



DRAFT REGULATORY GUIDE

Contact: M. Flanagan
(301) 251-7547

DRAFT REGULATORY GUIDE DG-1263

(Proposed New Regulatory Guide)

ESTABLISHING ANALYTICAL LIMITS FOR ZIRCONIUM-BASED ALLOY CLADDING

A. INTRODUCTION

Title 10, Section 50.46c, of the *Code of Federal Regulations* (10 CFR 50.46c) (Ref. 1), calls for the establishment of analytical limits on peak cladding temperature and integral time at temperature that correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material. This guide defines an acceptable analytical limit on peak cladding temperature and integral time at temperature for the zirconium-alloy cladding materials tested in the U.S. Nuclear Regulatory Commission's (NRC's) loss-of-coolant accident (LOCA) research program. This analytical limit is based on the data obtained in the NRC's LOCA research program.

The database developed in NRC's LOCA research program can be supplemented in order to establish an analytical limit, as called for in 10 CFR 50.46c. Draft Regulatory Guide (DG) -1262, "Testing for Postquench Ductility" (Ref. 2), provides an experimental technique acceptable to the NRC for measuring the ductile-to-brittle transition for zirconium-alloy cladding material through ring compression tests (RCT). This guide describes a method to demonstrate comparable performance with the established database in order to establish the analytical limit provided in this guide for a particular cladding alloy not tested in the NRC's LOCA research program. This guide also describes methods for establishing analytical limits for zirconium-alloy cladding materials not tested in NRC's LOCA research program, or establishing limits for zirconium-alloy cladding materials at conditions other than those used in NRC's LOCA research program.

In 10 CFR 50.46c, the NRC calls for measurement of the onset of breakaway oxidation for a zirconium-alloy cladding material based on an acceptable experimental technique, evaluation of the measurement relative to ECCS performance, and annual retesting and reporting of values measured (Ref. 1). DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior" (Ref. 3), provides an experimental technique acceptable to the NRC for measuring the onset of breakaway oxidation for zirconium-alloy cladding materials. DG-1261 also describes an acceptable method of meeting the annual

This regulatory guide is being issued in draft form to involve the public in the early stages of the development of a regulatory position in this area. It has not received final staff review or approval and does not represent an official NRC final staff position. Public comments are being solicited on this draft guide (including any implementation schedule) and its associated regulatory analysis or value/impact statement. Comments should be accompanied by appropriate supporting data. Written comments may be submitted to the Rules, Announcements, and Directives Branch, Office of Administration, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001; submitted through the NRC's interactive rulemaking Web page at <http://www.nrc.gov>; or faxed to (301) 492-3446. Copies of comments received may be examined at the NRC's Public Document Room, 11555 Rockville Pike, Rockville, MD. Comments will be most helpful if received by **[insert date - 75 days from issuance]**.

Electronic copies of this draft regulatory guide are available through the NRC's interactive rulemaking Web page (see above); the NRC's public Web site under Draft Regulatory Guides in the Regulatory Guides document collection of the Library at <http://www.nrc.gov/reading-rm/doc-collections/>; and the NRC's Agencywide Documents Access and Management System (ADAMS) at <http://www.nrc.gov/reading-rm/adams.html>, under Accession No. ML110871607. The regulatory analysis may be found in ADAMS under Accession No. ML112520277.

retesting and reporting requirements in 10 CFR 50.46c. This guide describes a methodology for establishing a specified and acceptable limit for the total accumulated time that the cladding may remain above a temperature at which the zirconium alloy has been shown to be susceptible to breakaway oxidation.

The NRC issues regulatory guides to describe to the public methods that the staff considers acceptable for use in implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated accidents, and to provide guidance to applicants. Regulatory guides are not substitutes for regulations and compliance with them is not required.

This regulatory guide contains information collection requirements covered by 10 CFR Part 50 that the Office of Management and Budget (OMB) approved under OMB control number 3150-0011. The NRC may neither conduct nor sponsor, and a person is not required to respond to, an information collection request or requirement unless the requesting document displays a currently valid OMB control number. This regulatory guide is a rule as designated in the Congressional Review Act (5 U.S.C. 801–808). However, OMB has not found it to be a major rule as designated in the Congressional Review Act.

Pre-Decisional

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B. DISCUSSION

Background

In 1996, the NRC initiated a fuel-cladding research program intended to investigate the behavior of high-exposure fuel cladding under accident conditions. This program included an extensive LOCA research and testing program at Argonne National Laboratory (ANL), as well as jointly funded programs at the Kurchatov Institute (Ref. 4) and the Halden Reactor Project (Ref. 5), to develop the body of technical information needed to evaluate LOCA regulations for high-exposure fuel. The research findings were summarized in Research Information Letter 0801, “Technical Basis for Revision of Embrittlement Criteria in 10 CFR 50.46,” dated May 30, 2008 (Ref. 6). Most of the detailed experimental results from the program at ANL appear in NUREG/CR-6967, “Cladding Embrittlement during Postulated Loss-of-Coolant Accidents,” issued July 2008 (Ref. 7).

The research results revealed that hydrogen, which is absorbed into the cladding during the burnup-related corrosion process under normal operation, has a significant influence on embrittlement during a hypothetical LOCA. When that cladding is exposed to high-temperature LOCA conditions, the elevated hydrogen levels increase the solubility of oxygen in the beta phase and the rate of diffusion of oxygen into the beta phase. Thus, for cladding exposed to high-temperature LOCA conditions, embrittlement can occur for times corresponding to less than 17% oxidation in corroded cladding with significant hydrogen pickup. The research results also revealed that an embrittlement mechanism referred to as “breakaway oxidation” may occur during prolonged exposure to elevated cladding temperature during a LOCA.

Summary of the NRC’s LOCA Research Program

Existing Embrittlement Database

The majority of the cladding embrittlement experimental results from the NRC’s LOCA research program are summarized in NUREG/CR-6967 (Ref. 7). Since the publication of NUREG/CR-6967 in 2008, additional testing was conducted, focusing on cladding materials with hydrogen contents in the 200- to 350-weight parts per million (wppm) range (Refs. 8–9, 11). Additional oxidation and postquench ductility (PQD) tests were conducted with cladding samples sectioned from high-burnup ZIRLO™ fuel rods. The two defueled segments used to prepare samples had 25–30 micrometers corrosion-layer thickness and 300–340 wppm of hydrogen in the cladding metal before oxidation (Ref. 8). Also, the ductility data for an oxidation sample with ≈600-wppm hydrogen was reassessed (Ref. 9). In addition, since the publication of NUREG-6967, oxidation and PQD tests were conducted with prehydrided cladding samples containing 200–300 wppm of hydrogen (Ref. 9).

The tests that were conducted after the publication of NUREG/CR-6967 were combined with the data reported in NUREG/CR-6967 to generate a more robust and informed description of cladding embrittlement as a function of hydrogen content.

Before combining the new data with the data reported in NUREG/CR-6967, two refinements were made in data assessment. The first refinement was to establish and verify the following ductility criteria: average permanent strain $\geq 1.0\%$ or, if permanent strain cannot be measured, the average ring compression test (RCT) offset strain $\geq 1.41\% + 0.1082$ Cathcart-Pawel equivalent cladding reacted (CP-ECR) (Ref. 10). Rounded to the nearest tenth of a percent, this correlation represents the one-sigma upper bound of offset strain values from 65 RCT data sets with 1.0 to 2.3% permanent strain. (DG-1262 and Appendix A to this regulatory guide provide discussion and details about a ductility criterion based

on RCT offset strain.) The second refinement was to develop and use a new methodology to determine the pretest hydrogen content in the cladding metal for corroded cladding (Ref. 8).

Ductility and hydrogen data presented in NUREG/CR-6967 were reassessed to determine embrittlement oxidation levels versus hydrogen content for prehydrided and high-burnup cladding. When the tests that were conducted after the publication of NUREG/CR-6967 were combined with the data reported in NUREG/CR-6967, and the refinements in hydrogen content and the relationship between offset and permanent strain were made, the resulting behavior description of cladding embrittlement as a function of hydrogen content could be depicted as shown in Figure 1.

For modern as-fabricated cladding (Zry-2, Zry-4, ZIRLO™, and M5), embrittlement thresholds cluster at 19–20% CP-ECR, as compared to 16% CP-ECR for older Zry-4 cladding. However, this improvement is negated with hydrogen pickup as low as 100 wppm. A bilinear function for CP-ECR versus hydrogen content was used to fit the embrittlement data for prehydrided and high-burnup cladding. The embrittlement rate is steep for cladding with ≤ 400 -wppm hydrogen. For higher hydrogen content, the embrittlement rate is more gradual because embrittlement occurs during the heating ramp at $\leq 1,180$ °C ($\leq 2,156$ °F). High-burnup ZIRLO™ with 600-wppm hydrogen is highly ductile at 4% CP-ECR, but the peak oxidation temperature was only 1,130 °C (2,066 °F). Embrittlement is highly sensitive to both hydrogen content and peak oxidation temperature.

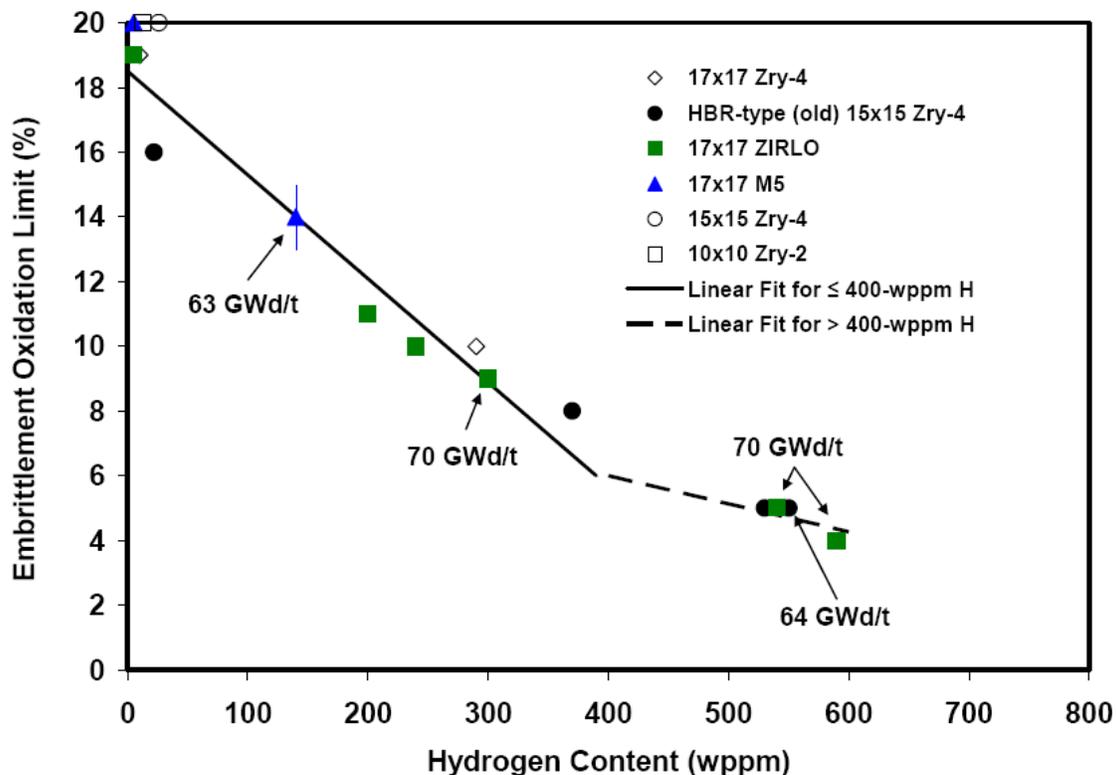


Figure 1. Ductile-to-brittle transition oxidation level (CP-ECR) as a function of pretest hydrogen content in cladding metal for as-fabricated, prehydrided, and high-burnup cladding materials. Samples were oxidized at $\leq 1,200$ °C ± 10 °C and quenched at 800 °C. For high-burnup cladding with about 550-wppm hydrogen, embrittlement occurred during the heating ramp at 1,160–1,180 °C peak oxidation temperatures (Ref. 8).

An Acceptable Analytical Limit on Peak Cladding Temperature and Integral Time at Temperature

In 10 CFR 50.46c, the NRC calls for the establishing of analytical limits on peak cladding temperature and integral time at temperature, which correspond to the measured ductile-to-brittle transition for the zirconium-alloy cladding material (Ref. 1). The ductile-to-brittle threshold defined in Figure 2 is an acceptable analytical limit on integral time at temperature as calculated in local oxidation calculations using the Cathcart-Pawel (CP) correlation (Ref. 11). This analytical limit is acceptable for the zirconium-alloy cladding materials tested in the NRC's LOCA research program, which were Zry-2, Zry-4, ZIRLO™, and M5. This analytical limit is based on the data obtained in the NRC's LOCA research program. Since PQD tests above 400-wppm hydrogen were conducted at a peak oxidation temperature below 1,204 °C (2,200 °F), a separate PCT analytical limit must be defined that is consistent with test temperature. A limit on peak cladding temperature of 1,204 °C (2,200 °F) below 400-wppm cladding hydrogen content and 1,121 °C (2,050 °F) at or above 400-wppm cladding hydrogen content is acceptable.

Demonstrating that ECCS performance is such that local oxidation and peak cladding temperature are calculated below the analytical limits defined in Figure 2 is acceptable to demonstrate compliance with 10 CFR 50.46c.

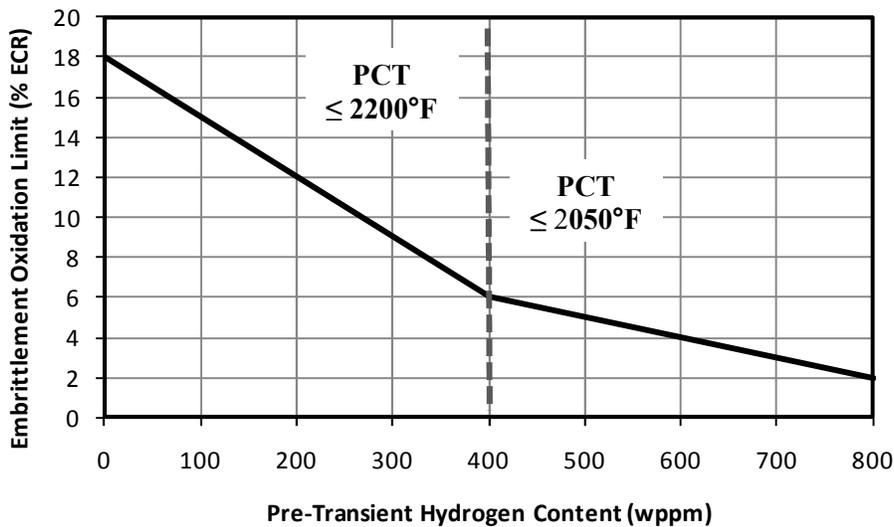


Figure 2. An acceptable analytical limit on peak cladding temperature and integral time at temperature (as calculated in local oxidation calculations using the CP correlation (Ref. 11))

For zirconium-alloy cladding materials not tested in the NRC's LOCA research program, a demonstration of comparable performance with the database established in the NRC's LOCA research program would be necessary in order to establish the analytical limit provided in this guide as the limit for that alloy. Draft Regulatory Guide (DG)-1262, "Testing for Postquench Ductility" (Ref. 2), provides an experimental technique acceptable to the NRC for measuring the ductile-to-brittle transition for zirconium-alloy cladding material through ring compression tests (RCT). This guide describes a method to demonstrate comparable performance with the established database in order to establish the analytical limit provided in this guide for a particular cladding alloy not tested in the NRC's LOCA research program.

The database established in the NRC's LOCA research program and the resulting analytical limit described in this regulatory guide are intended to provide a best-estimate limit for the ductile-to-brittle transition for zirconium alloys. The analytical limit described in this guide is applicable to Zircaloy-2 (Zry-2), Zircaloy-4 (Zry-4), ZIRLO™, and M5. In some instances, a zirconium-alloy cladding material may experience the transition from ductile to brittle behavior at a higher level of oxidation than the established database. This regulatory guide also describes a methodology to establish a zirconium-alloy-specific limit other than the limit provided in this guide.

The database established in the NRC's LOCA research program and the resulting analytical limit described in this regulatory guide are intended to bound emergency core cooling system (ECCS) performance. In the test program, experiments were conducted at maximum oxidation temperatures permitted by the criteria in 10 CFR 50.46. Some ECCSs may perform such that the maximum oxidation temperature is significantly below 1,204 degrees Celsius (°C) (2,200 degrees Fahrenheit (°F)). Oxidation at lower temperatures has been shown to increase the allowable calculated oxidation before embrittlement. Therefore, conducting tests at lower peak temperatures may provide additional margin for some zirconium-alloy cladding materials. This regulatory guide describes a methodology to establish analytical limits at peak oxidation temperatures less than 1,204 °C (2,200 °F).

Methodology for Demonstrating Consistency with the Existing Database for New Cladding Alloys

For zirconium-alloy cladding materials not tested in the NRC's LOCA research program, a demonstration of comparable performance with the established database is necessary. The objective of PQD testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide is to confirm that the transition to brittle behavior does not take place at a lower equivalent cladding reacted (ECR) than the provided limit. A range of material conditions can serve to provide a characterization of PQD behavior through the spectrum of conditions expected during operation and during a transient. Repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The methodology outlined in this regulatory guide uses the experimental procedure in DG-1262 to generate RCT data to demonstrate consistency with the analytical limit in Figure 2 of this regulatory guide.

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2, an ECR 1% above, and an ECR 1% below this limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A to this regulatory guide. This would generate nine RCT results for as-received cladding material.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels at each hydrogen level. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 for a given hydrogen content, an ECR 1% above, and an ECR 1% below this

limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A. This would generate nine RCT results at each hydrogen level.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The analytical limit provided in Figure 2 of this regulatory guide can be used to reduce the extent of testing by focusing on specific oxidation levels relevant for the hydrogen content of the irradiated material. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 for the irradiated material's hydrogen content, an ECR 1% above, and an ECR 1% below this limit. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A. This would generate nine RCT results at each hydrogen level, and a total of 18 RCT results for irradiated material.

Appendix B to this regulatory guide presents a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that could be used to demonstrate comparable embrittlement behavior with the analytical limit in Figure 2. It is intended to complement the test matrix guidance in DG-1262.

To demonstrate comparable performance with the existing database and adopt the analytical limits provided in this guide for a new fuel design, the applicant would submit experimental results as part of the documentation supporting the NRC staff's review and approval of the new fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the results of experiments conducted with as-fabricated, prehydrided, and irradiated cladding material. Provided that the experimental results for the new fuel design measured the transition from ductile to brittle behavior to be no lower than the analytical limit defined in Figure 2,¹ an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46c is demonstrating that ECCS performance is such that local oxidation is calculated below the analytical limit defined in Figure 2.

Methodology for Establishing a Zirconium-Alloy-Specific Limit

The existing database and resulting analytical limit described in this regulatory guide are intended to provide a best-estimate limit for the ductile-to-brittle transition for zirconium alloys. The analytical limit described in this guide is applicable to Zry-4, Zry-2, ZIRLO™, and M5. In some instances, a zirconium-alloy cladding material may experience the transition from ductile to brittle behavior at a higher level of oxidation than the established database.

The objective of PQD testing to establish an alloy-specific limit is to characterize a cladding alloy's embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory

¹ For accurate comparison to the research data, local oxidation calculations must be performed using the CP correlation.

guide includes testing of as-received, prehydrided, and irradiated material. The methodology uses the experimental procedure in DG-1262 to generate RCT data to establish a zirconium-alloy-specific limit.

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at a wide range of ECRs to scope out a zirconium-alloy cladding material's oxidation behavior in the as-received condition. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at two ECR levels (a total of six oxidation and quench tests). Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing at each hydrogen level than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2 and, based on the result of this test, proceed to an ECR 2% above or an ECR 2% below this limit (2% above if the initial test was ductile, 2% below if the initial test was brittle). Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The methodology outlined in this regulatory guide for establishing a zirconium-alloy-specific limit other than the analytical limit provided in Figure 2 includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined by the as-received and prehydrided testing described above. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or an offset strain ductility criterion presented in Appendix A.

Appendix B to this regulatory guide provides a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that could be used to establish an alloy-specific limit other than the analytical limit in Figure 2. It is intended to complement the test matrix guidance in DG-1262.

To establish a zirconium-alloy-specific limit for a new or existing fuel design, the applicant would provide experimental results as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the results of experiments conducted with as-fabricated, prehydrided, and irradiated material, as well as a specified analytical limit on peak cladding temperature and integral time at temperature that corresponds to the measured ductile-to-brittle transition for the zirconium-alloy cladding material.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46c is demonstrating that ECCS performance is such that local oxidation is calculated below the specified analytical limit provided.

Methodology for Establishing Analytical Limits at Peak Oxidation Temperatures Less than 1,204 °C (2,200 °F)

The existing database and resulting analytical limit described in this regulatory guide is intended to bound ECCS performance. In the test program, experiments were conducted at maximum oxidation temperatures $\leq 1,200 \text{ °C} \pm 10 \text{ °C}$ and quenched at 800 °C .² Some ECCS may perform such that the maximum oxidation temperature is significantly below $1,204 \text{ °C}$ ($2,200 \text{ °F}$). Oxidation at lower temperatures has been shown to increase the allowable calculated oxidation before embrittlement. Therefore, conducting tests at lower peak temperatures may provide additional margin for some zirconium-alloy cladding materials.

The objective of PQD testing to establish a limit at a peak cladding temperature lower than $1,204 \text{ °C}$ ($2,200 \text{ °F}$) is to characterize a cladding alloy's embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can serve to provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The methodology outlined in this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The methodology outlined in this regulatory guide uses the experimental procedure in DG-1262 to generate RCT data to establish a limit at a peak cladding temperature lower than $1,204 \text{ °C}$ ($2,200 \text{ °F}$).

As-received cladding material may be used to characterize an alloy's oxidation embrittlement behavior in the as-received condition. The methodology outlined in this regulatory guide for establishing an analytical limit at a peak oxidation temperature less than $1,204 \text{ °C}$ ($2,200 \text{ °F}$) includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at a wide range of ECRs to scope out a zirconium-alloy cladding material's oxidation behavior in the as-received condition. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at two ECR levels (a total of six oxidation and quench tests). Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

² These test conditions were selected with the objective of bounding the performance of ECCSs. They are considered relevant and bounding for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for ECCSs of advanced reactor designs. In addition, postquench ductility measurements were made at 135 °C . During the 1973 hearing, investigators suggested considering a test temperature no higher than the saturation temperature during reflood (i.e., $\approx 135 \text{ °C}$). This test condition is considered relevant for current light-water reactor ECCSs. However, it may be necessary to evaluate and possibly modify the conditions accordingly for ECCSs of advanced reactor designs.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy's oxidation embrittlement behavior. The entire range of a cladding material's anticipated hydrogen level should be characterized. To characterize the range of a cladding material's anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 wppm of hydrogen. One approach would be to conduct oxidation and quench testing at the transition ECR defined in Figure 2, and, based on the result of this test, proceed to an ECR 2% above or an ECR 2% below this limit (2% above if the initial test was ductile, 2% below if the initial test was brittle). Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Irradiated cladding material can be used to demonstrate that a cladding alloy's embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content. The methodology outlined in this regulatory guide for establishing an analytical limit at a peak oxidation temperature less than 2,200 °F includes more repeat testing for irradiated material than was outlined for demonstrating consistency with the established database. One approach would be to conduct oxidation and quench testing at the transition ECR defined by the as-received and prehydrided testing conducted as described above. Testing would then focus on the ECR range between ductile and brittle results and include three repeat oxidation and quench tests at the transition ECR level. Following the guidance of DG-1262, each oxidation and quench sample would be segmented into three RCT samples. The average of these three RCT samples would be compared to the ductility criterion defined in terms of $\geq 1.0\%$ permanent strain or the offset strain ductility criterion presented in Appendix A.

Appendix B to this guide presents a high-level overview of an acceptable test matrix. The test matrix overview is intended to provide a clear picture of the range of material and test conditions that could be used to establish a limit at a peak cladding temperature lower than 1,204 °C (2,200 °F). It is intended to complement the test matrix guidance in DG-1262.

To establish analytical limits at peak oxidation temperatures less than 1,204 °C (2,200 °F), the applicant would provide experimental results as part of the documentation supporting the NRC staff's review and approval of the new fuel design or existing fuel design (i.e., license amendment request or vendor topical report). The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1262) and the results of experiments conducted with as-fabricated, prehydrided, and irradiated material, as well as a specified analytical limit on peak cladding temperature and integral time at temperature that corresponds to the measured ductile-to-brittle transition for the zirconium-alloy cladding material.

For a given zirconium alloy, an applicant would be able to define analytical limits on integral time at temperature (CP-ECR as a function of cladding hydrogen) corresponding to different peak cladding temperature analytical limits. This approach may provide margin for high-burnup, high-corrosion, low-power fuel rods that experience a relatively benign temperature transient.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46c is demonstrating that ECCS performance is such that local oxidation is calculated below the specified analytical limit provided.

Methodology for Establishing Analytical Limits for Breakaway Oxidation

The purpose of the requirements in 10 CFR 50.46, “Acceptance Criteria for Emergency Core Cooling Systems for Light-Water Nuclear Power Reactors,” is to ensure core coolability during and following a LOCA. If breakaway oxidation occurs, the embrittlement process is accelerated. Therefore, the PQD analytical limits established in accordance with 10 CFR 50.46 are no longer effective to preclude embrittlement, and core coolability may not be maintained even if the analytical limits on peak cladding temperature and local oxidation (surrogate for time at temperature) are not exceeded.

In 10 CFR 50.46c, the NRC calls for measurement of the onset of breakaway oxidation for a zirconium cladding alloy based on an acceptable experimental technique, evaluation of the measurement relative to ECCS performance, and reporting of values measured (Ref. 1).

Based on data reported by Leistikow and Schanz (Ref. 12), zirconium alloys have been shown to be susceptible to the breakaway oxidation phenomenon at temperatures as low as 650 °C. At 650 °C, it took more than 4 hours (beyond LOCA-relevant times) for Zry-4 to accumulate 200-wppm hydrogen, while at 800 °C, the time to accumulate 200-wppm hydrogen was only 1 hour (within LOCA-relevant times). Thus, time spent in steam at ≤ 650 °C was benign with regard to breakaway oxidation and hydrogen accumulation because of the very low oxidation rate. Because NUREG/IA-0211, “Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions,” issued March 2005 (Ref. 4), did not present hydrogen-accumulation data for temperatures between 650 °C and 800 °C, there is no basis for *not* including time spent at temperatures >650 °C in establishing the analytical limit for transient time.

To establish a zirconium-alloy-specific limit for a new or existing fuel design, the applicant would provide experimental results for testing for breakaway oxidation behavior as part of the documentation supporting the NRC staff’s review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). DG-1261 provides an experimental technique to measure the onset of breakaway oxidation in order to establish a specified and acceptable limit on the total accumulated time that a cladding may remain at high temperature. The applicant would provide details of the experimental technique (unless the experiments were conducted in accordance with DG-1261) and the results of experiments conducted. Applicants would establish the time limit for the total accumulated time that the cladding may remain above 650 °C as part of the documentation supporting the NRC staff’s review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).

Applicants may elect to establish the analytical limit for breakaway oxidation with conservatism relative to the measured minimum time (i.e., reduce the time) to the onset of breakaway oxidation. This approach may reduce the likelihood of reassessing small-break LOCA cladding temperature histories in the event of a minor change in measured time to breakaway oxidation. For example, the minimum time to breakaway oxidation may be demonstrated to occur at 975 °C at a time of 4,000 seconds. An applicant may elect to establish an analytical limit of 3,000 seconds for the total accumulated time that the cladding may remain above 650 °C.

Upon review and approval of the fuel design, an acceptable method to demonstrate that licensees meet the requirements of 10 CFR 50.46c is demonstrating that ECCS performance is such that the total accumulated time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to this phenomenon is not greater than the proposed limit.

Applying Analytical Limits

Qualification of Hydrogen Pickup Models

An alloy-specific cladding hydrogen uptake model will be required if a licensee chooses to use the hydrogen-dependent embrittlement threshold provided in this regulatory guide. To establish an alloy-specific cladding hydrogen uptake model for a new or existing fuel design, the applicant would provide postirradiation examination hydrogen measurement data and a hydrogen uptake model as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The documentation should include a cladding-specific plot of predicted versus measured cladding hydrogen content. The post-irradiation examination data supporting the hydrogen uptake model should include values for multiple burnup levels, encompass all applicable operating conditions and reactor coolant chemistry, and should quantify axial, radial, and circumferential variability. (See the next section for further details.)

Accounting for Uncertainty and Variability in Hydrogen Content

Variation of hydrogen content across the radius of the cladding (hydride rim effect) and over short axial distances (pellet-pellet interface effect) has been observed by many investigators. Studies using prehydrided Zry-4 with dense hydride rims have demonstrated that the homogenization of hydrogen across the radius of the cladding is very rapid at >900 °C due to the affinity of the beta phase for hydrogen, as well as the high solubility of hydrogen in this phase. In the NRC's LOCA research program, significant circumferential variation (± 100 – 140 wppm) in hydrogen content was measured (by the LECO inert gas fusion thermal conductivity method) and observed (by optical microscopy) for high-burnup cladding alloys. For oxidation test times at $1,200$ °C up to the embrittlement CP-ECR level, no significant diffusion of hydrogen in the circumferential direction was observed. Hydrogen-concentration variations of 450 to 750 wppm measured for cladding quarter segments before LOCA testing remained after LOCA testing.

The uncertainty in the model can be characterized and quantified by supporting the model with postirradiation examination that include values for multiple burnup levels, encompasses all applicable operating conditions and reactor coolant chemistry, and quantifies axial, radial, and circumferential variability.

To apply the analytical limit in Figure 2 to an individual fuel rod (or fuel rod grouping), the allowable CP-ECR should be based on predicted peak circumferential average hydrogen content for the individual rod (or fuel rod grouping).

Postquench Ductility Analytical Limits

Based on the approved ECCS evaluation models and methods, the applicant should identify the limiting combination of break size, break location, and initial conditions and assumptions that maximize predicted peak cladding temperature and local oxidation (surrogate for time at temperature). Combinations of initial conditions and uncertainties will vary between Appendix K, "ECCS Evaluation Models," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," and best-estimate methods. Separate cases may be necessary to identify the limiting scenario for peak cladding temperature relative to local oxidation and vice versa. The applicant should demonstrate that predicted peak cladding temperature remains below the lesser of the regulatory limit of $2,200$ °F and the maximum oxidation PQD temperature. The applicant will also need to demonstrate that the maximum predicted local oxidation remains below the established PQD analytical limits.

Because of the strong function of allowable local oxidation with cladding hydrogen content (see Figure 1), the applicant may elect to subdivide the fuel rods within the core based on cladding hydrogen content, burnup, fuel rod power, or a combination. For example, peak cladding temperature and local oxidation calculations would be performed on three representative sets of fuel rods (e.g., 0–30 gigawatt-days per metric ton of uranium (GWd/MTU), 30–45 GWd/MTU, and 45–62 GWd/MTU) using bounding power histories for each fuel rod grouping. The predicted peak cladding temperature and local oxidation would then be compared to the analytical limits for that range of burnup/hydrogen.

Application in the Rupture Region

During a postulated LOCA, fuel rods may be predicted to balloon and rupture as a result of elevated cladding temperature and differential pressure (between rod internal pressure and system pressure, which is decreasing because of a break in pressure boundary). The regions of the fuel rod near the ballooned and ruptured location will thus be exposed to oxidation from the inside surface of the cladding. Combined with oxygen diffusion from the cladding outside diameter (OD), oxygen diffusion from the cladding inside diameter (ID) would further limit integral time at temperature to reach the analytical limit in Figure 2. In addition, local regions above and below the rupture opening will absorb significant hydrogen due to the steam oxidation on the ID, which may result in locally brittle regions above and below the rupture. Finally, the balloon region will experience wall thinning, which impacts the calculation of ECR because the value is taken to be a percentage of the preoxidation cladding thickness.

The LOCA acceptance criteria that limit peak oxidation temperature and maximum oxidation level versus hydrogen content are based on retention of ductility. As discussed above, ductility will not be retained everywhere in the balloon region.

To investigate the mechanical behavior of ruptured fuel rods, the NRC conducted integral LOCA testing, designed to experience ballooning and rupture, on as-fabricated and hydrogen charged cladding specimens and high burnup fuel rod segments exposed to high temperature steam oxidation followed by quench (Ref. 13). The integral LOCA testing confirms that continued exposure to high temperature steam environment weakens the already flawed region of the fuel rod surrounding the cladding rupture. Hence, limitations on integral time at temperature are necessary to preserve an acceptable amount of mechanical strength and fracture toughness. In addition, this research demonstrated that the degradation in strength and fracture toughness with prolonged exposure to steam oxidation was enhanced with pre-existing cladding hydrogen content.

Therefore, in regions of the fuel rod where the calculated conditions of transient pressure and temperature lead to a prediction of cladding swelling, an acceptable approach would be to define the cladding thickness as the cladding cross-sectional area divided by the cladding circumference, taken at a horizontal plane at the elevation of the rupture, and to calculate two-sided oxidation using the CP correlation and apply the analytical limit in Figure 2 (or an alternative specified and acceptable analytical limit).

Accounting for Double-Sided Oxidation Due to the Fuel-Cladding Bond Layer

The NRC's LOCA research program identified that, for high-burnup fuel, oxygen can diffuse into the cladding metal during a LOCA from the ID as well as from the OD, even when no steam oxidation is occurring on the ID (Refs. 5 and 6). The ID oxygen diffusion phenomenon was discovered in the United States in 1977, confirmed by tests in Germany in 1979, and is seen in the present results.

Combined with oxygen diffusion from the cladding OD, oxygen diffusion from the cladding ID would further limit integral time at temperature to nil ductility. To account for the observation that oxygen can diffuse into the cladding metal during a LOCA from the ID, one acceptable approach would

be to calculate two-sided local oxidation for fuel rods with a local (nodal) exposure beyond 30 GWd/MTU. It should be noted that there would be no metal-water-reaction heat associated with this process on the ID, in contrast to the situation in a rupture node. A threshold for the onset of this inside surface oxidation source other than 30 GWd/MTU may be proposed by a licensee and provided as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). A threshold other than 30 GWd/MTU could be supported by metallographic images of bonding layers as a function of burnup.

Breakaway Oxidation Analytical Limits

Based on the approved ECCS evaluation models and methods, the applicant should identify the limiting combination of break size, break location, and initial conditions and assumptions that maximize the total accumulated time that the cladding is predicted to remain above a temperature at which the zirconium alloy has been shown to be susceptible to this phenomenon. The applicant should demonstrate that this time interval remains below the established alloy-specific breakaway oxidation analytical limit.

The applicant may credit operator actions to limit the duration at elevated temperatures provided these actions are consistent with existing emergency operating procedures and the timing of such actions is validated by operator training on the plant simulator.

C. REGULATORY POSITION

Regulatory Positions 1 through 4 provide acceptable methods for establishing an analytical limit on peak cladding temperature and integral time at temperature for zirconium-alloy cladding materials. Applicants should use one of the four methods provided. Regulatory Position 5 provides an acceptable method for establishing an analytical limit for breakaway oxidation.

1. Apply the specified and acceptable limit defined in Figure 2 of this regulatory guide for cladding materials tested in the NRC's LOCA research program.
2. Demonstrate comparable behavior of cladding alloys not tested in the NRC's LOCA research program, with the database established in the NRC's LOCA research program, in order to apply the limit defined in Figure 2 of this regulatory guide.
 - a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing pre-hydrided material in increments not more than every 100 wppm hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at the transition ECR defined in Figure 2 for the each sample's hydrogen level, an ECR 1% above and an ECR 1% below this limit.
 - b. Determine the ECR at which the material transitions from ductile-to-brittle behavior using the results of ring compression testing conducted using the experimental procedure

and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 2.a³. Compare to the limit defined in Figure 2 of this guide.

- c. If the experimental results for the new fuel design measured the transition from ductile to brittle behavior to be no lower than the analytical limit defined in Figure 2, the analytical limit defined in Figure 2 may be established for the cladding alloy not tested in NRC's LOCA research program.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - e. Provide results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and integral time at temperature as part of the documentation supporting the staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.
3. Establish a zirconium alloy specific analytical limit on peak cladding temperature and integral time at temperature at a peak cladding oxidation temperature of 2200°F.
- a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing pre-hydrided material in increments not more than every 100 wppm hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at four oxidation levels for each material condition³, in increments not greater than 2% ECR.
 - b. With the results of four oxidation levels, for each material condition called for in (a) above, determine the ECR range in which the transition from ductile-to-brittle behavior occurs and conduct three repeat oxidation and quench tests at each ECR level within this range using the guidance provided in DG-1262.
 - c. Determine the ECR at which the material transitions from ductile to brittle behavior, using the results of ring compression testing conducted using the experimental procedure and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 3.a.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the NRC staff's review and approval

³ "each material condition" refers to the range of as-fabricated, prehydrided and irradiated material called for within the discussion section of this regulatory guide. For a zirconium alloy with an anticipated, end of life hydrogen content, the range of material conditions called for within the discussion section of this regulatory guide would include (1) as-fabricated, (2) pre-hydrided material at 100 wppm H, (3) pre-hydrided material at 200 wppm H, (4) pre-hydrided material at 300 wppm H, (5) pre-hydrided material at 400 wppm H, (6) irradiated material with a hydrogen content of 200 ± 50 wppm H, and (7) irradiated material with a hydrogen content of 400 ± 50 wppm H. See also Appendix B of this guide for a high-level overview of an acceptable test matrix.

of the new or existing fuel design (i.e., license amendment request or vendor topical report).

- e. Provide the results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and integral time at temperature as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.
4. Establish an analytical limit on peak cladding temperature and integral time at temperature at a peak oxidation temperature less than 2,200 °F.
 - a. Conduct oxidation and quench testing on (1) as-fabricated material, (2) prehydrided material for the entire range of a cladding material's anticipated hydrogen level (testing prehydrided material in increments not more than every 100 wppm of hydrogen), and (3) irradiated material for the entire range of a cladding material's anticipated hydrogen level (testing irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 50 wppm of half of the anticipated maximum hydrogen content) at four oxidation levels for each material condition³, in increments not greater than 2% ECR.
 - b. With the results of four oxidation levels for each material condition called for in Regulatory Position 4.a, determine the ECR range in which the transition from ductile to brittle behavior occurs and conduct three repeat oxidation and quench tests at each ECR level within this range using the guidance provided in DG-1262.
 - c. Determine the ECR at which the material transitions from ductile-to-brittle behavior, using the results of ring compression testing conducted using the experimental procedure and the guidance provided in DG-1262 for each material condition called for in Regulatory Position 4.a.
 - d. Provide details of experimental techniques, unless conducted using the guidance in DG-1262, as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
 - e. Provide the results of experiments conducted with as-fabricated, irradiated material and identify the specific analytical limit on peak cladding temperature and integral time at temperature as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report). The limit should correspond the ductile-to-brittle transition for the zirconium-alloy cladding material and the oxidation temperature of the oxidation and quench experiments.
 5. Establish an analytical limit for breakaway oxidation.
 - a. Follow the procedures in DG-1261 to establish the shortest time observed to lead to breakaway oxidation for a zirconium cladding alloy.

- b. Provide the results of the testing as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).
- c. Establish an analytical limit for the total accumulated time the cladding may remain above 650°C, which is less than or equal to the shortest time observed to lead to breakaway oxidation.
- d. Provide the analytical limit for breakaway oxidation as part of the documentation supporting the NRC staff's review and approval of the new or existing fuel design (i.e., license amendment request or vendor topical report).

D. IMPLEMENTATION

The purpose of this section is to provide information on how applicants and licensees⁴ may use this guide and information regarding the NRC's plans for using this regulatory guide. In addition, it describes how the NRC staff complies with the Backfit Rule (10 CFR 50.109) and any applicable finality provisions in 10 CFR Part 52.

Use by Licensees

Licensees may voluntarily⁵ use the guidance in this document to demonstrate compliance with the underlying NRC regulations. Methods or solutions that differ from those described in this regulatory guide may be deemed acceptable if they provide sufficient basis and information for the NRC staff to verify that the proposed alternative demonstrates compliance with the appropriate NRC regulations.

Licensees may use the information in this regulatory guide for actions which do not require NRC review and approval such as changes to a facility design under 10 CFR 50.59 that do not require prior NRC review and approval. Licensees may use the information in this regulatory guide or applicable parts to resolve regulatory or inspection issues.

Use by NRC Staff

During regulatory discussions on plant specific operational issues, the staff may discuss with licensees various actions consistent with staff positions in this regulatory guide, as one acceptable means of meeting the underlying NRC regulatory requirement. Such discussions would not ordinarily be considered backfitting even if prior versions of this regulatory guide are part of the licensing basis of the facility. However, unless this regulatory guide is part of the licensing basis for a facility, the staff may not represent to the licensee that the licensee's failure to comply with the positions in this regulatory guide constitutes a violation.

If an existing licensee voluntarily seeks a license amendment or change and (1) the NRC staff's consideration of the request involves a regulatory issue directly relevant to this new or revised regulatory guide and (2) the specific subject matter of this regulatory guide is an essential consideration in the staff's determination of the acceptability of the licensee's request, then the staff may request that the licensee

⁴ In this section, "licensees" refers to licensees of nuclear power plants under 10 CFR Parts 50 and 52; and the term "applicants," refers to applicants for licenses and permits for (or relating to) nuclear power plants under 10 CFR Parts 50 and 52, and applicants for standard design approvals and standard design certifications under 10 CFR Part 52.

⁵ In this section, "voluntary" and "voluntarily" means that the licensee is seeking the action of its own accord, without the force of a legally binding requirement or an NRC representation of further licensing or enforcement action.

either follow the guidance in this regulatory guide or provide an equivalent alternative process that demonstrates compliance with the underlying NRC regulatory requirements. This is not considered backfitting as defined in 10 CFR 50.109(a)(1) or a violation of any of the issue finality provisions in 10 CFR Part 52.

The NRC staff does not intend or approve any imposition or backfitting of the guidance in this regulatory guide. The NRC staff does not expect any existing licensee to use or commit to using the guidance in this regulatory guide, unless the licensee makes a change to its licensing basis. The NRC staff does not expect or plan to request licensees to voluntarily adopt this regulatory guide to resolve a generic regulatory issue. The NRC staff does not expect or plan to initiate NRC regulatory action which would require the use of this regulatory guide. Examples of such unplanned NRC regulatory actions include issuance of an order requiring the use of the regulatory guide, requests for information under 10 CFR 50.54(f) as to whether a licensee intends to commit to use of this regulatory guide, generic communication, or promulgation of a rule requiring the use of this regulatory guide without further backfit consideration.

If a licensee believes that the NRC is either using this regulatory guide or requesting or requiring the licensee to implement the methods or processes in this regulatory guide in a manner inconsistent with the discussion in this Implementation section, then the licensee may file a backfit appeal with the NRC in accordance with the guidance in NUREG-1409 and NRC Management Directive 8.4.

GLOSSARY

breakaway oxidation—For the purposes of this regulatory guide, the fuel-cladding oxidation phenomenon in which weight gain rate deviates from normal kinetics. This change occurs with a rapid increase of hydrogen pickup during prolonged exposure to a high-temperature steam environment, which promotes loss of cladding ductility.

corrosion—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with coolant water during normal operation.

loss-of-coolant accident (LOCA)—A hypothetical accident that would result from the loss of reactor coolant at a rate in excess of the capability of the reactor coolant makeup system, from breaks in pipes in the reactor coolant pressure boundary up to and including a break equivalent in size to the double-ended rupture of the largest pipe in the reactor coolant system.

offset strain—For the purposes of this regulatory guide, the value determined from a load-displacement curve by the following procedure: (1) linearize the initial loading curve, (2) use the slope of the initial loading curve to mathematically unload the sample at the peak load before a significant load drop (≈ 30 – 50%) indicating a through-wall crack along the length of the sample, and (3) determine the offset displacement (distance along the displacement axis between loading and unloading lines). This offset displacement is normalized to the outer diameter of the preoxidized cladding to determine a relative plastic strain.

oxidation—For the purposes of this regulatory guide, the formation of a zirconium oxide layer resulting from the reaction of zirconium with high-temperature steam during LOCA conditions.

permanent strain—For the purposes of this regulatory guide, the difference between the posttest outer diameter (after the sample is unloaded) and the pretest outer diameter of a cladding ring, normalized to the initial diameter of the cladding ring.

REFERENCES⁶

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2. DG-1262, "Testing for Postquench Ductility," U.S. Nuclear Regulatory Commission, Washington, DC.
3. DG-1261, "Conducting Periodic Testing for Breakaway Oxidation Behavior," U.S. Nuclear Regulatory Commission, Washington, DC.
4. NUREG/IA-0211, "Experimental Study of Embrittlement of Zr-1%Nb VVER Cladding under LOCA-Relevant Conditions," U.S. Nuclear Regulatory Commission, Washington, DC, March 2005. (ADAMS Accession No. ML051100343)
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9. May 15th email correspondence
10. ORNL/NUREG-17, "Zirconium Metal-Water Oxidation Kinetics IV. Reaction Rate Studies," U.S. Nuclear Regulatory Commission, Washington, DC, August 1977.
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12. Leistikow, S., and G. Schanz, "Oxidation Kinetics and Related Phenomena of Zircaloy-4 Fuel Cladding Exposed to High Temperature Steam and Hydrogen-Steam Mixtures under PWR Accident Conditions," *Nuclear Engineering and Design*, 103: 65–84.

⁶ Publicly available NRC published documents are available electronically through the NRC Library at: <http://www.nrc.gov/reading-rm/doc-collections/>. The documents can also be viewed on-line or printed for a fee in the NRC's Public Document Room (PDR) at 11555 Rockville Pike, Rockville, MD; the mailing address is USNRC PDR, Washington, DC 20555; telephone 301-415-4737 or (800) 397-4209; fax (301) 415-3548; and e-mail pdr.resource@nrc.gov.

13. USNRC staff report, "Mechanical Behavior of Ballooned and Ruptured Cladding" May 2011, Draft available as ADAMS Public Accession Number ML111370032

APPENDIX A

RELATIONSHIP BETWEEN OFFSET STRAIN AND PERMANENT STRAIN

For as-fabricated cladding compressed at room temperature (RT) or 135 degrees Celsius (°C) and at 0.033 millimeter per second (mm/s) to a total displacement of 2 millimeters (mm), the difference between offset displacement and permanent displacement is ≤ 0.2 mm, which corresponds to a strain difference of $\approx 2\%$. As the applied displacement is decreased, the plastic deformation decreases and the deviation between offset and permanent strain also decreases. This was demonstrated by conducting a set of ring compression tests designed to result in low permanent strains of 1.0 to 2.3%. Table A-1 shows the results of these tests.

Table A-1. Results of Ring Compression Tests Conducted with As-Fabricated Cladding Samples at RT and 2 mm/minute Displacement Rate. Total Applied Displacements Were Chosen to Give Low Permanent Strains (d_p/D_o) in the Range of 1.0 to 2.3% and Corresponding Low Offset Strains

Material (D_o , mm)	Sample ID IPS or AG No.	Offset Displacement δ_d , mm	Permanent Displacement d_p , mm	Permanent Strain d_p/D_o , %	Strain Difference $(\delta_d - d_p)/D_o$, %
15×15 Zry-4 (10.91 mm)	101B7	0.24	0.21	1.9	0.3
	101B8	0.20	0.17	1.6	0.3
	101B9	0.20	0.18	1.6	0.2
	101B10	0.16	0.14	1.3	0.2
17×17 ZIRLO™ (9.48 mm)	109D7	0.25	0.22	2.3	0.3
	109D8	0.17	0.16	1.7	0.1
	109D9	0.14	0.12	1.3	0.2
	109D10	0.14	0.12	1.3	0.2
17×17 M5 (9.48 mm)	636B2	0.18	0.19	2.0	0.0
	636B3	0.14	0.14	1.5	0.0
	636B4	0.15	0.15	1.6	0.0

For as-fabricated and prehydrided cladding oxidized at $\leq 1,200$ °C, the difference between offset and permanent displacement depends on both the oxidation level and the magnitude of the permanent displacement. For material with high ductility, the difference in displacements can be as high as 0.5 mm. For material with essentially no ductility, both offset and the permanent displacement values are in the "noise of uncertainty" and their difference can be as low as 0.01 mm.

However, what is relevant to the determination of the ductile-to-brittle transition oxidation level is the error in offset strain as determined by the difference between offset (δ_p/D_o in %) and permanent (d_p/D_o in %) strains for permanent strains in the range of 1.0 to 2.3%. Figure A-1 summarizes the data reported in Refs. 1 and 15, in Figures 1 and 2 of this procedure, and in Table A-1. The data are plotted as a function of Cathcart-Pawel equivalent cladding reacted (CP-ECR). Low values of permanent strain at low CP-ECR levels (e.g., 5–10%) are from prehydrided Zircaloy-4 (Zry-4), high-burnup Zry-4, and ZIRLO™ samples. Low values of permanent strain at intermediate CP-ECR levels (10–18%) are from high-burnup ZIRLO™ and M5 samples. Low values of permanent strain at high CP-ECR values (15–20%) are from as-fabricated cladding materials. The best linear fit to the data is given by:

$$\delta_p/D_o - d_p/D_o = 0.25 + 0.0863 \text{ CP-ECR} \quad (\text{A1})$$

The one-sigma upper bound to the data is given by:

$$\delta_p/D_o - d_p/D_o = 0.41 + 0.1082 \text{ CP-ECR} \quad (\text{A2})$$

Because of the large data scatter in Figure A-1, the one-sigma upper bound is used to establish the offset-strain ductility criterion. It is derived by setting the permanent strain (d_p/D_o) in Equation (A2) to 1.0%:

$$\delta_p/D_o \geq 1.41 + 0.1082 \text{ CP-ECR} \quad (\text{A3})$$

For multiple offset-strain data points at the same CP-ECR level, the average value for the data set, rounded to the nearest tenth of a percent, should be used for δ_p/D_o in Equation (A3). Similarly, the limit calculated from the right-hand side of Equation (A3) should also be rounded to the nearest tenth of a percent.

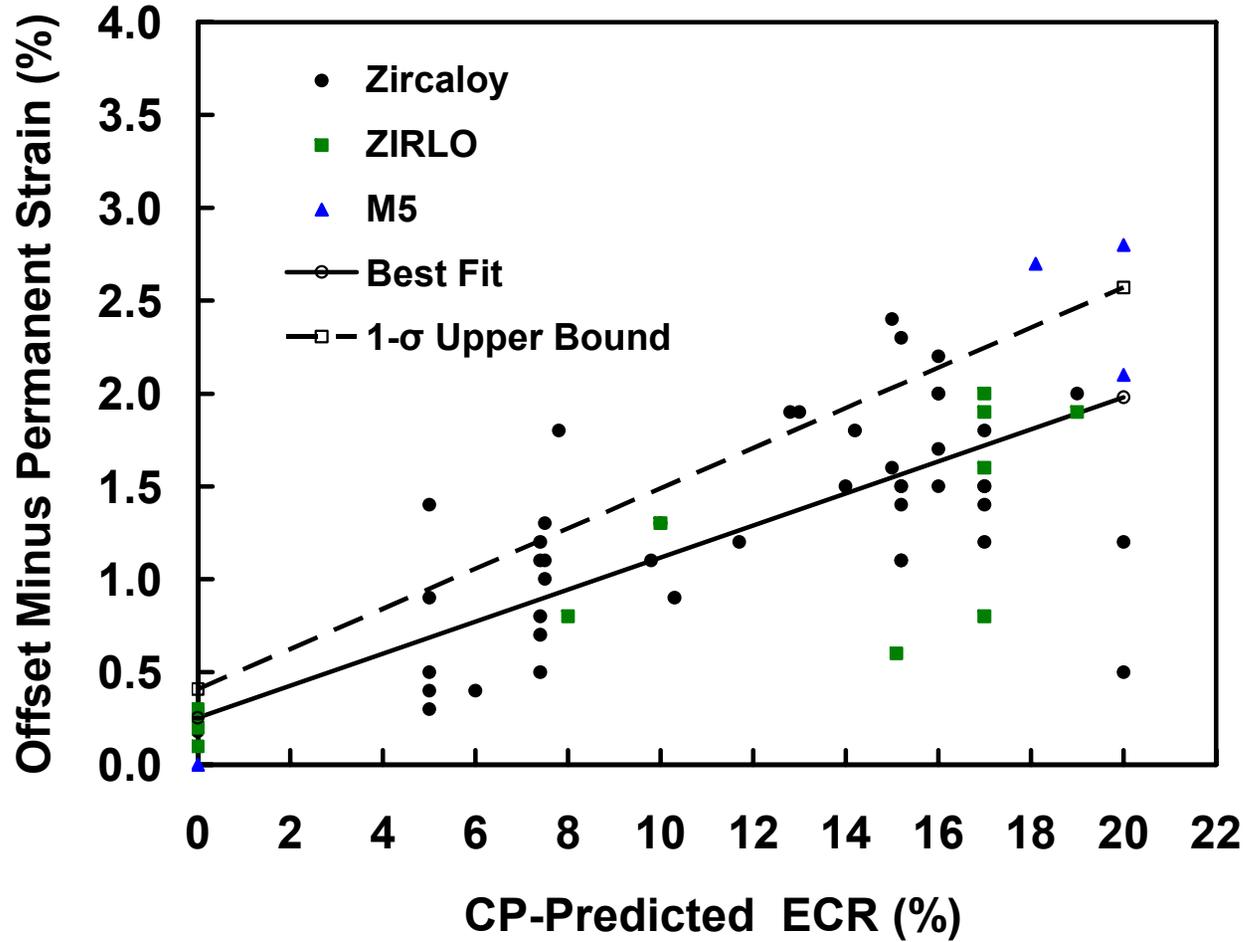


Figure A-1. Difference in offset strain and permanent strain as a function of calculated oxidation level (CP-ECR) for permanent strains near the embrittlement threshold (1.0% to 2.3%) for as-fabricated, prehydrided, and high-burnup cladding alloys oxidized at 1,200 °C and ring-compressed at RT and 135 °C and at 0.033 mm/s.

APPENDIX B

OVERVIEW OF ACCEPTABLE TEST MATRICES

Draft Regulatory Guide (DG)-1262, “Testing for Postquench Ductility,” provides a detailed test procedure that is acceptable for generating postquench ductility data through ring compression tests. This appendix is intended to provide a simple, straightforward overview of acceptable test matrices. The test matrix overviews provided in this appendix are consistent with the guidance in DG-1262.

This appendix will provide two examples. The first series of test matrices could be used to generate ring compression test data to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 degrees Fahrenheit (°F). The second series of test matrices could be used to generate ring compression test data to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide.

B-1. Overview of Sample Test Matrix To Generate Ring Compression Test Data To Establish an Alloy-Specific Limit or To Establish a Limit at a Peak Cladding Temperature Lower than 2,200 °F

The objective of postquench ductility testing to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 °F is to characterize a cladding alloy’s embrittlement behavior through the entire spectrum of conditions expected during operation. A diverse matrix of material conditions can provide a complete characterization, and repeat testing can be used to address expected variability in oxidation behavior. The test matrix to generate ring compression test data to establish an alloy-specific limit or to establish a limit at a peak cladding temperature lower than 2,200 °F provided here includes testing of as-received, prehydrated, and irradiated material.

As-received cladding material may be used to conduct scoping tests to identify the oxidation equivalent cladding reacted (ECR) where transition behavior likely occurs. Table B-1 provides a sample test matrix for this scoping test.

Table B-1. Sample Test Matrix for Scoping Tests for As-Received Cladding Material

Scoping test	Oxidation Level (ECR)	10% 			13% 			17% 			20% 		
	Ring compression Sample	1 	2 	3 	1 	2 	3 	1 	2 	3 	1 	2 	3 
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of 3 RTC samples	_____ %			_____ %			_____ %			_____ %		
	Average \geq Offset strain Criterion?	Offset strain Criterion of 10% ECR =	2.5	Yes / No	Offset strain Criterion of 13% ECR =	2.8	Yes / No	Offset strain Criterion of 17% ECR =	3.2	Yes / No	Offset strain Criterion of 20% ECR =	3.6	Yes / No

From the scoping test, a brittle result and a ductile result will likely be identified. For example, the average of three samples at 17% ECR may be determined to be ductile using the ductility criterion $\geq 1.0\%$ permanent strain or the offset strain criterion defined in Appendix A to this regulatory guide, while the average of three samples at 20% ECR may be determined to be brittle. Following the evaluation of results from the scoping tests, the next set of tests with as-received cladding material should be conducted within the range where the brittle and ductile results were observed, to identify the ECR at which the transition occurs. For example, if the average of three samples at 17% ECR was determined to be ductile, while the average of three samples at 20% ECR was determined to be brittle, the next set of tests should be conducted at 18% and 19% ECR. In the transition region, repeat tests provide improved characterization because of variability in oxidation behavior. Therefore, a sample test matrix for testing in this region includes multiple oxidation and quench tests at each oxidation level, as shown in Table B-2. The transition from ductile to brittle behavior should be identified to occur at the highest Cathcart-Pawel equivalent cladding reacted (CP-ECR) at which the permanent strain is $\geq 1.0\%$.

Table B-2. Sample Test Matrix for Testing As-Received Cladding Material in the Identified Transition Region

Transition Region	Oxidation Level (ECR)	18% 	18% 	18% 	19% 	19% 	19% 														
	Ring compression Sample																				
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %									_____ %										
	Average \geq Offset strain Criterion?	Yes / No									Yes / No										

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy’s oxidation embrittlement behavior. The entire range of a cladding material’s anticipated hydrogen level should be characterized. To characterize the range of a cladding material’s anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments not more than every 100 weight parts per million (wppm) of hydrogen. The test matrix below illustrates an acceptable test matrix for a cladding material that is anticipated to have a maximum hydrogen content of 400-wppm hydrogen at end of life. The embrittlement threshold provided in Figure 2 as a function of hydrogen content may be used as a guide in selecting the range of oxidation levels to be included in the test matrix. Table B-3 provides the embrittlement threshold in Figure 2 in tabular form for clarity. Table B-4 provides a sample test matrix for scoping the behavior of prehydrided material.

Table B-3. Tabulated Values for the Embrittlement Threshold in DG-1263

Hydrogen Content (wppm)	Embrittlement ECR
0	18%
100	15.5%
200	12%
300	9%
400	6%
500	5%
600	4%
700	3%
800	2%

Table B-4. Sample Test Matrix for Scoping Tests for Prehydrided Cladding Material

		100						200						300						400					
Scoping Tests	Hydrogen Level (wppm)	100						200						300						400					
	Oxidation Level (ECR)	1 st test at 15.5% 			If 15.5% was brittle, 2 nd test at 13.5% If 15.5% was ductile, 2 nd test at 17.5% 			1 st test at 12% 			If 12% was brittle, 2 nd test at 10% If 12% was ductile, 2 nd test at 14% 			1 st test at 9% 			If 9% was brittle, 2 nd test at 7% If 9% was ductile, 2 nd test at 11% 			1 st test at 6% 			If 6% was brittle, 2 nd test at 4% If 6% was ductile, 2 nd test at 8% 		
	Ring compression Sample	     						     						     						     					
	Offset Strain Measurement	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%	___%
	Average of RTC samples	_____ %			_____ %			_____ %			_____ %			_____ %			_____ %			_____ %					
	Average ≥ Offset strain Criterion?	Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			Yes / No					
	Ductile-to-brittle transition identified?	Yes - continue tests at ECR between ductile and brittle level; No - conduct test additional scoping tests						Yes - continue tests at ECR between ductile and brittle level; No - conduct test additional scoping tests						Yes - continue tests at ECR between ductile and brittle level; No - conduct test additional scoping tests						Yes - continue tests at ECR between ductile and brittle level; No - conduct test additional scoping tests					

The objective of the scoping tests for prehydrided material is to identify an ECR level at which ductile behavior is observed, and an ECR level at which brittle behavior is observed, and thus identify the range in which the ductile-to-brittle behavior is observed. Once this range of ECR levels is identified, the test matrix continues with testing at an ECR level between the ECR level at which ductile behavior is observed and the ECR level at which brittle behavior is observed. Table B-5 provides a test matrix that can be used at each hydrogen level to characterize embrittlement behavior at the ECR level at which the ductile-to-brittle transition is expected to occur.

Table B-5. Sample Test Matrix for Testing Prehydrated Cladding Material in the Identified Transition Region

Transition Region	Hydrogen Level	Repeat for each hydrogen level								
	Oxidation Level (ECR)	Transition ECR 	Transition ECR 	Transition ECR 						
	Ring compression Sample									
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %								
	Average \geq Offset strain Criterion?	Yes / No								

Irradiated cladding material can be used to demonstrate that a cladding alloy’s embrittlement behavior is accurately characterized by using prehydrated material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 100 wppm of half of the anticipated maximum hydrogen content. The test matrix below illustrates an acceptable test matrix for a cladding material that is anticipated to have a maximum hydrogen content of 400-wppm hydrogen at end of life. Table B-6 provides a sample test matrix for demonstrating that a cladding alloy’s embrittlement behavior is accurately characterized by using prehydrated material.

Table B-6. Sample Test Matrix for Testing Irradiated Cladding Material

Irradiated Testing	Hydrogen Level	Licensed Hydrogen Limit \pm 50 w ppm									Half of Licensed Hydrogen Limit \pm 50 w ppm									
	Oxidation Level (ECR)	Transition ECR		Transition ECR + 1%		Transition ECR - 1%		Transition ECR		Transition ECR + 1%		Transition ECR - 1%								
	Ring compression Sample																			
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %			_____ %			_____ %			_____ %			_____ %			_____ %			
	Average \geq Offset strain Criterion?	Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			
	Ductile-to-brittle transition comparable to pre-hydrided material?	Yes / No									Yes / No									

B-2. Overview of Sample Test Matrix To Generate Ring Compression Test Data To Demonstrate Consistency with the Analytical Limit Provided in DG-1263

The objective of postquench ductility testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide is to confirm that the transition to brittle behavior does not take place at a lower ECR than the provided limit. Because of this, the matrix of material conditions and oxidation levels can be significantly reduced from the matrix outlined in the previous section. A range of material conditions can serve to provide a characterization through the spectrum of conditions expected during operation, and repeat testing can be used to address expected variability in oxidation behavior. The test matrix provided here to generate ring compression test data to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide includes testing of as-received, prehydrided, and irradiated material. The transition from ductile to brittle behavior should be identified to occur at the highest CP-ECR at which the permanent strain is $\geq 1.0\%$. Consistency with the analytical limit provided in Figure 2 of this regulatory guide would be considered demonstrated when the transition from ductile to brittle behavior is not lower than the provided limit.

Prehydrided cladding material may be used to characterize the effect of hydrogen on an alloy’s oxidation embrittlement behavior. The entire range of a cladding material’s anticipated hydrogen level should be characterized. To characterize the range of a cladding material’s anticipated hydrogen content, an acceptable approach would be to determine the ductile-to-brittle transition for prehydrided material in increments

not more than every 100 wppm of hydrogen. The test matrix in Table B-7 illustrates an acceptable test matrix for a cladding material that is anticipated to have a maximum hydrogen content of 400-wppm hydrogen at end of life. The analytical limit provided in Figure 2 of this regulatory guide as a function of hydrogen content may be used as a guide in selecting the range of oxidation levels to be included in the test matrix. Table 3 of this regulatory guide provides the embrittlement threshold in Figure 2 in tabular form for clarity.

Irradiated cladding material can be used to demonstrate that a cladding alloy’s embrittlement behavior is accurately characterized by using prehydrided material. To demonstrate this, an acceptable approach would be to determine the ductile-to-brittle transition for irradiated material with hydrogen contents within 50 wppm of the anticipated maximum hydrogen content and within 100 wppm of half of the anticipated maximum hydrogen content. Table B-7 illustrates an acceptable test matrix for a cladding material that is anticipated to have a maximum hydrogen content of 400 wppm hydrogen at end of life.

Table B-7 provides a complete test matrix, including as-received, prehydrided, and irradiated material, acceptable to the NRC for using in postquench ductility testing to demonstrate consistency with the analytical limit provided in Figure 2 of this regulatory guide.

Table B-7. Sample Test Matrix for Testing As-Received, Prehydrided, and Irradiated Cladding Material To Demonstrate Consistency with the Analytical Limit Provided in Figure 2 of DG-1263

As-Received and Pre-hydrided Testing	Hydrogen Level (wppm)	As-Received									100 w ppm								
	Oxidation Level (ECR)	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1%	Transition ECR - 1%	Transition ECR from Fig.2	Transition ECR + 1%	Transition ECR - 1%	Transition ECR from Fig.2	Transition ECR + 1%	Transition ECR - 1%			
	Ring compression Sample																		
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %			_____ %			_____ %			_____ %			_____ %			_____ %		
	Average ≥ Offset strain Criterion?	Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			Yes / No		
	Ductile-to-brittle transition at or above limit of Fig.2?	Yes / No									Yes / No								

As-Received and Pre-hydrated Testing	Hydrogen Level (wppm)	200									300														
	Oxidation Level (ECR)	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 																		
	Ring compression Sample																								
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %			_____ %			_____ %			_____ %			_____ %			_____ %								
	Average ≥ Offset strain Criterion?	Yes / No			Yes / No			Yes / No			Yes / No			Yes / No			Yes / No								
	Ductile-to-brittle transition at or above limit of Fig.2?	Yes / No									Yes / No														

As-Received and Pre-hydrated Testing	Hydrogen Level (wppm)	400								
	Oxidation Level (ECR)	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 						
	Ring compression Sample									
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %
	Average of RTC samples	_____ %			_____ %			_____ %		
	Average ≥ Offset strain Criterion?	Yes / No			Yes / No			Yes / No		
	Ductile-to-brittle transition at or above limit of Fig.2?	Yes / No								

Irradiated Material Testing	Hydrogen Level (wppm)	Licensed Hydrogen Limit \pm 50 wppm									Half of Licensed Hydrogen Limit \pm 50 wppm								
	Oxidation Level (ECR)	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 	Transition ECR from Fig.2 	Transition ECR + 1% 	Transition ECR - 1% 			
	Ring compression Sample																		
	Offset Strain Measurement	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %	___ %			
	Average of RTC samples	_____ %			_____ %			_____ %			_____ %			_____ %					
	Average \geq Offset strain Criterion?	Yes / No			Yes / No			Yes / No			Yes / No			Yes / No					
	Ductile-to-brittle transition at or above limit of Fig.2?	Yes / No									Yes / No								