Technical Expert Panel Assessment of Existing Fuel Fragmentation, Relocation, and Dispersal Data

Current Understanding and Needs for Future Research

3002025542

Technical Expert Panel Assessment of Existing Fuel Fragmentation, Relocation, and Dispersal Data

Current Understanding and Needs for Future Research

3002025542

White Paper, September 2022

EPRI Project Manager

R. Ratnayake

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

EPRI PREPARED THIS REPORT.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

ACKNOWLEDGMENTS

EPRI prepared this report.

Principal Investigator
I. Arimescu

EPRI Technical Reviewer
S. Yagnik

This report describes research sponsored by EPRI.

The following Technical Expert Panel participated in the review.

R. Armstrong (Idaho National Laboratory – INL)

C. Jensen (Idaho National Laboratory – INL)

M. Boskov (Électricité de France – EDF)

N. Capps (Oak Ridge National Laboratory – ORNL)

L. Gerken (Framatome Inc.)

J. Karlsson (Studsvik Nuclear AB)

J. Kobelak (Westinghouse Electric Company)

J. Matsunaga (Global Nuclear Fuel – Japan Co., Ltd. – GNF-J)

I. Porter (Global Nuclear Fuel – Americas, LLC – GNF-A)

K. Sakamoto (Nippon Nuclear Fuel Development Co. Ltd.)

T. Tverberg (Institute for Energy Technology – IFE)

K. Yueh (EPRI)

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

Technical Expert Panel Assessment of Existing Fuel Fragmentation, Relocation, and Dispersal Data: Current Understanding and Needs for Future Research. EPRI, Palo Alto, CA: 2022. 3002025542.

ABSTRACT

This white paper presents a critical review of the currently available (FFRD) data performed by an expert panel of industry reviewers, where the related experimental and theoretical viewpoints are examined in detail.

Cracking occurs in uranium dioxide-based fuel pellets housed in cylindrical cladding in light and heavy water reactors under normal operation. The quasi-parabolic temperature radial distribution in the fuel pellets creates thermoelastic stresses and the ceramic uranium dioxide, being a brittle material, cannot withstand the tensile stresses in the circumferential and axial directions in the outer part of the pellet, and radial and transverse cracks develop. The resulting crack wedges are large and typically interlocked so that the pellets remain essentially as one piece, up to discharge at the end of irradiation, assisted by the cladding restraint; this level of cracking is referred to as *macrocracking*.

During abnormal and accidental conditions, thermal transients occur, and the fuel is subject to temperature excursions, which can lead to fuel fragmentation, where the pellets fragment into smaller pieces than those that have been created by macrocracking during prior base irradiation and cause additional macrocracking and microcracking. The latter is also called *fine fragmentation* or *pulverization*, which corresponds to a fragment size less than 1 mm in average diameter. In recent research, fine fuel fragmentation has been observed to occur, especially at high pellet local burnups just at or above the current fuel design limit. Prior research on fuel at mid-burnup range showed fragmentation by macrocracking only.

Additional pellet fragmentation to various degrees is more likely to occur in the outer pellet regions, during LOCA-type transients, in which the internal rod pressure is increased simultaneously with the cladding and fuel temperatures. Such conditions lead to cladding outward creep deformation, which if large enough, removes the mechanical cladding constraint on fuel pellets. As a result, the fuel fragments created by the temperature transient can potentially move axially within the fuel rod and into open spaces created by clad outward creep. Fuel fragments can accumulate in the local, larger areas of cladding deformation, called *balloons*, caused by local temperature maximums. This process is known as *relocation* and is implied that it is an axial movement of fuel fragments.

Excessive deformation in the localized balloons can lead to cladding rupture, a process called *cladding burst*. Depending on the burst opening size, it is possible for the fuel fragments in the rupture opening to eject from the fuel rod, assisted by the gas flow blowing from the inside of the fuel rod through the rupture opening. This process is called *dispersal*, and it has been observed to be enhanced by the fine fuel fragmentation at very high burnup in single-rod integral LOCA tests of in-pile and out-of-pile hot cell conditions.

These three processes, fuel fragmentation (FF), relocation (R), and dispersal (D), have been collectively referred to as *FFRD*. The FFRD processes have implications on fuel behavior during LOCA transients and affect the analysis that is required to demonstrate compliance with regulatory criteria. While relocation has been addressed in the past, dispersal is a more recent concern.

A review of the empirical methods and data includes a selected set of past and recent studies, identified to be the most relevant to FFRD phenomena. A review of the theoretical aspects consists of a review of current phenomenological understanding of processes and mechanisms underlying FFRD and approaches to deriving models and criteria to be used in LOCA analyses.

The body of separate-effects tests and integral LOCA tests with theoretical considerations was reviewed to identify the causes of fine fragmentation and their contributing factors. A complementary objective in this review was to evaluate to what extent those test conditions are prototypical and how the test results can be applied to an analysis of the actual LOCA scenarios.

This review concluded that both the in-pile and out-of-pile LOCA tests have been designed to maximize the effects of ballooning and hence provide upper bounding results for all FFRD component processes. The core-wide analysis of FFRD impact requires accounting for the full range of conditions, including the spectrum of ballooning and burst opening sizes; otherwise, the consequences of fuel fragment dispersal are not fully characterized and its effect on fuel coolability overestimated.

The existing separate-effects and integral test data are still a partial data set of the overall FFRD phenomenon, consisting of studies aimed at scoping and/or the confirmation or contradiction of different hypotheses that have been brought to the fore. More research is needed to obtain good data for developing models or establishing criteria. In that respect, more experimental investigations are needed that either remove the current non-representative features or assess the impact and formulate ways to account for them and be validated experimentally.

While the current rod average burnup limitation is generally considered not greatly affected by FFRD, unless the potential effects of fuel dispersal on coolability can be resolved, the implementation of an FFRD processes in the current LOCA methodologies, and methods require a realistic uncertainty treated best-estimate approach coupled with a risk-informed evaluation.

To that end, the knowledge and experimental data gaps related to FFRD are summarized at the end of Conclusions in Section 8.

Keywords
Cladding
Fragmentation
Fuel fragmentation, relocation, and dispersal (FFRD)
Loss of coolant accident
Macrocrack behavior
Microcrack initiation/propagation

ACRONYMS

AECL	Atomic Energy of Canada Ltd (now CNL, Canada National Laboratories)
ANL	Argonne National Laboratories
AOO	Abnormal Operating Occurrences
BWR	Boiling Water Reactor
CEA	Commissariat a l'Energie Atomique
DBA	Design Basis Accident
D	Dispersal
DEH	Direct Electrical Heating
ECCS	Emergency Core Cooling System
ECR	Equivalent Cladding Reacted
EDF	Électricité de France
EDX	Energy Dispersive X-ray
EPMA	Electron Probe Microanalysis
FBR	Fast Breeder Reactor
FF	Fuel Fragmentation
FIMA	Fission per Initial Metal Atom
FCI	Fuel Coolant Interaction
FFRD	Fuel Fragmentation, Relocation, and Dispersal
FGR	Fission Gas Release
GB	Grain Boundaries
HBRP	High Burnup Research Program
HBS	High Burnup Structure
HEDL	Hanford Engineering Development Laboratories
HRP	Halden Reactor Project
HT	Heating Test
IFE	Institute for Energy Technology
INL	Idaho National Laboratories

ITU	Institute for Transuranium Elements (now JRC)
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor
NFIR	Nuclear Fuel Industry Research
NOC	Normal Operating Conditions
NRC	Nuclear Regulatory Commission
OOP	Out of Pile
PCM	Power Cooling Mismatch
PCT	Peak Cladding Temperature
PIE	Post-Irradiation Examination
PWR	Pressurized Water Reactor
R	Relocation
SEM	Scanning Electron Microscopy
SFD	Severe Fuel Damage
SCIP	Studsvik Cladding Integrity Program
T/C	Thermocouple
ORNL	Oak Ridge National Laboratories
VVER	Water-cooled Water-moderated Energy Reactor (Voda-Vodyanoi Energetichesky Reacktor)

CONTENTS

1 INTRODUCTION

This report is a critical review of the currently available Fuel Fragmentation, Relocation, and Dispersal (FFRD) data, the experimental, and theoretical viewpoints. The empirical part includes a selected set of past and more recent experimental studies, considered directly or indirectly to be the most relevant to FFRD aspects. The theoretical aspects consist of a review of current phenomenological understanding of processes and mechanisms underlying FFRD and approaches to deriving models and criteria to be used in Loss of Coolant Accident (LOCA) analyses.

Throughout this report, knowledge data gaps are noted. Most critical gaps to be addressed through future research and modeling are identified at the end. The current review greatly benefited from previous reviews and studies, such as NUREG-2121, summaries of IFA-650 series, NFIR fine fragmentation threshold papers and dedicated reports, NEA reviews, and authors' review of the Studsvik Cladding Integrity Program (SCIP) body of research. Also, relevant information was gleaned from past fast breeder reactor (FBR) fuel research on the FFRD topic, which, although not directly applicable to light water reactor (LWR) LOCA analysis, involves the same underlying physical processes and offers complementary insights.

The driver for increased interest in FFRD is outlined in Section 1.1, which briefly describes its relevance in the licensing space and sets up the objectives for the FFRD studies. The rest of the manuscript is concerned with existing data sets and theoretical approaches, which are reviewed from the point of view of representativity to LOCA conditions and prototypicality to LWR fuels.

1.1 LOCA Design Basis Accident Salient Features

The operation of nuclear power plants (NPPs) and the fuel designs have established procedures and design and functional features, which aim at mitigating the impact of various anticipated operational occurrences (AOO) and of potential accidental conditions that are considered in the design of fuel and specific plant systems, known as *design basis accidents (DBA)*. As a result of analyzing the DBAs, certain mitigating plant systems were designed and enforced at all NPPS by regulation; also, design analysis is performed for each fuel type prior to its loading in the core of an NPP to establish the set trip points to scram and shut down the reactor and then to activate the corresponding plant emergency systems.

The main DBA scenarios are LOCA and Reactivity Insertion Accidents (RIA), in which potential fuel rod failures and their effects must be considered. Regulatory criteria with specific limits for certain fuel performance parameters are established to show compliance with high-level acceptance criteria, of which the ones relevant herein are concerned with radiological consequences from radioactivity release to the reactor coolant system (RCS) and outside the containment, recriticality, and potential impairment of short- and long-term post-LOCA core cooling.

The latter is of great importance for LOCA, which postulates a pipe break at various locations within the primary or secondary RCS, with the result of depressurization during the ensuing blowdown. This loss of coolant flow and pressure greatly worsens the heat transfer from the fuel to the coolant, and hence a temperature excursion occurs in both the fuel pellets and cladding. The rod internal pressure becomes larger than the outside coolant pressure, which has fallen to

lower values for small breaks, reaching almost atmospheric pressure for LBLOCA because of depressurization and hence drives the outward cladding deformation, which is greatly enhanced at high temperatures and could eventually cause cladding cracking, known as *burst*, under high-temperature rod internal gas pressure driven conditions.

The potential occurrence of cladding burst is relevant in addressing the general safety criteria because of the possibility of ensuing fuel disturbance, as characterized in either excessive cladding embrittlement that could lead to cladding fragmentation (shattering) during quench, away from the ballooned and ruptured area, or in fuel fragmentation and relocation inside the fuel rod with the potential dispersal in the surrounding coolant space through the burst opening.

The former aspect has been the subject of extensive and in-depth research that was finalized in specific safety acceptable fuel design limits (SAFDL), and compliance with them must be assured through design analyses. This topic has been reviewed and well summarized in several conference papers and dedicated reports [1-1 to 1-3].

The subject matter of this report is the latter aspect, namely, fine fuel fragmentation, relocation, and dispersal, which is usually referred to as *FFRD*, which commonly reads as "fuel fragmentation, relocation, and dispersal"; however, the often omitted "fine" qualifier should be included, and the full acronym should be ideally FFFRD.

The driver for FFRD studies, which gained momentum in the last 10 years, is the concern that fuel fragments could be expelled from the fuel rod through a rupture opening, especially a cladding burst during a LOCA event. In addition, movement of loose fuel fragments when the rod diameter increases in the ballooned area, which occurs prior to (not long before) cladding burst, allows to some extent, the fuel fragments' relocation downward into the ballooned area; this causes an increased heat generation in the ballooned region, and even after burst, could potentially enhance cladding inner-side corrosion and hydrogen uptake by the cladding, causing additional cladding embrittlement.

As an example, in Reference 1-4, the following is stated about axial fuel relocation in the ballooned area:

> "During normal operation, oxide fuel pellets develop many cracks because of thermal stresses. Some fragmented fuel particles located above the ballooned region of a fuel rod will thus relocate into the enlarged volume of the balloon under the influence of gravity and pressure differences. This effect was first noticed in 1980 in reactor tests in the United States and Germany, and recent tests at Argonne National Laboratory (ANL) and the Halden Reactor Project in Norway have confirmed it. The consequence of fuel relocation is an increase in heat generation in the ballooned region with corresponding increases in cladding temperature and oxidation compared with an undeformed length of the fuel rod."

Thus, relocation was related to the excessive embrittlement concern, which was identified during later research as an issue for the edges of the ballooned area, where additional transient hydrogen uptake can occur and is also the subject of a recent update to U. S. regulations, which is in the final stages of being issued [1-5].

The other parts of FFRD, namely, the topic of fine fuel fragmentation and dispersal, are not addressed in the current and soon-to-be updated LOCA regulation [1-5]. This topic has been brought up several times in the past; at one point, it was classified as a generic issue and then decided to be moved to the classification category of "dropped" [1-6], because in past studies, lower- to mid-burnup fuel rods showed that only macro, coarse, fragmentation occurred and, as such, no or negligible dispersal took place. Of special interest is the conclusion of the NRC-sponsored integral LOCA tests at ANL, which stated that:

> "Loss of fuel particles through the rupture opening in the ballooned region of a fuel rod was not expected based on any prior research. When integral loss-of-coolant accident (LOCA) tests were recently completed at ANL on high-burnup boiling-water reactor (BWR) rods with a local burnup of 64 GWd/t, a small amount of fuel loss was noticed (about the quantity of one fuel pellet). Because the amount of material was small, this observation was not thought to be important." [1-4]

However, in April 2006, a LOCA test was run in the Halden reactor on a fuel rod segment with a very high local burnup of 91.5 GWd/t. Results from this test were presented and showed gross loss of fuel material from above the rupture opening [1-7]. Online instrumentation indicated that this fuel loss occurred during the temperature transient rather than after the test was over.

Thus, FFRD has become a central issue in the framework of current industry activities to extend burnup, which is necessary for accommodating higher enrichment and advanced fuel management with existing or advanced fuel types.

The current review is focused on FFRD aspects, ranging from available experimental data to the interpretation of that data to develop models and their relevance to acceptance criteria and limits that are still to be defined. Because the prerequisite for FFRD is clad ballooning and burst, this topic is briefly reviewed in the following subsection, focusing on the aspects with direct impact on FFRD processes and also on representativity of various separate-effects and integral tests.

Before that, a succinct characterization of FFRD's final process, namely, fuel dispersal is in order. As stated above, the overarching concern regarding the effects of a LOCA event is impairment of core coolability. As expressed in 1967, an Advisory Task Force on Power Reactor Emergency Cooling appointed to provide "additional assurance that substantial meltdown is prevented" [1-8] by core cooling systems concluded that:

> "The analysis of (a LOCA) requires that the core be maintained in place and essentially intact to preserve the heat-transfer area and coolant-flow geometry. Without preservation of heat-transfer area and coolant-flow geometry, fuel-element melting and core disassembly would be expected… Continuity of emergency core cooling must be maintained after termination of the temperature transient for an indefinite period until the heat generation decays to an insignificant level, or until disposition of the core is made." [1-8]

Consistent with the conclusions of the Task Force, the U.S. Atomic Energy Commission (AEC) promulgated Criterion 35 of the General Design Criteria, which states that: "... fuel and clad damage that could interfere with continued effective core cooling is prevented" [1-9]. It also promulgated Criterion 3 of the Interim Acceptance Criteria for ECCS for LWR, which states that:

> "The clad temperature transient is terminated at a time when the core geometry is still amenable to cooling, and before the cladding is so embrittled as to fail during or after quenching." [1-9]

This rationale makes it abundantly clear that it is most important to preserve the heat transfer area and the coolant flow geometry, not only during the short-term portion of the core temperature transient but also for long-term. It is from this perspective that fuel dispersal must be analyzed. It is relatively easier to conclude that fuel dispersal has no impact on fuel rod embrittlement; on the contrary, it reduces the heat source and hence retards the oxidation and transient hydrogen uptake. Parenthetically, the fuel-clad bonding phenomenon that appears to occur at high burnup is also mitigating transient oxidation, and hydrogen uptake on the inner clad surface and fine fragmentation of a high-burnup pellet rim region may leave behind small wedges of fuel bonded to the cladding. However, the potential adverse effects of fuel fragments piled up at confined spaces, such as grids, which could provide additional heat-up for the cladding, must be investigated and resolved.

The other potential effects of fuel dispersal, namely, recriticality and fuel-coolant interaction (FCI) have been investigated and it was concluded that neither presents a risk. What is left open is the question of impact on the RCS in terms of local flow blockage at spacer grids, in the case of fuel fragments accumulating at those confined spaces or clogging other RCS flow interfaces (GSI-191) [1-10], if the fuel fragments are entrained in the flow after reflood and refill stages.

1.2 Cladding Ballooning and Burst

As mentioned above, LOCA scenarios imply that the fuel rod will undergo a temperature excursion transient after loss of coolant pressure because of a blowdown. Under these conditions, the high-temperature creep mechanisms are activated, and the cladding radius increases (called *swelling* in early reports). The permanent deformation of Zr alloys, in general, is dependent on stress and temperature, and both parameters increase during the LOCA transient, after the rod-to-coolant heat transfer deteriorates due to loss of flow and phase change to steam.

Research conducted with single- or multi-rod burst tests has shown that, initially, an axially uniform straining period of up to 5–10%, deformation is localized in one or several ballooned regions. Ballooning, that is, localized, enhanced clad outward creep (called *swelling* in licensing documents), is caused by axial temperature nonuniformity and/or variations in clad material properties and geometric characteristics. The main concern regarding ballooning is the reduction of the flow area, and many studies have been dedicated to quantifying the extent and distribution along the fuel assembly length of this flow area reduction impact, to assess the amount of flow blockage (a fraction of the flow area is occluded by ballooning) and also the net impact after considering the mitigating phenomena, such as an increase in the fuel rods heat transfer area, coolant droplet breakup, and increased turbulence.

During the heat-up, the pressure in the cladding will increase due to the heat-up of the mixture of the fill gas and the released fission gases. At the same time, the strength of the cladding is reduced and, eventually, the cladding will start to deform plastically, that is, creep will start. It is thus necessary to have a good understanding of the strength and creep properties of zirconium alloys under LOCA conditions and how they depend on alloy composition and other factors. There are, however, several complications involved, and these make both analytical modeling and interpretations of experimental results difficult.

The first complication is that zirconium alloys generally are very anisotropic when they are in the hexagonal α-phase condition. The typical anisotropy of a cladding tube is such that, when the diameter is increased, the material shrinks in the axial direction (see Appendix A for details). For an isotropic material, the diametral expansion by plastic deformation has no effect on other dimensions of the tube. The shortening becomes important in the case of a nonuniform temperature distribution around the circumference of the cladding, causing a larger deformation to occur on the hotter cladding side, which will then shrink more than the opposite cooler side, with the effect of causing cladding at that location.

This phenomenon is central to a successful modeling and understanding of a LOCA event and its consequences. Integral LOCA tests have been performed in-pile and out-of-pile in hot cells, in experimental rigs that simulate the temperature transient and low pressure and steam flow (or stagnant) around a single rod or in multi-rod configurations. The rod holding in the experimental rig was varied from free-to-expand axially at the top or at the bottom, to constrained axial deformation. The latter was achieved in some in-pile tests by a simulated pellet stack and associated plenum spring, which restrains cladding axial shrinking that occurs in the α-phase temperature domain. It was found that (KFK-3346) such in-pile tests showed very little, or even positive axial length change in the high alpha phase region, compared to noticeable axial shrinking for the out-of-pile tests, and the above explanation was considered valid. Some simulated fuel rods had a solid heater rod instead of a pellet stack, and this was more rigid and prevented rod bowing in comparison with pelleted simulated rods, which showed the same bending behavior and magnitudes as the empty out-of-pile burst tests.

The temperature nonuniformity around cladding circumference is caused by several factors external and internal to the fuel rod. Coolant flow and heat transfer to the cladding characteristics vary both axially and circumferentially for any fuel rod in the assembly because of the impact of flow area geometry and neighboring fuel rods. Internally, the pellet column has a nonuniform axial stacking with respect to pellet eccentricity inside the cladding. Both factors lead to the creation of hot spots on top of the macro axial and transverse temperature gradients caused by the heat generation rate distribution in the fuel assembly.

Tests have supported the theoretical calculations indicating a large reduction of the total (average) hoop strain when circumferential temperature gradients are present. In addition, the burst shape is significantly more ovalized, and the bending toward the cooler side is manifested. This bending orientation (due to more shrinking on the hot side that will eventually rupture) is a self-accelerating feedback effect in that the pellet-cladding contact is enhanced on the hot side, while a gap opens by bending on the cooler side, which leads to an increased temperature circumferential gradient.

In the following sections, the existing tests are examined with respect to these nonuniform temperature circumferential distributions and the axial bending, or lack thereof, both with clear impacts on the tests' representativity, with special focus on the impacts on FFRD.

1.3 References

1-1. G. Hache and H. M. Chung, "The History of the LOCA Embrittlement Criteria" (pp. 37–64), Topical Meeting on LOCA Fuel Safety Criteria held in Aix-en-Provence, NEA/OECD, 2001.

1-2. U.S. Code of Federal Regulations, Title 10, Part 50, Section 46, *Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors*, 1974.

1-3. H. M Chung and T. F. Kassner, "Embrittlement Criteria for Zircaloy Fuel Cladding Applicable to Accident Situations in Light-Water Reactors—Summary Report," NUREG/CR-1344, January 1980.

1-4. Memorandum, "Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46," RIL 0801, May 30, 2008.

1-5. R. Meyer, NRC Memorandum to J. Flack, "Update on Generic Issue 92: Fuel Crumbling During LOCA," February 8, 2001, Agencywide Documents Access and Management System (ADAMS) Accession No. ML010390163.

1-6. Draft Regulatory Guides, DG-1261, DG-1262, and DG-1263 (in final stages of issuance).

1-7. W. Wiesenack and L. Kekkonen, "Overview of Recent and Planned Halden Reactor Project LOCA Experiments," Presentation at the Japan Atomic Energy Agency's Fuel Safety Research Meeting, May 16–17, 2007 (ML081370546).

1-8. Report of Advisory Task Force on Power Reactor Emergency Cooling, TID-24226 (1967).

1-9. U.S. Federal Register, "Interim Acceptance Criteria for Emergency-Core-Cooling Systems for Light-Water Power Reactors," Vol. 36 (125), 1971, p. 12247–12250.

1-10. GSI-191 Technical Assessment, NUREG/CR-6762, Vol. 2, LA-UR-01-1800.

2
FUEL FRAGMENTATION PHENOMENOLOGY

A brief overview is provided with full details in Appendix A, of the physicochemical processes that have been identified as contributing to fuel fragmentation (FF) of irradiated oxide fuel during thermal transients, both heat-up and cooling; the second subsection concerns environmental conditions (steam and water ingress after burst), which can lead to specific cracking modes and cause additional FF during the later LOCA phases in the case of a fuel rod burst. As described in the outcome of the theoretical overview, overpressurized and elongated gas bubbles create a stress intensification factor, especially along grain boundaries, and promote microcracking, which upon crack interlinkage could result in macrocracking, resulting in grain separation and disintegration into fuel fragments. However, existing experiments led to the observations that gas bubble overpressures are not sufficient to trigger cracking, and the last subsection presents a hypothesis regarding the semi-volatile cesium (Cs) role in reaching the needed gas bubble overpressure, when Cs precipitated on gas bubble internal surfaces volatilizes at its boiloff temperature of ~ 700°C.

3 EXPERIMENTAL DATA SETS FOR FF

As briefly described in the introductory sections of this report, the evolution of cladding temperature and rod internal pressure during a LOCA event is complex and varied because of many different scenarios, depending on the location and size of the assumed pipeline break. This is further influenced by specific plant emergency core cooling system (ECCS) design and location, which can impact the flow during the different LOCA phases, from blowdown to refill and reflood, as it was found that the heat transfer and mass and flow velocity conditions can vary for different PWR designs, affecting the rates of heating and quenching, with implications on the amount of ballooning and coplanarity.

Therefore, a variety of testing methods and protocols have been devised to study the phenomena associated with fuel rod behavior during a LOCA. As for other fuel behavior aspects (for example, fission gas release, swelling), both separate-effects tests and semi-integral, or integral tests have been pursued to investigate and quantify fuel behavior in LOCA conditions.

The separate-effects tests are focused on specific phenomena/processes, which are investigated separately, but trying to assure, to the maximum extent possible, that the range of conditions covers the expected parameter range during a LOCA. In some cases, auxiliary outcomes of separate tests were indirect inferences to other processes of interest, for example, hot cell annealing tests on pellets or fragments of pellets to study transient FGR (tFGR), which were used to deduce fuel fragmentation onset.

Semi-integral tests are characterized by a setup that aims at mimicking the main fuel or cladding parameters' evolution during a LOCA, but specific, targeted processes are measured. An example of semi-integral tests are the burst tests performed on either a single or a multi-rod arrangement. The single-rod tests have been used to build and validate cladding high-temperature creep models and as such, different test protocols have been used: constant temperature and pressure, constant pressure or vice versa with temperature ramps at different heating rates, and complex pressure, temperature histories. Most of these tests have been out-of-pile, and some on irradiated cladding; it was proven that irradiation hardening is quickly annealed out at high temperature, and hence tests on unirradiated cladding can be used. More details about these tests are summarized in Section 4.

The main objective of separate-effects and semi-integral tests is to acquire data for a better understanding of the phenomena and for model building.

The integral tests are designed to follow a specific LOCA scenario for fuel rod behavior but with a scaled down fuel rod; the experimental fuel rod and test rig are instrumented to monitor online, mainly the evolution of parameters of interest and to detect fuel rod rupture. However, some processes cannot be followed online, such as fuel pellet fragmentation onset and evolution, and only post-test PIE, if exhaustively pursued, would be available to observe the final state of fuel fragmentation (with possible contributions from post-test handling). Nevertheless, indirect observations of fragmentation can be made by the online readings from instrumentation for temperature measurements attached to the cladding in several axial positions, so that downward

relocation of fragmented fuel can be monitored, because axial sections of the fuel rod from which fuel fragments have moved away by relocation show a rapid temperature drop as the heat source furnished by the fuel pellets becomes locally absent.

The integral tests can be in-pile or out-of-pile in a hot cell. For the latter case, heating is from the outside of the fuel rod, usually by heat radiation in a furnace or by infrared lamps. Further details of this aspect, as well as a full description of the existing tests and data sets are provided in Appendix B.

4 REPRESENTATIVITY OF LOCA INTEGRAL TESTS

The integral LOCA tests, which were summarized in the previous section, were designed to create the environmental coolant conditions and fuel rod temperature transients that are hypothesized to occur during a LOCA. There is quite a broad range of LOCA scenarios and specific conditions in LWRs, and, as such, it is not possible to define a unique “representative” case for all LWR types, or even within a given LWR type.

Moreover, limitations related to experimental rig dimensions and instrumentation impose perceivable differences in the evolution of the main fuel rod performance parameters during the test, which lead to significant differences between the simulated LOCA scenarios in the test and the reality. Therefore, it is arguable that the integral LOCA tests are not fully prototypical, and the features that are not entirely representative must be carefully analyzed before applying the test results to a LOCA analysis and, most importantly, to defining criteria and limits for a licensing analysis.

The following is a list of the main issues regarding the representativity of the integral LOCA tests performed either in a test reactor or in a hot cell.

4.1 Test Protocol

The tests were deliberately designed and carried out with conditions that would emphasize the occurrence of certain phenomena instead of trying to faithfully reproduce the reactor conditions expected during a LOCA. To that end, the temperature escalations that were allowed to continue after a rod burst were observed because the objective was to reach the licensing temperature limit (or its vicinity) to obtain data regarding transient oxidation and hydrogen uptake that are necessary to address the concern about cladding embrittlement in the ballooned area, which, if excessive, could potentially lead to rod shattering during quenching.

The additional heating periods in steam, which occurred in the Halden and SCIP tests (see Sections B.3.1.1–B.3.1.3 and B.3.2.2), were expected to impact the FFRD processes (see Section A.2.2), but were not possible to quantify during or after the tests. Regarding this aspect, there were a few integral LOCA tests performed in inert atmosphere (see Section B.3.1.5), which offered some insights into this issue by comparing them with the tests performed in steam and with a final quench by water.

4.2 Test Rod Pressure

The initial rod pressure was regularly chosen so that the burst would likely occur in the high alpha-phase temperature domain, for which maximum ballooning strain and burst opening would be achieved. Again, this was dictated by the cladding embrittlement concerns and the related fuel relocation issue, but this had significant implications on fuel dispersal.

The initial test rod pressure was not representative of the RT fuel rod pressure at the time of discharge from an NPP, based on known industry experience. Especially, the SCIP and NRC tests at Studsvik have used a considerably higher test rod pressure. This is exacerbated when

comparing both BWR and PWR rods, given BWR rods tend to be much lower in pressure due to the lower operating system pressure (given both designs have to meet the same steady-state criterion of no cladding liftoff).

4.3 Rod Design

In this respect, the plenum of the test rods is of high importance. To a large extent, test rig instrumentation constraints forced the test rod design to have a large plenum volume, including the required length of the pipeline connecting the test rod to the pressure gauge and pressurizing system, which extended outside the reactor core. The result is that the plenum volume of the test rod was not scaled down proportionally with the reduced test rod length in comparison to the actual fuel rods in the LWRs. In Reference A2-9, this issue of larger free volume to fuel ratio in the test rods is acknowledged, and it is explained that the choice was made deliberately to avoid loss of test rod pressure during ballooning. As explained next, the loss of test rod pressure would have made it very difficult to obtain a large balloon and predict burst temperature during tests.

The impact on fuel rod performance parameters evolution during the transient leads to suppression of test rod pressure by increasing the rod free volume due to cladding ballooning, which would occur for the real fuel rod. This is due to the large pipeline length, in which the gas remains unheated and dominates by its large fraction of the total test rod free volume, the pressure during the thermal transient. Consequently, the test rod pressure remains practically constant during the test, which, although convenient for anticipating the burst temperature during the test, is not representative of a prototypical LOCA.

Some very recent tests (see Section B.3.1.3 on SCIP III tests) have been performed to address this concern, but more work is needed to fully quantify the effect.

4.4 Single Rod Geometry

The single rod configuration and the very uniform circumferential heating boundary conditions in the integral LOCA tests have favored the occurrence of large ballooning due to the uniform cladding temperatures, significantly more uniform than in reality. Moreover, an extremely low corrosion layer, due to a special external liner, should also be considered a lack of representativity.

In prototypical fuel assembly configurations, circumferential asymmetry of coolant conditions and neighboring fuel rods create significant circumferential temperature gradients, which as shown by integral multi-rod FR2 and ORNL tests, have a large impact on the burst strain because of localization of deformation in the hottest circumferential segment of the cladding.

With all things considered, in more representative circumferential temperature gradients, the ballooning will be smaller than during the test due to the reasons stated above; therefore, there would be less fuel relocation into the ballooned area and, consequently, the change in the axial power profile caused by this redistribution would be less significant. In addition, a smaller burst opening can be expected, which in turn would limit, although may not entirely prevent, the loss of fuel from the rod by dispersal of fine fuel fragments.

4.5 Test Conditions—Fuel Temperature Distribution

An analytical evaluation of the temperature distribution and corresponding thermal stresses during OOP HT tests (applicable also to SCIP LOCA tests) was carried out, as follows.

The transient temperature evolution can be approximated with a cylinder heated from the outside with its outer surface temperature subjected to a linear heating rate [4-1]. Assuming the pellet outer surface follows almost instantaneously the temperature measured by the thermocouple attached to the cladding with a clamp, and an average constant heating rate, the surface temperature of the fuel varies linearly accordingly, and using generally accepted thermal properties of UO_2, it was estimated that the centerline temperature is lagging the outer surface temperature by ~ 7s. Therefore, the heating from the outside creates a temperature gradient with a decreasing temperature toward the center (the temperature difference between the outer surface and center is not greater than ~ 40°C).

The temperature gradient, as evaluated above, generates thermal stresses. These thermal stresses can be estimated based on a relevant case described in Reference 4-2 and were calculated to be tensile hoop stress of ~ 23 MPa at the pellet center and compressive hoop stress of ~ 47 MPa at the pellet outer radius.

This is different from the situation of mixed heating both within the pellet and from outside in the Halden LOCA tests and the actual LOCA for LWR fuel. It is also different from the actual case, in which the fuel temperature at the beginning of the LOCA event has a typical quasi-parabolic radial profile; after reactor scram and blowdown, the central part of the pellet cools off, while the outer pellet annulus heats up because of the decay heat and impaired heat transfer to the coolant. During the SCIP HT OOP and semi-integral LOCA tests, external heating leads to an inverted radial power profile, as mentioned above; more importantly, the central part of the pellet is heated-up from the preconditioning 300°C level, which is opposite to the real case.

The above analysis suggests a significant impact of the heating from the outside in the SCIP tests, notwithstanding the low magnitude of the thermal stresses. Therefore, it is concluded that the SCIP LOCA tests are not fully adequate with respect to the temperature distribution and its evolution during a LOCA scenario, which is representative only for the outer fuel pellet annulus.

4.6 Test Conditions—Axial Boundary Conditions

As mentioned in Section 4.4, in the actual fuel assembly geometry, circumferential temperature gradients exist, which cause hot spots around cladding circumference and corresponding hoop strain localizations. The consequence of this temperature nonuniformity around the cladding circumference is a circumferential gradient of the hoop strain and an associated axial strain circumferential gradient. As creep deformation is volume conserving and because of Zircaloy anisotropy, which causes little radial strain, a positive hoop strain requires a negative axial strain. Thus, circumferential expansion accompanied by axial contraction are greater on the high-temperature side of the cladding, where hoop strain is localized and burst eventually occurs. The resultant nonuniform axial stress around the cladding circumference creates a bending moment, which causes rod bending in the axial plane with concavity toward the hot spot burst location (see Section 1.2). Additional bending can occur after burst, because of a gas jet blast through the burst opening.

In most of the integral LOCA tests (NRC-ANL and Studsvik), the test rod was set up so that bending would be prevented by having the free end at the bottom and applying a certain axial load. This makes the hot cell LOCA tests not prototypical; the bending that occurs practically concomitant with ballooning and bursting (after reaching strain instability, the localized ballooning and burst occur in less than 1 s) has an impact on FF and RD, which is not captured in the tests.

4.7 Fuel Microstructure at the Beginning of the Thermal Transient

The hot cell separate-effects or integral LOCA tests are using mostly samples from fuel pre-irradiated in NPPs or in test reactors in the form of thin disks. These out-of-pile tests are carried out in the absence of the neutron (and gamma) flux that is present at the beginning of a LOCA event until the reactor is automatically shut down when depressurization occurs. Therefore, for the most part of the LOCA scenario, out-of-pile tests are representative because the reactor shutdown takes place very quickly after RCS depressurization.

However, there is a remaining question regarding the state of the fuel at the beginning of the out-of-pile tests because the fuel samples are subject to the thermal transient from RT, with an intermediate hold at zero-power shutdown conditions, that is, at typical coolant temperatures of 300–350°C. A succinct presentation of this topic is provided in Appendix C.

It is estimated that the effect of using cold samples in the out-of-pile tests is not the first order in most cases but needs to be factored in during analysis.

4.8 References

4-1 H. S. Carlsaw and J. C. Jaeger. *Conduction of Heat in Solids*. 2nd ed. Oxford University Press 1959.

4-2 W. Young. *Roark's Formulas for Stress and Strain*. 7th ed. McGraw-Hill 2001.

5
CURRENT UNDERSTANDING OF FF AND QUANTIFICATION APPROACHES

5.1 Definition of FF, Pulverization, and Other

As mentioned in the introduction, fuel cracking during NOC is a common phenomenon, driven by the thermal stresses created by the quasi-parabolic radial temperature distribution in fuel pellets. This is considered as macrocracking, as the cracked wedges due to radial cracking represent large fragments of the fuel pellet; moreover, the macro fragments are held in place by the tangled crack lines within the pellet. Pellets cracked in this manner can be removed as single pieces during PIE; however, some pellets showed different levels of disintegration because of handling and manipulation during transportation, as well as during sample preparation for PIE. This type of macrocracking was observed in the thermal transient tests performed on low burnup fuel, for example, FR2 tests.

Finer fragmentation of the fuel to the level of ~ 1 mm in size and below was observed in thermal transient tests with high burnup fuel and was associated with both HBS and non-HBS zones. Also, fine fragmentation was observed for mid-burnup fuel when subjected to high thermal stresses during quench cooling after high-temperature excursions, which is called *powderization* in the INL tests. Powderization also occurs if fuel is exposed to oxidizing conditions in air or steam even at low and moderate temperatures but is dependent on the exposure time duration.

The main concern regarding fine fragmentation is the increased likelihood of small fragments to be ejected through the rupture opening after cladding burst. This is discussed further in Section 6, but in terms of a definition of FF, a threshold suggested in the frame of the SCIP III program was generally accepted as follows: The mass of fuel fragments with a size less than 1 mm amounts to at least 10% of the total fragments' mass.

5.2 NFIR Empirical Threshold: Assumptions, Recent Considerations

In the framework of NFIR, an empirical FF threshold was recommended. This was based on separate-effects tests that used different techniques but had in common a small sample size, which was a small piece of a pellet at different radial locations within the pellet. In this way, the local burnup inside the pellet was the control variable and, as such, the threshold was expressed in terms of local burnup, and the temperature was taken as the maximum value during the temperature transient at which FF was observed for pellet pieces of the same (or similar) burnup. The quantification of FF was a mix of qualitative visual observations and size distribution measurements after the test. Also, in certain tests [B3-24], the FF surrogate parameter was the sudden increase in FGR during the temperature transient, which correlates with FF. The radial burnup profile is sharp at the pellet outer rim, which can be well extended inward for the disks used in the test program; thus, pieces collected from mid-radius and periphery of the disks have a nonuniform burnup, and an average burnup must be used as local burnup, thus affected by a non-negligible uncertainty. A flat profile exists, which is illustrated with a Nd radial profile in Figure 2 of Reference 5-1.

Other factors influence the HBS formation and growth, hence the consideration of burnup alone might not be sufficient.

A related burnup issue was noted. Namely, in some tests, the tested piece or the set of pieces tested together covered a large burnup range and it was assumed that FF was initiated in the highest burnup part of the sample(s). This was not confirmed by generalizing to more tests, and it was pointed out in as a desirable refinement of the NFIR empirical threshold [B3-23].

The initial analysis of the data to derive the NFIR threshold was largely driven by the presumed correlation between FF and HBS; both were observed to occur at high burnup, and the initial analysis seemed to indicate a very strong correlation between the burnup thresholds of the two phenomena (practically equal for the tested samples, albeit the HBS extent of the tested samples was not in full agreement with the balance of the HBS database). As noted above, this correlation was questioned in later studies, which showed that non-HBS areas can undergo FF. The NFIR report [B3-23] notes that FF can occur at higher temperatures. In Section A.2.1 of this report, it was found that pulverization of lower burnup restructured zones with large populations of intergranular bubbles (recently called *dark zones*) occurred during cooling from higher temperatures during PCM tests [1-1]; therefore, it is not surprising that non-HBS areas can undergo FF if the necessary conditions are met. In any case, the ITU laser flash fragmentation tests led to a conclusion that the non-HBS pellet interior can fragment if its burnup exceeds 65 GWd/MT-HM.

The initial NFIR FF threshold formulation was also based on the assumption that the last base irradiation temperature must be exceeded for FF to occur. However, this was not confirmed by the ITU tests with laser heating, from which it was concluded that a practically constant fragmentation temperature of 675°C is independent of the pellet burnup. This validates the constant temperature threshold in the NFIR FF threshold, as a good intuition. A possible explanation of this was suggested in Section A.2.3, to be based on the Cs boiloff effect on bubble pressure during the transients. This also explains the bubble pressure issue identified in NFIR reports, which concluded that the estimated bubble pressure based on experimental PIE data is below the value required for cracking.

The material for NFIR FF tests were the disks irradiated in HBWR in NFIR's IFA-649 irradiation, for which irradiation intentionally took place at relatively low temperatures, typical of LWR pellet periphery temperature, to promote HBS formation. The burnup threshold derived in NFIR from these samples therefore coincided with the burnup threshold for FF in HBS, and the temperature threshold ranges for the two processes overlapped. Therefore, it was believed that the HBS microstructure is prone to microcracking and pulverization and dominates the FF response of the fuel. Soon, it was noticed that other parts of the pellet, that is, non-HBS, can undergo microcracking and pulverization, which is known from past research on PCM studies at INL and at lower burnup. Nevertheless, with high enough burnup it is still required to create a large enough bubble density, so that percolated crack networks can develop.

To apply the NFIR (Bu,T) threshold to full pellets in a fully quantitative manner, the radial burnup profile across the pellet radius must be known and a criterion established regarding the fraction of the pellet mass that is prone to FF for the part of the pellet that is above the NFIR empirical threshold; this would map the pellet average burnup to the local burnup used in the NFIR threshold formulation.

An example of this conversion to pellet average burnup was shown in Reference 5-2 by using a burnup profile obtained through personal communication from Halden staff (W. Wiesenack, private communication) for a case of PWR fuel. It should be noted that the radial power profile and the ensuing radial burnup profile are highly dependent on fuel enrichment as well as other variables. Therefore, there is no unique radial burnup distribution formulation possible in either absolute or normalized form. The determination of the radial burnup profile is complex, which can be handled by modern reactor physics codes. However, precise estimates require specialized calculations, rather than reduced order models.

5.3 Chemical Effects

The chemical effects on FFRD can be noticed by comparing the semi-integral tests performed in steam and in inert atmosphere, which were described in Sections B.3.1.3 and B.3.1.5, respectively. The following was concluded, regarding the impact of these chemical effects [5-3]:

> "Although the duration of high temperature exposure to air in the OOP HT tests and to steam in the integral LOCA tests in SCIP is rather limited, some oxidation effects cannot be completely ruled out. However, it is considered that oxidation is an additional fragmentation factor, which affects fuel fine fragmentation after cladding burst in the LOCA tests, occurring more than in the OOP heat transients."

An interesting observation in this direction was made where SEM observations of oxidized and agglomerated fragments were noticed on and between larger fragments from the R2D5 LOCA 1 material, which had a large fraction of fine fragments [A2-5]:

> "The quench and soak of the LOCA tests [cause] surface oxidation, precipitation of secondary phases and agglomeration of fines." (p. 9)

5.4 Burnup Issue

Burnup was considered a first-order parameter for FFRD. Therefore, it needs to be clearly defined and understood so that coherent definitions are used in test interpretation and in design analyses. To that end, some issues regarding the definition and usage of this parameter are examined in this section.

Burnup, or exposure, is an engineering measure of the amount of irradiation. By definition, burnup is linear heat generation rate, LHGR (heat flux from the fuel rod to the coolant integrated over a unit length of the fuel rod), integrated over time, and is expressed as energy per unit mass of U, MWd/kgU, or GWd/MTU.

Both the neutron flux and the gamma flux need be considered within a given reactor core. Usually, for an NPP, average core-wide values are derived for the relative contributions of these two LHGR sources (a very minor contribution to coolant enthalpy comes from gamma heating of the cladding and other structural components of the core). It is customary to use a fraction of LHGR that does not include gamma heating to calculate the fission product generation and that leads to the so-called *fission burnup*.

Thus, if the interest is the microstructural features (as in the case of FF) created by the fission products and the point defects generated in the wake of fission fragment interaction with the fuel matrix (fission tracks and associated collision cascade), burnup is not fully representative. A more physically valid measure of the amount of irradiation is the accumulated number of fissions normalized by the initial metal (that is, all U isotopes present in the fresh fuel), known as FIMA.

FIMA can be quantified by neutronic codes and also determined experimentally by measuring certain fission products that are not decaying, or form pairs of isotopes in which one decays to the other that remains stable. The most used FIMA monitor is Nd-148 for the former case and the pair (Nd-145 + Nd-146) for the latter case.

The measurement of Nd and U (as well as other isotopes) after irradiation is a complex radiochemical procedure, which involves refined chemical separation techniques and a high-precision mass spectrometry. It is a specialized technique that requires qualified equipment in the hot cell. Therefore, as a cost reduction measure, the Nd FIMA determination is usually performed on one representative fuel rod, called the *reference rod*, and gamma scanning, typically of Cs-137, is used to determine the burnup by comparing the gamma scanning of the measured rod to that of the reference rod and normalizing to the Nd-determined burnup of the reference rod. This Cs-137 gamma scan combined with the Nd-measured burnup of a reference rod was the technique used for the fuel rods comprising the FFRD database (in one case of separate-effects tests, Nd was measured on samples).

The conversion from FIMA to the engineering unit of GWd/MTU is made by assigning a certain energy per fission value. As mentioned at the beginning of this section, it is not a trivial task, and different values have been used in different studies and contexts, so care must be exercised when using burnup values from different sources.

Moreover, there is a nonlinear radial power profile within the fuel pellets due to the self-shielding effect and resonant absorptions in U-239 that creates the fissile Pu-239. This leads to a radial burnup profile, characterized by a spike at the outer pellet rim region, which is quite small for low to medium burnup, but it becomes quite large at high burnup (creating the so-called *HBS zone*). Also, an axial burnup profile develops during irradiation owing to the neutron flux axial profile.

Therefore, burnup can be defined as rod (or test segment) average burnup (that is, integrated axially and radially over the full fuel rod or test segment), or rod local burnup, meaning burnup at a certain axial location along the fuel rod, or pellet local burnup, meaning the burnup of a certain annulus of the pellet at a given axial location. FFRD data have not always been reported by using the same burnup definition, and all three values defined here have been used in different reports. Unfortunately, in some cases, the meaning of the quoted burnup value was not explained, and further research was needed to clarify the meaning: rod average, local rod, or pellet local burnup. In some cases, mixed definitions were used in the same report and even in tables and figures were used to construct empirical correlations.

A reassessment of the burnup measurement by gamma scanning against the reference rod was performed at Studsvik by reviewing the radiochemical burnup measurement of the reference rod. There are reasons to review this reassessment as some assumptions have been made without sufficient justification. In addition, it is very important to compare the measured and the calculated burnups, because, in design analysis, calculated burnup is used and any bias in measured or calculated values needs to be addressed.

5.5 Fuel Structural Behavior in Non-LOCA Scenarios

A review of the experimental data identified from separate-effects and integral LOCA tests included several low burnup cases, and evidence of FF was noted for pellet regions with lower burnup, but higher maximum temperature was reached during the thermal transient. In addition, an appreciable amount of data was acquired during the Severe Fuel Damage (SFD) studies, mainly regarding fast breeder fuel, in the 1970s and 1980s. The highlights are summarized in Appendix D for completeness of the discussion on FF. However, it is recalled that fuel temperatures in a LOCA event do not reach the high values encountered for FBR fuel, or during an RIA event.

5.6 Conclusions: FF

The body of separate-effects tests and integral LOCA tests, together with theoretical considerations, lead to the following conclusions regarding the causes of fine fragmentation and the contributing factors, in general, and in the tests under review. A complementary objective was to assess whether the testing conditions are prototypical and hence whether and how, and to what extent, the test results can be applied to an analysis of the actual LOCA scenarios.

- It is generally accepted that the root cause of micro and fine fragmentation (pulverization, or powderization) of fuel at any burnup is the cracking at the tips of fuel bubbles, especially the intergranular bubbles, which are lenticular and hence have sharp edges that cause stress intensification and lead to cracking and crack propagation.
- The above phenomenon can be initiated during fast thermal transients so that the overpressurization of the bubbles cannot be relieved by diffusional processes (matrix creep, or vacancy diffusion) or when thermal or external loading creates tensile stresses within the pellets.
- During the thermal transient, there is a competition between fission gas release and fragmentation because the driving force for fragmentation, namely, gas bubbles overpressurization, can be relieved in the case of FGR, confirmed by double heating tests in the SCIP 3 test program; the explanation is that pellet regions with established GB bubble interlinkage release gas (after PCMI is relieved) and, in this way, do not cause FF.
- On the other hand, a “burst” FGR can be caused by fragmentation, as the microcracks can intersect grain boundary bubbles and vent out their gas inventory; moreover, the microcracking starting from intragranular or intergranular bubbles releases their inventory by themselves; the significance of this conclusion is that the so-called transient FGR is the burst FGR that occurs, practically during fragmentation, which will be later argued to occur just at, or very shortly before, the burst.
- Burnup was identified as a major contributing variable to FF because of the HBU zone at the outer pellet surface. The HBU microstructure is characterized by very large bubbles, which can be categorized as pores, which were shown to contain most of the fission gases in that region. It was shown by PIE that the HBU region is more prone to pulverization and hence it is believed that burnup can be considered the overriding factor causing pulverization.
- Separate-effects tests in NFIR and scoping tests in SCIP III tests showed that other parts of the pellet can undergo fine fragmentation, which is in accordance with previous considerations regarding the underlying physical mechanism for FF, namely, cracking caused by overpressurized bubbles (for example, zones with higher density of well-formed GB bubbles, called *dark zones*).

- Besides burnup, another important parameter is the compressive hydrostatic stress on the pellet, which is caused by PCMI. At high burnup, any fuel of any reactor type has a closed-gap condition and hence strong PCMI compressive forces on the fuel pellet, which restrains FF.
- During a LOCA thermal transient, the cladding expands diametrically under the overpressure created by coolant depressurization. When the PCMI constraint is relieved, that is, no compressive hydrostatic stress is exerted on the fuel, both FGR and fragmentation can occur.
- Tests performed with low plenum or with longer hold times at peak temperature, or terminated just after burst, showed only macro fragmentation, while the tests with large plenums and in which the temperature escalation was continued after burst showed extensive FF.
- It is considered that a large fraction of FF occurs after burst, due to gas outflow and continued heating of the fuel and cladding, if the peak temperature in the LOCA integral tests was chosen to be the maximum calculated value, which is quite close to the licensing limit. In fact, the test protocol for all integral LOCA tests in Halden, Studsvik, and ANL was based on maximizing these effects, namely, the largest balloon/burst and maximum peak temperature.
- Another controlling parameter for FF is the temperature during the transient (see role of Cs described earlier in this report). Nevertheless, in most LOCA scenarios, if burst occurs at high burnup, fuel temperature is most likely above the temperature threshold recommended for FF.
- A missing parameter is the pre-irradiation temperature. It was found that HBS does not form above ~ 1000–1100°C [D5-9, D5-10] (and cited references therein), therefore burnup alone does not capture all conditions for HBS across the pellet. Nevertheless, an allowance for FF of non-HBS zones must be made.
- New threshold: To derive a pellet Bu threshold, radial burnup profiles must be calculated for a family of power histories, and the criterion could be an extent of the rim (burnup > 70 GWd/MTU) and be greater than, say, 100 microns.
- Strain threshold: It was determined that an outward cladding strain lower than 4–5% prevents explosive fragmentation; however, cracking can still occur while the pellet is held together by cladding restraint, for example, the double heating test in SCIP III, in which microcracking caused interlinkage and FGR.
- Cs effect: Studies (see ITU report) concluded that the temperature threshold for FF is not dependent on the last, base irradiation temperature. Cs boiloff can explain this as an effect of a post-irradiation condition, as Cs precipitates on internal bubble surfaces and volatilizes during the T transient, providing the needed overpressure to cause cracking.

5.7 References

5-1 M. Kinoshita et al., "High Burnup RIM Project (II) Irradiation and Examination to Investigate Rim-Structured Fuel," in: *Proceedings of the ANS Meeting on Light Water Reactor Fuel Performance*, Park City, Utah, April 10–13, 2000, pp. 590–603.

5-2 J. A. Turnbull, S. K. Yagnik, M. Hirai, D. M. Staicu, and C. T. Walker, "An Assessment of the Fuel Pulverization Threshold During LOCA-type Temperature Transients," *Nuclear Science and Engineering*, Vol. 179 (4), 2015, pp. 477–485, doi:10.13182/NSE14-20.

5-3. V. I. Arimescu, “Review of FFRD Experimental Data and Modeling Approaches – Implications for SCIP LOCA and OOP HT Test,” STUDSVIK-SCIP III-256 (2019).

5-4. K. Une et al., “Fission Gas Release Behavior from High-Burnup UO_2 Fuels Under Rapid Heating Conditions,” *JNST*, Vol. 43 (9), 2006, pp. 1161–1171.

5-5. G. R. Keepin. *Physics of Nuclear Kinetics*. Addison-Wesley 1965.

6
RELOCATION AND DISPERSAL

Relocation is a prerequisite to dispersal, as fuel fragments that are generated under certain conditions must move toward the ruptured opening to be ejected. The causes of relocation are gravity, the effect of gas communication from the upper plenum, and potentially vibrations caused by fluid-rod interactions, which lead to a downward movement of fuel fragments that become dislodged from the fragmented fuel pellets to the enlarged cross-sectional areas of the ballooned region. The following subsection summarizes the best analyzed experimental relocation data available. It is worthwhile mentioning here that relocation is currently addressed within bounding methods, that is, by assuming a packing fraction, which is based on experimental data, such as that described below.

6.1 Relocation

The most relevant series of tests with respect to relocation have been performed in the FR2 reactor at KfK in an integral LOCA test rig, which used unirradiated rods, irradiated rods, and electric simulators. Reference 6-1 describes the tests performed on irradiated fuel to various burnups ~ 20 to 35 GWd/MTU.

The test rods were irradiated in the FR2 reactor and re-pressurized with He before the transient test. The base irradiation in FR2 was carried out at a non-prototypical low coolant temperature and pressure, of 60°C and 2.4 bar, respectively. Therefore, less gas atom diffusion to grain boundaries and correspondingly less gas bubble population occurred in the test rods during the pre-irradiation in FR2 than in a typical LWR. Also, the low enrichment of the fuel led to a larger depletion of the fissile content in the lower part of the test rod, so that under a quasi-constant neutron flux during the transient, the axial power peak was shifted toward the top of the higher burnup test rods.

The test protocol of these in-pile tests was aiming to reproduce the quasi-adiabatic phase of a large break LOCA, by employing the following steps:

1. An initial steady state under steam at 573 K, 6 MPa
2. The blowdown phase with stopping of the steam flow that led to a temperature rise at 12 K/s on average with neutronic power maintained around 40 W/cm
3. Near 1200 K, the reactor scram leading to the temperature turnover and in a given number of tests, followed by a steam quench near 1000 K activated by the re-opening of the steam inlet flow valve

Figure 11 [6-1] shows a typical example of the variations in the clad temperatures, where the temperature drop indicated by the T/C located in the ballooned region corresponds to the rapid clad deformation just before the rod burst.

During the base irradiation, the fuel pellets cracked, but the crack wedges were held in place by the constraint of the cladding. When clad ballooning takes place, cladding constraint disappears and cracked fragments, if pulverized, are free to move axially and radially and slump downward into the additional space created by ballooning. This is shown in Figures 23 and 31 [6-1] and is referred to as *fuel relocation*.

The important question of whether relocation occurs prior to or just at and after the burst was addressed by mounting three additional T/Cs in the upper part of the test rods, as it was known that the axial power peak occurs there. A decrease in those T/Cs positioned in the upper part of the rod indicated a loss of fuel at those locations, which signals relocation. Figure 33 [6-1] shows the online temperature measurements for one test (E4) and clearly reveals a sharp drop in the upper 3 T/Cs at the time of burst, which demonstrated that in this test fuel relocation occured only at or just after burst.

However, in another test (E5), an atypical temperature transient led to a large balloon without bursting, with an eventual through-pinhole type flaw developing, which led to depressurization. In this case, significant relocation occurred before burst, which showed that the push by the gas blast upon bursting may be a necessary but not sufficient cause of relocation, which may occur just by a gravity pull, provided there is a large clad distension, such as in this particular test.

A similar decrease in T/C reading was observed when relocation occurred in the IFA-650 test series at Halden [B3-20]. However, based on the LOCA test IFA-650.14, without burst, post-test examinations revealed some axial fuel relocation but, during the test itself, no change in the lower temperature measurements was noticed (opposite to the tests with burst and actual transient fuel relocation), suggesting that fuel relocation in IFA-650.14 occurred mostly after the test, during the test specimen handling. This suggests that part of the fuel relocation, which is observed in the LOCA test PIEs, might be due to the post-test handling of the fuel rods.

The fuel stack length reduction data were correlated to the overall relative volume increase as illustrated in Figure 32 [6-1]. The data points are well represented by a linear function, which shows the expected trend of larger relocation, caused by the large volume increase by ballooning.

Relocation may lead to larger cross-sectional fuel mass in the ballooned zone and reduction or complete removal of fuel in areas above the ballooned zone. Although the timing of relocation to the burst opening is still uncertain based on experimental evidence (see above), the former case could be a concern regarding the PCT criterion in the ballooned zone, while the latter is pertinent to the coolability in the short- and long-term. The important parameter here is the filling ratio or packing fraction in the ballooned area. This parameter is deduced from experimental data, if accounted for with conservative assumptions, and shows that by and large the fuel mass per unit length decreases with clad hoop deformation, which if not too large, it is similar or only slightly higher for large deformation zones in the balloon.

A counteracting factor to increased, relocation-driven heat generation rate in the balloon is the increase in the clad heat transfer area. According to results of the bounding analyses, the net effect is bounded by the conservative assumptions made in bounding LOCA methodologies. Empirical models have been developed based on specific test series, which were considered representative for the considered reactor type and fuel design.

6.2 Dispersal

6.2.1 Interpretation of SCIP III Data Regarding Dispersal

The interpretation of the SCIP III results regarding fuel fragment dispersal during LOCA tests is summarized and illustrated in Figure 73 [B3-6]. The only meaningful correlation was identified as dispersal mass versus burst opening, as it is intuitively expected and demonstrated in the cited figure. Two other potential correlations were investigated during this review. When the dispersal data were plotted versus burnup, the conclusion was that burnup is not a first-order parameter for the amount of dispersed fuel, but rather an indirect indicator of the apparent threshold for appreciable dispersal through the FF process. Second, the same dispersal data were plotted versus rod internal gas pressure, as it is expected that the gas jet would push more fuel fragments out through the ruptured opening with increasing the gas pressure. Indeed, such a dependency was noticed, but it was confounded by the dependency on the other first-order parameter, namely, the burst size, that is, the effect of gas pressure on dispersal is confounded by the burst opening area.

Regarding the dispersal statistics, the following example of the OL1L04 test from the SCIP III tests is illustrative [B3-7]:

- Mass dispersed during the test and collected from the test chamber: 11.2 g
- Another 2.2 g lost mass, by pre- and post-weighing of the test segment
- Mass of retained fuel, shaken out after test: 69.7 g
- Total mass of “movable” fuel: 83.1 g

The fraction of fragments less than 1 mm was 20% when combining dispersed and retained fuel fragments, but it was ~ 65% for the actual dispersed mass during the test and only 12% for the retained mass. Of course, fine fragments can disperse easier, and the fragments ejected during the test are, in majority, small and very small. Combining dispersed and retained fuel masses results in an irrelevant smeared percentage value of fine fragmentation and falsifies the strain thresholds (note the large difference in fine fragments’ percentage between dispersed and retained fragment populations), especially at the burnup threshold.

It is suggested that a better approach here is to consider the dispersed mass relative to the burst opening and the total mass in the balloon. The fragment size distribution is also useful and could be used for analyzing the behavior of ejected fuel fragments in the coolant sub-channels.

6.2.2 LOCA Forces

The fluid-structure interaction that occurs during a LOCA scenario can create dynamic loads on different parts of the core, reactor vessel, and other primary cooling loop components. These transient loads during a LOCA can be larger than the normal operating dynamic loads induced by vibration due to fluid fuel rod interactions, and the main concern is to avoid deformation to the fuel and control rods that could impair a safe shutdown. These issues are addressed in the mechanical design evaluation, in which LOCA loads are combined with seismic loads, by making the conservatively bounding assumption of simultaneous occurrence of a seismic event and a LOCA (presumably the LOCA is caused by the seism).

It has been suggested that vibratory dynamic loads can act on the fuel rod during a LOCA, which would cause fuel fragment expulsion from the fuel rod after burst. However, no specifics of these LOCA forces have been described, regarding either the intensity or the timing of their occurrence.

Based on Section 6.5.4 [6-2], strong loads (mechanical forces) that could be exerted on core structures, fuel included, occur during the very rapid initial decompression, that is, the blowdown phase of a LOCA, which is accompanied by the propagation of pressure waves through the system—especially the pressure pulses that create the water hammer impact load on coolant loop components.

The models describing the fluid-structure interaction have been restricted to single-phase behavior, because in a typical LOCA, the blowdown phase and corresponding pressure differentials become negligible in less than 50 ms [6-2]. Several studies have been published that show typical cladding temperature evolution during a LOCA in a PWR and indicate the expected burst time, which is tens of seconds, or at least several seconds, after the initial depressurization (exact timing depends on particularities of the RCS for different PWR designs).

Thus, both the blowdown and the associated pressure waves are of much shorter duration and occur well before cladding ballooning and burst. Therefore, these LOCA forces would not be present at and after burst. It is recalled that there has been no concern regarding dynamic vibratory loads with respect to the mechanical properties of the ballooned region after burst; the main concern was to avoid fuel rod shattering during quenching.

The invoked LOCA forces led to a “shaking” action after the integral LOCA test was completed, during which, the broken test rod was vigorously shaken after it (or the two halves of the test rod) was turned upside down so that all loose fragments could be removed from the test rod. In many cases, this shaking procedure followed a bend test, which had the objective of measuring the ductility of the burst balloon segment of the rod. It is considered that the bend test is a good representative measure of burst rod strength in relation to potential deformations during the final LOCA scenario phases and afterward. The tests described in Section 3 showed that some fuel fragments have been pushed out by the bending as the rod was severed at the burst location of the balloon section.

The bulk of the mass removed from the rod after the LOCA test was pushed out during shaking. Clearly, this shaking procedure is a non-representative exaggeration of any potential effect of vibratory dynamic loads on the fuel rod due to fluid-rod interactions. Especially, during blowdown, a steam, or two-phase mixture, flow runs past fuel rods, with much less induced vibration than in the case of a liquid phase.

This aspect of rod behavior after burst, in which dynamic vibratory loads can act, warrants both experimental and theoretical investigations to clarify the effects. In principle, the downward movement of fuel fragments toward the burst opening could be enhanced by rod vibration, provided that no clogging at the ruptured opening occurs, especially for the expected bent rod geometry after burst; after depressurization, with no other force but gravity, that would push fuel fragments toward the ruptured opening.

6.2.3 Behavior of Dispersed Fuel Fragments

The following excerpt from ANL LOCA test reports is consistent with the general view of fuel dispersal not being critical for the coolability criterion:

> "Although the fuel rods are in a vertical position during LOCA, thermal-hydraulic phenomena induce significant vibration of these rods. Depending on the size of the balloon and burst opening, the potential exists for fuel to fall out of the burst opening. The amount of fuel that might be emitted would have an insignificant effect on coolability. However, the effect of fuel fallout might have a significant effect on decay heat and cladding temperature reduction in the ballooned region." [B3-4]

Indeed, when fuel fragments are ejected from the rod, there is a competition between being trapped in confined spaces and being taken by the steam flow and dispersed through the cooling system:

- Fine fragments are quickly cooled down, hence no local steam buildup and potential FCI-like explosions are possible.
- Fine fragments (less than 1 mm in size) are the most prone to be entrained and carried away by the steam flow or reflood and refill fronts; therefore, they do not contribute to any potential local accumulation at confined spaces in the fuel assembly, such as spacer grids.

Nevertheless, fuel fragments have been assumed to get stuck at the confined grid spacer locations that could lead to a degree of flow blockage and affect the RCS coolability. The following is an overview of the known phenomenology and analysis regarding this issue.

The dispersal could lead to the formation of so-called debris beds on spacer grids, or in possible confined spaces between ballooned adjacent rods. The coolability of a debris bed has been considered in the frame of consequences of a severe accident for both LWR and FBR reactor types, especially the formation of a debris bed from molten material (cladding and fuel, and other structural materials, called *corium*) slumping down on the bottom of the reactor vessel. Such scenarios were analyzed, because of the risk of melting the structural components of the vessel and the potential fuel-coolant interactions and steam deflagrations. The figure of merit was the dryout heat flux (DHF) of the debris bed and its dependence on geometrical (size, porosity) and heat generation parameters of the debris bed.

One such evaluation was presented as an example in the 2016 CSNI report on FFRD [6-3]. The evaluation was based on the most thorough analysis of debris bed cooling [6-4], which was used in a SKI analysis [6-5] and further employed in a GRS evaluation [6-6]. It was a case study of a particle bed on a pedestal floor due to corium fragmentation for the OL NPP. Not highlighted in the description of the calculations is the important boundary conditions of bed permeability and the adiabatic conditions at the bottom, which is the most conservative condition for a corium bed on the floor of the reactor cavity. The evaluations were also reported [6-7] and a critical particle bed that was assumed to form on the spacer grids, but with the same impermeable condition as for the corium lying on the pedestal floor, flooded by water. Because of the unrealistic boundary conditions used, an extremely conservative critical particle bed height (or depths in some reports) was estimated.

This extreme calculation was performed for a debris bed with closed flow paths, with only heat conduction as the available cooling mechanism and the metric was melting at the bed midplane. Using data for a 55 GWd/MTU, a relative decay power of 1% corresponding to a nominal LHGR of 200 W/cm (corresponding to 24 hours after a LOCA), a 12.6 cm limit was estimated for midplane melting. If the midplane temperature is reduced to the cladding melting value, the critical bed height is reduced to 10.8 cm. While the simplicity of the above, highly conservative calculation is attractive, it must be emphasized that the assumed boundary conditions of adiabatic and impermeable to flow porous particle bed are very much departed from the actual particle pileup that can form in the spacer grid confined spaces.

The impermeable boundary condition is not representative of the particle heap that could form on the spacer grids or in-between deformed adjacent fuel rods in a fuel bundle. The particle heap formed by the accumulation of the fuel fragments ejected through the cladding rupture opening on spacer grids is correctly represented by a porous layer in a stream of either single phase (steam), or two-phase flow upward or downward, depending on the LOCA phase. Obviously, the piling up of fuel fragments in the confined space above spacer grids forms a layer of particles with a large porosity because the fragments have irregular shapes and are of different sizes. This pile up on spacer grids does not block the flow and it is cooled by the steam or two-phase stream flowing through this porous buildup of fuel fragments. As a supporting argument, the gas flow proceeds inside the fuel rod during the depressurization after burst, when the fuel fragments are relocated in the ballooned area.

This case of a permeable boundary condition at the bottom of the debris bed is described in Section 5.3 of the seminal Lipinski report [6-4], as a uniform bed on a permeable plate immersed in a pool of water and with flow entering the bed from below. For example, in a light water reactor, the degraded core may rest on the permeable grid spacers and core support plate, as in Figure 5-4 [6-4].

Without forced flow from the main pumps, liquid may still be driven through the bed either through coolant injection or an excess head in the downcomer and steam generator. Under these conditions, the inlet liquid mass flux (w) is nonzero. The situation illustrated in Figure 5-4 [6-4] has a water pool above the debris bed, which might be different from the situation in the blowdown phase of a LOCA but adequate for refill and reflood. Nevertheless, the example is illustrative for a more realistic analysis of debris bed cooling in a LOCA situation with fuel fragments ejected from burst fuel rods.

One PWR example with some specific dimensions for the porous layer and sub-cooled water conditions was analyzed [6-4]. The upward water flow from the bottom is heated as it penetrates the porous layer, and at a certain elevation boiling can occur if the uniform heat generation rate is sufficiently large. Afterward, a steam upward flow emerges combined with a downward water flow.

Of course, if the height (or depth) of the porous layer is less than the critical boiling elevation, coolability of the porous layer is not impacted. An additional benefit of an inlet liquid flux is its influence on post dryout behavior. For a deep bed on an impermeable support, the dry zone extends to nearly the entire bed with powers slightly above the dryout power. The temperature in the dry zone is very large since heat is removed solely by conduction and radiation until melt occurs. However, with an inlet liquid flux, the dry zone is limited to the top of the bed. This

causes the dry zone to be significantly thinner. In addition, inlet flow allows the dry zone to be cooled by steam flow. The temperature rise in the dry zone is then determined by the vapor specific heat and the mass flow, since mixing ensures good heat transfer from the debris to the vapor. The temperature at a particular elevation will increase approximately linearly with elevation and inversely with the inlet flux.

The problem was analyzed in terms of the pressure dop across the porous layer, which was proportional to the layer thickness. The results for a 50-cm thick bed with 40% porosity and 1-mm diameter particles are reported in Reference 6-4. The reference states:

> "As the inlet flux is increased, both the dryout power and the pressure drop across the bed increase. However, the increase in pressure drop is initially slower than the increase in dryout power. Thus, for example, a 16% increase in hydrostatic head across the bed will double the dryout power with respect to w = 0. This marks a substantial increase in debris coolability."

The model predictions may be compared with data obtained by Naik and Dhir [6-8] for water flowing into an inductively heated steel bed. Unfortunately, they used power low enough so that $q < wh$ (that is, the stagnation plane was pushed up past the top of the bed). Thus, dryout was never achieved.

6.3 References

6-1 E. H. Karb et al., "LWR Fuel Rod Behavior in the FR2 In-Pile Tests Simulating the Heatup Phase of a LOCA," Final Report, KfK 3346, March 1983.

6-2 L. S. Tong and J. Weisman. *Thermal Analysis of Pressurized Water Reactors*. 3rd ed. ANS 1996.

6-3 "Report on Fuel Fragmentation, Relocation, Dispersal," NEA/CSNI/R(2016)16.

6-4 R. J. Lipinski, "A Model for Boiling and Dryout in Particle Beds," NUREG/CR-2646, SAND82-0765, June 1982.

6-5 I. Lindholm, "A Review of Dryout Heat Fluxes and Coolability of Particle Beds," *SKI Report*, Vol. 02 (17), April 2002.

6-6 H. G. Sonnenburg, "Coolability of Relocated and Dispersed," Presentation from GRS for the LOCA Workshop on Fuel Fragmentation, Relocation, and Dispersal (FFRD), Experimental Basis, Mechanisms and Modelling Approaches, Session 3: Implications of FFRD, May 21, 2015.

6-7 F. Boldt and H. G. Sonnenburg, "Brennstabverhaltern im Betrieb und bei Stoerfaellen," GRS-609, September 2020.

6-8 A. S. Naik and V. K. Dhir, "Forced Flow Cooling of a Volumetrically Heated Porous Layer," ASME81-HT-46, 20th Joint ASME/AICHE National Heat Transfer Conference, Milwaukee, WI, August 2–5, 1981.

7
TFGR

The term *transient FGR* means, in general, the fission gas released during a thermal transient. However, depending on the context of the temperature excursion, different subcategories of the transient FGR have been addressed and, in other cases, the general term *transient FGR* was used without specifying the context.

First, a summary of an FGR process is presented to describe the frame of the FGR mechanism. Fission gas atoms are generated uniformly within the fuel but modulated by the radial power profile, with a sharp peak at the pellet rim.

The first phase of FGR is diffusion within the UO_2 grains toward grain boundaries taking place as a thermally driven process, and hence this mechanism is called *diffusional* FGR process.

The second phase of FGR is grain boundary gas bubble development and interconnection, with the final stage of interlinkage along grain edges and the creation of a percolation path to the open void volume. Thus, an inventory of gas atoms develops on the grain boundaries and their release to the open voidage occurs when a threshold grain boundary concentration is achieved. Both FGR phases described above are temperature, and hence power and burnup dependent, the latter being proportional to the irradiation time. That means that burnup by itself is only a surrogate variable because it is power integrated versus time, and the same burnup can be achieved with lower power and longer irradiation time, or vice versa. However, for typical NOC power histories, burnup is proportional to the irradiation time.

The gas accumulated on the grain boundaries (below venting threshold) is available for another FGR mechanism, namely, cracking, or fracture FGR, which consists of macrocracking or microcracking of the fuel that intersects grain boundaries loaded with gas and releases it. In some cases, the fracture can be along grain boundaries, which will enhance this type of cracking FGR. Because, in many cases, fuel fracture occurring during transients is fast, the cracking FGR is rapid and occurs more like a burst; therefore, this FGR process was called *(transient) burst FGR*.

This burst release is generally associated with microcracking during thermal transients, such as those associated with LOCA events. The NFIR threshold was based on the correlation between burst FGR and FF during post-irradiation annealing separate-effects tests (see Section B.3.3). The rationale was based on the large number of such post-irradiation transient heating tests, which revealed several stages of FGR, with the first one appearing as a spike of burst release at low temperatures. Although the higher temperature peaks showed diffusional characteristic kinetics, the mid-temperature peak showed mixed burst-diffusion appearance in several tests. This was interpreted as the low-temperature burst being caused by microcracking, while the one at higher temperature by grain boundary saturation and burst release of the grain boundary inventory.

Most of the transient heating (annealing) tests have been performed to a high maximum temperature, continuously, or in staircase fashion. The straight up ramps to higher temperatures were not monitored online in some tests, so that the final FGR value cannot discriminate the low temperature burst component.

As a preliminary conclusion, it is considered that tFGR prior to burst is minimal and does not contribute, but marginally, to the rod pressure increase, which could enhance ballooning. This topic requires more research, both of previous studies and confirmation with new experiments.

8 FINAL CONCLUSIONS

Empirical correlations/models are typically developed based on qualified prototypical and representative data. In the case of FFRD, if the above condition is not met, the applicability of such empirical correlations to actual LOCA scenarios, as intermediate models or criteria, is questionable as their conservatism or non-conservatism is difficult to assess. Based on the review presented herein, with the main points outlined below, it can be concluded that the results of the integral tests performed in SCIP III and Halden IFA-650 test series are not directly applicable for deriving empirical correlations based on them to analysis of the LOCA DBA.

The body of experimental data acquired so far on the FFRD topic offers a good basis for a phenomenological understanding of the different processes involved in FFRD and can be used to start formulating physically sound simplified models and correlations, generally of the semi-empirical in nature. This would account for the physicochemical mechanisms involved and address the features in the experiments, either fuel design or test conditions, which are not representative of postulated LOCA scenarios.

The existing separate-effects and integral test data are still a subset of the data applicable to FFRD, consisting of studies aimed at scoping and/or confirmation or contradicting of different hypotheses that have been brought to the fore. It is considered that more separate-effects testing, carefully designed to address open gaps, is needed to obtain good data for quantification in models or criteria.

In that respect, Sections 4 and 5.6 in this report summarized the issues that need more investigation by either removing the non-representativity or assessing the impact and formulating ways to tackle those non-representative features. However, a new series of integral rod tests that are carefully designed to eliminate gaps in realistic testing of LOCA FFRD by way of experiments would still be needed, based on the solid foundation built in the NFIR studies and complemented by the SCIP and Halden tests.

Some new insights have been gained during the review, which showed the need to reassess and upgrade the formulations of existing proposed thresholds. As pointed out in Sections 5.2 and 5.6, a viable existing framework for an FF correlation is the threshold developed in the frame of the NFIR program using burnup and temperature. The need to refine this threshold model is described in the abovementioned sections. It was pointed out that the NFIR threshold only defines the (abrupt) transition from a no-FF domain to an FF-prone domain, without a progression just before or within the FF-prone domain. Such a refinement would be needed to formulate quantitative estimates of the amount of fine fragmented mass within the FF prone domain. Moreover, it was shown in Section 5.5 that FF can occur at lower burnup than predicted by the NFIR threshold but at higher temperatures, and an extension in this direction of the NFIR threshold is needed.

Finally, the impact of previous base irradiation power history was evidenced in older and recent research programs (see Sections 2 and 5.5). This is consistent with the physical mechanism for FF, which was identified as related to microcracking caused by over-pressurized gas bubbles

during the thermal transient (heat-up transient), or by strong thermal stresses during fast cooling, that is, quenching (see Section A.2.1). The development of the gas bubbles in terms of distribution and morphology (intragranular or intergranular and HBS structure) progresses with burnup but also depends on the power level through the steady-state power history. In such testing, it will be necessary to recreate the microstructure of fuel at different power histories, for example, by short-term re-irradiation at corresponding power levels, to override the effects of shutdown protocols and prolonged storage of father rods, which could alter fuel microstructure. Hence at the same burnup, different fuel microstructures can exist with the consequence of different outcomes during the thermal transient. This points toward the need for more mechanistic modeling being required to fully describe the range of fuel states and behavior during a LOCA event.

Unless one or more of the key preconditions necessary for dispersal to occur are well understood and precluded, and the potential effects of fuel dispersal on coolability can be resolved, the implementation of FFRD processes in the LOCA methodology and methods require a realistic best estimate and uncertainties-based approach, coupled with a risk-informed evaluation. The integral LOCA tests in-pile or out-of-pile in the current database have all been designed to maximize the FFRD effects by selecting initial rod pressures that led to burst in the high alpha phase of Zr where the burst strain and the size were maximized. Also, the temperature excursion was continued after burst to values close to the licensing limit, to provide data related to post-quench ductility concern.

Generally, more mechanistic modeling is required, and future research is needed to cover the necessary range of conditions representative of LOCA scenarios, so that quantitative analysis can be performed and checked against quantitative criteria, biased conservatively but informed by representative tests. Currently, LOCA evaluation methods are designed to ensure maximum PCT and ECR values are obtained, which typically occur in low-burnup, high-powered rods. Moreover, today's LOCA analyses are mostly done on a cycle-independent basis (for example, for a given fuel product covering the full range of powers and exposures the fuel may experience). As stated previously, this is likely not consistent with the models and level of fidelity needed to capture the fundamental aspects of FFRD as well as the focus on the rods of interest (that is, not only the "hot rods"). Careful consideration of existing LOCA methods, in addition to the capturing of additional physics, is needed for any proposed methodology that will be used to evaluate FFRD.

Based on the review described above, the following data gaps have been identified for future research objectives, to provide a solid basis for accounting for potential FFRD impact on LOCA analysis:

- GAP #1: Clarify the nature and timing of the so-called "LOCA forces," which have been invoked in relation to fuel fragments dispersal through the burst ruptured opening.
- GAP #2: Study experimentally and theoretically the dispersal process from the expulsion of fuel fragments through the rupture opening to their entrainment by the flowing stream of fluid around the fuel rods (steam or water, or two-phase flow) to their potential settling as porous layers (beds) in confined spaces, such as spacer grids or reduced cross-sectional areas because of adjacent rods ballooning. This would be best achieved by multi-rod, bundle tests of reasonable length and with spacer grids included.

- GAP #3: Study experimentally and theoretically the cooling of the porous beds defined in previous item, to identify whether a detrimental impact on fuel rods coolability exists or not. This is considered a central topic; unless it can be demonstrated that the accumulations of fuel fragments in those confined spaces are limited and are coolable, the whole FFRD issue becomes a moot point. The other safety concerns, such as radiological, recriticality can be handled within existing LOCA safety methodologies.
- GAP #4: Refine relocation quantification, following a given FF event, based on state-of-the-art cladding high-temperature creep and burst modeling to inform gaps 2 and 3; that is, develop realistic (with quantified uncertainties) models to predict ruptured openings, which is the key parameter controlling fuel fragment expulsion, and also quantify the amount of dispersed fuel.
- GAP #5: External heating has been identified as a major influencer and still an unresolved non-representative feature of the semi-integral tests in the hot cell; the in-pile IFA-650 series of tests used a combination of internal nuclear and external heating, however, still not fully representative. It is desirable to perform representative in-pile tests under prototypical LBLOCA conditions.

A
DETAILS OF SECTION 2

A.2.1. Main Physical Mechanisms Leading to FF During a T Transient

A review of the existing research regarding the mechanisms of fuel fracture and potential subsequent fragmentation during thermal-mechanical transients can be summarized into the following categories:

A. Induced thermal stresses by temperature gradients during:
   i. Heat-up
   ii. Quenching
B. Macroscopic fracturing in regions with high local tensile stresses:
   i. Equicohesive temperature for grain boundary cracking at high temperature
   ii. Griffith-like stress riser at elongated voids and GB lenticular bubbles
   iii. Cottrell dislocation-assisted crack extension
C. Gas bubble diffusional processes: In the case of flat (or almost) temperature profile: mechanisms related to gas-filled bubbles and pores, depending on heating rate:
   i. Gas bubble growth assisted by gas atom/vacancy diffusion if heating rate is not too fast
   ii. Coalescence of network of bubbles (intergranular or intragranular) and crack opening
D. Chemically assisted cracking: oxidation, hydration leading to powdering

Regarding process A, it is well-known that significant nonlinear temperature radial profile in the cylindrical fuel pellet generates thermal stresses, which could cause cracking, or fine fragmentation and powdering. This powdering occurrence has been observed during Power Cooling Mismatch (PCM) in-pile tests at INL and reported in Reference A2-1.

Thermal stresses are the major cause of pellet cracking during normal operation because of the large thermal stresses created by the quasi-parabolic temperature distributions generated by the fission heat source inside the fuel pellet. The hot inner, central part of the pellet pushes outward to the outer pellet ring, which in turn, compresses the inner pellet core, so that central part is in compression and the outer part is in tension, in the hoop and axial directions.

In this thermal stress distribution in the UO_2, during normal operation, the pellet leads to macrocracking in the outer pellet zone because UO_2 is a ceramic with elastic/brittle behavior at low- to mid-temperatures and almost ideally plastic at higher temperatures. Consequently, the result is outer cracked wedges and an inner plastic core, and if the temperature is high enough, a so-called plasticity temperature delineates the low-temperature elastic domain from the high temperature plastic domain, which is heat rate dependent and also burnup dependent.

Thermal stresses are relaxed (become vanished) by cracking in the outer annulus and by creep/plastic deformation in the center. It is noted that thermal stresses are self-equilibrating over the whole body; hence relaxation in one part reduces thermal stress overall. The cracking pattern seen in hot cell PIE is a combination of cracks present in the hot state and cooling cracks, which occurred during the final shutdown, at the end of base irradiation in the NPP; practically, no residual thermal stresses exist in cold state, as cracking of UO_2 occurs at low stress levels.

Regarding processes B and C, they are alternative and competing mechanisms of relaxing the overpressure created in the gas bubbles due to temperature transients. In summary, the excess pressure inside bubbles can be relieved by bubble volume increase, which can occur because of the following three main processes:

i. Vacancy/interstitial and gas atoms' diffusion through lattice or on grain boundaries

ii. Matrix plastic/creep deformation

iii. Brittle cracking (decohesion) of grain boundaries

When the bubble-matrix interface is subject to a force imbalance, mechanical equilibrium can be restored by either stable matter transport (i) or (ii), depending on transient timescale and magnitude, or by grain boundary cracking (iii) [A2-2].

Regardless of how mechanical equilibrium is reached, it is considered that growth of the grain boundary bubble population would eventually lead to bubble interlinkage, which effectively means grain boundary decohesion. Under normal operating conditions, full bubble interlinkage occurs along grain edges to create the so-called "tunnels" that constitute a percolation pathway for releasing fission gas. In other words, the separation of neighboring grains during a temperature transient could trigger a microcrack to develop if sufficient contiguous grain faces are disrupted in the process. It is noted that a similar process can take place inside the grains if strings of intragranular bubbles are present, such as the observed line string of bubbles that precipitate along dislocation lines or in the wake of fission tracks.

Cracking along grain boundaries is the most likely fracturing mechanism because intergranular bubbles have a lenticular shape and hence already have a crack-prone wedge geometry; this creates a stress intensification factor (SIF) at the tip of the lenticular intergranular crack, so that the applied stress is amplified in the vicinity of the bubble tip on the grain boundary. More details are available in Reference A2-3.

In conclusion, fuel macro and fine fragmentation (called *pulverization*, or *powdering*) during temperature transients, in absence of large thermal stresses, is possible whenever and wherever within the pellet a sufficiently large population of gas bubbles, preferably intergranular, exists prior to the temperature transient. The occurrence of FF depends on the heating rate because of the abovementioned competing diffusional processes, which lead to just bubble growth and gaseous swelling. These, in turn, will preempt FF and most likely lead to some transient fission gas release, tFGR (of diffusional character), which will also sinter back the interlinked tunnels along grain boundaries, thus preventing cracking along grain boundaries.

The development of gas bubble microstructure depends on burnup and temperature as main parameters, and it is also influenced by the power history prior to the thermal transient of which the potential pellet cladding mechanical interaction (PCMI) caused compressive stresses on the pellet is a third parameter.

Under normal operating conditions, fuel restructuring and apparition of intergranular bubbles occur at higher temperatures (greater than ~ 1000°C), which are attained in the center part of the pellet and depending on the power level and PCMI intensity. These gas bubbles can be vented and their gas content released to the rod free voidage, in which case they don't contribute to FF. Thus, most vulnerable parts of the pellet are the mid-radius rings of restructured fuel with large but not fully interlinked gas bubbles on the grain boundaries (called *dark-etched zones* and more recently, *dark zones*). At high and very high burnup, high burn-up structure (HBS) develops in the pellet outer rim, which concentrates the vast majority of the fission gas in large bubbles, thus constituting an FF-prone zone that could undergo FF at lower temperatures.

It can be concluded that FF is possible at any mid to high burnup value, but at different temperatures, and dependent on previous power history. It is suggested that an actual burnup threshold does not exist a priori, but rather a temperature threshold can be envisaged, which is decreasing from high values for low-mid burnup to much lower values at high and very high burnup (the issue of which burnup is the relevant parameter is considered later). Evidence for this extended temperature threshold is provided by past research, mostly dedicated to severe fuel damage (SFD) and fast breeder reactor (FBR) behavior during accidental conditions (reviewed in the Database section).

Nevertheless, an apparent burnup threshold can be contemplated in the context of LOCA applications because the maximum fuel temperatures in those conditions (especially for high burnup fuel rods) are below the restructuring temperature.

A.2.2 Chemical Effects: Oxidation in Steam and Air, Enhancing Factors of FF

Fuel oxidation occurs even at low temperatures in air or steam. The stages and kinetics of fuel oxidation in both air and steam have been thoroughly studied [A2-4].

The temperature range of interest for the SCIP tests had the following conclusions [A2-4]:

- UO_2 can oxidize in air rapidly to U_3O_8 via U_3O_7 and U_4O_9.
- The higher oxide phases resulting from UO_2 oxidation have lower density and the accompanying volume increase leads to local stresses and fragmentation.
- The oxidation starts along grain boundaries and spreads inward afterward, occurring more toward the center of the pellet.
- Oxidation in air was observed as fragmentation and spalling of small U_3O_8 particles for $T < 600°C$, while at $T > 800°C$, rapid grain growth occurred.

Although the duration of high temperature exposure to air in the OOP HT tests [A2-3] and to steam in the integral LOCA tests in SCIP is rather limited, some oxidation effects cannot be completely ruled out. However, it is considered that oxidation is an additional fragmentation factor, which affects fuel fine fragmentation after cladding burst in the LOCA tests more than in the OOP HT tests.

An interesting observation in this direction was made, where scanning electron microscope (SEM) observations of oxidized and agglomerated fragments were noticed on and between larger fragments from the R2D5 LOCA 1 material, which had a large fraction of fine fragments [A2-5] (p. 9). The comment was made that, "The quench and soak of the LOCA tests causes surface oxidation, precipitation of secondary phases and agglomeration of fine fragments" [A2-5].

While the phase change to U_4O_9 needles formation in the outer pellet zone was observed in post irradiation examination (PIE) of commercial fuel, the quench in the LOCA tests is very rapid, and this phase change is less likely. In all LOCA tests but a couple, the heating continued after burst and afterward the fuel was exposed to steam at relatively high temperatures up to ~ 1000°C.

Therefore, oxidation cannot be ruled out and it is very likely that it is a contributing factor to the final FF state; as described in Section 3 of this report, tests performed in inert atmosphere showed appreciably less FF, which greatly supports the FF enhancing role of oxidation by steam following burst. While this feature is representative of the actual LOCA scenario, the test protocols to continue heating to values close to the maximum allowable peak cladding temperature (PCT) are questionable; this test feature was introduced to study the transient oxidation and hydrogen uptake of the cladding for the licensing bounding case.

A.2.3 Cs Role, a Potential Explanation for the Missing Bubble Pressure

Cesium is a prominent fission product being generated in both stable and radioactive forms; the stable and long-lived isotopes of Cs have a yield of ~ 0.2 in a thermal reactor with U-235 (comparable to fission gas species total yield of 0.31).

Cesium has a low boiling point of 670°C and a low dissociation temperature of its oxides (< 700°C) and a high chemical reactivity, in general [2-6]. Cesium is semi-volatile because it is in gaseous form only above the boil-off temperature. The external pressure has a strong influence on the boiloff point, which is raised as external pressure is increased.

Cesium has a low solubility in the UO_2 matrix, similar to fission gas atoms, Xe and Kr, and when in gaseous form contributes to the formation and growth of fission gas bubbles (although not generally accounted in gaseous growth models). It has been observed that Cs migrates axially and accumulates by condensation at pellet-pellet interfaces [PPI] and on cladding inner surface, with a general tendency to migrate down a temperature gradient. It was also speculated that Cs forms Cs uranates in the outer part of the fuel pellet at temperatures between 600 and 1000°C.

It was speculated that Cs in liquid form at low temperatures has little mobility and forms a film on the grain surfaces [A2-6], and hence it is detected as such by Electron Probe Micro Analysis (EPMA) of the HBS zone, because the new subdivided grains are much smaller than the volume of the X-ray excitation.

Several microscopy and micro gamma scanning studies indicated that Cs among other fission products lines up grains boundaries (GB) and could plate out inner surfaces of GB bubbles at room temperature (RT). One such study was reported [A2-7, A2-8], where it is mentioned that sequential X-Ray Photoelectron (XPS) analysis and Ar-ion sputter etching at AECL (Atomic Energy of Canada Limited) showed monolayer level coverage of GBs. Although not definitive, it was reported that chemical shift data are consistent with mixed Cs uranates.

Cs reacts with UO_2 and other fission products and could be a O/U buffer in colder parts of the pellet. According to a review of the state of fission products [A2-10], Cs is precipitated as Cs uranate and can be found as an intergranular layer by X-ray microanalysis. The chemical combination of Cs depends on fuel oxygen potential; in any case, in the hotter center part of the pellet, Cs is released as being in gaseous form and it was found that it is released similarly to the noble gases, Xe and Kr. H. Kleyklamp notes that Cs oxide as a gas is located mainly in bubbles and in closed pores [A2-10].

S. R. Dharwadkar et al. performed studies of the stability of the Cs uranate phase and confirmed to a large extent previous findings that Cs_2UO_4 (the main form of Cs uranate that can form in the fuel during irradiation) decomposes in air [A2-11]. In another informative review [A2-12], the role of Cs deposited on the GBs in the outer unrestructured (or HBS, which was not addressed at the time [A2-12]) pellet zone is emphasized. It stated that Cs on GBs will exert pressure between grains and support a sudden breakup of fuel into grain-sized particles as soon as the restricting force from the clad is relieved.

On the other hand, Cs uranates or molybdates are significant for fuel periphery. In the LWR conditions of oxygen potential, both molybdates and uranates are possible. In another study [A2-13], the properties and thermal stability of Cs_2UO_4 were studied on a synthetically made Cs uranate in the form of pressed powder. It was concluded that upon heating in dry air, decomposition into $Cs_2U_2O_7$ and CsO_2(g) occurs for temperatures as low as 500°C. Another interesting result of the CEA study [A2-13] is that the thermal expansion of Cs_2UO_4 is ~ 40% higher than UO_2, which could be consequential if layers of Cs_2UO_4 are plating GBs.

The results reported in the two studies above are further supported by ORNL (Oak Ridge National Laboratories) studies [A2-14], in which the release of CsO_2 in air was observed and higher Cs release (as well as I) was measured in dry air than in steam (relevant for the difference between OOP HT and LOCA tests in SCIP).

Finally, the results of the HEDL SFD tests that used direct electrical heating (DEH) to apply thermal transients and some of the findings of that study [A2-15] are relevant to the subject matter of this section and are described in Section 5.5 of the current report.

A.2.4 References

A2-1. A. W. Cronenberg and T. R. Yackle, "Intergranular Fracture of Unrestructured UO2 Fuel, during Film-Boiling Operation," *Journal of Nuclear Materials*, Vol. 84, 1979, pp. 295–318.

A2-2. J. R. Matthews et al., "Oxide Fuel Fragmentation in Transients," AERE Harwell Report 135, 1990.

A2-3. V. I. Arimescu, "Review of FFRD Experimental Data and Modeling Approaches – Implications for SCIP LOCA and OOP HT Tests," STUDSVIK/N-19/109, STUDSVIK-SCIP III-256, 2019.

A2-4. D. R. McCracken, "Oxidation of UO2 at 400 to 1000 °C in Air and Its Relevance to Fission Product Release," AECL-8642, 1985.

A2-5. A. Puranen and P. Tejland, "Subtask 1.1 – R2D5 SEM, Position and Morphology of Fuel Fragments," Presentation 12 at the SCIP III Beijing Meeting, October 2016.

A2-6. C. T. Walker et al., *JNM* 240, 1996, pp. 32–42.

A2-7. W. H. Hocking, "Impact of Fuel Chemistry on Fission Product Behavior," in: SCK-CEN Workshop, June 16–17, 1999.

A2-8. W. H. Hocking et al., "Investigation of Grain-Boundary Chemistry in Used CANDU Fuel by X-ray Photoelectron Spectroscopy," Proceedings of a TCM, Cadarache, IAEA-TECDOC-822, October 17–21, 1994.

A2-9. "Report on Fuel Fragmentation, Relocation, Dispersal," NEA/CSNI/R(2016)16.

A2-10. H. Kleyklamp, "The Chemical State of Fission Products in Oxide Fuels, *JNM*, Vol. 131, 1985, pp. 221–246.

A2-11. S. R. Dharwadkar et al., "Basic Thermodynamic and Transport Properties of Some Fission Products in Oxides and Intermetallic Systems Relevant to the Behavior of Nuclear Fuel," IAEA IWGFPT/25, 1985.

A2-12. W. Breitung and G. Schumacher, "The Significance of Cesium in LMFBR and LWR Safety Analysis," KFK 3716, May 1984.

A2-13. J. P. Berton et al., "Chemical Stability and Physical Properties of Cesium Uranates," IAEA TCM IAEA-TECDOC-1036, 1998.

A2-14. J. L. Collins et al., "Fission Product Iodine and Cesium Release Behavior under LWR Accident Conditions," *Nuclear Technology*, Vol. 81, April 1988.

A2-15. G. R. Fenske et al., "The Response of Irradiated Mixed-Oxide Fuel Subjected to Thermal Transients Using Direct Electrical Heating Techniques," ANL-83-29, May 1983.

B
DETAILS OF SECTION 3

B.3.1 Integral Tests in a Hot Cell

B.3.1.1 NRC-ANL Tests

The ANL research program regarding fuel behavior during LOCA was sponsored by the NRC to assist the post-quench ductility issue for Zircaloy-based claddings in support of a potential revision to 10 CFR 50.46. Initial cladding oxidation tests in a test chamber were followed by integral LOCA tests in an upgraded test chamber, which allowed rod pressurization, heating up the rods at given heating rate in a stagnant steam atmosphere and final quenching after reaching the pre-determined high-temperature target and a hold time at the temperature.

The main objective of the ANL integral LOCA tests was to address the adequacy of the embrittlement criteria and the impact of hydrogen on the equivalent cladding reacted (ECR) correlation, which was under development at the time. As such, a four-point bending test was performed on the fuel rod after the LOCA test and cladding microstructure, and hydrogen uptake were investigated by electron microscopy and metallography in the ballooned area. In addition, the fundamental behavior of high-burnup fuel and cladding as exposed to a LOCA transient was investigated and characterized.

Four LOCA tests were performed in 2002–2004 on high-burnup BWR samples from Limerick fuel rods, with a rod average discharge burnup of 56 GWd/MTU. These tests used external heating of the rods in a steam environment. The test protocol was to ramp up temperature to 1,200°C, hold it for a predetermined period (approximately 12 min.), and ramp down to 800°C, at which point quench occurred, but variations occurred from test to test.

The ICL#1 test specimen was heated to bursting in argon, and slowly cooled. The ICL#2 specimen was exposed to the LOCA test sequence, except the quench. The ICL#3 specimen achieved partial quench (800°C to 470°C) before failure of the quartz chamber that surrounded the specimen. A full LOCA sequence was completed in ICL#4.

The results of the in-cell tests with high-burnup fueled Limerick cladding (ICL series) were compared with companion out-of-cell tests in argon. The burst temperatures, pressures, and maximum diametral strains were remarkably close for these two cladding conditions. In terms of these parameters, high-burnup operation had little effect on cladding burst conditions and strains, confirming the same conclusion drawn from separate-effects burst tests.

The primary differences observed between the high burnup cladding and the unirradiated cladding was in the pre-burst bending (less for high burnup), the axial extent of the ballooned region (less for high burnup), and the shape of the burst region (oval for high burnup).

The ANL program focused on the details of cladding oxidation, hydriding, and ductility, rather than on the fuel behavior, and methods that could be used to freeze the fuel particles in place (for example, epoxy) conflicted with cladding characterization. Therefore, for tests such as ICL#2,

no attempt was made to prevent fuel fallout during handling. For the ICL#3 and ICL#4 samples, the burst areas were taped following the test to minimize fuel fallout and the samples were gamma-scanned prior to other nondestructive characterizations to determine the axial distribution of fuel in and beyond the ballooned region.

For the axial locations with little-to-no permanent strain, gamma counts received from the fuel most likely represent the condition of the fuel at the end of the LOCA test. For the ICL#3 and ICL#4 ballooned regions, some redistribution of fuel particles is likely to have taken place between the end of the LOCA test and the gamma scan due to the sample handling and transfer [B3-2].

Conclusions on NRC-ANL Integral LOCA Tests

The burnup of the test segments was ~ 64 MWd/kgU, cut from a father rod irradiated in Limerick BWR to a rod average burnup of 56 MWd/kgU.

Regarding the test protocol, the following excerpt clearly expresses the motivation to maximize the effects of the bounding LOCA scenario simulation [B3-3], which will be emphasized in a separate section:

> "The gas volume is the minimum that can be achieved in-cell and less than the room-temperature void volume (30 cm^3) measured for a full Limerick BWR rod. The pressure differential (Pg) across the cladding wall is an upper bound for these Limerick BWR rods during a large-break BWR LOCA if the rods had achieved the full 62 GWd/MTU, as opposed to the 56 GWd/MTU for the F9 rod used to prepare the LOCA Integral Test specimens. However, the primary reason for choosing this pressure was to induce large ballooning and burst in the alpha phase (T<800°C), so that fuel relocation - if it did occur - could be characterized. The 1204 °C peak temperature was chosen to test the adequacy of the LOCA Acceptance Criteria in 10 CFR 50.46."

With respect to FFRD, the following excerpt [B3-3] summarizes the observations made for the ANL tests:

> "Loss of fuel particles through the rupture opening in the ballooned region of a fuel rod was not expected based on any prior research. When integral loss-of-coolant accident (LOCA) tests were recently completed at ANL on high-burnup boiling-water reactor (BWR) rods with a local burnup of 64 GWd/MTU, a small amount of fuel loss was noticed (about the quantity of one fuel pellet). Because the amount of material was small, this observation was not thought to be important."

As mentioned above, the amount of FF and dispersal was not an objective of the tests, and therefore a quantitative characterization is not available. However, as summarized in the quote above, there was minimal fuel dispersal for these test rods with a segment burnup ~ 64 MWd/kgU and for a large burst opening of 11-15 mm long and 4.6-5.1 mm wide. Evidence of relocation was provided by gamma scans after the test, although it was noted that some movement of fuel fragments was probably caused by test segment handling and transfer after the test. PIE ceramography of some test segments showed considerable FF close to the burst center (12 mm above burst center), with some fine fragments noted and interestingly, a mid-radius ring with circumferential tearing, which was visible as a dark ring on the fuel prior to the LOCA

testing. It is considered that this observation shows the potential FF of non-HBS zones, as stated in the FF mechanisms section, and observed in other cases.

B.3.1.2 NRC Tests at Studsvik

The LOCA tests performed at Studsvik used segments taken from three different North Anna pressurized-water reactor (PWR) rods. For the first four tests (189, 191–193), the segments were taken from rods with a rod average burnup level between 68–69 GWd/MTU, but the test segments' burnups ranged from 72 to 78 GWd/MTU. The last two segments, 196 and 198 were taken from rods with a rod average burnup level of 55 GWd/MTU, and the test segments' burnup was ~ 60 GWd/MTU. Two of the tests (189, 196) were terminated just after rupture, while the other four tests experienced some degree of high-temperature steam oxidation, followed by quench.

Following the LOCA simulation, four-point bend tests were conducted to measure the residual mechanical behavior of the ballooned and ruptured region. After the four-point bend test, a shake test was performed to determine the mobility of fuel fragments that remained in the fuel rod. The shake test consisted of an intentional inversion (turning them upside down) of the two halves of the broken fuel rod, followed by vigorous shaking to dislodge any loose fuel fragments. The shake test was conducted approximately two days after the LOCA simulation. The total voided length was measured for each segment using a wire probe.

In all four of the 72 GWd/MTU tests, significant fuel loss through the rupture opening was observed during the LOCA transient. This can be correlated with the large rupture opening after LOCA testing for the first four specimens tested are shown in Reference B3-5. Photographs showing the ruptured opening after LOCA simulation indicated that they were smaller for tests 196 and 198 [B3-5] than those in tests 189 through 193. This correlates well with the observation that in contrast to tests 189 through 193, during tests 196 and 198 at 55 GWd/MTU, essentially no fuel was found outside of the fuel rod following the LOCA simulation. All fuel found outside of the fuel rod was measured after the broken rods were "shaken."

Fuel fragment size measurements were performed by processing the total mass of fuel material found outside of the fuel rod after all steps of the experimental procedures for each of the six tests were completed. The fragments were processed through a series of six sieves to determine the particle size distribution. One of the first observations from the pictures of the fuel fragments shown in the report [B3-5] is that there are visibly significant differences in the particle size distributions between tests 191 to 193 and tests 196 and 198. In tests 191–193, all fuel fragments measured less than 4 mm (except a small amount from test 193). The mass of fuel fragments from these tests was approximately evenly distributed between the size groups separated by the six sieves used. In contrast, the fuel fragments in tests 196 and 198 were predominately larger than 4 mm (larger than 1 mm used later in the SCIP III program).

Although it is not obvious by an examination of the figures in Reference B3-5, Table 4-1 of that report indicates that the total mass found outside of the fuel rod for tests 191-193 was about the same as that measured in tests 196 and 198; therefore, the difference in size distribution is a clear difference in the amount of fine fragmentation that has occurred in the two test rod groups.

The burst opening is approximately the same in size for tests 189, 191–193, all of which had high burnup fuel, while the burst opening for the lower burnup fuel tests, 196 and 198, were “very small” and “small,” respectively. There was practically no fuel dispersal after the LOCA tests for these two lower burnup fuel tests, indicating that no fine fragmentation has occurred. This was also evident by the sieving of the fuel removed from the rods after inverting the two cladding halves (created by the bending test) and shaking them. As the size distribution in the report shows [B3-5], most of the fragments removed from the two lower burnup rods were in the large fragments bin, of greater than 4 mm. This was also confirmed visually by the photos of the mass removed by shaking, which show powder-like appearance for tests 192 and 193, in contrast to large pieces of the pellet for tests 196 and 198, reminiscent of macrocracking of the pellets due to thermal stresses during normal operation.

The effect of gravity on relocation was observed in tests 192 and 193, where the voided volume above the burst region was larger than that below the burst region. No measurements were performed right after the LOCA test for test 189, and no clear effect of gravity was observed in test 191. In the figures provided in the report, fuel dispersal from the volume below the burst region occurred only after the LOCA- tested fuel rods were broken into two pieces in a subsequent mechanical test, and the fuel was shaken out of the ends of the fuel rods.

Conclusions on NRC Tests at Studsvik

A large difference was noted for the burst opening of the two lower burnup rods, which was smaller than that of the other high burnup rods. Burst openings were larger than expected, in comparison to the historical database, and were observed for the higher burnup rods with the same initial rod pressure for which, burst occurred at about the same temperature. This can be rationalized for the two lower burnup rods by the lower burst temperature, as the burst strain has an increasing trend in the alpha-Zr temperature domain. However, the reason for this lower burst temperature was not identified in the report. One possible explanation is that a higher internal rod pressure and hence hoop stress existed during the test of those two rods, and for some reason the pressure transducer indicating the lower values recorded. This could be due to either a biased pressure gauge reading, or some obstacles along the gas line, or internally to the rods that caused higher pressure in the central part of the test segments. Then the opposite explanation would be required for the higher burnup rods, that is, higher actual burst temperature due to higher-than-expected axial temperature gradient, which was not captured by the thermocouple (T/C) that was at an appreciable distance from the burst location.

However, an important observation was noted when comparing the two low burnup tests, namely, 196 and 198: Test 196 was terminated right after rupture and the almost pinhole-sized burst opening showed the impact of continuing the temperature transient in steam on the crack opening (note that the rod depressurization upon burst is not instantaneous), which led to a larger rupture in the case of test 198.

In all high burnup (~ 74 GWd/MTU) fuel tests, significant fuel dispersal was noted, while practically no dispersal was observed for the lower (~ 60 GWd/MTU) fuel. FF size distribution measurements were performed after the shake test and the wire probe examination of the test segments, suggesting that additional FF was most likely caused by the bending test, shaking and wire probing, so that the fragment size distribution was very conservatively biased in comparison to the state of the fuel right after the LOCA test.

The gamma scanning was performed one year after testing on the portions of the rodlets created by the bending test after being kept in storage. It was noted that additional fuel fell out during manipulation of the stored rodlet pieces. The figure that overlaid the gamma scan and the profilometry with lines indicating the voided length measured by wire probing shows practically no dispersal from below the burst opening.

B.3.1.3 SCIP III LOCA Tests

As described in the previous section, NRC commissioned at Studsvik the same type of LOCA testing as done earlier at the Argonne National Laboratory, employing a purpose-built test apparatus similar to the one used at ANL; this was used for the initial tests in SCIP III.

The apparatus was designed to externally heat a 30-cm long rod segment up to 1200°C by infrared (IR) radiation. The furnace consisted of four infrared (IR) lamps at equally spaced angles around the rod. The furnace contained mirrors that focus IR light onto the rod. It is important that the rod is centered to obtain a low circumferential temperature gradient. In this arrangement, the system provides a heating rate of 10°C/s. The test segment temperature was measured with a thermocouple attached on the rod surface approximately 50 mm above the axial mid plane of the rodlet. The segment was pressurized with helium or argon and placed in a cylindrical quartz glass chamber in a flowing steam environment. An air or inert atmosphere was also possible. A flow steam atmosphere was produced by a boiler/steam coil arrangement. A condenser was positioned at the upper outlet to trap the steam. In a typical integral LOCA test, the fuel segment is internally pressurized to 40–100 bar and heated with a 5°C/s heat-up ramp, so that at around 650–800 °C, the rod balloons typically at mid-height and ruptures.

Heating continues to 1000°C, where the temperature is held for a predetermined period. Afterward, the rod is cooled down to a preselected quench temperature, typically 700–800°C, before the test chamber is quenched in water. The transient parameters, for example, ramp rate, maximum temperature, oxidation time at peak temperature, quench/no-quench, quench temperature and rod inner pressure, are all controlled and can be chosen according to the test objective.

A new test apparatus was built in the frame of SCIP III program as an upgraded version of that described above, and it was used for the remainder of the tests in SCIP III. The added features to the test setup were 1) application of an axial load to the test segment and 2) LVDT to measure axial length changes of the test segment.

The test protocol includes the three phases of a LOCA scenario: the temperature excursion during blowdown, the temperature plateau and small drop during reflood, and rapid decrease in the temperature due to quenching during refill. It is noted that the heating rate of 5°C/s used is lower than the estimated ~20°C/s by modeling of LOCA scenarios, although a broad range of heating rates results from LOCA calculations, which included the 5°C/s, as a lower bound, while the upper bound is significantly above 20°C/s.

The SCIP III test program consisted of 13 LOCA tests performed in the Studsvik hot cells, 7 with the old LOCA test device, and 6 with the new LOCA test device described. One of the tests (36U-N06- LOCA1) was performed as a counterpart test to an in-reactor test at Halden and is described in Section B.3.2.3 of the report. Four tests were performed with the primary objective of studying the burnup threshold for fuel fragmentation. The main objective of three of the tests was to identify a strain threshold for burst and the difference in fuel fragmentation with and without burst. Another test was performed to investigate the effect of a different temperature ramp rate.

The results of all the LOCA tests, including five other LOCA-type tests in other tasks of the SCIP III program, were analyzed as a complete set to derive the implications of their results on FFRD. The test segment burnups for these LOCA tests span the range from 61 GWd/MTU to 76 GWd/MTU, with several test segments originating from the same father rod that was irradiated in a LWR NPP. Therefore, the segment burnups were lumped up around 65 GWd/MTU and 75 GWd/MTU, with one singular case at 61 GWd/MTU.

As for all the other hot cell and in-pile LOCA tests, the initial pressure was selected so that burst would occur in the high alpha-Zr domain, where the rupture opening is maximum. Indeed, the estimated burst temperatures (T/C not at the burst location, but not too far from it) were in the expected temperature range, which was distributed around 760°C for most of the initial cases at 80 bar. The case of the lowest initial pressure at 1 bar did not burst, while in the case of the second lowest initial pressure of 20 bar, the burst occurred at the highest temperature of all cases, namely, 942°C.

The typical PIE methods were used, and in some cases advanced microscopy techniques were employed to investigate the microstructure of the fuel before and after the test. This was beneficial in detecting sub-grain formation in the non-HBS zones and confirming microcracking tendency of these non-HBS, restructured zones to FF, called *dark zones* (as they appear darker) when the fuel sample was etched.

There was evidence from the videos of the tests that fuel fragments were ejected through the ruptured opening (the videos of the tests showed ejection occurred at the time of burst and not afterward) and the amount collected after the test was weighed, and in most cases the fragment size distribution was quantified by sieving. However, the test rods were flipped upside down followed by vigorous shaking, causing all fuel fragments to fall out that were not ejected during the test. The concept of “movable” or “dispersible” mass was introduced as representing all fuel mass collected both just after the test and after shaking the broken test rod. The usefulness of this “dispersible” mass as a parameter for FFRD is further discussed in Sections 5.6 and 6. It is mentioned here only to elaborate the remark made in SCIP reports that the test rod handling involved in moving it to measurement stations in the hot cell, as well as the vigorous shaking, which most likely have caused additional FF and relocation.

Also, a metric was proposed in SCIP to define an FF threshold as fragments smaller than 1 mm being less than 10% by weight of the total pellet (based on the fragment size distribution). While this is a reasonable quantification of fine fragmentation, the manner in which it was estimated for the SCIP tests is affected by the “bake, break, and shake” procedure used to collect all fragmented or potentially fragmentable mass either ejected during the test or remained inside the fuel rod but pulled out by effort. Thus, the said weight percent for the fine fragments class is normalized to the sum of FF and non-FF parts of the fuel.

As stated in this report, a general conclusion of all LOCA tests was that FF prone parts of the fuel pellet are the outer HBS zone and the so-called dark zones in the interior of the pellet. Technically, it would make more sense to define a percentage threshold of fine fragments below a certain limit relative to the mass of the FF-prone regions of the pellet. Arguably, it is practically impossible to achieve in practice, as the location of the fragment origination is lost in the collected pile of movable mass fragments after the test.

In addition, the abovementioned parameters are deduced from a limited number of tests, which are not prototypical (several test conditions and methods, as well as test fuel rod design are not adequately representative). Thus, while the dispersible mass and FF fraction are perfectly applicable to the tests, there is no clear basis for using them, as defined, in LOCA analysis methodology.

The main limitations of the experimental setup, which led to a non-representative fuel design being tested and test conditions are summarized in Section 4.

One of these non-representative fuel design features is the high test rod internal pressure, considering its remaining constant during the temperature transient and thus, not reflecting the negative feedback loop of pressure decrease when cladding ballooning occurs; however, considering the extended burnup fuel rods, a higher test rod internal pressure range should be explored (with an adequate maximum temperature). The influence of rod internal pressure on burst and depressurization, and on fuel fragmentation was assessed by means of two integral LOCA test subsets. In the first subset of tests [B3-9], pairs of fuel segments cut from three fuel rods were tested with and without burst. The second subset [B3-10] included three samples from the same fuel rod but with different fill pressures. Based on these results, it can be concluded that the depressurization shock after the burst greatly influences fuel fragmentation. The burst and depressurization may act as violent initiators of fuel fragmentation, and as a likely result of which, videos of the test chamber recorded during LOCA tests confirmed appreciable fuel dispersal during the burst from higher fill-pressure test segments.

The test subset to study the influence of burst pressure on fragmentation was performed at 20 bar, 40 bar, and 80 bar. Figure 66 in Reference B3-10 shows the fragment size distribution of the tests and Figure 67 in Reference B3-10 shows the amount of fine fragmentation as a function of the gas pressure. A clear increase in fine fragmentation is observed with increasing initial fill-pressure. The reported analysis found the result hard to explain and suggested a hypothesis that in the case of a larger plenum volume, it is easier to maintain the pressure inside the balloon prior to burst. However, the burst strain and size, as well as the burst temperature, were practically the same for the two tests, so this hypothesis is not consistent with the difference in dispersed mass. It is more likely that the intensity of the depressurization shock was different in the two cases, and that had caused more FFRD for the larger fill-pressure segment.

Several SCIP III tests were performed to assess one of the variables which are different between the test rods and actual fuel rods, namely, the plenum volume, which is oversized for the test rods, because of the long pipeline needed for gas communication form the test rod for the pressurizing and the pressure gauge located outside the test chamber.

To study the effect of plenum volume, two tests were performed on material from the same fuel rod, the first test with a total free volume of 5.1 cm^3 and the second with 10.2 cm^3 [B3-8]. The test conditions and main results are summarized in Table 19 of the study in Reference B3-8. The test with the larger plenum volume revealed significantly more fuel fragmentation, fuel dispersal, and a larger mass fraction of fine fragments.

Although it was not an initial test objective, the effect of gas flow impingement on the fuel during the gas blast following cladding burst became inadvertently evident in the OL1L04 test [B3-7]. In this case, the clamp that attached the thermocouple about 50 mm above the midplane of the test rod was probably more rigidly attached and exerted a stronger pressure on the cladding than in other cases, so that it prevented cladding ballooning, and in addition, probably lowered the temperature at that location due to a fin effect. The consequence was that two balloons developed in the two halves of the test rod, as separated by the clamp, as shown in the post-test profilometry.

The first burst occurred at 695°C and 8 MPa, followed by a second burst at 852°C, approximately 29.5 seconds later, at ≈ 2.8 MPa. The video of the test chamber and timing of fragment release indicate the lower half burst with a larger burst opening occurring first. The two balloons and the burst openings are shown in Reference B3-7. Regarding test rod pressure evolution, it was noticed that a slow gas depressurization followed the first burst, which is explained by the "bottle-neck" constriction at the thermocouple clamp location, which has likely caused a reduction of the flow area, which slowed down the gas flow from the test rod upper half and plenum volume (gas pressure transducer located at the top of the upper plenum).

The FFRD, especially dispersal, was greatly reduced for the upper half of the test rod, which shows the effect of gas flow impingement on the process of both additional FF and relocation of fuel fragments followed by ejection through the rupture opening.

The SCIP III findings regarding dispersal are discussed in Section 6.

B.3.1.4 ORNL LOCA Tests

The ORNL integral LOCA tests were performed by adapting the Severe Accident Test Station (SATS) rig to simulate the LOCA stages for a single fuel test rod and replicating it for operation in the hot cell. These tests were conducted with specimens made from 17×17 PWR Zircaloy-4 (300 mm long, 9.50 mm outer diameter, 0.570 mm wall thickness) filled with dense zirconia pellets, leaving a cold radial gap of ~ 0.1 mm. The quad-elliptic radiant furnace used during the experiments caused specimen bowing, inducing significant axial (ΔT_z) and circumferential (ΔT_θ) variations in temperature. This issue was addressed by providing support for the test train at the top. A figure of the apparatus is provided in Reference B3-13 that shows a LOCA test-segment within the test chamber. The quartz tube encasing the test train provides an enclosed volume for steam flow and water quench, both of which are introduced at the bottom of the test train. The total gas volume in the test segment is 10 cm^3, most of which is outside the heated zone.

The high-burnup fragmentation tests were conducted in a steam environment up to a terminal temperature of 1000°C, but without water quench. It should be noted that the test sequence is in line with the procedures described in the ANL LOCA program B3-1, B3-4. Furthermore, the NRC used the same procedure for the Studsvik LOCA test designed to investigate high-burnup fuel fragmentation, relocation, and dispersal [B3-5]. The full ORNL LOCA fragmentation test sequence is described below.

1. Heat in flowing steam to 300°C and pressurize fuel segment to 8.27 MPa
2. Heat in flowing steam at a rate of 5°C/s from 300°C to 1000°C
3. Hold in steam for 120 s at 1000°C
4. Cool at a rate of 3°C/s to 800°C
5. Cool in furnace from 800°C to the room temperature

The temperature and pressure evolution for the H. B. Robinson (HBR) segment (HBR#1) and the North Anna segment (NA#1) displayed the same trend as those of the previous integral LOCA tests [B3-1, B3-5). The ORNL in-cell test was run with a full LOCA sequence like the ANL ICL#4 test, with the exception of a shorter hold time. Although the sample size and cladding material were different between the two tests, the burst temperature and pressure of the HBR#1 and NA#1 tests closely resemble those of the ANL ICL#4 test. Additionally, the burst pressure for HBR#1 and NA#1 agree very well with the NRC sponsored test. However, appreciable differences in test outcomes were noted for two aspects.

First, burst temperature was lower for the NRC tests at Studsvik with lower burnup fuel (~ 60 GWd/MTU), but similar for ORNL and ICL#4 from the ANL tests. However, the burst opening for NRC-Studsvik tests were about twice that of ORNL and ANL tests. This issue is discussed previously in Section B.3.1.2. The underlying cause for this unexpected outcome remains unresolved according to the authors of the papers describing those tests [B3-5, B3-13], but it is clear that the small axial load applied in the Studsvik setup is not a contributing factor, which would favor the opposite,that is, a smaller burst opening.

Second, regarding dispersal, sieve analysis and strain measurements were performed on the two rods, as well as a third integral LOCA test, NA#2. The fragments for all three tests were collected and size distributions were determined immediately following the LOCA and shake tests. The particle sizes were quantified into five categories and the results for the three tests are provided in [3-13]. It was remarked that ORNL test results clearly showed less fragmentation than the NRC-sponsored tests performed in the same burnup range and initial pressure and fuel rod dimensions.

B.3.1.5 Tests in Inert Atmosphere at Kjeller

A couple of semi-integral LOCA tests have been performed in the hot cell rig at Kjeller, in which an inert atmosphere was present in the chamber where the test segment was placed [B3-14, B3-15].

The out-of-pile LOCA-test device in Kjeller consists of a hot cell furnace surrounding a glass tube test channel. The same Kjeller hot cell furnace was used in Reference B3-14 as for the E.on tests in Reference B3-15, but the LOCA test rig was upgraded with more instrumentation (thermocouples, gas line, and a microphone) for the EDF tests in Reference B3-14.

The top and bottom ends of the glass tube are plugged with insulation materials to mitigate the axial heat losses. The capsule is inserted by the upper aperture of the test channel when the target furnace temperature is stabilized. This process is used to achieve a heat-up rate of the capsule and the segment close to 5°C/s. The time needed for inserting the capsule is of importance because it can lead to axial temperature gradients between the bottom and the top of the capsule and thus may impact fragmentation mechanisms and phenomena.

Prior to the test, the test segment is inserted into an insulated capsule. Figure 2 in Reference B3-14 shows a drawing of a segment inserted into a capsule. This capsule has two main roles: first, to prevent fuel or fission gases dispersing out of the device and, second, to allow the collection of the fission gases after the test, in case cladding burst occurs. The capsules are made of Inconel (20 mm diameter) and filled with helium (1 bar). The capsule can host a 20-cm length test-segment with its instrumentation. Axial T gradient during heat-up is 25 to 75°C, over 10 cm around the maximum temperature (max T) position and almost flat during the max T hold. Capsule and segments can be instrumented with T/C's (cladding or capsule surface temperature) and a gas line (segment or capsule inner pressure).

B.3.1.5.1 EDF Tests at Kjeller IFE Hot Cells

A series of four parametric out-of-pile LOCA tests was initiated by EDF (France) in the IFE hot cells, involving irradiated MOX and UO_2 fuel rodlets from PWR father rods, with M5 cladding. Local burnup is ~ 57 GWd/MTU for MOX, 65 GWd/MTU for UO_2.

The goal of these tests is to evaluate and compare the MOX fuel fragmentation behavior with standard UO_2. To enrich the approach, tests with various boundary conditions had been performed on both types of fuel (that is, impact of initial rod internal pressurization, initial free volume). In particular, a test series had been run with a segment with no plenum, pressurized with typical end of life rod internal pressure, to simulate the impact of limited gas communication between the plenum and the hot spot in a 4-m fuel rod (follow-up from IFA-650.16 test, discussed below in Section B.3.2.2).

The experimental procedures of test series 1 and 2 were slightly different at the end of the tests. In test series 1, the furnace is turned off after cladding burst occurs. In test series 2, the furnace is turned off when the cladding temperature is stabilized and after a significant segment internal pressure decrease was observed, which was interpreted as an indication that a significant cladding balloon has formed.

The procedure for test series 1 and 2 is similar, with the exception of these specific "transient termination" conditions:

1. Heating the furnace up to 900°C, with no segment inside.
2. Fast insertion of the capsule containing the test segment into the furnace.
3. When the "transient termination conditions" are reached, the furnace is turned off.
4. The capsule is first cooled down inside the furnace, then removed when the furnace temperature has decreased below ~ 400°C.

To maximize the heat-up rate (to be as prototypical as possible of a LOCA transient), the tests were performed using one capsule at a time. The following parameters were recorded every second during the test:

- Cladding temperature (2 T/Cs)
- Plenum temperature (test series 2 only)
- Segment pressure (test series 2 only)
- Capsule pressure
- Capsule temperature (4 T/Cs)

Series 1: No Plenum, 40 bar Initial Rod Pressure

Temperature transient was up to ~ 850°C until burst occurred, with representative end of life (EOL) rod pressure and free volume condition corresponding to a location far from the top-end plenum, assuming low or limited gas flow. Both rod (UO_2 and MOX) bursts occurred at practically the same temperature, 840°C and 836°C, respectively, with localized balloons (2 cm long and very small burst opening, so no dispersal) and almost no fragmentation and no relocation visible after testing. It was noted that some pellets and fragment displacement was observed, which was considered to have occurred during the specimen handling before the neutron radiography was performed. Macro fragmentation was noticed for most pellets, like what is expected for NOC. Sieving showed similar size distributions of fragments, with less than 3% sub-millimetric fragments, more for the UO_2 rod, which had a higher burnup (65 GWd/MTU for UO_2 vs 57 for MOX).

Series 2: With Plenum and 5 bar Initial Rod Pressure

The plenum and gas line (total free volume: 8 cm^3) had an initial rod pressure of 5 bar. The MOX rod burst occurred after 15 min., the UO_2 rod stayed at max T of ~ 900°C for 30 minutes with no burst.

As expected, both tests showed a large ballooning each, extending to the full length of the segment. Cladding strain is ~ 25% to 57% over the length of the UO_2 segment, and ~ 25% to 63% over the 2/3 length of the MOX segment. Differences are obviously related to heating time. Fragment relocation occurred (enhanced by handling before neutron radiography was performed, evident from the difference between gamma scans and neutron radiography for the UO_2 rod) but with no column gaps and no FF observed. MOX burst opening was extremely small and could not be located, hypothesized to be under the T/C welding, which is also a high strain location. Sub-millimetric fragments make up only 0.9 to 1.6% of the total mass, therefore no FF.

B.3.1.5.2 E.on Sponsored Tests at Kjeller

The present separate-effect test made use of three fuel rod segments having the same burn up, of about 52 MWd/kgU, and were subjected to the following boundary conditions:

- Fuel segment 1, Cladding ballooning without burst: to study the fuel fragmentation, removing the constraint provided by the cladding.
- Fuel segment 2, Cladding ballooning and burst: to study fuel fragmentation, removing the constraint provided by the cladding and the rod internal pressure.
- Fuel segment 3, No ballooning and no burst: to study fuel fragmentation, keeping the constraint provided by the cladding and the rod internal pressure.

Fuel Segment 1: A sufficient large internal rod pressure is required to ensure the beginning of ballooning. However, to avoid burst, a small upper free volume is provided so that as the ballooning starts, the internal rod pressure quickly decreases.

Fuel Segment 2: An appropriate level of internal rod pressure is required to ensure the development of ballooning. A large upper free volume is provided so that the internal rod pressure does not decrease too rapidly, the ballooning is sustained for a longer time, and the burst criteria are met.

Fuel Segment 3: A level of pressure inside the rod that is comparable or smaller with respect to the capsule pressure (atmospheric) so that the pressure difference between the inner and outer sides of the rod is negligible.

The separate-effect test was designed as an out-of-pile test in an electric oven located in the hot cell at IFE Kjeller, as described in the introduction to Section B.3.1.5. In these tests, the assembly of three capsules was used, so that all three were at the same axial location inside the oven. Figure 3 in Reference B3-15 shows details of the capsule and the rod mechanical design. The capsule was made of ferritic steel, with diameter 20 mm, and filled with helium at 0.1 MPa. Thermocouples were installed on one of the capsules. Capsule 2 pressure showed a sudden increase when T approached ~ 843°C, indicating burst of segment 2.

Fuel segment 1: The neutron radiography (neutron radiography) indicated a large cladding strain along the entire axial length and, consequently, the complete removal of the cladding's geometrical constraint. The fuel pellets slightly moved radially, and no fuel fragmentation could be detected. Fuel cracks along the entire axial length and powder at the bottom of the rod were observed (“dust” at position 12 cm).

Fuel segment 2: The cladding ballooning did not appear along the entire axial length of the rod and was limited to the ballooning and burst region at the middle bottom of the rod (pos. 13.5 cm). Fuel fragmentation occurred in three pellets (pos. 13 cm and 16 cm) near the burst opening. Away from the burst region, only cracks in the pellets were visible. Fuel relocation occurred and partially filled the fuel-cladding gap of the second and third pellet from the bottom of the rod.

Fuel segment 3: There was no evidence of cladding deformation, fuel fragmentation, or relocation.

Very limited/no FF was observed with only 5% fragments less than 4 mm in comparison with NRC test 198, which had 7.4 MPa pressure, compared to 4 MPa for segment 2.

B.3.2 In-pile Integral Tests

B.3.2.1 VVER LOCA Tests

The MIR-LOCA series of in-pile integral LOCA tests have been performed by RIAR on VVER fuel rodlets. The testing rig could accommodate a mini bundle which represented the VVER assembly geometry, with 19 rods in hexagonal geometry, but only 3 of them pre-irradiated in an NPP and the other 16 rods with fresh fuel. The considerable length of the rodlets (1 m fuel pellet stack length) allowed for a mid-length fixture which simulated a spacer grid. The testing rig was instrumented with thermocouples and pressure transducers, and the test protocol was the most prototypical of all in-pile tests. The most relevant test performed was MIR-LOCA70, with one refabricated fuel rodlet from a segment burnup of ~ 70 MWd/kgU, which ballooned and burst during the test.

Similar behavior was noted for MIR-LOCA70 and OL1L04-LOCA SCIP tests, with respect to the following observations. Two balloons were created by constriction enabled by geometric features representing spacers, but only a T/C clamp for the two middle ones in the former case and a T/C clamp in the latter.

Two balloons formed above and below the central spacer, as illustrated in Figure 7 of Reference B3-16. The balloon below the central spacer had a burst rupture more than 6 mm long and 3 mm wide, while the balloon above the central spacer had a burst rupture of 3 mm length and 1 mm width.

The upper burst was much smaller. A video of the test shows the burst occurring after the lower burst and at lower gas pressure, as the rod depressurized partially after the first burst in the lower half. No visual monitoring of the LOCA70 test is available, but the scenario was probably the same; pressure transducer connected to the bottom of the rod, while at the top of the rod for the latter.

The test report [B3-16] stated that two balloons occurred, on either side of the central spacer, and Figure 7 in that report [B3-16] showed the central part of the fuel rod showing two balloons after extraction from the irradiation rig. The bottom balloon had a rupture more than 6 mm long with a ruptured opening less than 1 mm long.

Neutron radiography showed that the lower balloon section of ~ 50 mm length was empty of fuel pellets. The top balloon was filled with fuel fragments as shown in Figure 8 of the same report [B3-16]. Radiographs of the fuel rod taken inside the shroud, after removal of the shroud and the spacers, showed axial displacement of the fuel stack as the result of these manipulations. It was noted that fuel relocation through the upper bound of the fuel stack at the spacer position (475 mm) was not observed.

Fuel fragmentation is observed mainly in the peripheral region of fuel pellets (hollow pellets used in VVER fuel design). The largest number of small fragments is formed in this region. Fuel dispersed into the coolant through the cladding burst in the lower ballooning region. The spacer grid in a section of 500 mm limited the fuel relocation from the upper part of the fuel stack.

B.3.2.2 In-Pile Halden LOCA Tests

LOCA testing in the IFA-650 series started in 2003 with the first high burnup segment IFA-650.3 conducted in 2004, after having completed two initial commission tests IFA-650.1 and 650.2. In total, 16 tests have been conducted on PWR, BWR, and VVER fuel segments, with full consensus still not achieved on FFRD behavior.

Each test consisted of a single segment re-fabricated from its parent fuel rod contained within a pressurized flask connected to a water loop. A low level of nuclear heating, 10-30 W/cm was used to reproduce decay heat while an electric heater surrounding the segment simulated decay heat from the adjacent rods. In addition to neutron detectors and coolant thermocouples, the segment was instrumented with an upper and lower clad thermocouple, a cladding extensometer, and an internal pressure transducer.

The protocol for carrying out an experiment can be summarized as follows:

Phase 1, forced circulation

Phase 1, preconditioning

1. Steady state operation at a pre-determined linear heat rate and forced circulation at a loop pressure of ~ 7 MPa.
2. Linear heat rate decreased to ~ 10 W/cm by decreasing reactor power. The electric heater turned on to a preset value to achieve the required Peak Cladding Temperature (PCT), typically around 800°C in Phase 4.

Phase 2, natural circulation

3. Disconnection of the rig from the outer loop after reaching the correct power level with the flow separator in the rig to enable natural circulation to occur, with water flowing upward between the test segment, heater, and flow separator and downward past the separator and flask wall.
4. The temperature in the rig was allowed to stabilize for a few minutes before blowdown.

Phase 3, blowdown

5. Valves were opened to the coolant dump tank, resulting in a decrease in channel pressure to 0.3–0.4 MPa with the rig emptying water in some tens of seconds.

Phase 4, heat-up and hold at PCT

6. The stagnant superheated steam surrounding the segment provided inadequate cooling, so the segment cladding temperature increased rapidly. The heater power was kept constant before switching off stepwise, ~ 150 seconds after the burst. Ballooning and burst were detected by the change in segment internal pressure, the clad elongation, and temperature signals during the heat-up phase.
7. Spray injection started after the burst was detected (not used in the later tests).
8. Test ended with a reactor SCRAM.

Phase 5, cooling

9. The heater switched off a few seconds before the SCRAM.
10. The rig filled with helium to secure dry storage.

The tests performed in the IFA-650 LOCA tests series have been tabulated elsewhere [B3-18, B3-19] (not presented here, but to be provided in a separate report). Disregarding the commissioning tests, seven tests were performed on PWR fuel and four on BWR fuel. The fuel of the PWR fuel tests was mostly of very high burnup: Four tests on fuel with test rod burnup between 80 and 90 GWd/MTU, the other three with test rod burnups between 61 and 65 GWd/MTU. The BWR test rod burnups were at 71 GWd/MTU for three tests and a singular one at 44 GWd/MTU. Two VVER tests had fuel at 55 GWd/MTU. Although the VVER fuel had annular fuel pellets (less compressive hydrostatic stress), the tests were useful for FF at low burnup and low temperatures.

The second commissioning test, which used fresh fuel, was taken to cladding burst at the expected burst temperature of ~ 850°C, corresponding to the initial rod pressure of 40 bar that increased to ~ 75 bar during the heat-up phase. Very coarse fuel fragmentation was observed by neutron radiography (automated system that could be used to examine the rod in place after the

test, minimizing the artifacts of rod handling after the test, but not always used) and visual inspection; no visible relocation occurred because of the large fuel fragments—only some fragments protruding into the ruptured opening.

After the results of IFA-650.4 became known, which showed extensive FF at the ultra-high burnup of 92 GWd/MTU, the focus of the planning and discussion shifted to ballooning and its effects on fragmentation and relocation.

The first item of discussion is the ballooning results, and in that sense, the PWR tests IFA-650.3 and IFA-650.5 are compared to IFA-650.4 and IFA-650.9. The initial cold rod pressure was set to 40 bar for the PWR tests and 20 bar for the BWR tests. The maximum temperature, called peak cladding temperature (PCT), was around 850°C, with one BWR test at 1100°C, so that burst would occur in this high alpha-Zr domain (for this test, the cold rod pressure was 6 bar). In general, burst occurred at the estimated temperature; however, two tests, namely, 3 and 5 had a lower burst temperature and a lower burst strain. To explain the results for these outliers, it was speculated that the higher hydrogen content of the cladding in tests 3 and 5 embrittled the cladding and caused lower ductility to result in a lower burst temperature and strain.

However, this explanation can be questionable because of the following reasons. First, the cladding for those tests was duplex cladding, with an outer liner that was expected to be better corrosion resistant than the underlying Zry-4 substrate. However, during base irradiations in PWRs, the duplex liner variant (DX ELS0.8b) for tests 3 and 5 did not perform as was anticipated and corroded more with an associated higher hydrogen pickup (HPU), compared to tests 4 and 9, which had a better duplex liner material (DX Zr2.5Nb). In either case, the HPU during base irradiation was concentrated at the interface of the outer duplex liner with the inner bulk cladding and hence the properties of the bulk of the cladding were not affected. Second, there were indications that hydride dissolution was fast, so that the thermal transient during the test quickly dissolved the hydrides present at reactor trip (RT) and the embrittling effect of hydrogen, which acts through the hydrides, largely disappears; however, this aspect needs more investigation.

It is more likely that other reasons existed for the outlier tests 3 and 5 from the point of view of burst temperature and strain. An analysis of the test evolution and post-test PIE revealed the following:

- The rupture of the cladding for the IFA-650.3 test was determined to have occurred in the axial segment of the cladding that was affected by the welding of a T/C. This apparently caused a microstructure change at that location with the consequence of a premature crack occurring at a temperature below the expected burst temperature and hence ballooning had not started yet, and the hoop strain remained at relatively low values along the rod length. This was further supported by the long test rod depressurization time which most likely resulted because of slower gas communication.
- In the IFA-650.5 case, online measured temperatures and axial elongation showed a different trend from all other tests in that the temperature increased at the upper end, as measured by TCC3, started with a delay, and lagged behind TCC1 at the lower end. This was attributed to some water dripping back into the flask from the inlet line and providing some cooling. Erratic temperature oscillations during the first 30 seconds after the completion of the blowdown support this hypothesis. Consequently, the temperature difference between the

lower and upper ends was more pronounced than in the preceding test IFA-650.4 (ΔT = 90 K vs. ΔT=60 K at the time of burst). Consequently, ballooning was confined to a very short bottom section of the cladding, while the middle and upper sections of the cladding deformed very little.

With regard to FF, the majority of the tests used fuel with very high burnup and the observed FF was as expected from the separate-effects tests. An increasing degree of FF was noted for burnups in the 60 to 90 GWd/MTU range. However, it was noticed that the extent of RD was influenced by the size of the balloon and ruptured opening.

An interesting case in point for the play of different underlying factors is IFA-650.10, which was planned to be a repeat of the test conditions of IFA-650.4 but with a fuel of appreciably lower burnup, namely, ~ 65 GWd/MTU, compared to the 92 GWd/MTU in the case of IFA-650.4. Indeed, less FF and no significant relocation was seen, partly because the temperature continued to increase after burst, and hence T/Cs did not show the temperature drop characteristic, indicating potential relocation. A post-test gamma scan did not show any visible sign of relocation but showed some missing fuel in the ballooned area and fuel fragments were evidenced at the bottom of the flask. This is in the context of a moderate ballooning and burst opening. A very small axial gap in the upper section of the rod by neutron radiography indicated a small relocation movement of the pellets below the four uppermost pellets. Nevertheless, ceramography revealed pellet fragmentation where the larger fragments seemed to have separated mainly along cracks stemming from base irradiation. In addition, fine fragments seemed to have originated from the high burnup structure in the pellet periphery (see micrometer size pores in fragments in the lower left detail insert of Figure 57 of Reference B3-18).

Therefore, it could be inferred that fine fragmentation to a reduced extent can occur at a burnup of 61 GWd/MTU in the HBS rim region, while at 92 GWd/MTU, a large part of the pellet is pulverized. However, this inference must be correlated with the reduced balloon and ruptured opening for the lower burnup test, which has an inhibiting effect on RD.

The results of test IFA-650.5 are particularly interesting, in that the level of restraint was insufficient to prevent fragmentation, but the cladding distension was such as to retain the resulting fragments at their positions of origin. Also, it was noticed that inner rings of the fuel pellet at the maximum cladding strain position underwent fine fragmentation without being HBS and at the lower end of the burnup range determined for FF from other tests. This will be further discussed in Section 5.5.

Next, the four tests with BWR fuel are reviewed separately [B3-19].

The first test with BWR fuel, IFA-650.7, used fuel of low burnup, around 44 GWd/MTU. A low initial rod pressure allowed reaching higher PCT before rupture at ~ 1100°C. Based on the only T/C readings, it appears that the upper part of the fuel rod was cooler because of the water dripping down from a tube and cooling the rod, similar to what happened in IFA-650.5. A large bow with an inflexion at the bottom part was observed by gamma scan and when pulled out of the flask, the rod broke into two pieces just below the burst location. PIE revealed a small crack opening of 10 mm long and 2 mm wide (consistent with the rupture temperature in the alpha + beta domain, where the burst strain is minimum), which continued downward from the lower tip of the rupture split with an axial crack to where the transverse crack occurred when handling the

rod. The inadvertent cooling of the upper part of the rod during blowdown makes this test less usable for FFRD interpretation; nevertheless, PIE showed mainly large fragments, with a few finer fragments close to the rupture split.

The two tests that were terminated just before burst, namely 12 and 14, showed that mainly coarse fragmentation occurred with finer fragments in the maximum ballooning region. The neutron radiography and gamma scanning showed that downward relocation occurred, although the amount of relocation was most likely affected by the handling of the tested segments during their movement from the LOCA test rig to the gamma-scanning and neutron radiography stations. It was remarked that the fine fragments have an elongated appearance, which was speculated to be due to stress field caused by cooling at the end of the test (see figure in Reference B3-19).

In some tests, there was evidence of fuel dispersal through the burst opening, as found by gamma tomography of the flask after the test, but no quantitative analysis of the ejected fuel was made.

IFA-650.13 was designed to replicate the conditions of IFA-650.12 but with higher initial rod pressure so that burst occurred before the planned PCT of 850°C, at around 810–827°C. The gamma scan after the test showed a similar ragged appearance and large fragment as in IFA-650.12 with some variation in local fragment distribution. The rod was fairly straight with moderate ballooning but with an expected large maximum strain of ~ 50%.

Neutron radiography (Figure 33 in Reference B3-19) shows the extent of fuel cracking and fragment separation. The features that can be observed are similar to those seen in the neutron radiography image of IFA-650.12:

- Pellet cracking (as visible in neutron radiography) is correlated with cladding distension. There are four pellets at the lower end (where the cladding distended less), which appear to be intact. At the upper end, two pellets came out unscathed, also due to lower clad distension there. In between, the pellets show a spectrum of fragmentation, where clad distension was greater than the 5% threshold identified as threshold for fuel fragment movement.
- An axial gap at the upper end indicates fuel relocation. However, the gap appears to be larger than shown by gamma scanning and may have been caused by the movement and handling that followed.

The burst opening (Figure 34 in Reference B3-19) is larger than the one in IFA-650.12 as may be expected due to the larger amount of fill gas in IFA-650.13. It is about 8 mm long and 2 mm wide (maximum) defining an area of about 8 mm^2. Despite the fourfold area and the much larger amount of gas available for driving out the particles, the gamma signal from the bottom of the pressure flask seems to indicate that less fuel expulsion occurred in IFA-650.13. The fuel was not examined by ceramography, as it was decided to empty the fuel rod and measure the distribution of the fuel fragments.

When analyzing the tests with BWR fuel, it is important to bear in mind that the objectives of these tests were somewhat different from the other ones, which targeted delayed ballooning and burst in the higher temperature domain corresponding to alpha + beta or beta domains, characterized by a smaller burst strain, or by avoiding burst altogether.

The fragment size distribution was determined for all three high burnup BWR fuels by shaking the debris out of the cladding tube and sifting using a sieve stack with six different mesh sizes. Further, different amounts of fuel in IFA-650.13 and 650.14 were stuck in the cladding tube (blocked fuel described in Table 9 of Reference B3-19). These facts may have introduced several biases and it should be kept in mind when comparing the results. Nevertheless, the normalized weight fraction shows an insignificant amount of small particles with regard to the extent of fracturing.

In IFA-650.5, the ceramography taken at a position where cladding distension was about 5% shows much less fragmentation than at a position close to the burst opening with > 10% distension. For the BWR fuels, the transition from intact to visibly cracked pellets occurs in the range of 7–10% distension.

An observation was made regarding the effect of loss of pressure on FFRD. The loss of pressure starts at the point of burst and moves through the fuel stack. The ensuing shock on the pellets will be mitigated with increasing distance from the point of burst. However, the existence of such an effect is not well supported by the experimental evidence in the IFA-650 series, since the fragment size distributions measured for IFA-650.13 and 650.14 are quite similar (similar test conditions), although IFA-650.14 did not suffer a pressure loss, which eliminates the possibility that the sudden pressure drop on burst plays a dominant role for fuel fragmentation. It is noted that a conclusion to the contrary was drawn from a pair of SCIP III tests, but the related analysis is complicated due to the difference in burst temperatures (caused in part by different rod pressures) and different sizes of the balloon and ruptured opening. It is recalled that Halden tests were performed in stagnant steam, while flowing steam was used in the SCIP III tests (more representative). This aspect is also discussed in Section 4 of this report.

Fuel relocation and ejection were observed in several experiments of the IFA-650 LOCA test series. The most notable, extreme examples are tests numbered 4 and 9 with similar, very high burnup fuels (burnup > 90 GWd/MTU). Fuel relocation and ejection occurred to a much lesser extent in the LOCA tests with high burnup BWR fuel, but the conclusions drawn overall are the same, because the BWR fuel tests had low rupture and balloon sizes.

B.3.2.3 “Counterpart” Test SCIP-Halden

SCIP test 36U-N05 is the counterpart test of Halden IFA-650-15. A cursory comparison of the test methods in Studsvik and Halden concluded the following:

- Heating method: The in-pile test has 50% external heating (electrical heaters), 50% internal (nuclear) heating. The out-of-pile test has 100% external heating (IR furnace).
  - Segment and heated length: The out-of-pile test was performed with a fuel length of 296 mm, the in-pile test with 442.5 mm.
  - Plenum temperatures: The in-pile test has plenum temperatures of 160–260°C, whereas the out-of-pile test has a plenum temperature of 30–100°C.
- Plenum volumes: The in-pile test system has a plenum of about 18 cm^3, the out-of-pile system has plenums of 9.6 cm^3 (top) and 3.0 cm^3 (bottom).
- Steam: The in-pile test has stagnant steam from cooling water remnants, while the out-of-pile test has a flowing steam environment.

- Test chamber: For the in-pile-test, the test segment is located inside a flask with an inner diameter of 34 mm, which limits the maximum deformation of the cladding. The cladding can also contact the external heaters, which are positioned corresponding to a diameter of about 22 mm. In the out-of-pile test, the segment is placed in a quartz chamber with an inner diameter of 4 cm.
- Chamber pressure: The pressures of the chambers also differed. For the out-of-pile test, the pressure in the chamber is close to 1 bar. For the in-pile test, the pressure in the flask is changing after blowdown.
- Pre-irradiation: In the out-of-pile test, the specimen is tested after base irradiation without any additional irradiation. In the in-pile test, the segment is pre-irradiated at lower power in the test reactor for a few days before running the test.

The cladding axial temperature gradients also differed between the two test methods, mainly due to different segment lengths and heated lengths. In the out-of-pile test, the axial cladding temperature gradient was measured by thermocouples during device qualification. It was determined either for constant temperature or for a heating rate of 5°C/s, which was faster than the ramp rate in this test. The in-pile axial temperature gradient is not measured and must be estimated from the rod power distribution and the power of the external heaters. Figure 81 of Reference B3-6 shows estimates of the temperature gradients of the two test methods. For the in-pile test, two different axial temperature gradients have been estimated, one based on the fuel (nuclear) heating gradient and the other against the total heating gradient (nuclear + external heating). It is important to note that the axial cooling effect for the in-pile test is unknown. When the plenum above and below the specimen is at a temperature of 160 to 240°C and the specimen at a much higher temperature, there must have been a cooling effect at the end of the test segments.

The in-pile test plenum is larger than both plenums combined, in the out-of-pile tests. This was interpreted to indicate that gas communication from the plenum to the burst is easier for the in-pile test, which might influence the balloon development. However, a more likely explanation for this is the sharper axial temperature profile in the out-of-pile test.

A shorter length of the center region with uniform temperature limits the cladding strain and ballooned region. In the lower than 5% strain regions, the fuel remained bonded to the cladding and restricted axial gas communication. In comparison, the in-pile test with a longer center region allows for more cladding strain and opening of the fuel-cladding gap, with increased axial gas communication. Increasing the balloon strain also increases the free volume of the test segment. A larger free volume will decrease the rod inner pressure, which prolongs the ballooning phase before burst. This agrees with the measured differences in ballooning time and burst pressures. This is a reiteration of the issue of temperature conditions not being prototypical for most of the semi-integral tests, including the SCIP tests.

The gamma-scan of the in-pile test performed at the Halden test reactor is shown in Figure 86 of Reference B3-6, and the gamma-scan of the out-of-pile test before emptying of loose fuel fragments is shown in Figure 87 of the same study [B3-6]. The in-pile test results show slight rod bending and accumulated fuel in the ballooned region. Some empty regions can also be observed, mainly at the top of the fuel stack, but also in the smaller regions at the bottom and at the top of the balloon. Altogether, this indicates both fuel fragmentation, relocation, and some fuel dispersal. The out-of-pile test results show an intact fuel column with visible pellet-pellet

interfaces at the top and bottom of the specimen. In the center, fuel has relocated downward into the lower part of the ballooned region. In the upper part of the ballooned region, above the burst opening, the rod is empty. The difference in fuel dispersal between the two tests may be related to the fact that in the in-pile test, the cladding came into contact with the heater, thus limiting dispersal, especially of larger fragments.

B.3.2.4 CEA FLASH Tests

A section of 300 mm length was selected out of a fuel rod irradiated in the Fessenheim 2 power plant for four standard cycles to a segment burnup of 50.3 GWd/MTU. During the base irradiation, the average power was in the range of 17 kW/m, except during the second cycle (22 kW/m). This section was refabricated in the LECI hot laboratory at Saclay with end plugs and a large plenum (6.7 cm^3) to simulate the behavior of a long fuel rod, having enough gas available for cladding strain and burst to occur during the accident sequence. The fuel rodlet was filled with helium at 3.2 MPa and re-irradiated for three weeks in the SILOE test reactor. The Griffon irradiation loop (in the SILOE test reactor) used for this experiment was modified to control the coolant removal, to follow the cladding temperature evolution during the sequence, and to reflood the fuel rod in hot conditions. Figure 1 in Reference B3-27 shows a schematic description of the fuel rod in the loop and of the pipes, valves, and storage or pressure volumes used to control the sequence.

The LOCA sequence was conducted at the end of the second in-pile cycle (performed at 17.2 kW/m) to have access to the behavior of short-lived fission products. The irradiation device was then slightly retreated from the core to reduce the power to 7.2 kW/m, while a valve was opened to depressurize the loop from 12.4 to 0.5 MPa. The blowdown period and expelling of the coolant lasted 4 s. The rod being uncooled and heated by the low power of 7.2 kW/m, the temperature of the fuel rod started to increase; the average rate measured by the 4 TCs surrounding the fuel rod at the maximum power level was 28 K/s.

The neutron radiographies taken after removal of the reflood water and the measurements performed in the hot cell have shown that the rod failure occurred slightly above the plane of maximum power (at (93 mm), in the direction of the center of the reactor core and with a limited cladding strain. The oxide pellets were found to be fractured with water filling the cracks and the dishings. Deformation of the fuel rod was small and no significant clad ballooning was observed in opposition to the case of the tests performed with fresh fuel cladding outlined in the study [B3-21]. In the lower part of the fuel rod, where the power was maximum, the cladding strain was in the range of 7%. The failure occurred in the region where the neutron power was 93% of the maximum power, with a local mean strain of 16%. The fuel rod cladding deformation and a blowup of a portion near the failure zone is shown in Figure 4 of Reference B3-21. The rupture appeared as a thin slit (3 mm by 0.3 mm wide). On the two sides of the slit, the local strain was high enough to induce cracking in the primary oxide layer, leading to a corrugated appearance.

At the plane of maximum flux (Figure 5 of Reference B3-21), the fuel was highly fragmented, with the central region of the pellet broken into small pieces of about 100 µm, most of which had an average grain size of 14 µm, showing significant grain growth during the transient (the initial grain size was 7.5 µm). The outer part of the fuel was broken into large pieces of 1–2 mm. The boundary between the regions is marked by a grain growth plane driven by oxidation, spanning from the center behind which there is evidence of grain boundaries decohesion (Figure 5.b of a study in Reference B3-21).

Compared to the other FLASH experiments referred to in that study [B3-21], which were performed with fresh cladding and fresh UO_2, the following differences were noted for the FLASH-5 test:

- The clad rupture occurred away from the plane of maximum power, with limited cladding stain.
- The fission product release rate was much higher than expected.
- The fuel was found to be highly fragmented and partially oxidized.

Regarding the first bullet point item, the low cladding strain could be explained by the circumferential temperature gradient, four thermocouples, each 90° apart, providing online information regarding the cladding temperature during the test. At the time to failure, the maximum temperature difference was 110°C, the hottest part being in the direction of the center of the test reactor. This large azimuthal thermal gradient is sufficient to reduce the fracture strain to the level observed.

For the fuel behavior aspect, the most critical aspect is the fuel pellet damage. In the case of other LOCA tests of irradiated rods [B3-1], pellet disintegration was observed in the ballooned regions filled with small fragments of fuel. The observation of some oxidation present in the fuel fragments was interpreted by the authors of the test paper [B3-21], to have happened in the later phase of the test sequence. Indeed, during the heating-up phase, the time between rod failure and reflood, during which some fuel oxidation could have occurred (12 s), was very limited. Grain growth and oxidation of the UO_2 could not be obtained at the level observed. Therefore, it was assumed that fuel degradation occurred in the later phase of the test sequence when the fuel stack was maintained under moderate power for 12 minutes. Then, under a large gap filled with steam at 1.5 MPa, and a power of 7.2 kW/m, the fuel temperature would have raised above 800°C, a temperature at which the observed kinetics can be achieved. It has been shown that in water vapor, oxidation of UO_2 is indeed associated with considerable grain growth (see Section A.2.2).

B.3.3 Separate-Effects Tests

B.3.3.1 Data Used for NFIR Empirical FF Threshold

An empirical threshold for FF was recommended in the frame of NFIR program [B3-29] by T. Turnbull and coauthors, based on detailed evaluation of separate effects hot cell annealing tests on NFIR's small samples of fuel. This empirical threshold was compared with additional information and data on FF pertinent behavior acquired in the frame of the NFIR program and elsewhere [B3-23]. These recent NFIR separate-effects tests were focused on understanding the mechanism of FF in essentially HBS transformed samples.

The threshold was formulated as minimum local burnup and minimum local temperature (maximum temperature achieved during the temperature transient in the tests) necessary for FF to occur. It was an empirical threshold because the data used for the FF threshold were essentially qualitative in nature, that is, the degree of fragmentation was characterized after the test as unchanged, cracked, and fragmented, based on visual examination, coupled with characterization of the fragment size distribution in one case. It was considered that the threshold can be used only as a guide to indicate when a given volume of high burnup fuel achieved the conditions where a significant instantaneous change of geometry, that is, FF would occur, with an associated generation of small particles of fuel (from microcracking or fine fragmentation or pulverization).

It was not possible to characterize the evolution of FF inside the (burnup, temperature) FF-prone region derived from the tests; hence, it can only be used as a binary response functionality, with fuel above both the burnup and temperature thresholds being considered fully fragmented. The empirical FF threshold recommended by NFIR can be employed to assess fragmentable material

(hydrostatic restraint not captured by the empirical threshold) in an LWR rod subjected to LOCA-type transient, using a fuel performance code, which has the capability to calculate a radial burnup profile in the fuel pellets.

The key data points defining the NFIR threshold are a couple of data points from the NFD studies [B3-24], the U8 data [B3-25], and the ITU data covering ultra-high burnup in the rim region, reported in EPRI report 3002017467 [B3-23]. Also, the CEA studies [B3-22] were used to verify the initial NFIR threshold. In addition to the considerations presented in the corresponding NFIR reports, it is worthwhile mentioning the issue of the uncertainty regarding the sample burnup in the NFD data. It was argued (see description of the tests in Section 4) that the use of highly enriched (11% U-235) small pellets irradiated in HBWR at Halden have a much flatter radial power and burnup profiles than in the LWR case and, therefore, an almost constant radial burnup profile can be assumed.

Consequently, the burnup value for the tested samples was taken as the average pellet burnup from which the samples were cut. However, the central part of the pellets had lower burnup than the pellet average burnup, while the outer rim has higher burnup than the pellet average burnup. According to the reports, samples were cut from a region spanning 0.34 to 0.88 fractional radii. It has been considered that a refinement of the sample burnups is needed.

The NFIR threshold applies only to unrestrained fuel, that is, after sufficient ballooning of the cladding cancels the PCMI restraint of the pellet by the cladding. This was captured in later FFRD thresholds, by a qualitative strain threshold.

Another feature of the tests underlying the NFIR FF threshold is the environmental condition of inert atmosphere, because the focus was a mechanistic understanding of FF in HBS pellet region. As detailed in Section A.2.2, it is considered that significant additional FF occurs after burst by steam (water) ingress through the burst opening.

B.3.3.2 ITU Knudsen Cell Tests

Another out-of-pile annealing study was reported [B3-26] and consisted of Knudsen cell annealing tests at 10 K/s. During that study, several tests were interrupted at several temperatures, namely, 900, 1500, and 1860 K, to determine FGR at those terminal temperatures:

"The samples were small pieces of 4 and 6 μg originating from the periphery ($0.91 < r/r_o < 1$) of a fuel pellet of average burn-up 102 MWd/kgHM. The radial width of the samples was ~800 μm. A microscopic image of the sample as obtained by SEM is shown in Fig. 1 of [3-26]. The area of the sample close to the pellet periphery (Za ~ 1/3 of the sample) shows larger pores of ~4 μm in diameter with the typical 'cauliflower' structure of the HBS visible inside. In the other parts (Zb ~ 2/3 of the sample) pores of ~ 2 μm are homogeneously distributed. The grain size in the sample is ranging from 0.2 to 0.5 μm. The maximum local burnup in these samples is ~ 240 MWd/kgU in Z_a and 160 MWd/kgU in Z_b, while the estimated average pellet burnup being 200 +/- 20 MWd/kgU."

The samples were then examined by SEM (scanning electron microscopy) and EDX (energy dispersive X-ray analysis) and the following observations were made: FGR of Xe, Kr and other volatiles occurred in four steps: ~ 1% of inventory between 600 and 800 K, 20% of the inventory between 900 and 1000 K, 70% between 1400 and 1500 K, and the balance at higher temperatures.

For Cs (Rb), I and Te, a well-marked stage I with low activation energy is observed at 980 K. This concerns about 10–30% of the inventory. As deduced from the microscopy observations (Figure 8 of Reference B3-26), these fission products appear to form an amorphous-like phase around the pores.

In terms of the microstructure evolution, the following observations were made:

- 300–920 K: One sample broke into 2–3 large pieces of ~ 200 x 300 µm, while another fragmented more finely into small pieces of 10–30 µm. The former sample was closer to the pellet periphery and had fully developed HBS with large pores of ~ 4 µm in diameter, while the latter was still in HBS, but with smaller and homogeneously distributed pores of ~ 2 µm in diameter.
- 300–1500 K: Sample was entirely pulverized, with most of the pieces between 10 and 20 µm and completely HBS restructured.

It was noted that the measured FGR was proceeding continuously, except for some step changes, mainly at 1000 K and 1500 K, which were characterized by explosive gas release that was evident from the pressure transients observed on the vacuum gauges. It was proposed that these pressure spikes were the result of burst release of the gas contained in closed pores. This was correlated, according to the authors, to the stepwise loss of integrity of the sample annealed at 900 and 1500 K.

An interesting inference was made from the measured FGR and pore sizes of the two peripheral HBS samples, in that the gas pressure is the same for small and large HBS pores, which is not surprising, considering that the pressure exerted by surface tension is rather small for these large micron-size pores. Further deductions in the paper estimated the HBS pore gas pressure was at 30+/-2 MPa at RT. This is significantly higher, or at least, at the upper bound of the data shown in Figure 4 of Reference B3-27. A similar pressure was estimated in a study [B3-28] that was reviewed in the section on bubble pressure in this report.

B.3.3.3 OOP Heating Tests at Studsvik

Any integral or separate-effects test, in-pile or in the hot cell, by definition, does not fully reproduce actual conditions under LOCA scenarios; moreover, it is considered that there is no universal LOCA scenario that could be applied to any PWR or BWR reactor and/or fuel burnup. Nevertheless, within the confines of these acknowledged variations of the test conditions from the presumed LOCA scenario and actual conditions in LWRs (most notably, the azimuthal temperature gradient, which tends to limit burst opening), questions remain regarding the differences between the LOCA tests performed in Halden and the SCIP LOCA and OOP HT tests.

The temperature and stress distribution for the out-of-pile heating tests was modeled and are described in Section 4.5. The results showed that the outer pellet rim was subjected to a compressive hoop stress, while the pellet center was in tension. This stress profile is due to the test condition of heating from the outside and is different from the situation in the actual LOCA

scenario. The effects are to promote FF in the center of the pellet and retard FF in the outer pellet rim. The results of the HT OOP tests in SCIP3 can only be interpreted as qualitative observations, which by and large support the Cs hypothesis formulated in Section A.2.3, but the lack of analysis of emanated gases during the test still has to be overcome.

B.3.4 References

B3-1. U. S. Nuclear Regulatory Commission. NUREG-2121, “Fuel Fragmentation, Relocation and Dispersal During the Loss-of-Coolant Accident,” Washington, D. C., March 2012.

B3-2. Y. Yan, M. C. Billone, T. A. Burtseva, and H. M. Chung, “LOCA Integral Test Results for High-Burnup BWR Fuel,” ML051920402.

B3-3. Y. Yan et al., Presentation at the NSRC, Washington, D. C., October 28–30, 2002.

B3-4. *Interim Report on the Analysis of ANL LOCA Tests*. EPRI, Palo Alto, CA: 2003. 1002867.

B3-5. U. S. Nuclear Regulatory Commission. NUREG-2160, “Post-Test Examination Results from Integral, High-Burnup, Fueled LOCA Tests at Studsvik Nuclear Laboratory,” Washington, D. C., August 2013.

B3-6. P. Magnusson, et al., “STUDSVIK/N-19/105 STUDSVIK-SCIP III-253—Subtask 1.1: Fuel Fragmentation, Relocation and Dispersal, Final Summary Report,” Studsvik Nuclear AB, Nykoping, Sweden, 2020.

B3-7. L. Mileshina and P. Magnusson, “STUDSVIK-SCIP III-235, Integral LOCA Test to Study Burnup Threshold on Fuel Fragmentation: 09-OL1L04 LOCA2,” Studsvik Nuclear AB, Sweden, 2019.

B3-8. L. Mileshina, P. Tejland, and P. Magnusson, “STUDSVIK-SCIP III-254, Integral LOCA Test to Study Effect of Gas Volume on Fuel Fragmentation: 09-VUR1 LOCA, ” Studsvik Nuclear AB, Sweden, 2019.

B3-9. L. Mileshina and P. Magnusson, “STUDSVIK-SCIP III-216, Integral LOCA Test to Study Cladding Strain and Non-Depressurization Effects on Fuel Fragmentation: R2D5 LOCA3,” Studsvik Nuclear AB, 2018.

B3-10. L. Mileshina and P. Magnusson, n. d., “Studsvik/N-18/074 Studsvik-SCIP III-225 Integral LOCA Test to Study Effect of Pressure on Fuel Fragmentation: VUL2 LOCA2,” s.l.: Studsvik Nuclear AB.

B3-11. Y. Yan, Z. Burns, K. Linton, and K. A. Terrani, “Results from In-cell Integral LOCA Testing at ORNL,” 2017 WRFPM, Jeju Island, Korea, September 10–14, 2017.

B3-12. Y. Yan et al., “LOCA Fragmentation Test with High Burnup HBR Fuel Rod,” ORNL/TM-2019/1239 (2019).

B3-13. N. Capps et al., “Integral LOCA Fragmentation Test on High-Burnup Fuel,” N.E.D. 367, 110811 (2020).

B3-14. B. Baurens et al., "Fuel Fragmentation during LOCA Simulated Transients: Investigation of Irradiated MOX vs UO2 Fuel," TopFuel, Seattle, WA, September 22–27, 2019.

B3-15. A. Bianco, et al., 2015. "Experimental Investigation on the Causes for Pellet Fragmentation," *Journal of Nuclear Materials*, Vol. 465, 2015, pp. 260–267.

B3-16. P. V. Fedotov et al., "LOCA Test with High Burnup VVER Fuel in the MIR Reactor," Topfuel, 2015.

B3-17. V. I. Kuznetsov et al., "Researches of VVER High-Burnup Fuel Behavior under LOCA Conditions," Joint Halden Reactor Project – NEA Working Group on Fuel Safety LOCA Workshop, Aix-en-Provence, France, May 20–21, 2015.

B3-18. W. Wiesenack, "HRP-380, Summary of the Halden Reactor Project LOCA Test Series IFA-650, " Halden Reactor Project, Halden, Norway, 2013.

B3-19. W. Wiesenack, "HPR-383, Summary and Comparison of LOCA Tests with BWR Fuel in the Halden Reactor Project Test Series IFA-650, " Halden Reactor Project, Halden, Norway, 2015.

B3-20. R. Tradotti, "LOCA Testing at Halden, The BWR Fuel Experiment IFA-650.14, " OECD Halden Reactor Project, Halden, Norway, 2014.

B3-21. M. Bruet, C. Lemaignan, J. Harbottle, F. Montagnon, and G. Lhiaubet, "High Burnup Fuel Behavior During a LOCA Type Accident: The FLASH 5 Experiment," IAEA Technical Committee Meeting: Behaviour of Core Materials and Fission Product Release in Accident Conditions in LWRs Aix-en-Provence, Vol. TECDOC-706, 1992.

B3-22. Y. Pontillon, et al., "Experimental and Theoretical Investigation of Fission Gas Release from UO2 up to 70 GWd/t Under Simulated LOCA Type Conditions," The GASPARD Program International Meeting on LWR Fuel Performance, Orlando, 2004, pp. 490–499, Paper 1025.

B3-23. *A Critical Review of Fuel Fragmentation of High Burn-up Fuel During Temperature Transients*. EPRI, Palo Alto, CA: 2020. 3002017467.

B3-24. K. Une et al., "Fission Gas Release Behavior from High Burnup UO2 Fuels under Rapid Heating Conditions," *Journal of Nuclear Science and Technology*, Vol. 43, 2006, pp. 1161–1171.

B3-25. S. Yagnik and T. Turnbull, "Specific Heat and Density of High Burnup Fuel," TopFuel, Salamanca, 2006.

B3-26. J. P. Hiernaut et al., *JNM*, Vol. 377, 2008, pp. 313–324.

B3-27. C. Cagna et al., "A Complementary Approach to Estimate the Internal Pressure of Gas Bubbles by SEM-SIMS-EPMA in Irradiated Nuclear Fuels," *Materials Science and Engineering*, Vol. 109, 2016.

B3-28. J. Spino et al., *Journal of Nuclear Materials*, Vol. 231, 1996, p. 179.

B3-29. J. A. Turnbull et al., “An Assessment of the Fuel Pulverization During LOCA-Type Temperature Transients,” *Nuclear Science and Engineering*, Vol. 179, 2015, pp. 1–5.

C
DETAILS OF FUEL MICROSTRUCTURE ISSUE (SECTION 4.7)

The effects of a rapid (scram) or longer progressive cooldown from the point of view of impact on thermal transient behavior must be taken into account. A brief analysis of the potential microstructural aspects of using “cold” samples is as follows.

The PIE of fuel irradiated in NPPs showed that various cracking patterns occurred not only during irradiation but also during the cooling period at shutdown. The radial cracks in the outer pellet annulus are formed during irradiation because of the radial temperature gradient (described in Section A.2.1) and are only slightly lower in causing crack opening due to thermal contraction during cooldown and are usually extended to the pellet center. If high enough power was attained during irradiation, a circumferential crack is observed during PIE, which is the effect of reversed stress distribution during cooling, which delineates the elastic outer region from the viscous-plastic inner region of the pellet. Upon reactor restart, this circumferential crack is healed, and it is believed that the cracking pattern prior to shutdown is recovered at the same power level. As discussed in Section 4.5, the temperature radial profile in the pellets during hot cell LOCA tests is not fully representative, and the cracks might not follow the same healing process as in-pile. This could affect fuel microcracking because of the potential free surfaces inside the pellet, which are areas of discontinuity in mechanical restraint caused by PCMI.

Other microstructural features, such as grain size, are not affected by the duration of the cooldown. Nevertheless, the distribution of fission gas atoms and gas bubbles could be affected, as discussed in Section A.2.1, regarding the potential impact of a pretest microstructure.

Another aspect is the chemical state of U as affected by a cooldown. It was found that fuel becomes hyperstoichiometric with burnup and it is possible that phase change to U_4O_9 occurs during cooldown in the pellet outer zone, where the temperature is below the phase boundary line between U_4O_9 and UO_2. This was observed in several PIEs as a circular needle-like appearance of the fuel. A reverse phase change will occur during heating.

D
DETAILS OF SECTION 5.5

D.1 SFD Program

Several in-pile and hot cell tests were conducted to investigate fuel behavior during rapid heating transients reaching high temperatures, in the context of Loss of Flow (LOF) accident analysis for FBR fuel [D5-7]. In-pile, well instrumented tests were performed in SANDIA's Annular Core-Pulse Reactor, which are similar to the NSRR pulsed core RIA tests for LWR fuel. Fuel disruption was noted for fuel samples with mature enough gas bubble structure, especially on the grain boundaries, and FF was observed for lower burnup but at higher temperatures. Energetic fragment expulsion, called *spallation*, was observed at very high temperatures for the unrestrained pellets, which were uncovered by the melted cladding.

Transient heating tests performed at HEDL are also applicable. The experimental technique is to transiently heat a two-inch fuel pin section rapidly in a resistively heated tungsten capsule, record capsule temperatures and pressures during the run, and observe fuel motion using continuous gamma radiography. A series of experiments using unirradiated and irradiated fuel specimens were carried out to characterize the fuel motion and gas release during transient heating; these tests are quite similar to SCIP III heating tests and the separate-effects test reviewed in Section B3.10.

The results of the main tests are presented in a report [D5-7], which also includes predictions based on an overpressurized gas bubble interlinkage and cracking model.

It is noted in that report that low burnup fuel showed no dispersal in accordance with no fracture predicted, but medium burnup fuel (PNL-9) dispersal and spallation were observed, again in agreement with calculations. Of course, high burnup fuel showed spallation of the outer half of the pellet.

The analysis in Reference A2-15 attributed the different fragmentation of samples from the same rod to a difference in fission gas content of the fuel samples. Moreover, the actual observation [A2-15] was that samples that spalled showed no restructuring. This can be correlated better with the local power level in two ways:

- Lower power, especially toward the end of the base irradiation, leads to enhanced resolution effects, similar to what was described in Reference D5-8; this could also be a potential explanation why some samples with low power during the last irradiation cycle showed less fine fragmentation.
- The intergranular bubble network is small, or not at all developed, so that the fission gas present in the grain boundary (GB) bubbles is small or negligible. So, the gas inventory cannot be quickly vented to the fuel rod open volume. However, intragranular bubbles can become overpressurized in response to fast temperature transients that can lead to cracking and fuel fine fragmentation.

The main conclusion from the interpretation of the findings of the HEDL and ANL experimental programs recognizes the paramount importance of the retained fission gas content in the fuel and the role of gas retention, rather than burnup, which also explains why PNL-9 at 4.7 at. % Bu spalls, while PNL-10 (except lower region) at 6.2 at. % Bu and Numec-F at 5.6 at. % Bu fail to spall. Indeed, PNL-9 was a low-power (~5.5 kW/ft) while PNL-10 and Numec-F fuel were medium- to high-power pins at 8.3 and 9.8 kW/ft, respectively. So, even if the latter fuel has higher burnup, the lower burnup fuel experienced lower power and hence higher gas retention, resulting in the observed spallation behavior. The apparent threshold related to the retained gas content is illustrated in Figure 32 of Reference A2-5.

D.1.1 FLASH-5

The results of the FLASH-5 test on a fuel pre-irradiated to ~ 50 GWd/MTU were reviewed in Section B.3.2.4. Here, the findings from the PIE are of interest, namely, the grain microcracking/separation observed in the mid-radius zone of the fuel pellet, which is referred to in Figure 5 of Reference B3-21. This FF feature at mid-radius was different from the relatively coarser fragmentation of the pellet central region, which was interpreted as the result of fuel oxidation, because the fuel was kept at power for 12 minutes after reflood.

D.1.2 ANL LOCA Program, ICL #2

A similar observation to the previous one, regarding a mid-radius fine fragmentation was made during the PIE of the ICL # 2 test segment in the ANL LOCA test program, reviewed in Section B.3.1. The fine fragmentation, tearing the mid-radius zone is illustrated in Figure 11 of Reference B3-2 and is considered an example of FF in non-HBS zones at higher temperatures.

D.1.3 IFA-650.5

A detailed cross section at the position of maximum clad strain is shown in Figure 39 of Reference B3-18, and it can be seen that the rim region of the pellet where the HBS is situated is highly fragmented into very fine particles; this is as expected from all the small sample experiments. However, a high degree of fragmentation, albeit of slightly larger size, is noticed at intermediate pellet radii. Thus again, rim HBS is not the only microstructure that renders the fuel susceptible to fragmentation. Also, it was noted that fragmentation into much larger pieces of millimeter size has occurred in regions between these radii.

D.2 References

D5-6. E. A. Fisher, "In-pile Determination of Fuel Disruption Mechanisms," *European Applied Research Reports – Nuclear Science and Technology*, Vol. 5 (6), 1984, pp. 1393–1433.

D5-7. O. D. Slagle, C. A. Hinman, and E. T. Weber, "Experiments on Melting and Gas Release Behavior of Irradiated Fuel at Hanford," HEDL-TME-74-17, 1974.

D5-8. R. J. White, "Fission Gas Release, Swelling & Grain Growth in UO2," HPR-368, February 2008R.

D5-9. K. Une et al., "Rim Formation in Isothermally Irradiated UO_2 Fuel Discs," *JNM*, Vol. 288, 2001, pp. 20–28.

D5-10. K. Une et al., *Journal of Nuclear Science and Technology*, Vol. 668 (Suppl. 3), 2002.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

3002025542

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com