in the rod. However, a worst case scenario may involve fully pulverized fuel and significant relocation of fuel within the rod, following ballooning and rupture. Generally, it seems that FFRD is likely to be more serious during a LOCA then in an RIA or an FHA, since in the latter case, the amount of material ejected is expected to be limited. A small amount of ejected material may not have a major impact on the flow and the coolability, so understanding the maximum amount of fuel fragments that can be released is of critical importance in assessing the overall potential for damage due to the accidental release of highly fragmented fuel. Generally, the Panel members believe that FFRD during a LOCA is unlikely to cause serious coolability issues and, to an even lesser extent, during an RIA or an FHA. This opinion applies to burnup levels of up to approximately 75 GWd/MTU, the peak rod average currently considered by the industry, and might not necessarily be applicable to higher burnups. Some panelists saw it as preferable to define the burnup limits in terms of peak rod burnup instead of peak rod average burnup, because at 75 GWd/MTU rod average burnup, the local burnup will exceed 80 GWd/MTU for a large part of the (PWR) fuel, at which point the fuel undergoes considerable changes (compare Halden LOCA experiments with fuels of 80 GWd/MTU and 90 GWd/MTU burnups).

Sections 4.1.1 through 4.1.3 summarize, for each PIRT individually and in some detail, the main outcomes and observations specific to each FFRD PIRT developed by the Panel.

4.1.1 FFRD PIRT Outcomes Related to Loss-of-Coolant Accidents

This section provides a phenomenological summary outline related to EE and HBU fuel FFRD and the related consequence from the viewpoint of considering two very distinct groups of phenomena: (1) those occurring in the fuel and the cladding as burnup increases during normal operation (section 4.1.1.1), and (2) those taking place outside of the fuel rod following burst (section 4.1.1.2). Section 4.1.1.3 discusses LOCA-related phenomena from the FOM perspective of the FFRD consequences on coolability, recriticality, and radiological release.

4.1.1.1 Phenomena Developing in the Fuel and Cladding as Burnup Increases during Operation

Experiments on LOCA fuel behavior have identified developments that potentially aggravate the fuel performance and impact on current safety criteria requirements. The phenomena concern the changes to the fuel microstructure with burnup, the fragmentation of HBU fuel into fine particles, TFGR, and the impact of TFGR on local pressure buildup and ballooning, as well as the possibility of fuel relocation into the balloon with an impact on the local cladding temperature.

In light of experimentally observed developments from LOCA tests performed with HBU fuel during the recent two decades that have indicated aggravating fuel performance as burnup increases, the impact on LOCA safety criteria deserves a careful evaluation when considering an increase in licensing burnup limits.

Concerning fuel relocation into the balloon, it needs to be shown that the local cladding temperature and oxidation do not exceed the safety limits. Fuel relocation is a phenomenon that depends on both fuel behavior (fragmentation) and cladding behavior (general distension and ballooning), and it is therefore not a trivial task to predict its occurrence and extent. On the more unknown side would also be the filling ratio, which depends on the movability (degree of axial relocation) and size distribution of the fragments.

HBU fuel potentially has a high rod pressure both from normal operation and through TFGR during the LOCA. This does not necessarily worsen the LOCA performance, since an earlier burst at a lower temperature and with a smaller balloon could be on the positive side. In general, however, both balloon size and burst opening have been recognized as sources of high uncertainty.

4.1.1.2 Consequences for Outside of the Fuel Rod

The consequences for outside of the fuel rod are mainly related to ensuring coolability in consideration of the following key phenomena:

- fuel fragment ejection following the burst of the rod and the accumulation of these fragments on the spacer grid and elsewhere in a way that impedes coolability

  This item depends on several factors. One is the burst opening, whose shape and size is a source of considerable uncertainty. Another is the driving force of the rod pressure that developed both from normal operation and through TFGR. A third is the burnup-dependent fragment-size distribution in relation to the burst opening. Once ejected, there is limited knowledge on the particles' mobility and how and where they can be transported, which also impacts radiological consequences.

  Finally, the role of the spacer grid design, which is vendor dependent, requires consideration and will make it difficult to formulate a general definition of what and how much can be deposited or trapped. The knowledge on how these phenomena develop and influence each other is limited, and the uncertainty is high.

  On the positive side, the quantities of dispersed fuel are likely to be small up to a burnup level of about 75 GWD/MTU, and the impact on recriticality is considered to be low.

- impact of multiple ballooning and coplanar balloons on reflood and coolability

  The balloon location and coplanar balloons do not seem to represent a serious problem for coolability.

4.1.1.3 LOCA PIRT Figure of Merit-Related Considerations

LOCA Coolable Geometry Impact (FOM-1)

The LOCA PIRT was the most extensive area of deliberation, and within the LOCA PIRT, the impact of FFRD on coolable geometry was the dominant area of discussion and the area with the largest expected impact. Although not explicitly established, the impact is considered to be primarily due to the potential for FFRD material to clog the spacers and the associated effects on the coolability of fuel rods in the vicinity of a clogged spacer.

FFRD impact risks associated with coolable geometry extend beyond clogged spacer considerations. The Panel discussed the following additional FFRD impact risks:

- Regarding the impact of clogging the fuel inlet, the Panel agreed that there was potential for FFRD to drop into or be recirculated into the fuel inlet. At this location, FFRD decay heat was not expected to impact the flow (from above or below) into the fuel bundle (or fuel channel for a BWR). Furthermore, clogging of the inlet was considered less severe than that related to ECCS suction strainers.

- The impact of clogging at the core exit or elsewhere in the RCS was not viewed as a substantial risk for core cooling.

- The impact of HBU ballooning, a topic that the Panel considered in great detail, included a discussion of coplanar ballooning, which was viewed as credible. The Panel discussed the potential for ballooning-related flow blockage, based on what had been previously evaluated for LWRs. It was the general consensus that the FFRD-susceptible fuel rods would not be expected to present a more severe blockage scenario.

Although not ranked specifically, the Panel considered other 10 CFR 50.46 criteria, such as peak cladding temperature (PCT) and equivalent cladding reacted (ECR). FFRD-related phenomena that can affect current design-basis practice for PCT and ECR include the impact of fuel relocation and the impact of TFGR on incipient burst (and associated two-sided oxidation). The Panel did not view the dispersal of material as significantly impacting the margins to PCT or ECR, since the timing of impact of clogging-related phenomena would be delayed relative to the thermal-hydraulic conditions that turn around PCT, including the time to reduce PCT enough to terminate accelerated oxidation, and considering that HBU fuel is inherently cooler than low burnup fuel.

The clogged spacer impact is judged important because (1) the spacer flow area restriction is able to stop the FFRD particles (first larger and then smaller, as the area becomes more restricted), (2) spacers are located in regions of the highest expected fuel temperatures associated with reduced LOCA cooling, and (3) the FFRD material will heat the region.

Given the clogged spacer as the primary effect, the phenomena discussed by the Panel can be related to their potential impact on clogged spacers as a surrogate for loss of coolable geometry. From the perspective of clogging spacers, the following questions regarding FFRD-related phenomena are important.

(1) How large are the particles that exit the fuel rods?

(2) How much material exits the fuel rod, including the composite of all fuel rods within the bundle lattice?

(3) What is the timing of the material exiting the fuel rods?

(4) Can the material exiting the fuel rod be carried into the spacers?

(5) Will the material clog the spacer (not pass through or break up and then pass through)?

(6) Will the clogged spacer be porous such that cooling flow can pass through or around?

(7) What impact will the decay heat associated with fuel material have on the clogged region?

The discussion of each of these questions is based on known, read, presented, or Panel-based perceptions.

Question 1, related to particle size: The data indicate the existence of particles that would be able to clog a spacer. Larger particles have the greatest potential for clogging a spacer. There is a tradeoff between this question and question 2 because larger particles are less likely to exit the fuel rod.

Question 2, related to material amount: This is a subject to which the Panel devoted a significant amount of discussion. The burst size and geometry are of primary importance. Certain burst shapes release more material. There was no consensus on the expected burst opening shape. Although increased hydrogen content of HBU fuel does impact at least the burst temperature, and while it is reasonable to conclude that burnup and hydrogen would impact burst strain as well, the experimental data are decidedly mixed regarding the effect of these factors on the rupture opening dimensions. Coplanar burst and burst orientation were also discussed. Dispersal from multiple rods within the lattice would be expected. The region of available material was expected to be within a single balloon bounded by one spacer span.

Question 3, related to timing: There was not a great deal of discussion on this, but the general consensus was that the material was primarily ejected during the burst. Much less material would spill out after the burst.

Question 4, related to material transport: Assuming that the material is ejected during the burst, the material transport environment can be estimated based on the thermal-hydraulic conditions coincident with the burst. Of course, settled material may be transported later. These later conditions can be highly variant as ECCS systems inject or if the RCS is depressurized. Little detail was known regarding the transport outcome.

Question 5, related to potential for clogging: As long as the particles are big enough, they can clog and form a debris bed. It is possible that the particles accelerated into a spacer will break up and pass through. Little detail was known regarding this outcome.

Question 6, related to flow blockage: The degree of porosity depends on the particle size and the thickness of the debris bed. Little detail was known regarding this outcome. It was generally agreed that fuel downstream of the debris bed would be cooled by cross flow as would occur in the case of core blockage by containment debris bypassing the ECCS suction strainer, while the core would still be adequately cooled.

Question 7, related to debris decay heat: The debris bed will generate heat. For the debris bed to be cooled, the reactor core fluid must be able to remove the decay heat plus the heat from the fuel rod or the fuel rod will fail.

For the most part, the above seven questions are covered by the majority of the FFRD LOCA PIRT items of high importance according to the PIRT rankings. It is also notable that state of knowledge is low and uncertainty is high for many of these questions, particularly questions 2, 4, 5, and 6.

LOCA Coolable Geometry Outcome

Given the available data and understanding of the above-discussed factors, questions 1 through 7 (FOM-1), related to the possible formation of a debris bed and its effects on coolability, it is believed that a reasonably bounding debris bed problem can be defined and analyzed. It is expected that sufficient cooling can be demonstrated.

LOCA Criticality Impact (FOM-2)

For the most part, the impact of FFRD on the potential for recriticality was scored as having low importance (impact), high state of knowledge, and low uncertainty. The Panel suggested that a bounding criticality assessment problem could be developed and analyzed.

LOCA Release Impact (FOM-3)

RG 1.183 defines the basis for the LOCA source term. As defined, the process determines the releases based on a severe accident scenario up to the point of vessel failure. Given this basis, the Panel could not envision impacting or exceeding this basis as a result of FFRD. HBU does impact the isotopic content and will lead to higher dose (for the same isotopic release fraction); however, this is also a required input to the RG 1.183 analysis.

4.1.2 FFRD PIRT Outcomes Related to Reactivity-Initiated Accidents

LOCA testing in the past two decades has identified important phenomena related to HBU fuel behavior. The outcomes of these tests with HBU fuel provide clues as to the potential behavior of the fuel in RIA conditions. The most important of them seems to be fragmentation of the fuel microstructure, including that of the rim, associated with TFGR.

A pressurized-reactor cooling system should mitigate the consequences that were observed in LOCA testing. It is conceivable that the counteracting pressure on the cladding, when the system is not depressurized, will restrain the fuel from fragmentation and lead more to PCMI-induced failures with small split openings, rather than ballooning and larger burst openings. These factors would then make fuel ejection more limited than that observed under LOCA conditions.

Overall, the RIA consequences would also be less significant than for a LOCA, since an RIA is mostly affecting the assemblies close to the ejected or dropped control rod. The following discussion provides some additional observations specific to the FOMs considered in the RIA FFRD PIRT.

RIA Fuel Failure Impact (FOM-1)

The Panel focused most of the discussion associated with the RIA PIRT on the impact of HBU on RIA consequences. It will be expected that HBU fuel rods will operate at higher power than assumed in prior DBA analyses. It is also known that HBU fuel has a propensity to fail at lower energy deposition than lower burnup fuel. Of particular note is the impact of cladding hydrogen content, which makes the cladding more brittle and susceptible to PCMI failure. There was a general consensus that PCMI would be the limiting failure mechanism and even more so at HBU. Reduced HBU thermal conductivity is another exacerbating factor. The Panel would not expect ballooning and burst during an RIA, based on the nature of the RIA and lack of driving differential pressure, particularly when the RCS is not depressurized. The lack of differential pressure is also a factor in the mitigation of fuel dispersal following cladding failure.

Fuel-cycle-specific assessments, specifically in the case of BWRs, include an evaluation of rod worth as the basis for demonstrating margin to the design basis. It is expected that HBU fuel will be less reactive and therefore at a lower rod worth before the RIA event. Fuel suppliers are required to demonstrate compliance with design-basis limits for an RIA. They will need to analyze reloads to ensure compliance.

The PIRT scoring by one panelist differed from that of the majority of panelists, since it focused on the relative difference between HBU with FF versus fuel without FF. In that regard, the panelist scored much of the failure impact as having low importance. With little or no data to demonstrate this relative behavior, most panelists scored the state of knowledge and uncertainty as “M.” There was some discussion by the Panel that indicated that pellet fragmentation would tend to “soften” the pellet, and therefore FF could decrease the potential for PCMI failure.

Any future efforts should be focused on the relative effects of FF on PCMI-related failure.

RIA Release Impact (FOM-3)

There is a potential for an RIA to lead to dispersal; however, this would be expected to be bounded by a LOCA, considering the smaller number of susceptible fuel rods and the expectation that less material will be ejected into the coolant.

4.1.3 FFRD PIRT Outcomes Related to Fuel Handling Accidents

Although no serious implications are recognized for HBU fuel in FHAs, the following provides some additional discussion regarding the impact on radiological release for such FHAs.

FHA Release Impact (FOM-3)

The impact of FFRD for an FHA, in terms of fuel dispersal and TFGR, is expected to be small compared to a LOCA. For the most part, the impact was scored as low. The Panel was less familiar with the basis for the existing RG 1.183 release (Revision 1), and this led to some lower scores for state of knowledge and higher scores for uncertainty. HBU does impact the isotopic content and will lead to higher dose, but, as for the LOCA, the FHA RG 1.183 analysis will need to consider this impact. A release assessment would need to consider higher fission gas pressure and the potential FFRD dispersal.

4.2 Main FFRD Implications and Proposed Next Steps

The Panel discussions were substantial, comprehensive, and thoughtful. The outcomes that resulted did not yield surprising or unknown observations that were unanticipated or unexpected in relation to safety and their correlation with specific phenomena. The areas of research are generally those that are identified with a low state of knowledge, a high uncertainty, a high importance, or a general combination thereof that motivated the need for further understanding. The discussions from the Panel resulted in a general agreement that no significant barriers exist to exploring extended burnup or increased enrichment from a technical perspective for vendors.

The behavior of HBU fuel observed in LOCA tests is the result of property-degrading developments occurring in both the fuel and cladding as burnup increases during normal operation as well as of complex interactions of phenomena taking place during the transient itself. In the Panel's view, it must be recognized that uncertainties and lack of knowledge contribute to doubts and uncertainties regarding the suitability of the present LOCA safety criteria for HBU fuel.

LOCA experiments have used test segments that were pushed to HBU without having an extended initial fissile content. The current state of knowledge would benefit from additional experimental data for peak rod burnups beyond 75 MWd/kgU.

While much progress has been made to couple detailed core physics calculations, thermal-hydraulics, and fuel behavior modeling to define the initial conditions for LOCA and RIA DBAs, the task of modeling the processes occurring during these transients remains complex and difficult. To this end, one possible approach would be to limit the number of failed rods and thus the consequences from FFRD, especially since HBU fuel does not seem to be able to reach the high temperatures sufficient for rod failure. Such an approach would ensure that lower burnup fuel is protected by the current safety criteria, and HBU fuel does not induce severe consequences if the number of rod failures is limited to a degree found acceptable. An alternative option would be to assume that all rods fail and focus on assessing the FFRD consequences.

The exact state of the fuel, including its fragmentation and the size distribution of fragments, as well as the state of the cladding, is likely to require results from fuel subjected to conditions experienced in an actual reactor. Similarly, identification of the places most likely to rupture depends on the fuel rod operating history, which requires reactor data or data from conditions as similar to reactor conditions as possible. This includes the exact state of the fuel, including fragmentation and the distribution of the fragments for HBU fuel.

The rest of the FFRD process should, however, be accessible to investigations of much less complexity that can be conducted in a relatively standard laboratory setting or possibly by computational examination of simplified setups. This includes how temperature and pressure cause the rupture of the rods and the size and the shape of the opening, the initial ejection of the fuel fragments from the burst rod, their subsequent dispersal by the flow, the fragment accumulation on obstacles like the spacer grids, and their effect on the local heat transfer. Similarly, exactly how much accumulation of fragments is required to disturb the flow in a significant way, or how much can be tolerated without affecting coolability, can be examined in the laboratory. Even some aspects of the cladding degradation, such as the effect of the spacer grid (item 7 in section 3.1.3), may be accessible by laboratory studies. The OSU experiments on the ejection of particulates through a hole in a rod, although preliminary and done under possibly too idealized flow conditions, already suggest what can be learned. Such studies not only would provide much needed understanding of the consequences of many aspects of FFRD but also provide data for model and code validations.

The following items identify some main areas perceived as needing further attention and formulate proposed modeling approaches as they relate to evaluating FFRD and its consequences for EE and HBU fuel:

- Using HBU as a driver for improved fuel management strategies will potentially increase the number of fuel rods subject to failure during a LOCA. The failure locations will depend on the fuel's initial three-dimensional (3D) power and burnup distribution, which can be modeled with high accuracy today. Therefore, 3D core simulator methods will be more important for HBU, as they can identify bounding configurations for different HBU loading strategies. This includes using fuel rod census approaches that identify the number of failures and the potential clustering of failures that could create coolability issues.

- Bounding analyses can determine the dispersal amounts for rod failures, the amount of debris bed formation, and the coolability. This can be used for particle size distribution, burst opening size, and the effects of grid spacers as a trapping mechanism for debris. This is especially true for the upper grid spans where rod failures are typically expected to occur.

- There is a need to improve fuel performance models specifically for rim formation and fragmentation, axial gas communication, and the release of stored fission gas. In the absence of model improvements, bounding analyses with higher uncertainties are necessary.

- Improvements in modeling without the necessary data to support code and model validation will not reduce uncertainties. This applies to both fuel performance codes and, to some extent, 3D subchannel thermal-hydraulic codes important for assessing coolability and particle transport. It is noted that data are sparse above 75 GWD/MTU burnup that would allow the characterization of particle size distribution.

As stated in section 4.1 , the following more specific concerns are recommended as the highest priority for future analysis work or testing:

(1) With respect to coolable geometry during an FFRD LOCA, the impact of debris beds around spacer grids needs to be evaluated.

(2) With respect to radiological release during FHAs, the potential for some FF dispersal should be evaluated.

(3) With respect to fuel rod failure during an RIA, the impact of FFs on PCMI should be evaluated.

These three items do not necessarily require additional test data. Each could be evaluated with existing tools.

Regarding item 1, a preliminary conservative assessment of a debris bed around a spacer grid could be performed. This could be done with a subchannel fuel thermal-hydraulic code, possibly coupled with a 3D fuel rod performance analysis code. The analysis would need to be able to determine whether the fuel rod could fail. If no failure is predicted, this approach could evolve into the bases for adequacy. If not, more detail would be required to remove conservatism associated with the characterization of the debris bed.

Regarding item 2, a radiological assessment of release that includes FFRD material could be conducted with a source term transport code like RADTRAD. If the results are challenging, the material release assumptions could be refined.

Regarding item 3, an analysis of PCMI that includes a treatment of FFs could be conducted using a fuel rod analysis code with two-dimensional or 3D thermomechanical modeling capabilities with a focus on the relative effect of the FFs. If the effect of FFs is conservative or nearly the same, this could evolve into the basis for adequacy.

5 REFERENCES

[1] U.S. Nuclear Regulatory Commission, “Staff Requirements—SECY-21-0109—Rulemaking Plan on Use of Increased Enrichment of Conventional and Accident Tolerant Fuel Designs for Light-Water Reactors,” SRM-SECY-21-0109, Washington, DC, March 16, 2022 (Agencywide Documents Access and Management System Accession No. ML22075A103).

[2] U.S. Nuclear Regulatory Commission, “Phenomenon Identification and Ranking Tables (PIRTs) for Loss-of-Coolant Accidents in Pressurized and Boiling Water Reactors Containing High Burnup Fuel,” NUREG/CR-6744, LA-UR-00-5079, Washington, DC, December 2001 (ML013540584).

[3] U.S. Nuclear Regulatory Commission, “Phenomenon Identification and Ranking Tables (PIRTs) for Rod Ejection Accidents in Pressurized Water Reactors Containing High Burnup Fuel,” NUREG/CR-6742, LA-UR-99-6810, Washington, DC, September 2001 (ML012890477).

[4] U.S. Nuclear Regulatory Commission, “Phenomenon Identification and Ranking Tables (PIRT) for Power Oscillations Without Scram in Boiling Water Reactors Containing High Burnup Fuel,” NUREG/CR-6743, LA-UR-00-3122, Washington, DC, September 2001 (ML012850300, ML012850315).

[5] Beyer, C., V. Palazov, M. Bradbury, J. Spore, M. Ortiz, and D. Fletcher. “Literature Review for Fuel Dispersal to the Reactor Coolant System,” NUREG/CR-XXXX, U.S. Nuclear Regulatory Commission, in press.

[6] Bielen, A., J. Corson, and J. Staudenmeier, “NRC’s Methodology to Estimate Fuel Dispersal during a Large Break Loss of Coolant Accident,” In: *20th International Topical Meeting on Nuclear Reactor Thermal Hydraulics* (NURETH-20), Washington, DC, August 20–25, 2023.

[7] Phillips, J.G., I.E. Porter, and P.A. Raynaud. “Mobility Analyses for Fuel Particles Dispersed during a LOCA,” In: *TopFuel 2015 Conference*, Zurich, Switzerland, September 3–17, 2015.

[8] Powers, D.A., and R.O. Meyer. “Cladding Swelling and Rupture Models for LOCA Analysis,” NUREG-0630, U.S. Nuclear Regulatory Commission, Washington, DC, April 1980.

[9] Campos, S.D., T.K. Howard, S. Yamasaki, G. Mignot, W. Marcum, G. Wissinger, and L. Gerken, “Identifying Important Parameters Affecting Fuel Dispersion and Relocation Phenomena Under Loss of Coolant Accident (LOCA) Conditions,” In: *American Nuclear Society Winter Meeting 2023*, Vol. 129, No. 1, pp. 1112–1115, Washington, DC, November 12–15, 2023.

[10] Vlassopoulos, E., D. Papaioannou, R. Nasyrow, V. Rondinella, S. Caruso, and E.W. Schweitzer, “Experimental Study on the Mechanical Stability of a 59 GWd/tHM Nuclear Fuel Rod,” In: *TopFuel 2021 Conference*, Santander, Spain, October 24–28, 2021.

[11] Organisation of Economic Co-operation and Development, Nuclear Energy Agency, “State-of-the-art Report on Nuclear Fuel Behaviour Under Reactivity-initiated Accident Conditions,” Report No. 7575, Paris, France, 2022.

[12] U.S. Nuclear Regulatory Commission, “Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors,” Regulatory Guide 1.183, Revision 1, Washington, DC, October 2023 (ML23082A305).

APPENDIX A

FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL PHENOMENA IDENTIFICATION AND RANKING TABLE EXPERT PANEL MEMBERS

FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL PHENOMENA IDENTIFICATION AND RANKING TABLE EXPERT PANEL MEMBERS

Francis Bolger: Mr. Bolger received his bachelor's degree in chemistry from Saint Joseph's University and his master's degree in nuclear engineering from the University of California, Berkeley. Since 2020, Mr. Bolger has been a Principal Technical Leader in the Nuclear Risk and Safety Management Program at the Electric Power Research Institute (EPRI). He leads the Modular Accident Analysis Program (MAAP) User Group and has successfully developed the modernized MAAP6 severe accident thermal-hydraulic code. Mr. Bolger also supports the Fuel Reliability Program as the lead for modeling the QUENCH accident tolerant fuel (ATF) tests with MAAP and is the technical content lead for the EPRI/U.S. Nuclear Regulatory Commission (NRC) submittal for fuel fragmentation, relocation, and dispersal (FFRD)-susceptible small- and intermediated-break pressurized-water reactor (PWR) loss-of-coolant accidents (LOCAs). This PWR LOCA analysis (using vendor methods) demonstrates that burst is not likely to occur in this portion of the break spectrum.

Before EPRI, Mr. Bolger worked for GE Hitachi (GEH) for 33 years. He managed GEH's New Product Introduction team for 8 years, focused on boiling-water reactor (BWR) fuels and services. He was the primary author for the GEH contribution to EPRI's ATF Safety Benefits program, including personally performing the ATF fuel rod analysis. He coordinated the Oak Ridge National Laboratory (ORNL) ATF testing of ATF tubing, including burst testing. His technical expertise is primarily associated with thermal-hydraulic modeling of corewide transients and accidents. He managed the GEH LOCA and Containment team, which submitted and obtained NRC approval for the TRACG BWR LOCA methodology. He was the lead author for GEH's NRC-approved Licensing Topical TRACG Application for Anticipated Operational Occurrences.

Nathan Capps: Dr. Capps received his bachelor's degree, master's degree, and PhD in nuclear engineering from the University of Tennessee. His current roles and responsibilities include managing the ORNL Advanced Fuels Campaign, vendor Accident Tolerant Fuel and High-Burnup Qualification Program, and ORNL's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. Dr. Capps' research focuses on areas in which advanced modeling and simulation capabilities might be applied to advance nuclear power and inform experimental test programs. His PhD focused on developing and applying high-fidelity tools for the Consortium for Advanced Simulation of Light Water Reactors (CASL) to understand mechanisms driving fuel rod failure due to pellet-cladding interaction. This work involved developing the BISON fuel performance code at Idaho National Laboratory, evaluating each material model required to determine fuel performance, and developing a suite of validation cases to compare BISON results with critical fuel performance characteristics. This validation allowed Dr. Capps to then develop a methodology using the Virtual Environment for Reactor Analysis and using BISON for full-core pellet-cladding interaction analysis in two-dimensional and three-dimensional cases.

More recently, his work has focused on using NEAMS tools to develop a methodology for investigating full-core FFRD susceptibility. The methodology developed through his work has been presented in NRC public meetings on high burnup fuel and is used to inform NRC and vendor methodologies. In parallel, Dr. Capps has actively worked with the U.S. Department of

Energy (DOE) to develop a high burnup LOCA test plan. He initiated this effort by publishing a critical review of high burnup fuel fragmentation, which served as the basis for the high burnup elements outline in the NRC Research Information Letter (RIL) 2021-13, “Interpretation of Research on Fuel Fragmentation, Relocation, and Dispersal at High Burnup,” dated December 17, 2021, for which he served as a technical reviewer. Dr. Capps also extensively participates in the Studsvik Cladding Integrity Program, where most of the data associated with high burnup have been generated. Additionally, Dr. Capps leads the high burnup testing program at ORNL, which has resulted in six high burnup LOCA tests and two transient fission gas release tests. Finally, Dr. Capps currently serves as the U.S. representative to the International Atomic Energy Agency’s working group on light-water-reactor (LWR) fuel performance.

David Kropaczek: Dr. Kropaczek is the Chief Executive Officer (CEO) of Veracity Nuclear, a startup company founded to commercialize software developed under DOE nuclear energy programs. Formerly, he was a distinguished research staff member at ORNL and served as deputy technical director for the DOE NEAMS program. Before that, he was Director of the CASL program, which focused on high-fidelity, coupled multiphysics reactor applications for the nuclear industry. These included solving challenging problems in fuel performance, thermal-hydraulics, and reactor kinetics, with applications for ATFs, LOCAs, and reactivity-initiated accidents (RIAs).

Dr. Kropaczek joined ORNL in 2018 after serving as CASL Chief Scientist and Duke Energy Distinguished Professor of Nuclear Engineering at North Carolina State University for 3 years. He has over 30 years of experience in nuclear energy, with a focus on computational methods development in nuclear fuel cycle optimization, reactor physics, and thermal-hydraulics for both light-water and advanced reactors. Previous experience included positions in research and development and leadership within Westinghouse, General Electric, and Studsvik Scandpower as CEO.

Dr. Kropaczek has published and presented over 100 papers in reactor physics and fuel cycle optimization and holds 28 patents related to nuclear fuels. Dr. Kropaczek is a Fellow of the American Nuclear Society (ANS). He has served in many roles in the ANS, including Chair of the Reactor Physics Division and General and Technical Program Chairs for several division-sponsored topical meetings (including MC 2021 and Advances in Nuclear Fuel Management).

Wade Marcum: Dr. Marcum is the Henry W. and Janice J. Schuette Professor in Nuclear Science and Engineering within the School of Nuclear Science and Engineering and the Senior Associate Dean for the College of Engineering at Oregon State University. He has taught courses spanning both the undergraduate and graduate levels that include introduction to engineering, thermal-hydraulics, advanced thermal-hydraulics, nuclear reactor operator training, nuclear systems design, and experimental thermal-hydraulics, among others. His research focuses on nuclear reactor safety and thermal-hydraulic aspects related to nuclear components and reactor certification and qualification testing. His research group operates within an NQA-1-compliant quality assurance program and has testified to support licensing of several nuclear plan designs as a part of the experimental data collected within this capacity. He is an author or co-author of more than 200 peer-reviewed archival publications on nuclear reactor safety and thermal-hydraulics. As Senior Associate Dean, he is responsible for the operations of the College of Engineering—the seventh largest in the Nation by enrollment, including budget, student success, hiring, infrastructure, facilities, information technology, and the ABET accreditation of all programs within the College of Engineering. Dr. Marcum has won several awards for his research, scholarship, and contribution to the advancement of science and technology within the field of nuclear engineering, including the Institute of Nuclear Materials Management Annual Meeting Best Paper Award (2016), the Oregon State University Research Collaboration Award (2017), the Oregon State University Kearney Faculty Scholar Award (2017), the ANS Landis Young Member Engineering Award (2018), the International Topical Meeting on Nuclear Reactor Thermal Hydraulics Young Professional Best Paper Award (2019), and the American Society for Engineering Education Best Campus Representative Award (2021). He is a member of the ANS, the American Society of Mechanical Engineering, and the American Society of Engineering Education.

Kurshad Muftuoglu: Dr. Muftuoglu is a Technical Executive in the EPRI Fuel Reliability Program. His primary focus is on technical and regulatory support. Dr. Muftuoglu joined EPRI in 2022. He leads the Collaborative Research on Advanced Fuel Technologies for LWRs (CRAFT) framework. He also supports the QUENCH-ATF project that investigates the chemical, mechanical, and thermal-hydraulics behavior of ATF claddings in design-basis accident and beyond-design-basis accident scenarios. Dr. Muftuoglu's background includes computational thermal-hydraulics and nuclear reactor safety. He holds a PhD from the Pennsylvania State University in nuclear engineering. He has 25 years of experience in LOCA analysis and best estimate methodology development with various nuclear fuel vendors. Before joining EPRI, Dr. Muftuoglu worked at GEH, Global Nuclear Fuels, as a principal engineer. His responsibilities included regulatory and commercial interface on issues related to LOCA, advancement of fuels and system technologies, and implementation of domestic and international licensing of realistic methodology. He has supported the ATF effort and was responsible for defending the benefits, determining applicable safety limits, and developing models for licensing calculations, as well as addressing the FFRD issues with high burnup fuel. While at GEH, Dr. Muftuoglu led an engineering team to develop best-estimate LOCA application methodology for BWRs using the TRACG code. He was one of the lead authors for GEH's NRC-approved Licensing Topical TRACG Application for LOCA. Dr. Muftuoglu's experience also includes a 10-year tenure with Westinghouse, where he championed the realistic LOCA methodology called ASTRUM for PWR applications.

Gretar Tryggvason: Dr. Tryggvason is the Charles A. Miller, Jr., Distinguished Professor at Johns Hopkins University, and the head of the Department of Mechanical Engineering. He received his PhD from Brown University in 1985 and was on the faculty of the University of Michigan in Ann Arbor until 2000, when he moved to Worcester Polytechnic Institute as the head of the Department of Mechanical Engineering. Between 2010 and 2017, he was the Viola D. Hank professor at the University of Notre Dame and the chair of the Department of Aerospace and Mechanical Engineering. Professor Tryggvason has made several contributions to computational fluid dynamics, particularly the development of methods for computations of multiphase flows and for pioneering direct numerical simulations of such flows. He is, in particular, well known for the development of the front tracking numerical method and simulations of bubbly flows; flow with phase change, including boiling; and the effect of turbulence on multiphase disperse flows. He has supervised the research of around 30 doctoral students and published many extensively cited papers, in addition to coauthoring two books on numerical simulations of multiphase flows. His research has been funded by various U.S. Government agencies, including the National Science Foundation, National Aeronautics and Space Administration, Office of Naval Research, and DOE. Between 2010 and 2020, he was a member of CASL, a DOE Nuclear Energy Innovation Hub, led by ORNL. In addition to regularly giving invited talks about his research, he has, for over 20 years, given lectures as part of the "Short Course on Modeling and Computation of Multiphase Flow," at ETH Zurich, in Switzerland. He has served on several editorial boards and was the editor-in-chief of the

Journal of Computational Physics from 2002 through 2015. He is a fellow of the American Physical Society, American Society of Mechanical Engineers (ASME), and American Association for the Advancement of Science, and the recipient of several awards, including the 2012 ASME Fluids Engineering Award and the 2019 American Society of Thermal and Fluids Engineers Award.

Wolfgang Wiesenack: Dr. Wiesenack holds a master's degree in nuclear engineering and a PhD (1983) from the University of Hanover, Germany, on LWR fuel behavior modeling.

He joined the Organisation for Economic Co-operation and Development (OECD) Halden Reactor Project in 1984. As the senior reactor physicist, he was responsible for the core physics calculations of the Halden reactor and nuclear design studies of experimental rigs. As head of the division for Data Acquisition and Evaluation, he had direct contact with many aspects of fuels and materials behavior under steady-state and ramping/transient conditions.

He became the general manager of the Halden Project in 1999 and held this position until 2009, when he assumed an advisory position as Chief Scientist with special responsibility for the planning, execution, and evaluation of the LOCA test series IFA-650.

From 2000 through 2008, he was Chairman of the OECD-Nuclear Energy Agency (NEA) "Special Experts Group on Fuel Safety Margins" and Vice Chairman of its successor "Working Group on Fuel Safety" until his retirement in 2017. He was also a member of the NEA Nuclear Science Committee and the International Atomic Energy Agency Technical Working Group on Fuel Performance and Technology. He is a member of the German Nuclear Society.

APPENDIX B

FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL PHENOMENA IDENTIFICATION AND RANKING TABLE ON HIGH BURNUP FFRD AND ITS CONSEQUENCES FOR WHOLE-CORE THERMAL EVENTS

Table B-1 High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 1, "Fuel Initial Conditions"

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
1. Fuel Initial Conditions	1.1	Fuel cycle design, including rod power history (power uprated cores), transitional vs. equilibrium cycle	Determines rod failures, gap released, initial oxidation, and most likely FFRD amount	12/5/23	GT	M	H	L/M	L	H	L	General Comment: FOM-1 U = L (PWR)/M (BWR).
				12/5/23	WW	M	H	L/M	L	M	L	
				12/5/23	NC	H	H	L/M	L	H	L	
				12/5/23	FB	M	H	L/M	L	H	L	
				12/5/23	WM	M	H	L/M	L	H	L	
				12/5/23	DK	H	H	L/M	L	H	L	
				12/5/23	KM	M	H	L/M	L	H	L	
	1.2	Core axial power distribution	Impacts fuel thermal response	12/5/23	GT	H	H	L	L	H	L	
				12/5/23	WW	H	H	L	L	M	L	
				12/5/23	NC	H	H	L	L	H	L	
				12/5/23	FB	H	H	L	L	H	L	
				12/5/23	WM	H	H	L	L	H	L	
				12/5/23	DK	H	H	L	L	H	L	
				12/5/23	KM	M	H	L	L	H	L	
	1.3	Fuel assembly peaking factor	Determines rod failures, gap releases, initial oxidation and most likely FFRD amount	12/5/23	GT	H	H	L	L	H	L	
				12/5/23	WW	H	H	L	L	H	L	
				12/5/23	NC	H	H	L	L	H	L	
				12/5/23	FB	H	H	L	L	H	L	
				12/5/23	WM	H	H	L	L	H	L	
				12/5/23	DK	H	H	L	L	H	L	
				12/5/23	KM	H	H	L	L	H	L	
	1.4	Pin peaking factor	Rod failure location, local oxidation and most likely FFRD, including importance	12/5/23	GT	H	H	L	L	H	L	General Comment: Bounding approach can be applied. Flat profile rod-to-rod.
				12/5/23	WW	H	H	L	L	H	L	
				12/5/23	NC	H	H	L	L	H	L	
				12/5/23	FB	H	H	L	L	H	L	
				12/5/23	WM	H	H	L	L	H	L	

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
			of flatness of pin peaking	12/5/23	DK	H	H	L	L	H	L	
				12/5/23	KM	M	H	L	L	H	L	
	1.5	Pellet radial power distribution	Burnup profile / high burnup rim thickness	12/5/23	GT	H	M	M	L	H	L	
				12/5/23	WW	H	M	M	L	H	L	
				12/5/23	NC	H	M	M	L	H	L	Depends on methodology selected by licensee.
				12/5/23	FB	H	M	M	L	H	L	
				12/5/23	WM	H	M	M	L	H	L	
				12/5/23	DK	H	M	M	L	H	L	
				12/5/23	KM	H	M	M	L	H	L	
	1.6	Initial stored energy in fuel	Rod failure	12/5/23	GT	M	H	M	L	H	L	
				12/5/23	WW	M	H	L	L	H	L	
				12/5/23	NC	L	H	M	L	H	L	
				12/5/23	FB	M	H	M	L	H	L	
				12/5/23	WM	M	H	M	L	H	L	
				12/5/23	DK	M	H	M	L	H	L	
				12/5/23	KM	M	H	L	L	H	L	
	1.7	Initial stored energy in structures	Impacts RCS and core thermal hydraulic response (e.g., downcomer boiling)	12/5/23	GT	L	H	L	L	H	L	
				12/5/23	WW	L	H	L	L	H	L	
				12/5/23	NC	L	H	L	L	H	L	
				12/5/23	FB	L	H	L	L	H	L	
				12/5/23	WM	L	H	L	L	H	L	
				12/5/23	DK	L	H	L	L	H	L	
				12/5/23	KM	L	H	L	L	H	L	
	1.8a	Fuel assembly spacer grid	Locations where debris, dispersed fuel can be trapped	12/5/23	GT	H	L	H	L	H	L	
				12/5/23	WW	H	L	H	L	M	L	
				12/5/23	NC	H	L	H	L	H	L	
				12/5/23	FB	H	L	H	L	H	L	
				12/5/23	WM	H	L	H	L	H	M	
				12/5/23	DK	H	L	H	L	H	L	
				12/5/23	KM	H	L	H	L	H	L	

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
	1.8b	Fuel assembly inlet nozzle design	Locations where debris, dispersed fuel can be trapped	12/5/23	GT	L	L	M	L	H	L	
				12/5/23	WW	M	M	M	L	H	L	
				12/5/23	NC	L	M	M	L	H	L	
				12/5/23	FB	L	L	M	L	H	L	
				12/5/23	WM	L	L	M	L	H	L	
				12/5/23	DK	L	L	M	L	H	L	
				12/5/23	KM	L	L	M	L	H	L	
	1.9	Hydrogen pickup in cladding material	Impact on cladding high-temperature mechanical performance (balloon and rupture size)	12/5/23	GT	M	H	M	L	H	L	
				12/5/23	WW	H	H	L	L	H	L	
				12/5/23	NC	L	M	M	L	H	L	
				12/5/23	FB	M	M	M	L	H	L	
				12/5/23	WM	M	H	M	M	H	L	
				12/5/23	DK	M	H	M	L	H	L	
				12/5/23	KM	M	H	M	L	H	L	
	1.10	Cladding oxidation—inner	Pre-transient cladding oxidation due to fuel clad bonding	12/5/23	GT	L	H	L	L	H	L	
				12/5/23	WW	L	H	L	L	H	L	
				12/5/23	NC	L	H	L	L	H	L	
				12/5/23	FB	L	H	L	L	H	L	
				12/5/23	WM	L	M	L	L	H	L	
				12/5/23	DK	L	H	L	L	H	L	
				12/5/23	KM	L	M	L	L	H	L	
	1.11	Cladding crud deposits	Initial cladding temperatures	12/5/23	GT	L	H	L	L	H	L	
				12/5/23	WW	L	H	L	L	H	L	
				12/5/23	NC	L	H	L	L	H	L	
				12/5/23	FB	L	H	L	L	H	L	
				12/5/23	WM	L	H	L	L	H	L	
				12/5/23	DK	L	H	L	L	H	L	
				12/5/23	KM	L	H	L	L	H	L	
	1.12			12/5/23	GT	L	H	L	L	H	L	
				12/5/23	WW	L	H	L	L	H	L	
				12/5/23	NC	L	H	L	L	H	L	

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		Pre-transient reactor coolant conditions	Higher exit temperature results in higher corrosion/crud	12/5/23	FB	L	H	L	L	H	L	
				12/5/23	WM	L	H	L	L	H	L	
				12/5/23	DK	L	H	L	L	H	L	
				12/5/23	KM	L	H	L	L	H	L	
	1.14	Core-wide 3D spatial burnup distribution—pin-to-pin in the core	Most important factor for determining when you perform FFRD analysis	12/5/23	GT	H	H	L	L	H	L	
				12/5/23	WW	H	H	L	L	H	L	
				12/5/23	NC	H	H	L	L	H	L	
				12/5/23	FB	H	H	L	L	H	L	
				12/5/23	WM	H	H	L	L	H	L	
				12/5/23	DK	H	H	L	L	H	L	
				12/5/23	KM	H	H	L	L	H	L	
	1.15	Rod gas pressure	Rod failure/dispersal	12/6/23	GT	H	H	M				General Comment: Moving forward, FOM-2 will not be ranked unless there is a difference of opinion (I=L, S=H, U=L).
				12/6/23	WW	H	H	M				
				12/6/23	NC	H	H	M				
				12/6/23	FB	H	M	M				
				12/6/23	WM	H	M	M				
				12/6/23	DK	H	H	M				
				12/6/23	KM	H	M	M				
	1.16	Rod gap size	Gap most likely closed at initial rod powers and moderate burnups	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	1.17	Rod gas composition	Gap conductance	12/6/23	GT	L	H	L				General Comment: Steady state.
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	1.18	Rod free volume	Possible FFRD effect	12/6/23	GT	M	H	L				
				12/6/23	WW	M	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	M	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	M	H	L				
				12/6/23	KM	H	H	L				
	1.19	Rod gas volume communication	Number of burst locations and FFRD	12/6/23	GT	H	M	M				
				12/6/23	WW	H	M	M				
				12/6/23	NC	H	M	M				
				12/6/23	FB	H	M	H				
				12/6/23	WM	H	M	M				Dr. Marcum ranked I=L/M—selected I=M.
				12/6/23	DK	H	M	M				
				12/6/23	KM	H	L	M				
	1.20	Fuel thermal properties	Initial stored energy	12/6/23	GT	H	H	L				
				12/6/23	WW	H	H	L				
				12/6/23	NC	H	H	L				
				12/6/23	FB	H	H	L				
				12/6/23	WM	H	H	L				
				12/6/23	DK	H	H	L				
				12/6/23	KM	H	H	L				
	1.21	Burnable absorber (IFBA/WABA/Gadolinia)	Generally at lower burnups than fuel rods but can operate at moderate to higher powers at moderate/high burnups	12/6/23	GT	M	H	M				
				12/6/23	WW	M	M	M				
				12/6/23	NC	M	H	M				
				12/6/23	FB	M	M	H				
				12/6/23	WM	M	M	H				
				12/6/23	DK	M	H	M				
				12/6/23	KM	M	H	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
			(conductivity, rod internal pressure, high-burnup structure and fragmentation behavior)									
	1.22	Fissile material composition	Radioactive isotope inventory, recriticality	12/6/23	GT	L	H	L	M	H	L	
				12/6/23	WW	L	H	L	M	H	L	
				12/6/23	NC	L	H	L	M	H	L	
				12/6/23	FB	L	H	L	M	H	L	
				12/6/23	WM	L	H	L	M	H	L	
				12/6/23	DK	L	H	L	M	H	L	
				12/6/23	KM	L	H	L	L	H	L	
	1.23	Fuel pellet cracking/ relocation—normal operation	Impact on conductivity, stored energy	12/6/23	GT	M	H	L				
				12/6/23	WW	M	H	L				
				12/6/23	NC	H	H	L				Relevant to startup and fresh fuel only.
				12/6/23	FB	H	M	M				When considering high burnup.
				12/6/23	WM	H	H	L				
				12/6/23	DK	M	H	L				
				12/6/23	KM	H	H	L				
	1.24	Fission gas release	Radiological and initial pressure	12/6/23	GT	H	H	M				
				12/6/23	WW	H	H	M				
				12/6/23	NC	H	H	M				
				12/6/23	FB	H	H	M				
				12/6/23	WM	H	H	H				
				12/6/23	DK	H	H	M				
				12/6/23	KM	H	H	L				

Table B-2: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 2, “Transient Power Distribution”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
2.Transient Power Distribution	2.1	Moderator reactivity feedback	Impact on fission power	12/6/23	GT	L	H	L	L	H	L	
				12/6/23	WW	L	H	L	L	H	L	
				12/6/23	NC	L	H	L	L	H	L	
				12/6/23	FB	L	H	L	L	H	L	N/A to a LOCA.
				12/6/23	WM	L	H	L	L	H	L	
				12/6/23	DK	L	H	L	L	H	L	Look at incrementally.
				12/6/23	KM	L	H	L	L	H	L	
	2.2	Fuel temperature reactivity feedback	Impact on fission power	12/6/23	GT	L	H	L	L	H	L	
				12/6/23	WW	L	H	L	L	H	L	
				12/6/23	NC	L	H	L	L	H	L	
				12/6/23	FB	L	H	L	L	H	L	
				12/6/23	WM	L	H	L	L	H	L	
				12/6/23	DK	L	H	L	L	H	L	
				12/6/23	KM	L	H	L	L	H	L	
	2.3	Decay heat	Decay heat of actinides and FPs (deposited mainly in fuel) impacts temperature	12/6/23	GT	M	H	L				
				12/6/23	WW	M	H	L				Incrementally.
				12/6/23	NC	H	H	L				
				12/6/23	FB	M	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	M	H	L				
				12/6/23	KM	L	H	L				
	2.4	Delayed neutron fraction	Impact on fission power	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	KM	L	H	L				
	2.5	Energy deposition in fuel and outside	Impact on fuel thermal response	12/6/23	GT	L	H	L				
				12/6/23	WW	M	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				

Table B-3: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 3, “Transient / Steady-state Heat Transfer from Cladding (Blowdown, Refill, Reflood, Core Spray)”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	So K	U	Imp.	So K	U	
3. Transient/steady-state heat transfer from cladding (blowdown, refill, reflood, core spray)	3.1	Single-phase convection	Impact on cladding temperature	12/6/23	GT	L	H	L				General Comment: Debris is discussed in subsequent categories. See categories 7 and 8.
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.2	Boiling (subcooled, nucleate, bulk)	Impact on cladding temperature, mixture level	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.3	Liquid droplet entrainment	Impact on cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.4	Liquid droplet vaporization	Impact on cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.4	Critical heat flux	Impact on cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.5	Film boiling (inverted annular, dispersed flow)	Impact on cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.6	Fuel rewet	Impacts cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.7a	Rod-grid interaction (thermal)	Limits ballooning, results in cooler spot	12/6/23	GT	H	M	M				
				12/6/23	WW	M	M	M				
				12/6/23	NC	H	H	L				
				12/6/23	FB	H	H	L				
				12/6/23	WM	H	H	L				
				12/6/23	DK	H	M	M				
				12/6/23	KM	M	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
	3.8	Spacer grid rewetting, droplet breakup	Impact on cladding temperature	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	3.9	Coplanar rod ballooning and packing fraction at more than one location impact on heat transfer	Rod failure of adjacent rods and coolability	12/6/23	GT	M	M	H				
				12/6/23	WW	H	L	H				
				12/6/23	NC	M	M	H				
				12/6/23	FB	M	M	H				
				12/6/23	WM	M	M	H				
				12/6/23	DK	M	M	H				
				12/6/23	KM	M	M	H				

Table B-4: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 4, “Transient Core Coolant Conditions”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
4. Transient Core Coolant Conditions	4.1	Pressure	Contributes to differential pressure and cladding stresses	12/6/23	GT	M	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	M	H	L				
				12/6/23	FB	M	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	M	H	L				
				12/6/23	KM	L	H	L				
	4.2	Temperature (fluid outside cladding)	Impact on coolability	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	4.3	Void fraction	Impact on core mixture level, fuel uncovery	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	4.4	Flow quality	Impact on coolability	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	KM	L	H	L				
	4.5a	Mass flux, direction (CCFL)	Impact on coolability	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	4.5b	Coolant mass flux	Impact on coolability	12/6/23	GT	M	H	L				
				12/6/23	WW	M	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	M	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	4.5c	Coolant mass flux	Impact on particle mobility	12/6/23	GT	H	L	H				
				12/6/23	WW	M	L	H				
				12/6/23	NC	H	L	H				
				12/6/23	FB	H	L	H				
				12/6/23	WM	H	L	H				
				12/6/23	DK	H	L	H				
				12/6/23	KM	M	L	H				
	4.6	Formation, transport, and deposition of coagulants in the core	Clogging of debris beds formed by dispersed fuel and/or containment debris	12/6/23	GT	H	L	H	M	H	L	
				12/6/23	WW	M	M	M	L	M	L	
				12/6/23	NC	H	L	H	M	H	L	
				12/6/23	FB	H	L	H	M	M	M	
				12/6/23	WM	H	L	H	M	H	L	
				12/6/23	DK	M	L	H	M	H	L	
				12/6/23	KM	M	L	H	M	H	L	

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
	4.7	Boron precipitation from boiling in the core	Flow blockage	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L	L	H	L	
				12/6/23	KM	L	H	L				
	4.8a	Effects of flow blockage—inlet nozzle	Impact on core coolability	12/6/23	GT	L	M	M				
				12/6/23	WW	M	M	M				
				12/6/23	NC	L	M	M				
				12/6/23	FB	L	M	M				
				12/6/23	WM	L	M	M				
				12/6/23	DK	L	M	M				
				12/6/23	KM	L	M	M				
	4.8b	Effects of flow blockage—grid spacers	Impact on core coolability	12/6/23	GT	H	L	H				
				12/6/23	WW	M	M	M				
				12/6/23	NC	H	L	H				
				12/6/23	FB	H	L	H				
				12/6/23	WM	H	L	H				
				12/6/23	DK	M	M	M				
				12/6/23	KM	M	M	M				
	4.9	Coplanar rod ballooning	Impact on core coolability	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	M	H	L				
				12/6/23	DK	M	H	L				
				12/6/23	KM	L	H	L				

Table B-5: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 5, “Fuel Rod Transient Response”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
5. Fuel Rod Transient Response	5.1a	Clad plastic deformation (thinning, ballooning, burst)	ECR, cladding failure, fuel relocation	12/6/23	GT	H	M	M				
				12/6/23	WW	H	M	M				
				12/6/23	NC	H	M	M				
				12/6/23	FB	H	M	M				
				12/6/23	WM	H	M	H				
				12/6/23	DK	H	M	M				
				12/6/23	KM	H	M	M				
	5.1b	Extent of axial ballooning	Impact on fuel relocation and extent of fuel fragmentation	12/6/23	GT	H	M	H				
				12/6/23	WW	H	M	H				
				12/6/23	NC	H	M	H				
				12/6/23	FB	H	M	H				
				12/6/23	WM	H	M	H				
				12/6/23	DK	H	M	H				
				12/6/23	KM	H	M	H				
	5.1c	Rod-grid interaction (mechanical)	Mechanically impacts ballooning and amount of dispersal	12/6/23	GT	H	M	M				
				12/6/23	WW	H	M	M				
				12/6/23	NC	H	M	H				
				12/6/23	FB	H	M	H				
				12/6/23	WM	H	M	H				
				12/6/23	DK	H	M	M				
				12/6/23	KM	H	H	L				
	5.3	Clad differential pressure load	Rod failure and dispersal	12/6/23	GT	H	H	M				
				12/6/23	WW	H	M	M				
				12/6/23	NC	H	H	M				
				12/6/23	FB	H	M	M				
				12/6/23	WM	H	M	H				
				12/6/23	DK	H	M	H				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	KM	H	H	M				
	5.4	Clad loading during quench	Rod failure	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				12/6/23	WM	L	H	L				
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.5	Clad thermal deformation	Clad azimuthal thermal bending deformation	12/6/23	GT	L	M	M				
				12/6/23	WW	L	M	M				
				12/6/23	NC	L	M	M				
				12/6/23	FB	L	M	M				
				12/6/23	WM	M	M	M				
				12/6/23	DK	L	M	M				
				12/6/23	KM	L	M	M				
	5.6	Clad elastic deformation	Contributes to rod dimensional changes	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.7	Pellet thermal deformation	Enhances fragmentation	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/6/23	KM	L	H	L				
	5.8	Pellet swelling	No immediate correlation to FFRD	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.9	Transient fission gas release	Contributes to cladding rupture, dispersal, and radiological release	12/6/23	GT	H	L	H				
				12/6/23	WW	H	M	M				
				12/6/23	NC	H	L	H				
				12/6/23	FB	H	L	H				
				1/15/24	WM	H	L	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	H	M	H				
				12/6/23	KM	M	L	H				
	5.10	Fuel temperature distribution—pellet radial	Fuel fragmentation, transient fission gas release	12/6/23	GT	M	H	L				
				12/6/23	WW	M	H	L				
				12/6/23	NC	M	H	L				
				12/6/23	FB	M	H	L				
				1/15/24	WM	M	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	M	H	L				
				12/6/23	KM	M	H	L				
	5.11a	Clad temperature	Ballooning and burst location	12/6/23	GT	H	H	L				
				12/6/23	WW	H	H	L				
				12/6/23	NC	H	H	L				
				12/6/23	FB	H	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		distribution—axial		1/15/24	WM	H	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	H	H	L				
				12/6/23	KM	H	H	L				
	5.11b	Clad temperature distribution—azimuthal	Ballooning and burst location	12/6/23	GT	L	M	M				
				12/6/23	WW	L	M	M				
				12/6/23	NC	L	M	M				
				12/6/23	FB	L	M	M				
				1/15/24	WM	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	M	M				
				12/6/23	KM	L	M	M				
	5.13	Clad thermal resistance—radial, axial	Cladding oxidation/hydriding	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.14	Clad oxide layer thermal resistance—radial	Transient oxidation/hydriding and ECR	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.15			12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		Clad oxidation—inner, outer surface	Transient oxidation/hydriding and ECR	12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	M	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist. Clad oxidation compounds over the life of a fuel rod; it further amplifies under extended burnup conditions. This, in turn, thins cladding and results in a lower required burst-pressure for failure. This plays a role measurably into coolable geometry and thus why I ranked it medium.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.16	Metal-water oxidation heat release	Transient oxidation/hydriding and ECR	12/6/23	GT	L	H	L				
				12/6/23	WW	L	H	L				
				12/6/23	NC	L	H	L				
				12/6/23	FB	L	H	L				
				1/15/24	WM	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	L	H	L				
				12/6/23	KM	L	H	L				
	5.17	Fuel fragmentation mass during heatup	Mass source term for dispersal	12/6/23	GT	H	M	M				
				12/6/23	WW	H	M	H				
				12/6/23	NC	H	M	M				
				12/6/23	FB	H	M	M				
				1/15/24	WM	H	M	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/6/23	DK	H	M	M				
				1/15/24	KM	H	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
												As the relevance indicates, it will directly affect the mass source term for dispersal and only a concern for coolability (no criticality concerns).
	5.18	Fragmented fuel size distribution	Radiological, coolability, and criticality	12/7/23	GT	H	H	L				
				12/7/23	WW	M	H	L				
				12/7/23	NC	M	H	L				
				12/7/23	FB	M	M	M				
				12/7/23	WM	H	M	M				
				12/7/23	DK	M	H	M				
				12/7/23	KM	M	M	M				
	5.19	Fuel relocation and packing fraction in ballooning regions	Coolability	12/7/23	GT	M	M	M				
				12/7/23	WW	H	M	M				
				12/7/23	NC	H	M	M				
				12/7/23	FB	M	M	M				
				12/7/23	WM	H	M	M				
				12/7/23	DK	H	M	M				
				12/7/23	KM	H	M	M				
	5.20a	Fuel relocation (in between grid spacers)	Limits dispersed mass	12/7/23	GT	H	M	M				
				12/7/23	WW	H	M	M				
				12/7/23	NC	H	M	M				
				12/7/23	FB	H	M	M				
				12/7/23	WM	H	M	M				
				12/7/23	DK	H	M	M				
				12/7/23	KM	H	M	M				
	5.20b	Effect of grid spacer on relocation	Limits dispersed mass	12/7/23	GT	H	M	M				
				12/7/23	WW	H	M	M				
				12/7/23	NC	H	M	M				
				12/7/23	FB	H	H	L				
				12/7/23	WM	H	H	L				
				12/7/23	DK	H	M	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/7/23	KM	H	H	L				
	5.22	Cladding phase changes	Cladding ductility/burst	12/7/23	GT	L	H	L				
				1/16/24	WW	H	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	L	H	L				
				12/7/23	FB	L	H	L				
				12/7/23	WM	L	H	L				
				12/7/23	DK	L	H	L				
				12/7/23	KM	L	H	L				
	5.23	Fuel properties—thermal, mechanical	Fuel temperature response	12/7/23	GT	M	H	L				
				1/16/24	WW	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	L	H	L				
				12/7/23	FB	M	H	M				
				12/7/23	WM	M	H	L				
				12/7/23	DK	M	H	L				
				12/7/23	KM	M	H	L				
	5.24a	Clad rupture—criteria	Rod failure and burst size	12/7/23	GT	H	H	L				
				1/16/24	WW	H	H	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	H	H	L				
				12/7/23	FB	H	H	L				
				12/7/23	WM	H	H	L				
				12/7/23	DK	H	H	L				
				12/7/23	KM	M	H	M				
	5.24b	Clad rupture geometry (width, length, shape)	Rod failure, dispersal	12/7/23	GT	M	M	H				
				1/16/24	WW	H	L	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	M	H	H				
				12/7/23	FB	M	M	H				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/7/23	WM	M	M	H				
				12/7/23	DK	M	M	H				
				12/7/23	KM	M	M	H				
	5.26	Gap transient behavior—size, heat resistance	Fuel/cladding temperature vs. time	12/7/23	GT	L	M	L				
				1/16/24	WW	M	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	L	H	L				
				12/7/23	FB	L	H	L				
				12/7/23	WM	L	H	L				
				12/7/23	DK	L	M	L				
				12/7/23	KM	L	M	L				
	5.27	Clad burst—size, shape, single, multiple	Dispersal mass	12/7/23	GT	H	M	M				
				12/7/23	WW	H	M	H				
				12/7/23	NC	H	H	L				
				12/7/23	FB	M	M	H				
				12/7/23	WM	H	M	M				
				12/7/23	DK	H	M	M				
				12/7/23	KM	M	M	H				
	5.28a	Core axial location of burst	Dispersal (burnup axial distribution)	12/7/23	GT	M	M	M				
				1/16/24	WW	M	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	M	M	M				
				12/7/23	FB	M	M	M				
				12/7/23	WM	M	M	M				
				12/7/23	DK	M	M	M				
				12/7/23	KM	M	M	M				
	5.28b	Grid span axial location	Dispersal	12/7/23	GT	M	M	M				
				1/16/24	WW	M	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	M	M	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/7/23	FB	M	M	M				
				12/7/23	WM	M	M	M				
				12/7/23	DK	M	M	M				
				12/7/23	KM	M	M	M				
	5.28c	Burst azimuthal orientation	Dispersal	12/7/23	GT	M	M	H				
				1/16/24	WW	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	M	M	H				
				12/7/23	FB	M	M	H				
				12/7/23	WM	M	M	H				
				12/7/23	DK	L	M	H				
				12/7/23	KM	L	M	M				
	5.29	Time of burst	Dispersal	12/7/23	GT	M	H	M				
				1/16/24	WW	L	H	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				12/7/23	NC	M	H	M				
				12/7/23	FB	M	H	M				
				12/7/23	WM	M	H	M				
				12/7/23	DK	M	M	H				
				12/7/23	KM	L	H	L				
	5.30	Axial gas communication in the fuel rod	Rod ballooning, burst, and dispersal	12/7/23	GT	H	M	H				
				12/7/23	WW	H	M	H				
				12/7/23	NC	H	M	H				
				12/7/23	FB	H	M	H				
				12/7/23	WM	H	M	H				
				12/7/23	DK	H	M	H				
				12/7/23	KM	H	L	M				

Table B-6: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 6, “Fuel Dispersal”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
6. Fuel Dispersal	6.1	Rod internal pressure differential	Rod burst and dispersal	12/7/23	GT	M	L	H				
				1/16/24	WW	H	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist
				12/7/23	NC	M	L	H				
				12/7/23	FB	M	L	H				
				12/7/23	WM	M	L	H				
				12/7/23	DK	M	L	H				
				12/7/23	KM	M	L	H				
	6.2a	Particle size-to-opening width ratio	Dispersal mass	12/7/23	GT	H	L	H				
				1/16/24	WW	H	L	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist
				12/7/23	NC	H	M	H				
				12/7/23	FB	H	M	M				
				12/7/23	WM	H	L	H				
				12/7/23	DK	H	L	H				
				12/7/23	KM	H	M	H				
	6.2b	Burst opening—size, shape	Dispersal mass	12/7/23	GT	H	M	M				
				1/16/24	WW	H	L	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist
				12/7/23	NC	H	H	M				
				12/7/23	FB	H	M	M				
				12/7/23	WM	H	L	H				
				12/7/23	DK	H	M	M				
				12/7/23	KM	H	M	H				
	6.3a	Rod opening axial location—single (NC)	Dispersal mass. Axial location of dispersed mass	12/20/23	GT	L	M	M				
				12/14/23	WW	L	M	M				
				12/21/23	NC	M	H	M				
				12/18/23	FB	L	M	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
				12/20/23 01/15/24	WM	L	M	M				
				12/26/23	DK	M	M	M				
				01/10/24	KM	L	H	L				
	6.3b	Rod opening axial location—multiple (NC)(6)	Dispersal mass. Axial location of dispersed mass	01/19/24	GT	M	M	M				It seems likely that, once a rod bursts, it will reduce the probability of further failure in the same rod.
				01/19/24	WW	L	M	M				
				12/21/23	NC	L(6)	L6)	L6)				(6) There is very limited or likely no data documenting multiple rupture events. I think one Halden test exists. Therefore, it is possible, but the probability is incredibly low. My recollection is the Halden test had a second rupture with a pin whole. This aligns with high rupture temperature, smaller balloon rupture conditions.
				01/19/24	FB	L	M	M				
				01/19/24	WM	M	L	H				The impact of multiple failures in a single rod versus one rod failure will play a role in the overall impact of dispersal. However, there are multiple factors that compete against one another in this instance. Depending upon the location of the multiple failures (within the same axial region or distanced) will lead to more or less fuel dispersal. We do not have much of any knowledge as to the impact of this, although we do have a number of testing campaigns that have been conducted historically, such as PFB and PHEBUS, as an industry, that show the likelihood of this occurring.
				01/19/24	DK	L	L	H				Multiple failures within a single rod (double balloon) will reduce the opening size, resulting in reduced burst opening and, most likely, reduced dispersal. Single burst would be most limiting.
				01/19/24	KM	M	H	L				Burst opening in an array of rods would be different than single rod experiments. There are competing effects: physical limit on the ballooning because of potential rod-to-rod touching and preferential

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
												azimuthal deformation due to radiative heating from neighboring rods. Accounting for these effects in the LOCA modeling would ultimately govern the burst opening size and can potentially affect the dispersal mass. Therefore I ranked it H, with M/M for SoK and Uncertainty.
	6.4	Surrounding coolant conditions—vapor, liquid. Surrounding coolant flow characteristics—vapor, liquid (FB)	Fuel coolant interaction. Transportability of dispersed mass (FB)	12/20/23	GT	H	M	M				Given the higher velocity more likely to be seen in the vapor than in liquid, the surrounding coolant is important.
				12/14/23	WW	H	M	M				
				12/21/23 01/19/24	NC	M	H	L				
				12/18/23 01/19/24	FB	H	M	M	M	M	M	
				12/20/23 01/15/24	WM	M	H	M				We have a good understanding of the conditions and their respective coolant states under a variety of fuel failure scenarios (High SoK); this, however, doesn't preclude the nominal uncertainties that are drawing from these unique scenarios (M U). There doesn't exist, at present, a mechanistic ability to predict the basis behind fuel failure due to and/or during a specific set of coolant state conditions and as such I believe this caries a medium importance.
				12/26/23	DK	M	H	M				Rod burst into vapor faces has greater opportunity to carry entrained particulates throughout the system, with potential for deposition on structures, such as grids, that could accumulate. This will relate also to time of burst. Coolant vapor condition may also be favorable to larger mass release vs. liquid due to "dam" effect.
				01/08/24	KM	M	H	L				Surrounding coolant conditions affect the cooling of the fragments. Coolant conditions are fairly well determined from the thermal hydraulic calculations.

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
	6.5	Effect of fragmented fuel size distribution and characteristics on dispersal	Coolability(1) and criticality	12/20/23 01/30/24	GT	H	M	H				The size of the fragments is critical in determining whether the fragments are carried away with the flow or fall down.
				12/14/23	WW	M	M	M	L	M	M	
				12/21/23	NC	H	M(7)	H				(7) There are data available on size distribution, but the uncertainty is fairly high. Through nonnuclear sources, we know something about transport characteristics about dispersal.
				12/18/23	FB	H	M	H	L	M	L	(1) Affects how material will be carried by the flow stream and how much may build up on spacers.
				12/20/23 01/15/24	WM	H	M	H				We have demonstrated this empirically to be one of the single most influential factors that drive overall dispersal quantities from fuel and thus will lead to coolable geometry. Very important parameter. There exists some level of knowledge, but this knowledge leads to high quantities of uncertainty.
				12/26/23	DK	H	L	H	M	H	L	Fragment fuel size distribution is a key parameter to the amount of mass released through clad rupture and subsequent transport. Large fragments may have the 'dam' effect on material through the breach while smaller particulate size would likely be released and transported upon burst. This is closely related to 6.2a and 6.2b. Criticality would be due to ability to form coagulants as per 4.6.
				01/08/24 01/19/24	KM	H	H	M				It would be easier to disperse smaller particles compared to large ones. Size distribution has a moderate effect on dispersal.

Table B-7: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 7, “Multiple Rod Effects—Mechanical”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
7. Multiple Rod Effects - Mechanical	7.1	Rod-to-rod interactions(8)	Rod burst and coolability	12/20/23 01/19/24	GT	M	M	M				It seems unlikely that minor changes in the relative location of other rods would have much impact.
				12/14/23	WW	M	M	M				
				12/21/23	NC	L(8)	H(8)	L(8)				(8) There have been a number of bundle tests intended to make a worst case ballooning condition. Anything we should expect in reactor should be less severe.
				12/18/23	FB	L	M	M	L	H	L	
				12/20/23 01/15/24 01/19/24	WM	M	M	M				We know that rods fail toward other rods, and we also have seen that this, in fact, plays a role in the quantity of fuel loss, further, it also impacts ballooning shape. We do not have a comprehensive level of knowledge on this topical area for reactor-relevant conditions, as those tests were done in extreme scenarios and their respective uncertainty was nontrivial from test to test.
				12/26/23	DK	L	M	M				Rod-to-rod interactions with respect to rod burst would be minimal along with coolability as relates to HBU.
				01/08/24 01/19/24	KM	L	M	M				Rod-to-rod touching would ultimately limit the amount of ballooning. This would affect the relocation and ultimately the burst.
	7.2	Rod bowing between spacer grids(9)	Rod burst and coolability	12/20/23 01/19/24	GT	L	M	M				It seems unlikely that bowing of the rods has much effect, particularly if they all bow in the same direction.
				12/14/23	WW	M	M	M				
				12/21/23	NC	L(9)	H(9)	M(9)				(9) We know bowing is possible during the rupture event, but the data and experimental conditions suggest this is exacerbated by the experimental conditions and the fact that a 12″ rod was used for the test instead of a 12′ long rod.
				12/18/23	FB	L	M	M	L	H	L	

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				12/20/23 01/15/24	WM	M	M	M				Bowing will in fact impact the coolable geometry as it alters a subchannels cross-sectional area and thus the coolant subchannel. The significance of this specific aspect on the overall influence of dispersal and/or coolable geometry is not entirely known. Most rods should bow in the same direction, causing a generally complementary direction and impact their geometric translation.
				12/26/23	DK	L	M	M				Historical fuel rod bowing in PWRs seen during normal operation tends to occur as displacement in a common direction for all rods within the lattice due to power gradients or mechanical stresses. It would be expected that bowing, if it occurs during the LOCA transient response, would follow a similar behavior. Bowing could place additional stresses on the fuel pre-transient that could exacerbate susceptibility to rod burst but this would exist regardless of HBU fuel.
				01/08/24	KM	L	H	L				Deformation of rods between spacer grids has no significant relevance on coolability.
	7.3	Surrounding rod impact on fuel dispersal	Rod burst propagation(2) and dispersal consequences (NC)(10)	12/20/23	GT	M	L	H				In general, the effect of complex geometry on dispersal of particles is not well understood, but it is known that relatively minor changes can have significant impact.
				12/14/23	WW	L	M	H				
				12/21/23	NC	M	L(10)	H				(10) The possible concern I see is multiple rods rupturing towards each other, creating a “pile” of fuel.
				12/18/23	FB	M	M	M				(2) Similar to 7.1. Like the azimuthal burst location 5.28c but more of a secondary effect.
				12/20/23 01/15/24	WM	M	L	M				I don’t differentiate 7.1 and 7.3 much in a significant way. Rods adjacent to the failed rod have empirically shown to impact the quantity of fuel dispersed.
				12/26/23	DK	M	M	H				Evidence was presented that rod burst propagation is impacted by surrounding fuel rods, which serve to limit the amount of material dispersed.

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/08/24 01/19/24	KM	M	M	M				The surrounding rods would have an effect of limiting the dispersal by physically blocking the amount of ballooning. This aspect can be bounded.
	7.4	Flow constraining/ blockage from coplanar ballooning/burst of multiple rods and locations(11)	Coolability(3)	12/20/23 01/19/24	GT	M	M	M				This seems very unlikely to happen, but is likely to significantly increase the probability of blockage if it did.
				12/14/23 01/19/24	WW	M	M	M				
				12/21/23	NC	L(11)	H(11)	L(11)				(11) Again, worst case bundle experiments tell us this isn't possible, as 90% flow blockage will promote cooling.
				12/18/23 01/19/24 01/30/24	FB	L	M	M	L	H	L	(3) Similar to 7.1
				12/20/23 01/15/24	WM	M	M	M				We've seen this occur in PHEBUS tests. It can and does impact flow geometry and directly, which impacts coolable geometry. Further, the form-losses impact the total quantity of fuel that can be dispersed from a failed location.
				12/26/23 01/19/24	DK	L	M	M				The axial burnup and power dependence for rods within the same fuel lattice would have similar behavior, so the risk of coplanar ballooning and burst would need to be evaluated for flow blockage. This would be especially true if flow blockage at the downstream grid were a possibility as per 4.8b.
				01/08/24 01/19/24	KM	L	M	M				No coolability concerns exist with coplanar ballooning.

Table B-8: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 8, "Multiple Rod Effects—Thermal"

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
8. Multiple Rod Effects—Thermal	8.1	Heat transfer between rods and fuel debris bed(12)	Cladding failure(4)	12/20/23	GT	M	L	H				A large enough debris bed could decrease the cooling.
				12/14/23	WW	L	L	H				
					NC	M(12)	H(12)	H(12)				(12) Heat transfer is a fairly common practice between rods, and now an additional heat source term has been added. An analysis is possible, but I am unaware of any data to support those conclusions.
				12/18/23	FB	H	L	H	L	H	L	(4) This is critical to understanding if the geometry will remain coolable.
				12/20/23 01/15/24	WM	M	L	M				We have information from fuel debris bed heat transfer through TMI studies increasing the state of knowledge a bit, but still, under high-burnup scenarios, this is limited given the fragmentation size changes that occur and the localization of a fueled rod. This will lead to low knowledge and some quantity of uncertainty that is nonprescriptive within our existing state of knowledge.
				12/26/23 01/19/24	DK	M	H	L				Cross flow would still be expected to provide sufficient convective cooling in the event of multirod failures, but a sufficient fuel debris bed such as around grid spacers could decrease locally the amount of cooling.
				01/08/24	KM	M	L	M				Cladding failure is unlikely since the particles would be well cooled when dispersed. (Assuming bounding assumptions can be applied.)
	8.2	Heat transfer between bundle structure	Coolable geometry	12/20/23	GT	M	L	H				It seems unlikely that this is significant, but my impression is that relatively little is known.
				12/14/23	WW	L	L	H				
					NC	L(13)	H(13)	M(13)				(13) I assume this refers to grid-spacer and mixing veins. I fail to see how this could be a high or medium important issue. A heat transfer analysis would be

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		elements(13) and fuel debris bed										able to capture the phenomenon, however, I see a lack of data driving the uncertainty.
				12/18/23	FB	M	L	M				
				12/20/23 01/15/24	WM	M	L	M				Similar to 8.1, we do have some knowledge of this, but it is not applicable under the conditions detailed under the scope of this PIRT; the impact of overall heat transport is relevant from this particular mode as it relocates the distribution of solid storage heat transport term to a less favorable heat removal geometry. The total impact is unknown, thus a medium uncertainty.
				12/26/23	DK	L	M	M				For the bundle structure, there should still be sufficient cross flow to provide cooling despite a potentially larger fuel debris bed.
				01/08/24	KM	L	H	M				Dispersed particles are expected to be well cooled and are unlikely to cause adverse effects on the bundle structures.
	8.3	Rod-to-channel box radiative heat transfer (BWR)	Clad temperature(5)		GT	L	M	M				
				12/14/23 01/19/24	WW	L	M	M				
					NC	L	H	L				
				12/18/23	FB	L	H	L	L	H	L	(5) This (and 8.4) is typical BWR phenomena that I don't see changing with HBU or FFRD.
				12/20/23 01/15/24	WM	L	H	L				This will have little to no impact of overall coolable geometry under extended burnup conditions.
				12/26/23	DK	L	M	M				FFRD itself would not change radiative heat transfer cooling from the fuel rods except in ballooned regions with a larger heat source due to relocated material. This would be expected to be accommodated by other convected heat transfer.
				01/08/24	KM	L	H	L				From an incremental point of view, there is no impact of high burnup fuel or dispersed fragments on rod-to-channel box radiative heat transfer.

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
	8.4	Rod-to-water rod radiative heat transfer (BWR)	Clad temperature	12/20/23	GT	L	M	M				Unlikely to be important
				12/14/23	WW	L	M	M				
					NC	L	H	L				
				12/18/23	FB	L	H	L				
				12/20/23 01/15/24	WM	L	L	L				This will have little to no impact on overall coolable geometry under extended burnup conditions.
				12/26/23	DK	L	M	M				Similar to 8.3, FFRD itself would not change radiative heat transfer cooling from the fuel rods except in ballooned regions with a larger heat source due to relocated material. This would be expected to be accommodated by other convected heat transfer.
				01/08/24	KM	L	H	L				From incremental point of view, there is no impact of high burnup fuel or dispersed fragments on rod-to-water rod radiative heat transfer.
	8.5	Rod-to-spacer grid local heat transfer(14)	Clad temperature	12/20/23	GT	L	M	M				While debris accumulation on spacer grids can affect flow and thus cooling, it seems unlikely that rod to spacer grid heat transfer is significant
				12/14/23	WW	H	M	M				
					NC	L(14)	H(14)	L(14)				(14) These topics are common in standard LOCA analysis practices.
				12/18/23 01/19/24	FB	L	H	L	L	H	L	
				12/20/23 01/15/24 01/19/24	WM	L	H	L				This will have little to no impact on overall coolable geometry under extended burnup conditions.
				12/26/23	DK	M	M	M				Spacer grids would have the potential for flow blockage, which could increase with multirod failures. Crossflow cooling affects would most likely be degraded locally.
				01/08/24	KM	L	H	L				No incremental impact.

Table B-9: High Burnup FFRD PIRT on Whole-Core Thermal Events for Phenomena Category 9, “Dispersed Fuel Transport and Its Consequences”

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
9. Dispersed Fuel Transport and Its Consequences	9.1a	Fuel particle sedimentation and porous bed formations at spacer grids	Flow blockage, debris bed coolability	12/7/23	GT	H	M	H				
				2/7/23	WW	M	M	H				
				2/7/23	NC	M	M	H				
				1/12/24	FB	H	M	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	H	M	H				
				2/7/23	DK	M	M	H				
				2/7/23	KM	M	M	H				
	9.1b	Fuel particle sedimentation and porous bed formations at inlet nozzle grids	Flow blockage, debris bed coolability	2/7/23	GT	L	M	H				
				2/7/23	WW	L	M	H				
				2/7/23	NC	L	M	H				
				1/12/24	FB	L	M	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	H				
				2/7/23	DK	L	M	H				
				2/7/23	KM	L	M	H				
	9.2	Fuel particle sedimentation in lower plenum	Impact on distribution of dispersed fuel	2/7/23	GT	M	M	M				
				2/7/23	WW	L	M	H				
				2/7/23	NC	M	H	M				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	H				
				2/7/23	DK	M	H	M				
				2/7/23	KM	L	M	M				
	9.3	Fuel particle fluidization in	Coolability of debris beds (CHF)	2/7/23	GT	L	M	H				
				2/7/23	WW	L	M	H				
				2/7/23	NC	L	M	H				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		porous beds residing within the core		1/12/24	FB	L	M	H				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	H				
				2/7/23	DK	L	M	H				
				2/7/23	KM	L	M	H				
	9.4	Fuel particle entrainment and transport by coolant flow in the RCS	Dispersed fuel distribution	2/7/23	GT	L	H	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	H	H				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	H				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				
	9.5	Fuel particle ejection into the containment by break flow (LOCA)	Radioactive release	2/7/23	GT	L	M	L				
				2/7/23	WW	L	M	L				
				2/7/23	NC	L	M	L				
				1/12/24	FB	L	M	L				Team requested Fran's perspective on FOM-3.
				2/7/23	WM	L	M	L				
				2/7/23	DK	L	M	L				
				2/7/23	KM	L	M	L				
	9.6	Fuel particle sedimentation/ trapping in upper plenum and other RCS locations	Dispersed fuel distribution, coolability	2/7/23	GT	L	L	M				
				2/7/23	WW	L	L	M				
				2/7/23	NC	L	L	M				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	L	M				
				2/7/23	DK	L	L	M				
				2/7/23	KM	L	L	M				
	9.7		Coolability	2/7/23	GT	L	L	M				
				2/7/23	WW	L	L	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		Fuel particle trapping/filtration at fibrous beds in the core		2/7/23	NC	L	L	M				
				1/12/24	FB	L	L	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist. Assume Imp. is rated low since this excludes trapping in spacer grid 9.1a.
				2/7/23	WM	L	L	M				
				2/7/23	DK	L	L	M				
				2/7/23	KM	L	L	M				
	9.8	Fuel particle sedimentation/ trapping at various locations in the containment	Radioactive release, coolability	2/7/23	GT	L	L	M				
				2/7/23	WW	L	L	M				
				2/7/23	NC	L	L	M				
				1/12/24	FB	L	L	M				Team requested Fran's perspective on FOM-3.
				2/7/23	WM	L	L	M				
				2/7/23	DK	L	L	M				
				2/7/23	KM	L	L	M				
	9.9	Fuel particle filtration by fibrous beds on containment sump strainer surfaces	Coolability	2/7/23	GT	L	M	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	H	L				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	H	L				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				
	9.10	Suspension of fine fuel particles in coolant fluid resulting in	Impact on temperature, recriticality	2/7/23	GT	L	H	L				
				2/7/23	WW	L	H	L				
				2/7/23	NC	L	H	L				
				1/12/24	FB	L	H	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	H	L				
				2/7/23	DK	L	H	L				
				2/7/23	KM	L	H	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
Cat	No.	Phenomena	Relevance			FOM-1 (Coolability)			FOM-2 (Criticality)			
						Imp.	SoK	U	Imp.	SoK	U	
		coolant-particle mixtures										
	9.11	Heat transfer from porous fuel debris beds to coolant	Coolability	2/7/23	GT	M	M	L				
				2/7/23	WW	L	M	L				
				2/7/23	NC	M	M	L				
				1/12/24	FB	M	L	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist. Since it is unclear what type of debris bed geometry will be, it is difficult to define the heat transfer.
				2/7/23	WM	M	M	L				
				2/7/23	DK	M	M	L				
				2/7/23	KM	M	M	L				
	9.12	Heat transfer from porous fuel debris beds to protruding fuel rods and structural elements	Structural integrity	2/7/23	GT	L	M	L				
				2/7/23	WW	L	M	L				
				2/7/23	NC	L	M	L				
				1/12/24	FB	M	L	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	L				
				2/7/23	DK	L	M	L				
				2/7/23	KM	L	M	L				
	9.13	Heat transfer from fuel debris beds to supporting structures (e.g., spacer grids, other RCS structures, sump strainer)	Coolability, structural integrity	2/7/23	GT	L	M	L				
				2/7/23	WW	L	M	L				
				2/7/23	NC	L	M	L				
				1/12/24	FB	L	M	L				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	L				
				2/7/23	DK	L	M	L				
				2/7/23	KM	L	M	L				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
	9.14	Flow blockage by porous fuel debris beds in the core	Core coolability	2/7/23	GT	L	H	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	H	M				
				1/12/24	FB	M	H	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist. Considering the impact just above the debris bed with little flow for heat transfer. Eventually radial flow will cool the fuel.
				2/7/23	WM	L	H	M				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				
	9.15	Porous fuel debris beds clogging by chemical precipitants and/or containment debris (particulates, fiber)	Bed coolability	2/7/23	GT	L	M	M				
				2/7/23	WW	L	L	H				
				2/7/23	NC	L	M	M				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	L	H				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				
	9.16	Heat transfer from debris beds with clogged pores to coolant, fuel rods, and other structures	Structural integrity	2/7/23	GT	L	M	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	M	M				
				1/12/24	FB	L	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	L	M	M				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
	9.17	Flow blockage by clogged fuel debris beds in the core	Impact on core coolability	2/7/23	GT	L	M	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	M	M				
				1/12/24	FB	M	M	M				Note: Ranking provided subsequent to in-person Panel meeting due to temporary absence of panelist.
				2/7/23	WM	M	M	M				
				2/7/23	DK	L	M	M				
				2/7/23	KM	L	M	M				
	9.18	Recriticality of core containing EE fuel	Recriticality **(FOM-2)**	2/7/23	GT				L	H	L	
				2/7/23	WW				M	H	L	
				2/7/23	NC				L	H	L	
				2/7/23	FB				L	H	L	
				2/7/23	WM				L	H	L	
				2/7/23	DK				L	H	L	
				2/7/23	KM				L	M	M	
	9.19	Recriticality of coolant-fuel homogeneous mixtures	Recriticality **(FOM-2)**	2/7/23	GT				L	H	L	
				2/7/23	WW				L	M	L	
				2/7/23	NC				L	H	L	
				2/7/23	FB				L	M	M	
				2/7/23	WM				L	H	L	
				2/7/23	DK				L	H	L	
				2/7/23	KM				L	H	L	
	9.20	Impact on reactor core coolable geometry	Coolability	2/7/23	GT	M	M	M				
				2/7/23	WW	L	M	M				
				2/7/23	NC	L	M	M				
				2/7/23	FB	M	M	M				
				2/7/23	WM	M	M	M				
				2/7/23	DK	M	M	M				
				2/7/23	KM	L	M	M				

Phenomena				Input Date	Panel Member	FOM Importance, State-of-Knowledge, and Uncertainty Ranking						Panel Discussion Notes
						FOM-1 (Coolability)			FOM-2 (Criticality)			
Cat	No.	Phenomena	Relevance			Imp.	SoK	U	Imp.	SoK	U	
	9.21	Radioactivity release fraction due to fragment-coolant interaction (chemical reactions, dissolution)	Radiological release **(FOM-3)**	2/7/23	GT	L	H	M				General Comment: Several panelists did not feel comfortable ranking this phenomenon.
				2/7/23	WW	M	M	M				
				2/7/23	NC	L	H	M				Panelists expressed lack of expertise in this area.
				2/7/23	FB	L	H	M				Panelists expressed lack of expertise in this area.
				2/7/23	WM	L	H	M				Panelists expressed lack of expertise in this area.
				2/7/23	DK	M	H	M				
				2/7/23	KM	L	M	M				
	9.22	Radioactivity release fraction due to fragment propagation into the containment	Radiological release	2/7/23	GT							General Comment: Several panelists did not feel comfortable ranking this phenomenon.
				2/7/23	WW	L	M	L				
				2/7/23	NC							
				2/7/23	FB							
				2/7/23	WM							
				2/7/23	DK							
				2/7/23	KM							

APPENDIX C

FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL PHENOMENA IDENTIFICATION AND RANKING TABLE ON HIGH BURNUP FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL AND ITS CONSEQUENCES FOR LOCAL CORE EVENTS (REACTIVITY-INITIATED ACCIDENTS) WITH PANEL VOTES

C.1 PIRT on High Burnup FFRD and Its Consequences for Local Core Events (Reactivity-Initiated Accidents) with Panel Votes

Table C-1 PIRT on High Burnup FFRD and Its Consequences for Local Core Events (RIAs) with Panel Votes

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
						FOM-1 (Fuel Rod Failure)$^{(1)}$			FOM-3 (Release)			
Cat	No.	Description	Relevance			Imp.	So K	U	Imp.	So K	U	
	1.1	Fuel cycle design, including HBU placement initial condition	Determines the number of fuel rods susceptible to RIA failure	01/30/24 02/05/24	GT	H	H	L	H	M	M	Likely to affect both failure and particle release.
				01/25/24	WW	H	H	L	M	M	M	
				01/26/24	NC	H	H	L	H	M	M	Release—High burnup = more FGR, and data are limited compared to lower burnup conditions. Also fuel dispersal and its impact on dose are not accounted for.
				01/29/24	FB$^{(4)}$	L	M	M	M	M	M	L Imp. for FOM-1, based on relative effect of HBU with FFs vs. HBU w/o FFs. FF formation might mitigate PCI and might actually reduce likelihood of failure, M,M based on lack of expertise on the impact FFs may have. M for FOM-3 Imp. based on possible release of FFs plus potential for larger # of fuel rods. If this release is already known to be bounded by design-basis assumption, Imp. can be reduced to low.
				01/23/24	WM	H	H	L	H	H	L	Design and fuel-loading configuration (including HBU) will drive many subsequent phenomena that lead to the number of rods that fail. This is paramount to understand. We have ready and accurate means of predicting. These means of predicting loading/power density, absorber quantities, and impact on criticality are quite precise and accurate. This is a macro-scale and macro-design category that may not be best suited at a bottom-up-level PIRT.
				01/29/24	DK	H	H	L	M	H	L	EE and HBU are expected to impact the severity of RIA transients due to changes in fuel initial conditions, transient power response, transient clad heat transfer, and fuel rod transient response. EE and HBU, taken together, are the enablers for longer fuel cycles, power uprates, and more efficient fuel assembly and core designs. There are a number of advanced fuel and core design features that would be expected

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
												with EE/HBU, including (1) increased use of axial and radial zoning of enrichment and burnable poisons, both within the fuel rod and within the fuel assembly, (2) the reuse of low reactivity HBU fuel assemblies in high power interior locations (HBU surrounded by fresh), and (3) atypical fuel rod and assembly power histories that depend on multicycle core design and fuel reuse strategies. A consequence will be that rod power histories and burnup distribution, a key input to FFRD modeling, will be highly dependent on the fuel product, fuel design, and core loading.
				01/30/24	KM	H	H	L	M	M	M	Determination of the HBU fuel susceptible to RIA failure is important. Incremental release due to high burnup fragmentation and dispersal is minimal. Lower reactivity of HBU rods is a competing effect.
	1.2	Core-wide pin-by-pin spatial power distribution initial condition	Determines maximum uncontrolled rod worth and the adjacent HBU fuel rods susceptible to failure	01/30/24 02/05/24	GT	H	H	L	M	M	M	
				01/25/24	WW	H	H	L	M	M	M	
				01/26/24	NC	H	H	L	H	M	M	Release—High burnup = more FGR, and data are limited compared to lower burnup conditions. Also fuel dispersal and its impact on dose are not accounted for.
				01/29/24	FB	L	M	M	M	M	M	Same as 1.1.
				01/23/24	WM	H	H	L	H	H	M	The overall pin-by-pin spatial power is important, but particularly the relative location as compared to control rods or blades is as relevant if not more. In short, nodal kinetics shows that fuel rods adjacent to the absorber (control rods/blades) during ejection have higher localized power peaking during the transient than those shadowed by other fuel rods, thus creating local fuel. We have a strong knowledge of this, the fractional release is medium in uncertainty, as it is unclear as to specifically the quantity of release that is given based on core-wide transient (we don't have much data on this as an industry).

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/29/24	DK	H	H	L	M	H	L	The rods susceptible to fuel failure will depend upon the pin-by-pin spatial power distribution. A key conclusion is that it is increasingly likely with EE/HBU that the limiting initial conditions will engage many more high burnup fuel assemblies in locations adjacent to the maximum uncontrolled rod-worth location. This follows directly from the reuse of HBU fuel in the high-power core interior. Cladding failure thresholds are reduced with HBU, and using EE potentially places more HBU fuel at risk for failure during RIA. A limiting scenario analysis would need to combine location-dependent fuel rod census information with limiting time during the cycle to define the worst case.
				01/30/24	KM	L	H	L	L	H	L	Core-wide pin-by-pin power distribution is a secondary effect. Limiting pin power can be bounded in analyses.
	1.3	Pellet radial power distribution initial condition	Determines fuel temperature profile and its impact on melting	01/30/24 02/05/24	GT	H	M	M	M	M	M	Probably more effect on the initial rupture than the fragment release.
				01/25/24	WW	H	H	M	H	M	H	Similar to the burnup distribution, the power distribution of HBU fuel is peaked to the outer part (rim part) of the pellet, which has a strong influence on the temperature distribution during a short RIA pulse. Models should be able to calculate the distributions (SoK H), but the knowledge about the consequences for release are probably less well known (experiments and models).
				01/26/24	NC	H	H	L	L	H	L	Release data across a wide range of testing conditions (e.g., PCI, RIA, LOCA) do not indicate the pellet radial power distribution will drive any additional release.
				01/29/24	FB	L	M	M	M	M	M	Same as 1.1.
				01/23/24	WM	M	H	L	M	H	L	The radial temperature distribution will diffuse even during an RIA transient. This isn't a significant correlator unless it is extreme. One can refer to pulsing reactor literature as a resource to confirm this phenomenon.
				01/29/24	DK	H	M	M	M	M	M	With HBU, melting will become more limiting for the pellet periphery with RIA due to the radial power distribution and burnup profile.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)$^{(1)}$			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/30/24	KM	L	M	M	L	M	M	Initial pellet radial power distribution has a secondary effect on fuel melting compared to the transient energy deposition.
	1.4	Pellet radial burnup distribution initial condition	High-temperature cladding failure mechanisms including FF	01/30/24 02/05/24	GT	H	M	M	H	M	M	Probably has strong effect on both the initial rupture and fragment release.
				01/25/24	WW	H	H	M	H	M	H	Similar comment as to 1.3. The HBU rim will experience a sudden temperature increase, which causes thermal expansion and possibly expansion driven by the gas pressure in the rim pores. It is conceivable that the heatup of the overpressurized pores in the rim will exert an extra load on the cladding and thus produce more failures. Compared to LOCA, fuel fragmentation may be mitigated by the RCS pressure.
				01/26/24 02/26/24	NC	H	H	L	H	M	M	
				01/29/24	FB	L	M	M	M	M	M	Same as 1.1. HBU FFs in outside of pellet could make the release worse if they relocate.
				01/23/24	WM	L	M	M	M	M	M	The burnup distribution will have an effect on the overall temperature distribution but doesn’t impact significantly the maximum temperature or time at temperature, which is the primary cause of fuel failure. Burnup radially will drive radial fragmentation size, which will result in the plausibility of fuel quantity released in some capacity.
				01/29/24	DK	H	M	M	M	M	M	
				01/30/24	KM	M	M	M	L	M	M	Burnup distribution will potentially impact fuel pulverization.
	1.5	Clad excess hydrogen initial condition		01/30/24 02/05/24	GT	H	H	M	M	M	M	Probably more effect on the initial rupture than the fragment release.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
						FOM-1 (Fuel Rod Failure)$^{(1)}$			FOM-3 (Release)			
Cat	No.	Description	Relevance			Imp.	SoK	U	Imp.	SoK	U	
			PCMI cladding failure as a function of enthalpy including geometry for FFR	01/25/24 02/26/24 02/29/24	WW	H	M	M	M	M	M	Depends on whether hydrides are dissolved during the short duration of cladding overheating or not. PCMI-type failure seems more likely than ballooning.
				01/26/24 02/08/24	NC	H	H	L	L	H	L	Cladding failure is simply the criteria to trigger a fission gas release/dose consequence analysis. There is no delta when moving to high burnup.
				01/29/24	FB	L	M	M	M	M	M	Same as 1.1. Will contribute to potential for HBU rods to fail during RIA.
				01/23/24	WM	H	H	L	M	H	L	Initial hydrogen production/content will be a driving determinant for internal initial pressure and thus be a direct indicator of likely fuel rod failure.
				01/29/24	DK	H	H	M	M	M	M	HBU will increase local oxidation and clad hydrogen and depends on the initial condition established by the fuel rod's local power/temperature and burnup history. This highly depends on the multicycle core design and operating history, as well as the initial clad treatment. Engagement of a larger population of HBU rods, with higher hydrogen content and lower cal/g thresholds for failure, would be expected during RIA.
				01/30/24	KM	H	M	M	M	M	M	There is a greater uncertainty in hydrogen pickup with increasing burnup. Therefore, the SoK and U are rated M.
	1.6	Fuel pellet cracking/ relocation initial condition	Impact on RIA enthalpy and fuel conductivity	01/30/24 02/05/24 02/26/24	GT	L	H	L	L	H	L	Probably has strong effect on both the initial rupture and fragment release.
				01/25/24	WW	L	H	L	L	H	L	I would not expect pellet cracking caused by normal operation to have an important effect on failure or release.
				01/26/24 02/08/24	NC	L	H	L	L	H	L	Nothing changes beyond current expectation as burnup increases.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
												The fuel-cladding are mechanical and chemically bonded at high burnup. Cracking and relocation behavior in fuel performance occurs early in life and during a transient; however, pellet displacement during an RIA is a higher factor.
				01/29/24 02/26/24	FB	L	H	L	L	H	L	Same as 1.1.
				01/23/24 02/26/24	WM	L	H	L	L	H	L	This will drive ballooning and local failure location specifically during RIA in a steam environment (more so than in a liquid environment).
				01/29/24 02/26/24	DK	L	H	L	L	H	L	
					KM	L	H	L	L	H	L	Compared to the fuel pulverization caused by the energy deposition, the initial cracking of the fuel has a less dominant effect.
	1.7	Fuel temperature reactivity feedback	Impact on peak enthalpy (cal/g)	01/30/24 02/05/24	GT	M	H	L	L	M	L	
				01/25/24	WW	L	H	L	L	H	L	The plutonium content increases in HBU fuel. Core physics calculations should calculate the effect with good accuracy.
				01/26/24 02/08/24 02/26/24	NC	L	H	L	L	H	L	Cladding failure is driven by the pellet displacing the cladding until failure occurs. Pellet displacement is driven primarily by thermal expansion and at high burnup's gaseous swelling. Fuel temperature reactivity feedback is an important component and should already be considered in existing evaluations. The only difference is the higher burnup component, which does impact fuel thermal conductivity, but it's already degraded at existing conditions and the change shouldn't be significant beyond current operation.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/29/24	FB	L	H	L	L	H	L	Doppler feedback is expected to increase at HBU. Expect power pulse to be reduced relative to lower burnup bundles due to lower reactivity and rod worth.
				01/23/24 02/26/24	WM	M	H	L	L	M	L	Temperature reactivity feedback yields the temperature of fuel, which leads to fuel cladding failure and with small changes (high sensitivity) to feedback coefficient can dramatically impact the maximum temperature. The importance to fuel failure is high. We are very well equipped to predict this with accuracy. The overall correlation to release is somewhat predictable generally, and the higher the max temperature the larger the fuel failure, but it's not directly correlated to release quantity, thus medium importance on FOM 3.
				01/29/24	DK	M	H	L	L	H	L	Factors that impact the transient power response for RIA with EE/HBU include the fuel reactivity coefficient and delayed neutron fraction. HBU will make the fuel reactivity coefficient more negative due to the conversion of Pu-240 from U-238 via Pu-239. Pu-240 is a significant resonance absorber. Using EE fuel will reduce the amount of U-238 while increasing the amount of U-235, reducing resonance absorption in both U-238 and Pu-240. The balance between HBU and EE effects would need to be assessed for its impact on RIA accident progression.
				01/30/24	KM	L	H	L	L	H	L	This parameter is among the important phenomena for RIA events. However, it is not directly affected by high burnup fuel and is only deemed of low importance from the point of view of incremental evaluation.
	1.8	Delayed neutron fraction(2)	Impact on peak enthalpy (cal/g)	01/30/24 02/05/24 02/26/24	GT	L	H	L	L	M	L	
				01/25/24	WW	L	H	L	L	H	L	Same comment as for 1.7.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/26/24 02/08/24 02/26/24	NC	L	H	L	L	H	L	While this will need to be accounted for in the analysis, it is known fairly well. Additionally, it has no impact on release and would only impact cladding failure.
				01/29/24	FB	L	H	L	L	H	L	Would not expect this to have much impact on the RIA kinetics. Expect power pulse to be reduced relative to lower burnup bundles due to lower reactivity and rod worth.
				01/23/24 02/26/24	WM	M	H	L	L	M	L	I perceive the importance and impact of 1.7 and 1.8 being the same.
				01/29/24	DK	L	H	L	L	H	L	Delayed neutron fractions also impact the RIA accident progression. U-235 has a delayed neutron fraction of ~0.0065, while Pu-239 is much smaller at ~0.002. Increasing the proportion of U-235 with EE will change the behavior of the average core delayed neutron fraction over the fuel cycle as fission power due to U-235 is replaced by fission in Pu-239 (which today is 30% at the end of the cycle). How this changes with longer cycle lengths and HBU will need to be assessed for its impact on RIA accident progression.
				01/30/24	KM	L	H	L	L	H	L	Similar to fuel temperature reactivity feedback, delayed neutron fraction is deemed of low importance for incremental impact of high burnup fuel and fuel dispersal during RIA events.
	1.9	Fissile material composition	Source term for radiological release	01/30/24	GT	L	H	L	L	M	L	
				01/25/24	WW	L	H	L	L	H	L	Same comment as for 1.7.
				01/26/24 02/26/24	NC	L	H	L	H	H	L	

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/29/24	FB	L	H	L	M	H	L	Similar to 1.1 but would not expect FFs to impact the composition and composition distribution. Composition could impact release.
				01/23/24	WM	L	H	L	M	H	L	Will impact a number of factors, but not to the extent of others indicated in this table for fuel failure. The source term (if alternate fuel fissile composition is considered) will in fact impact potential releases and thus is ranked at a medium for FOM-3.
				01/29/24	DK	L	H	L	M	H	L	The fissile fuel inventory is well known for HE/HBU fuel and can be calculated. Its core distribution will depend highly on the fuel and core design. The increase in fission product material due to HBU would be expected to have some impact on source term. (Note: 1.9 might be changed to isotopic inventory to make it more general.)
				01/30/24	KM	M	H	L	M	H	L	Fissile material composition is important in reactivity response and somehow affects the potential fuel failures and dispersal.
	1.10	Fuel thermal properties	Transient peak fuel temperature and clad temperature gradient (heat flux)	01/30/24 02/05/24 02/26/24	GT	H	H	L	L	H	L	Probably more effect on the initial rupture than the fragment release.
				01/25/24	WW	M	H	M	L	H	L	Fuel conductivity decreases with increasing burnup. This affects the heat flux from the fuel to the cladding. The porous rim is an extra resistance. Therefore not assumed to make it worse for HBU fuel.
				01/26/24 02/08/24	NC	H	H	L	L	H	L	Fuel thermal properties are known and will not impact dose.
				01/30/24 02/08/24	FB	M	H	L	L	H	L	As stated in 1.7 and 1.8, expect reduced RIA power peak; however, conductivity effect could lead to some increase in severity.
				01/23/24	WM	M	H	L	L	H	L	This will impact max temperature, but unless an extreme quantity, won't impact in dramatic ways the overall peak fuel

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
												temperature (considering the thermophysical property differences of high and ultrahigh burnup regions of fuel thermal properties only).
				01/29/24	DK	H	H	L	L	H	L	Thermal conductivity will impact transient heat flux as fuel conductivity degradation will result in higher fuel temperatures with larger temperature gradients at the clad surface. This will lead to higher stored energy, centerline temperature, and heat flux due to increased temperature gradient at the clad surface, decreasing the margin to CHF limits.
				01/30/24 02/26/24	KM	H	H	M	L	H	L	Fuel thermal properties ultimately drive the transient peak fuel temperature. They vary with burnup and are important for accurate modeling.
	1.11	Single and two-phase heat transfer	Critical heat flux and peak cladding temperature and critical heat flux; also, RCS system pressure	01/30/24 02/05/24	GT	M	M	M	M	M	M	
				01/25/24 02/26/24	WW	M	M	M	M	M	M	Similar to the reasoning in 1.10, the transient cladding heat flux is not expected to be adversely affected for HBU fuel.
				01/26/24 02/08/24	NC	M	M	M	L	H	L	Regarding item 1.11, panelist commented: “I would suggest breaking this into two separate line items —(1) single and (2) two.” The thermal boundary conditions impact cladding failure.
				01/29/24	FB	L	H	L	L	H	L	As stated in 1.7 and 1.8, expect reduced RIA power peak and therefore more DNB margin.
				01/23/24 02/26/24	WM	M	M	L	M	M	M	The coolant conditions and phase will drive heat removal of the fuel cladding during RIA but primarily it will impact the rate at which fuel temperature drops post peak power/temperature during an RIA and thus the overall impact that the enthalpy fuel has experienced.
				01/29/24	DK	M	H	L	L	H	L	Single and two-phase heat transfer is important for determining margin to critical heat flux following prompt-criticality as heat is removed from the fuel.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
						FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
Cat	No.	Description	Relevance			Imp.	SoK	U	Imp.	SoK	U	
				01/30/24	KM	L	H	M	L	H	M	The failure mechanism for high burnup fuel rods during RIA event is PCMI, not DNB. Therefore, effect of this parameter on CHF is inconsequential for dispersal concerns. Additionally, RCS system pressure is a controlled parameter, and it is not directly influenced by the transient heat transfer.
	1.12	Transient clad differential pressure	High-temperature cladding failure threshold (brittle and ductile failure) as a function of peak enthalpy (cal/g)	01/30/24	GT	H	M	M	L	M	M	Probably more effect on the initial rupture than the fragment release.
				01/25/24	WW	H	H	L	M	M	L	An RCS still pressurized will make many of the LOCA-related FFRD observations less relevant.
				01/26/24 02/08/24 02/26/24	NC	M	H	L	L	H	L	This phenomenon impacts cladding failure. Postcladding failure, the dose analysis will remain the same.
				01/29/24 02/26/24	FB	L	M	M	L	M	M	Same as 1.1. Although this will be impacted by HBU, do not expect that HBU with FF will make it worse.
				01/23/24	WM	H	H	M	M	M	H	ORNL has shown this to be a primary factor contributing toward fuel failure. We have data to support this. Failure drives potential for release, but the fragmentation size contributes to quantity of release and thus was ranked as a medium for importance under FOM-3.
				01/29/24 02/06/24 02/26/24	DK	M	M	M	L	M	M	This is a primary factor for fuel failure, which will drive the release but have minimal impact in terms of amount.
				01/30/24	KM	M	H	M	L	H	M	PCMI being the dominant failure mechanism for high burnup fuel, this parameter plays a smaller role.
	1.13			01/30/24	GT	H	L	H	M	M	M	Probably more effect on the initial rupture than the fragment release.

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
		Transient fission gas release	Impacts clad differential pressure and source term for radiological release	02/05/24								
				01/25/24	WW	H	M	H	M	M	M	
				01/26/24 02/08/24	NC	M	L	H	M	M	M	There are no data associated with RIA TFGR. However, we do know that TFGR will increase as burnup increases and we know the severity of the temperature transient will likely increase the amount of TFGR. What remains unclear is if or how much TFGR is required to impact cladding failure.
				01/29/24	FB	L	M	M	M	M	M	Same as 1.12. It is not clear if gas release through the failure has potential to eject material like in LOCA.
				01/23/24 02/27/24	WM	H	M	L	M	M	L	I assume this is fission gas release post failure, which would correlate to fuel failure already and thus it would result in high importance. I believe the release term would be medium as I correlate this to be a result of source-term of fuel primarily, therefore a medium on FOM-3.
				01/29/24 02/27/24	DK	H	L	H	M	M	M	Of the phenomena listed, transient fission gas release is considered of high importance, low SoK, and high uncertainty for fuel failure. This applies to HBU and is important to determining clad failure and the subsequent radiological source term. A bounding calculation on fission gas release can be performed for source term.
				01/30/24	KM	M	L	H	M	L	H	Transient fission gas release has importance for clad ballooning and creep burst, a less likely mechanism for HBU fuel.
	1.14	Fuel fragmentation release to coolant	Impacts coolability of fuel and source term	01/30/24 02/05/24 02/27/24	GT	M	M	M	M	L	H	
				01/25/24 02/27/24	WW	M	M	M	M	M	M	FFRD as seen in LOCA experiments is not expected to occur to the same extent: most failures probably are PCMI-induced cracks with small openings; the cladding is more in contact with the fuel (RCS pressurized) and thus less fine fragmentation; less or no driving force for fragment dispersal (RCS pressurized).

Phenomena				Input Date	Panel Member	Rankings						Panel Discussion Notes
Cat	No.	Description	Relevance			FOM-1 (Fuel Rod Failure)(1)			FOM-3 (Release)			
						Imp.	SoK	U	Imp.	SoK	U	
				01/26/24	NC	H	L	H	H	L	H	I believe the biggest issues may be control room habitability, which will not be bounded by the severe accident source term.
				01/29/24 02/27/24	FB	M	M	M	M	M	M	Even if FFR does occur, the fuel will be covered and would not expect any risk of clogging or loss of cooling. Release of material may increase source term relative to the design-basis assumption.
				01/23/24	WM	H(3)	M(3)	H(3)	H	M	H	It is unclear precisely whether this is intended to be fragmentation size or fragmentation generally. Either way, this is important in the event of fuel failure phenomena. It also drives the coolability of the core, as well, given that this occurs under liquid conditions and fuel dispersion remains more prominently within the adjacent subchannel when fuel failure occurs.
				01/29/24	DK	M	M	H	M	L	H	Additional fission gas release due to fragmentation would be minimal but fragment size distribution would potentially increase the amount of mass release through clad rupture and subsequent transport throughout the system.
				01/30/24 02/27/24	KM	M	L	H	M	L	H	This has potential damaging effects and ranked high for failure.

NOTE (1): Panelist commented: “I assume this is considered as defined by the NRC—breach of cladding and not necessarily correlated to fuel quantity loss.”

NOTE (2): Panelist commented: “If we’re considering reactivity feedback coefficient and delayed neutron fraction, we should also consider mean neutron generation.”

NOTE (3): Panelist commented: “... in short, fuel fragmentation would be released to the coolant in the event of fuel failure, because these are corollaries the phenomena is High importance.”

NOTE (4): Panelist noted in his email of 02/08/2024: “I am largely disagreeing with the panel on FOM-1. If this were a HBU PIRT I would agree with them but this is a FFRD PIRT and I feel the relative effect FFs would be small and perhaps advantageous in mitigation of PCI failure since the FFs could help relieve stress at the PCI site.”

C.2 Summary of Panel Input on Extended Enrichment and High Burnup Fuel FFRD Impact on Reactivity-Initiated Accident Consequences

As part of the development of the fuel fragmentation, relocation, and dispersal (FFRD) reactivity-initiated accident (RIA) phenomena identification and ranking table (PIRT), the members of the FFRD PIRT Panel were asked to provide their views on how pressurized-water reactor (PWR) and boiling-water reactor (BWR) operation with extended enrichment (EE) and high burnup (HBU) fuel above currently allowed limits could potentially worsen unfavorable consequences from RIA design-basis accidents (DBAs), due to known possibly new or additionally introduced phenomena associated with HBU FFRD. Specifically, feedback was solicited from the panelists on factors such as (1) phenomena (known or new), (2) understanding of phenomena and related processes, (3) conditions (including initial), (4) parameters (e.g., rod internal pressure with reactor coolant system (RCS) not depressurized), (5) consequences, (6) associated uncertainty, (7) level of knowledge, (8) other relevant items (e.g., approved fuel rod thermal-mechanical performance codes) to explain how introduction of EE and HBU fuel could influence FFRD and thus impact the consequences of an RIA, and (9) data availability and additional data needs to address items (1) through (8). Following the formal FFRD RIA PIRT development by the Panel, the primary feedback from the panelists was summarized and documented in the remaining part of this section.

Considering FFRD consequences associated with the behavior of EE and HBU fuel during RIAs in PWR and BWR systems, a panelist noted that EE/HBU fuel was expected to affect the severity of the transients due to effects impacting (1) initial fuel conditions, (2) transient power response, (3) transient clad heat transfer, and (4) fuel rod transient response. The panelists pointed out that use of EE/HBU fuel could enable transitioning to longer fuel cycles, employment of more efficient fuel assembly and core designs, and power uprates. A panelist expected the following advanced fuel features and core design characteristics to be of relevance to EE/HBU fuel: (1) increased use of axial and radial zoning of enrichment and burnable poisons (both within the fuel rod and within the fuel assembly), (2) reuse of low reactivity HBU fuel assemblies in high-power interior locations (HBU fuel surrounded by fresh fuel), and (3) atypical fuel rod and assembly power histories that would depend on multicycle core design and fuel reuse strategies. Consequently, the panelist recognized that key inputs to FFRD modeling defined by rod power histories and burnup distributions would be highly dependent on the fuel product, fuel design, and core loading strategies.

Addressing the need to consider initial reactor conditions across the entire range of anticipated operating conditions during a core cycle for RIA analyses, including zero-, partial-, and full-power conditions, the panelist recognized that use of EE/HBU fuel would increase the likelihood of limiting initial conditions involving an increased number of HBU fuel assemblies placed adjacent to an affected maximum-worth control rod due to possible reuse of HBU fuel in the high-power core interior. The panelist noted that this was in contrast to the traditional placement of HBU fuel assemblies in high-leakage and low-power peripheral core locations. Citing guidance in Regulatory Positions 2.2.1.5 and 2.2.2.5 in Regulatory Guide (RG) 1.236, “Pressurized-Water Reactor Control Rod Ejection and Boiling-Water Reactor Control Rod Drop Accidents,” that “a more comprehensive search for the limiting conditions may be necessary to ensure that the total number of fuel rod failures is not underestimated,” the panelist recognized that cladding failure thresholds would be reduced with HBU, and using EE would potentially place more HBU fuel at risk for failure during an RIA. Accordingly, it was concluded that a limiting scenario analysis would need to combine location-dependent fuel rod census information with limiting time-in-cycle considerations when determining worst case scenarios.

Noting the fuel rod failure thresholds described for RIA transients in RG 1.236 (1) high-temperature cladding failure threshold, (2) clad failure threshold from pellet-cladding mechanical interaction (PCMI) due to fuel expansion, and (3) molten fuel cladding failure threshold, the panelist elaborated on pertinent aspects related to EE/HBU fuel, describing the high-temperature cladding failure as based on brittle and ductile failure modes that depend on peak radial average fuel enthalpy (calories/gram (cal/g)) and clad differential pressure. In addition, it was explained that increased fission gas release (FGR) in HBU fuel would result in a higher clad differential pressure, making the high-temperature cladding failure more severe. Concerning the PCMI failure threshold, the panelist noted that fuel rod failure curves were based on average fuel enthalpy as a function of excess cladding hydrogen. At the same time, HBU would increase local oxidation and clad hydrogen, consistent with the initial conditions established by the rod local power, temperature, and burnup history of the fuel rods, which would be highly dependent on the multicycle core design, operating history, and other factors, such as initial clad treatment. As a result, the engagement of a larger population of HBU rods with higher clad hydrogen contents and lower failure thresholds, in terms of energy deposition (cal/g), would be expected for RIAs.

Regarding the third failure threshold, the panelist noted that EE and HBU fuel could also impact the critical heat flux (CHF) fuel rod failure mechanism, as EE would likely result in HBU fuel carrying higher local power due to fuel and core design efficiencies. It was further noted that fuel conductivity would degrade with increased burnup, resulting in higher initial stored energy, centerline temperature, and heat flux due to increased temperature gradient at the clad surface that would decrease the CHF margin. Related to this, it was recognized that degraded thermal conductivity would also impact (reduce) the rate of heat release from the fuel. In addition, HBU fuel in high-power interior core regions would result in higher rod average powers being driven by the neighboring fresh and once-burned fuel, based on the core loading pattern with the HBU pellet periphery experiencing the strongest peaking in both power and burnup. This rim effect, which would depend on the initial uranium (U)-235 enrichment, would reflect the increased buildup of fissile plutonium due to neutron capture in U-238 at the pellet surface. The higher initial rim power would increase the initial rim temperature, potentially reducing the margin to fuel melt for HBU fuel during an RIA. A secondary related effect of HBU was identified as caused by a potential reduction in the HBU fuel melting temperature, generally considered to decrease with increasing burnup due to buildup of fission products, with the reduction being greatest at the pellet periphery where the burnup is the highest. EE was explained to reduce the strong peaking of power and burnup in the rim region due to decreased U-238 capture, thus having a potentially opposite effect of increasing the margin to melt.

Discussing EE/HBU effects on reactor neutronics that could impact the transient power response during an RIA through the fuel reactivity coefficient and delayed neutron fraction, the panelist noted that HBU would make the reactivity coefficient more negative due to the conversion of U-238 through plutonium (Pu)-239 into Pu-240. Being a significant resonance absorber, Pu-240 would act as a mitigating factor for the power excursion. At the same time, using EE fuel would reduce the amount of U-238, while increasing the amount of U-235, thus reducing resonance absorption in both U-238 and Pu-240. Accordingly, it was noted that the balance between such HBU and EE effects would need to be assessed for their impact on the RIA transient progression. Regarding the delayed neutron fraction, it was explained that U-235 has a delayed neutron fraction of ~0.0065 that is much larger compared to Pu-239, which has a delayed neutron fraction of ~0.002. Accordingly, increasing the proportion of U-235 with EE would change the effective delayed neutron fraction of the core over the fuel cycle as the power contribution from U-235 fission would be gradually replaced by fission from Pu-239, which contribution could reach about 30 percent at the cycle end for currently operating reactors. The panelist noted that related effects associated with extending cycle lives and using HBU would need to be assessed for their related impacts on the RIA transient progression.

Notes provided by another panelist identified the following phenomena, viewed as most important for HBU fuel with regard to a loss-of-coolant accident (LOCA), mentioning that the understanding gained for LOCAs could be used in assessing the occurrence and importance of the listed phenomena for RIAs: (1) disintegration of the HBU structure into fine fragments (local burnup exceeding 70 megawatt days per kilogram of uranium (MWd/kgU), (2) axial and radial fuel relocation, (3) possibility for the entire pellet cross-section to fragment into medium and small pieces for burnups exceeding 80 MWd/kgU, and (4) dispersal of fine fragments on burst of the cladding. In this regard, it was noted that additional uncertainties related to the extent of axial and radial fuel relocation in conjunction with uncertainties related to the size of the balloon and burst opening would need to be considered. The following summarizes the panelist's insights regarding each of the identified phenomena.

In the panelist's view, the primary condition for disintegration of the HBU structure, aside from sufficient burnup, appeared to be related to the heatup of the fuel pellet and specifically the rim region to temperatures not experienced before and, consequently, a pressure increase in the already overpressurized pores that would ultimately cause fuel fragmentation. While this condition would be present during an RIA, the counteracting force of the cladding in contact with the pellets would require consideration. A secondary condition for disintegration of the HBU structure was identified as cladding creep-out under rod overpressure and pellet-cladding gap opening, which cannot be decoupled from the temperature increase during a LOCA. It was noted that this former condition was less likely to be present during an RIA, as far as the RCS would not be depressurized. Regarding the second phenomenon of axial and radial fuel relocation, it was noted that such processes would require a minimum cladding distension of a few percent to open a gap between the pellets and the cladding. Again, it was explained that this condition was less likely to be present as far as the RCS would not be depressurized and, possibly, due to the short time of an RIA event (pulse) that would limit creep.[3] Concerning the third phenomenon related to the entire pellet cross-section fragmenting into medium and small pieces for burnups exceeding 80 MWd/kgU, it was stated that it would be hard to judge how to account for the consequences of such a possibility. Of relevance to this phenomenon, it was noted that the counteracting force of the cladding in contact with the pellets would require consideration. While stating that the condition for this phenomenon to occur would probably not be present during an RIA, the panelist noted that this judgment was uncertain.

Elaborating on the fourth phenomenon, dispersal of fine fragments upon cladding burst, it was noted that it would need to be judged in conjunction with two governing factors related to (1) the geometry of the burst opening and (2) the presence of a driving force in terms of rod overpressure relative to a still-pressurized RCS. Regarding the first factor, it was noted that, according to the panelist's knowledge, the burst opening in an RIA would be an axial split, rather than a large opening as observed in a LOCA. The burst process would be similar to a failure induced by PCMI, a biaxial stress state with tensile forces in both the axial and hoop directions of the fuel cladding, only noting that iodine would not play a role during the short pulse of an RIA. Regarding the second factor, the panelist recognized the possibility that released fission

---

[3] It is noted that numerous examples of uranium dioxide (UO_2) fuel rodlets failing by high-temperature clad ballooning and bursting under RIA conditions in test reactors have been experimentally observed, as illustrated in figure 54 of Organisation of Economic Co-operation and Development (OECD) Nuclear Energy Agency Report No. 7575, "State-of-the-art Report on Nuclear Fuel Behaviour Under Reactivity-initiated Accident Conditions," issued 2022. Tests that look at post-CHF behavior under RIA conditions are ongoing as part of the CABRI International Project.

gas would be locally stored in cavities (chamfer, dishing, fuel cracks) and that the local pressure might exceed the system pressure in a still-pressurized RCS, exacerbated by the heatup, as Halden tests on FGR had repeatedly shown. In summary, the panelist concluded that the conditions for dispersal of fine fragments would mostly not be present in an RIA since (1) the burst opening would be small, (2) fine fragmentation would be limited or even not present (as discussed above regarding disintegration of the HBU structure), and (3) there would be no overpressure to a still-pressurized RCS, except for extreme cases, which was identified as the most important situation when limiting RIAs would occur under pressurized-reactor conditions. With regard to the last cognition concerning an RIA occurring under pressurized-RCS conditions, it was underscored that it represented a decisive difference compared to a LOCA, as in a pressurized system, the pressure difference would act in the opposite direction, potentially influencing many of the new phenomena identified in LOCA testing and related to FFRD.

Summarizing FFRD consequences from phenomena associated with HBU fuel because of an RIA, it was noted that one could assume that there would be limited additional consequences compared to the behavior already observed in experiments such as the REPNa test series in the CABRI experimental reactor. In this regard, the panelist identified two opposing effects: (1) on the one hand, it was deemed conceivable that the heatup of the overpressurized pores in the rim could exert an extra load, in addition to the load applied due to the fuel thermal expansion on the cladding, thus increasing the likelihood of more failures, and (2) on the other hand, HBU fuel would respond less to reactivity insertion. Accordingly, the panelist pointed out that the combined consequences from these two counteracting effects could only be judged through detailed modeling of the fuel behavior, based on sufficient understanding that might require experiments with HBU fuel. Pertinent uncertainties were recognized mainly with regard to the influence of the HBU fuel and rim region expansion and cladding failure that could possibly affect the failure geometry and amount of fuel fragments available for dispersal in extreme cases. The panelist also considered the likely possibility that an extended in-core residence time would affect cladding properties in an unfavorable manner in the case of HBU fuel.

Regarding the level of knowledge, modeling capabilities, and data availability, it was concluded that, while LOCA testing had provided considerable insight into the HBU fuel behavior under extreme temperature conditions, using this important database for evaluating fuel performance during RIAs would require accounting for significant dissimilarities to LOCAs. Specifically noted was the possible condition of reversed pressure difference, which would affect certain phenomena, as discussed previously. Pointing to the considerable progress in recent years in modeling fuel performance during steady-state operation, load follow, and transients, the panelist noted the decisive importance of further improving models for rim formation and fragmentation for a well-founded safety analysis of EE and HBU fuel performance. In this regard, it was stated that the correctness of RIA modeling and underlying assumptions for safety criteria could only be assured through obtaining data from prototypical experiments. The importance of using test specimens obtained from lead test assemblies where the HBU is achieved in a natural way using EE fuels was emphasized, noting that relevant test fuels seem to be currently lacking.

In notes provided by another panelist, FFRD phenomena and related consequences associated with EE and HBU fuel were summarized as they relate to (1) heat generation, (2) fuel burnup and structure, (3) cladding response, (4) fuel dispersal, (5) channel blockage, and (6) dispersed fuel final location. Regarding area (1), heat generation, it was noted that the balance of fuel composition, along with blended and graded absorber materials, would inherently increase the potential for higher potential peak factors locally, within a single fuel rod, and globally, across the core, which could have implications for FFRD. Concerning area (2), fuel burnup and structure, it was noted that an increased enrichment and a corresponding increase in power peaking factors (inter and intra rod) would correlate with increased thermal stresses within the fuel pellet and fuel rod that would accelerate and amplify, to an extent not understood, the fragmentation process during burnup. Regarding area (3), cladding response, it was recognized that hardening of existing qualified cladding materials, correlated to an increase in burnup, would result in generally smaller failure sizes and shapes than those associated with more ductile clad states. Elaborating on area (4), dispersal, it was noted that a rod failure during an RIA would be expected to occur in a liquid coolant environment, either subcooled or saturated, which would increase the drag and reduce the projectile distances of dispersing particles (i.e., more fuel fragments likely to remain in the subchannel region directly adjacent to the failed fuel rod) when compared to a LOCA. Concerning area (5), blockage, it was noted that it was unclear how the effect of potential additional fuel quantities being co-located within an adjacent subchannel, combined with reduced general failure strain quantities in HBU fuel, would impact coolable geometry. The importance of understanding this interaction was identified as critical, as it was viewed as driving coolable geometric implications locally and globally throughout the core. Related to area (6), dispersed fuel final location, it was noted that fuel would be less likely to settle down in the bottom of a fuel bundle or assembly or in the lower plenum region in the event of a failure during an RIA, due to the increased advective forces that would transpire under liquid flow conditions and potentially subcooled coolant states. Accordingly, it was stated that the fuel would finally relocate to either grid spacers within the fuel bundle or assembly, upper or lower support plates, or throughout the RCS, which could be different and distinct from a LOCA-based failure.

Discussing FFRD phenomena related to HBUs, another panelist noted that, beyond the known FFRD phenomena such as fuel fragmentation and pulverization, a new phenomenon a “violent fuel-coolant interaction (FCI)” had been reported. This phenomenon resulted in severe fragmentation and fuel dispersal leading to a “shock wave” effect during an RIA test. The panelist noted that, while observations of the identified phenomenon had been made, related test data were limited, as detailed investigations or focused experiments appeared to be lacking. While RIA-induced consequences, including fuel dispersal, were described as limited to a very local region in the core and bounded by the LOCA evaluation, it was pointed out that the amount of data on HBU fuel testing under RIA conditions was fairly low with publicly available analysis and data generally lacking. While speculating that a safety analysis could show that the enthalpy in HBU rods would be sufficiently low to avoid failure, so that FFRD would not be an issue, it was emphasized that it remained unclear how severe HBU failures were during RIAs. Accordingly, experimental data in the burnup regimes with appropriate hydride concentrations from tests performed under prototypic power pulses were deemed appropriate in support of dispositioning safety concerns related to HBU fuel performance under RIA conditions.

Elaborating on transport aspects of dispersed fragmented fuel following a rod failure, another panelist noted that the particles were likely to come in many sizes, ranging from a maximum dimension, comparable to the size of the rupture, to nearly dust, and in highly irregular shapes including sharp corners. Whereas the panelist described the motion of solid particles in both liquid and gas (such as vapor) as a very well-studied problem, it was noted that hot fragments injected into water and possibly causing vapor generation would result in complex multiphase flow patterns with solid particles moving in a vapor-liquid two-fluid environment involving significantly more complex processes than those usually studied. In addition, complex flow geometries due to the presence of fuel rods and spacer grids were identified as further contributing to the uncertainties of predicting the transport of dispersed fragmented fuel particles. It was noted that the fragments could result in changed flow patterns and reduced or nonuniform cooling, as well as cause damage to the RCS and possibly other areas. The panelist's expectation was that large fragments would drift down and collect on spacer grids and possibly block the flow, whereas small fragments would be carried upward and either accumulate on spacer grids or be carried further with the flow and out of the core. The panelist also noted that, although it was likely that the amount of material injected would be relatively limited, there would be considerable uncertainties in exactly how the flow would be affected.

Discussing possible effects related to HBU fuel for a control rod drop accident (CRDA) in BWRs, another panelist referred to General Electric report NEDO-10527, "Rod Drop Accident Analysis for Large Boiling Water Reactors, Addendum No. 1 Multiple Enrichment Cores with Axial Gadolinium," issued July 1972, for a phenomena description, while pointing out the following factors that would prevent or mitigate the consequences of rod burst during such an RIA: (1) low temperatures, (2) fuel being covered under CRDA conditions of interest, and (3) reduced CRDA severity for HBU fuel. Regarding the first two factors, it was noted that rod burst would not be expected at such low temperatures, considering the level of stress needed. The panelist believed even if FFRD were to occur, fuel would be covered and cooled with clogged spacers presenting no concern under such conditions. Furthermore, it was noted that the rod internal pressure would be lower compared to that at hot operating conditions due to the fission gas temperature, mentioning that a gas pressure of 7 megapascal (MPa) at an operating temperature of 300 degrees Celsius (°C) would approximately correspond to 5 MPa at 160°C, according to the ideal gas law. Regarding the third factor, the panelist cited NEDO-10527, according to which "rod drop accident results will become less severe with increasing exposure due to the increased Doppler feedback with the accumulation of Pu-240." Further elaborating on this aspect, the panelist noted that a CRDA involving a configuration of four HBU bundles would be expected to be less reactive compared to other possible four-bundle configurations, although the possibility for a configuration involving one HBU and three fresh fuel bundles driving the HBU bundle's response was also recognized.

Discussing effects related to HBU fuel for a control rod ejection accident (CREA) in PWRs, the panelist noted the similarity between nuclear-related phenomena in BWRs and PWRs and pointed out that a CREA involving an HBU bundle would reduce the severity of the transient due to the lower reactivity. Regarding the core thermal conditions, it was noted that the rod internal pressure at hot zero power conditions would be close to that at hot operating conditions. It was further mentioned that, while cold conditions would result in higher reactivity, hot status would be closer to departure from nucleate boiling (DNB), thus making DNB occurrence and associated rod failure more likely under such conditions.[4] In similarity to BWRs, the panelist noted no concerns regarding fuel rod burst or clogged spacers, if FFRD were to occur. Concerning data availability, the panelist noted his lack of knowledge regarding what data were available for fuel failure during a CRDA or CREA in BWRs or PWRs, respectively, and how HBU could change the impact from such RIAs. In relation to this, and while noting that a Transient Reactor Test (TREAT) experiment would be obviously useful, the panelist's expectation was that it would not be necessary.[5]

Notes provided by another panelist identified key phenomena, including power pulse amplitude and width, coolant pressure and temperature, flow rates, fuel gap size, and rod internal pressure, among other fuel parameters, and described them as assumed to be known. In

---

[4] It is noted that, while rod failure due to high-temperature phenomena (ballooning and burst, oxidation) is more likely, it remains less clear that rod failure in general is more likely at high temperature. PCMI failure may be more likely at lower temperature due to reduced cladding ductility.

[5] Tests on high burnup rods under RIA conditions are ongoing under the CABRI International Project and the High Burnup Experiments in Reactivity Initiated Accident (HERA) project.

addition, in the panelist's opinion, there were no new phenomena with respect to EE and HBU fuel in RIA failure mechanisms. It was also recognized that increased enrichment could affect the kinetics response, and HBU fuel would adversely affect the rod internal pressure by potentially increasing it and impacting ductile failures. HBU fuel would be readily fragmented during the temperature transient. Regarding the core conditions, it was noted that the reactor initial conditions would be transient specific (CREA versus CRDA) and could be accordingly defined in a bounding manner (e.g., hot zero power, cold zero power). It was stated that, although fuel-related parameters could be different for EE/HBU fuel, they could be modeled by fuel thermal-mechanical performance codes updated accordingly to eventually extend their applicability ranges for EE and HBU fuel with no concern about increased uncertainty. While recognizing that the RIA consequences for EE/HBU fuel would be the same as, or slightly worse than, those for fuel at the current burnup limits, it was noted that no additional coolability concerns would arise from FFRD, as the dispersed fuel amount would be limited for an RIA, which is a local core event. It was specifically noted that the last assertion was made considering the incremental effect of EE/HBU fuel. Concerning data availability, the panelist noted the existing fairly extensive level of knowledge regarding RIA-induced failures, mentioning tests performed at the Special Power Excursion Reactor and the Power Burst Facility in the United States, the CABRI experimental reactor at the Cadarache Research Center in France, and the Nuclear Safety Research Reactor in Japan.

APPENDIX D
FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL PHENOMENA IDENTIFICATION AND RANKING TABLE ON HIGH BURNUP FUEL FRAGMENTATION, RELOCATION, AND DISPERSAL AND ITS CONSEQUENCES FOR FUEL HANDLING ACCIDENTS WITH PANEL VOTES

Table D-1 PIRT on High Burnup FFRD and Its Consequences for FHAs with Panel Votes

Phenomena				Input Date	Panel Member	FOM-3 (Release)			Panel Discussion Notes
Cat	No.	Description	Relevance			Imp.	SoK	U	
1. Fuel initial conditions	1.1	Rod powers and burnups that bound operating release	Regulations state that radiological consequences should not be underestimated; bounding values assure this is met	12/20/23 01/19/24 01/19/24	GT	M	H	L	
				12/19/23	WW	M	H	M	
				12/21/23	NC	L	H	L	
				12/19/23	FB	L	H	L	Independent of FFRD, this is required by FHA analysis.
				01/15/24	WM	L	H	L	The impact of rod burnup and bounding operations in fact drives significant influence over almost all safety-related outcomes as detailed within this PIRT study. The uncertainty is well-quantified with characterized confidence.
				12/26/23	DK	M	H	L	EE and HEU will change how fuel is utilized within the core of operating reactors with the precondition of the fuel dependent on the linear power density and burnup histories. This will impact locally the fission gas, isotopic distribution, stored energy (decay heat), and fuel fragment distribution. Rod powers, burnups, and isotopics can be calculated to high accuracy with low uncertainty.
				01/05/24	KM	L	H	L	
	1.2	Gap volatile radioactive release	Radiological	12/20/23 01/19/24	GT	M	M	M	
				12/19/23	WW	L	M	M	
				12/21/23 01/19/24	NC	L	H	M	
				12/19/23	FB	M	L	H	RG 1.183 specifies the gap release. The question is whether FF could occur during FHA and if any additional gap source term could be added initially or after the fuel is wetted. Low SOK and H uncertainty is primarily due to lack of expertise with topic.
				01/15/24 01/19/24	WM	M	M	M	I believe there is measurable influence of this in relation to overall safety implications. However, I want to disclose my limited personal/professional individual knowledge on gap volatile radioactive release.
				12/26/23	DK	M	M	M	Total fission product inventory is known but the amount and distribution of fission gas throughout the rod has higher uncertainty. This will not impact coolability or criticality but may impact the gas release under a fuel handling accident.
				01/05/24	KM	L	H	L	

Phenomena				Input Date	Panel Member	FOM-3 (Release)			Panel Discussion Notes
Cat	No.	Description	Relevance			Imp.	SoK	U	
	1.3	Fuel bundle structural design characteristics	Fewer rods per bundle generally result in higher release (e.g., PWR 14x14 vs. 17X17)	12/20/23 01/19/24 01/19/24	GT	M	M	L	
				12/19/23	WW	L	M	M	
				12/21/23	NC	L	H	L	We have sufficient information to provide initial conditions. Extending burnup, while it might change gas content, is a delta but not an unknown. We know the gas in the fuel and will have data and analysis to know the gas in the gap.
				12/19/23	FB	L	H	L	
				01/15/24 01/19/24	WM	M	M	L	The design parameters (including clad dimensions) drive hoop strain limits and internal pressure levels along with yield stresses, which are the primary correlation to failure or impact from a safety perspective.
				12/26/23	DK	M	M	L	EE and HBU combined with ATF will result in changes to fuel pellet diameters, increased fissile mass loading, and potentially the amount and size distribution for fragmented fuel that could be released in a fuel handling accident.
				01/05/24	KM	L	H	L	

Phenomena				Input Date	Panel Member	FOM-3 (Release)			Panel Discussion Notes
Cat	No.	Description	Relevance			Imp.	SoK	U	
2. Mechanical Impact	2.1	Additional fuel fragmentation from mechanical shock	Increases radiological release	12/20/23	GT	M	M	H	
				12/19/23	WW	L	M	M	
				12/21/23	NC	M	M	H	SCIP IV has some data, but the amount of fragmented fuel beyond what occurs during a LOCA is near negligible. The fragments formed are very small (<<0.1mm) and there may be some concern for this material to be in aerosol form.
				12/19/23	FB	M	L	H	See 1.2, this item includes consideration of the impact on Iodine release in the event that FFs come in contact with water.
				01/15/24 01/19/24	WM	L	H	L	I don’t see this having a significant role on the overall outcome from a safety perspective.
				12/26/23 01/19/24 01/29/24	DK	L	M	M	Mechanical shock could potentially break the clad fuel bonding and additional breakup of the fuel into smaller fragments. This would not be expected to increase the release of fission gas. A minor concern is the interaction of small fragments with coolant.
				01/05/24	KM	L	H	L	Radiological releases would be most dominantly governed by fission gas release.
	2.2	Additional gas release from mechanical shock	Increases radiological release	12/20/23	GT	L	L	H	
				12/19/23	WW	L	M	M	
				12/21/23	NC	L	M	H	Gas could be released during mechanical shock. But FGR is typically driven by FG bubble overpressurization. An external force could cause local FGR, but global FGR is not possible.
				12/19/23	FB	L	L	H	See 1.2, but think gas release is of lesser importance than the potential impact of FFs in 2.1.
				01/15/24 01/19/24	WM	L	H	L	This should not play a significant role in any of the FOMs considered within this study.
				12/26/23 01/19/24	DK	L	M	M	Fuel breakup due to mechanical shock would release additional fission gas resulting in greater potential for release.
				01/05/24	KM	L	H	L	Fission gas release is driven by the fuel temperature. Mechanical effect on fission gas release is low.

NRC FORM 335
(12-2010)
NRCMD 3.7

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC, Add Vol., Supp., Rev., and Addendum Numbers, if any.)

NUREG/CR-7307

2. TITLE AND SUBTITLE

Phenomena Identification and Ranking Tables on High Burnup Fuel Fragmentation, Relocation, Dispersal, and Its Consequences for Design-Basis Accidents in Pressurized- and Boiling-Water Reactors

3. DATE REPORT PUBLISHED

MONTH	YEAR
May	2024

4. FIN OR GRANT NUMBER

5. AUTHOR(S)

Vesselin Palazov (1), Francis Bolger (2), Nathan Capps (3), David Kropaczek (4), Wade Marcum (5), Kurshad Muftuoglu (2), Gretar Tryggvason (6), Wolfgang Wiesenack (7)

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

1. Information Systems Laboratories, Inc., Tysons Corner, VA 22182; 2. Electric Power Research Institute, Palo Alto, CA 94304; 3. Oak Ridge National Laboratory, Oak Ridge, TN 37830; 4. Veracity Nuclear, Lenoir City, TN 37771; 5. Oregon State University, Corvallis, OR 97331; 6. Johns Hopkins University, Baltimore, MD 21218; 7. Halden Reactor Project (retired), Halden, Norway

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above", if contractor, provide NRC Division, Office or Region, U. S. Nuclear Regulatory Commission, and mailing address.)

Division of Systems Analysis
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555-0001

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

This report presents the results from the U.S. Nuclear Regulatory Commission's expert elicitation effort to develop phenomena identification and ranking tables (PIRTs) in support of addressing technical issues related to fuel fragmentation, relocation, and dispersal (FFRD) and its consequences during design-basis accidents related to the use of extended enrichment (EE) and high burnup (HBU) fuel in domestically operated pressurized- and boiling-water reactors. The developed PIRTs identify phenomena seen as relevant to EE/HBU FFRD and its consequences from a safety viewpoint and assess the importance, level of knowledge, and related uncertainty for the considered phenomena. The PIRTs enhance the agency's knowledge base related to FFRD and its potential consequences for EE/HBU fuel use.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

Fuel fragmentation, relocation, and dispersal (FFRD)
Loss-of-coolant accidents
Reactivity-initiated accidents
Fuel handling accidents

13. AVAILABILITY STATEMENT
unlimited

14. SECURITY CLASSIFICATION
(This Page)
unclassified
(This Report)
unclassified

15. NUMBER OF PAGES

16. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, DC 20555-0001

OFFICIAL BUSINESS

@NRCgov

NUREG/CR-7307

Phenomena Identification and Ranking Tables on High Burnup Fuel Fragmentation, Relocation, Dispersal, and Its Consequences for Design-Basis Accidents in Pressurized- and Boiling-Water Reactors

May 2024