framatome

Realistic Thermal-Mechanical Fuel Rod Methodology For Boiling Water Reactors
Supplement 2: Mechanical Methods Additional Information

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Topical Report

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Framatome Inc.

Summary

Framatome Inc. (f/k/a AREVA Inc.) is requesting approval to use Zry-2 recrystallized (RXA) material for cladding and Z4B™ material for water channels in addition to approval for the use of various mechanical models with this topical report. A telephone call was held with the NRC staff on December 15, 2017 and Framatome agreed to provide the following additional information:

1) Additional text in the topical report to clarify the use of the mechanical models for Zry-2 RXA cladding.
2) A description of the material properties of Z4B™ and the mechanical analysis that would be performed for Z4B™ water channels in addition to fuel assembly growth.
3) A summary of the additional data that Framatome has gathered for Z4B™ water channel fuel assembly growth and of the recalculation of the growth model.

The additional information is provided in the form of markup pages for the topical report. To address item 1 above, the application of the rod bow model and rod growth model to RXA cladding has been clarified with markups to Appendices A and B, respectively. A new Appendix D is provided to address item 2. Markup pages for Appendix C are provided to address item 3. Markups of various pages in the topical report are provided to clarify that we will use both Zry-2 CWSR and RXA for cladding and Zry-4 and Z4B™ will be used for water channels.

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fuel rod exposure limit for the realistic fuel rod thermal-mechanical methodology has been established in Reference 1.

The mechanical methods described in this report will be applied to all BWR fuel designs. The fuel rod cladding will be either Zry-2 SRA or RXA cladding. The water channel will be made from either Zry-4 or Z4B™[1] material.

[1] Z4B is a trademark of AREVA Inc.

correlations for fuel rod bow, fuel rod growth, and fuel assembly growth due to the incorporation of recent operating experience data. Note that the fuel rod growth correlation presented in this supplement is based on the total axial rod growth measured in post-irradiation exams, and therefore does not affect the RODEX4 stress-free irradiation growth model in Reference 1.

The rod bow correlation is constructed from fuel rod-to-rod gap closure data measured on a broad selection of AREVA BWR fuel designs in varied operating environments. The rod-to-rod gap closure predicted as a function of fuel assembly exposure is used as an input to thermal limit evaluations (i.e. MCPR) for AREVA BWR fuel designs.

The BWR rod growth correlation is updated with the most recent data from AREVA's Zircaloy-2 stress-relief annealed (SRA) cladding, [

] . The BWR fuel assembly growth correlation is built from post-irradiation length measurement data taken from ATRIUM™[1] fuel assemblies. This model is applicable to all ATRIUM™ fuel assembly designs for which assembly growth is controlled by the water channel growth, including the ATRIUM™ 11 with Z4B™~~[2]~~ water channels. The combination of the fuel rod and assembly growth correlations is used to define the maximum fuel rod length which will not interfere with the upper tie plate at end of life. This is the only mechanical method defined in this report which is limiting at end of life, and the growth databases support the maximum requested fuel assembly exposure limit.

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1 ATRIUM is a trademark of AREVA Inc.

~~2 Z4B is a trademark of AREVA Inc.~~

4.0 ANALYTICAL METHODOLOGY

4.1 *Mechanical Methods*

The methods described in this section cover the topics included in SRP Section 4.2 II.1.A for fuel system damage except those already addressed in the base topical report (Reference 1). These methods support AREVA's generic BWR fuel design criteria approved in Reference 3 throughout the design lifetime of the fuel and cover handling, normal operation and AOO conditions. The only changes to the previously approved BWR fuel mechanical methods are updates to fuel rod bow, fuel rod growth, and fuel assembly growth correlations and extension to Zry-2 RXA cladding and Z4B™ water channels.

4.1.1 Stress, strain or loading limits

The strength of the fuel assemblies and fuel rods is assured by evaluating the margin to conservative stress and deformation design limits under various shipping, handling and operational loads. The loads are applied to the fuel rod cladding, upper and lower tie plates, grid spacers, water channel (or tie rods) and connecting hardware, fuel assembly cage and springs where applicable. AREVA defines a maximum axial handling design load equivalent to [ ].

As described in Reference 3, AREVA uses Section III of the ASME Boiler and Pressure Vessel Code as guidance for establishing the acceptable stress, strain, or load criteria for assembly components and the corresponding analysis methods which may be used to evaluate those criteria. These methods include elastic and plastic analysis techniques as well as load rating from prototype testing. Analysis methods include use of conventional, open-literature equations, elasticity formulations, general purpose finite element stress analysis codes such as ANSYS, or testing.

The minimum specified yield and ultimate strength for unirradiated material are used in the analyses. This is a conservative assumption since strength will increase under

irradiation. Since loads often stay the same or decrease over time, the beginning of life (BOL) strength evaluations tend to be the most limiting. This is true even when the material loss due to oxidation that would be expected at end of life (EOL) is factored in. The oxide is either insignificant, as observed on stainless steel and nickel alloy components; or the oxide is on relatively thick components such as the ~~Zircaloy~~ zirconium alloy water channel and fuel channel. Zircaloy fuel rod cladding (SRA or RXA) is the only component with a specific EOL analysis requiring the assumed loss of material due to corrosion. However, even in this case the EOL analysis is not limiting due to the reduced loads at EOL.

While all load bearing fuel assembly components have some analysis or test to validate that criteria are met for the given design loads, a few of the components have standard evaluations as described below.

4.1.1.1 Fuel rod cladding

Various normal operation and AOO loads create stresses on the fuel rod cladding. Each individual stress is calculated at the inner and outer surfaces of the cladding at both the mid-span between spacer grids and at the spacer grid. The stresses at each location are then combined to determine the maximum stress intensities. The analysis is performed at BOL and EOL and at cold and hot conditions with unirradiated material strength. The stress analysis assumes maximum fuel rod power, minimum fill gas pressure, and the most conservative fuel rod geometry including a reduced wall thickness at EOL due to oxidation. The methods are applicable to both Zry-2 SRA and RXA cladding.

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] The cladding stress analysis method has not changed from what was documented in Section 3.4.3 of Reference 4. The stress calculations use conventional,

Flow testing is used to confirm acceptable bypass flow characteristics. The seal spring is designed with adequate deflection range for accommodating the maximum expected channel bulge while maintaining an acceptable leakage rate. Seal spring stresses are analyzed using a finite element method or handbook equations.

4.1.2 Strain fatigue

Fatigue of structural components is generally low because the cyclic loadings on the structural components typically have either a small number of cycles (i.e. reactor startup) or small amplitude (i.e. flow-induced vibration). Cyclic loading associated with relatively large changes in power can cause cumulative damage which may eventually lead to fatigue failure. The O'Donnell and Langer fatigue curves are used in the analysis of ~~Zircaloy~~ zirconium alloy components (Reference 7). These fatigue curves incorporate the NRC recommended "2 or 20" safety factor. This safety factor reduces the stress amplitude by a factor of two or reduces the number of cycles by a factor of twenty, whichever is more conservative. The fatigue curves provide the maximum allowed number of cyclic loadings for each stress amplitude. The fatigue usage factor is the number of expected cycles divided by the number of allowed cycles. The total cumulative usage factor is the sum of the individual usage factors for each duty cycle.

4.1.3 Fretting wear

Fretting wear is a concern for the fuel rod cladding. Fretting wear may occur on the fuel cladding surfaces in contact with the spacer grids if there is a reduction in grid spacer spring loads in combination with small amplitude, flow induced, vibratory forces.

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APPENDIX A BWR FUEL ROD BOW CORRELATION

Introduction

AREVA has gathered post-irradiation rod-to-rod gap closure measurements from a variety of BWR fuel designs as shown in Figure A-1. Both the absolute and the percent gap closure data for all measured AREVA BWR designs (7x7, 8x8, 9x9, and 10x10) reveal [

] This new correlation will provide a bounding estimation of fuel rod-to-rod gap closure that will be used for all current and future AREVA BWR fuel designs in the United States for both SRA or RXA cladding.

Measurement Description

AREVA has conducted PIE campaigns both in the U.S. and in Europe to collect fuel rod-to-rod gap measurements. This global database contains fuel rods with both SRA and RXA cladding. The fuel rod-to-rod gap database includes AREVA's legacy designs with 7x7, 8x8, and 9x9 rod arrays which are no longer in operation, and also the ATRIUM™-10 design still in use today.

Fuel rod-to-rod gap measurements are typically taken at each span between spacer grids (usually 8 spans) and at each fuel rod-to-rod gap. In addition, measurements can

APPENDIX B BWR FUEL ROD GROWTH CORRELATION

Introduction

The fuel rod growth correlation was most recently approved in 1998 using Zircaloy-2 (Zry-2) Stress Relief Annealed (SRA) growth data obtained from post irradiation examination (PIE) campaigns. This correlation has been updated to include the Zry-2 SRA rod growth data obtained from PIE campaigns since 1998. It is also conservative to use this rod growth correlation for Zry-2 RXA cladding since it has been observed to have less axial growth than SRA cladding.

Measurement Description

Figure B-1 shows the fuel rod growth correlation containing the data presented in the rod growth correlation from 1998, the data in open blue markers, as well as the new data collected since 1998, the closed red markers. The data include fuel rods from 7x7, 8x8, 9x9 and 10x10 arrays (ATRIUM™-10). [

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Correlation Development

The fuel rod growth data (expressed as percent of active fuel length) versus assembly average burnup is shown in Figure B-1. [

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Summary

The results of the fuel rod growth linear correlation are summarized in Table B-1. The maximum fuel assembly exposure level represented by the data is [

] Based on the data and similarity in manufacturing processes, the BWR rod growth correlation is fully applicable to AREVA BWR fuel rod designs with SRA and RXA Zry-2 cladding.

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Table C-1 BWR Fuel Assembly Growth Correlation

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[

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Figure C-1 BWR Fuel Assembly Growth Correlation

APPENDIX C REFERENCES

C-1 Factors for One-Sided Tolerance Limits and For Variables Sampling Plans, D. B. Owen. Sandia Corporation Monograph (SRC-607), March 1963.

APPENDIX D Z4B™ WATER CHANNEL ASSEMBLY

Introduction

BWR fuel assemblies have used a zirconium alloy tie structure for several decades. The tie structure can consist of fueled tie rods, water rods, a water channel, or a fuel channel. Most BWR fuel designs have used either Ziraloy-2 or Zircaloy-4 alloys as defined in ASTM B352/B352M (Reference D-1) for fuel channels with acceptable performance. However, the behavior of these alloys can be improved for use in the tie structure. More corrosion occurs on Zircaloy-4 than Zircaloy-2 in a BWR coolant environment, and there is a higher hydrogen pickup fraction in Zircaloy-2 than Zircaloy-4. The ideal alloy would have both low corrosion and low hydrogen pickup. A proprietary zirconium alloy has been developed, Z4B™, which optimizes the alloying element concentrations for improved corrosion and hydrogen pickup when used for a BWR fuel structural component. This appendix provides additional information on Z4B™ and its application to a water channel assembly used as part of a BWR fuel assembly tie structure.

Alloy Composition

The composition of Z4B™ is shown in Table D-1 and is similar to that of Zircaloy-4 (Zry-4) as defined in ASTM B352/B352M (Reference D-1), though Z4B™ has slightly higher iron (Fe) and chromium (Cr) contents. [

] Both alloys are composed of about 98 wt% zirconium and have a hexagonal crystal structure at room and service temperatures. The small differences in composition between Z4B™ and Zry-4 do not result in any significant differences in fabrication methods or processes.

Table D-1 Alloy Composition

Element	Composition (weight percent)	
	Zry-4 (UNS R60804)	Z4B™
Zirconium (Zr)	~ 98	~ 98
Tin (Sn)	1.20 – 1.70	[ ]
Iron (Fe)	0.18 – 0.24	[ ]
Chromium (Cr)	0.07 – 0.13	[ ]
Nickel (Ni)	-	[ ]

The motivation for increasing Fe and Cr in Z4B™ is to improve the corrosion resistance and hydrogen uptake relative to Zry-4. Industry experience indicates that increases in Fe and Cr act to reduce the corrosion rate of Nb-free alloys such as Zry-4 and Z4B™ (Reference D-2). Table D-2 indicates that the "best alloy content" for Fe is greater than 0.3% and for Cr is above 0.15 % with respect to corrosion resistance and hydrogen pickup fraction. These values compare well with the ranges listed above for Z4B™ (Table D-1). As indicated in Table D-2, the solubility of Fe and Cr in the zirconium matrix is very low, which means that these elements exist primarily in second phase particles (SPPs). Given the similarity in composition and crystal structure of Z4B™ and Zry-4, that the solubility of Fe and Cr in the alloy matrix is similar for these alloys, the additional concentrations of these elements in Z4B™ could result in a larger number of SPPs, a larger average SPP size, or both depending on the details of material processing. The processing of Z4B™ targets [ ]. The superior corrosion and hydrogen uptake performance of Z4B™ relative to Zry-4 has been demonstrated through a material test program for Z4B™ spacer grids and recent measurements collected on Z4B™ Lead Use Fuel Channels (Reference D-3).

Table D-2 Effect of Alloying Elements on Corrosion of Zirconium Alloys (Reference D-2)

Element	Solubil. (%)	Best alloy content (%)	Out-pile corrosion	In-PWR corr.	LiOH corr.	In-BWR corr.	HPUF
Sn	2	0/>1	—	=	+ +	+	0
Nb	0.5	0.5/>2	+ +	+ +	0	—/+	+/0
Fe	<0.01	≥0.3	+ +	+ +	+ +	+	0/+
Cr	<0.01	≥0.15	+/—	+	+ +	+	+ (>0.15)
Ni	<0.01	0.05	+ +	+		+	=/0
V	<0.01	≥0.15	+/—	+	+ +	+	+
Cu	<0.1	≥0. 5	+				0
0: no effect, — increase, = strong increase, + reduction, ++ strong reduction, 0/+ effect differs in different environments.							

Water Channel Assembly

The water channel is made from sheet material and formed into the shape of a square duct with rounded corners. End fittings are welded to the ends of the water channel which allow the upper and lower tie plates to be secured to the water channel assembly. Inlet and outlet holes in the end fittings permit the flow of single-phase water through the water channel. Spacer stops are welded to the sides of the water channel to control the axial position of the spacer grids. The water channel plus the spacer stops and end fittings constitute the water channel assembly. See Figure D-1 for an illustration. Although not shown in the figure, some water channel assemblies also have 'crowns' which are thin metallic strips welded to the water channel with the purpose of diverting single-phase water toward the fuel rods. All water channel assembly components are made from a zirconium alloy, i.e. Z4B™.

The structural tie between the lower tie plate (LTP) and the upper tie plate (UTP) is provided by the water channel assembly. Within the ATRIUM™ family of BWR fuel designs, there have been a few variations of the water channel assembly design. Currently the upper end fitting contains an integrated connecting rod which extends

from the water channel up to the UTP locking hardware. The LTP is secured to the water channel lower end fitting by a threaded connection. Large cross-sectional threaded fasteners and connecting hardware ensure a strong connection between the two tie plates.

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Figure D-1 Water Channel Assembly

Design Loads and Requirements

The generic design criteria for BWR fuel designs have been defined in Reference D-4. Requirements for the fuel design have been developed based on the guidance in the Standard Review Plan, including some specific requirements related to the tie structure. The specific requirements applicable to the tie structure have been defined in Section 3.3.1 of Reference D-4 for stress, strain or loading limits, Section 3.3.6 for axial growth, and Section 3.3.9 for fuel assembly handling (see Table D-3 which quotes the criteria from Reference D-4).

Table D-3 Generic BWR Design Criteria Applicable to the Tie Structure during Handling, Normal Operation, and AOO (Reference D-4)

Section in Ref. D-4	Topic	Criteria
3.3.1	Stress, Strain, or Loading Limits	[ ]
3.3.6	Axial Irradiation Growth	[ ]
3.3.9	Fuel Assembly Handling	[ ]

The primary mechanical function of the BWR fuel assembly tie structure is to allow the fuel assembly to be lifted by a grapple attached to the upper tie plate. However, the Fuel Handling Accident evaluation assumes the fuel assembly is dropped over the core which could occur either from a crane failure or a break of the fuel assembly tie structure itself. In order to provide substantial design margin against such an accident occurring, Section 3.3.9 of Reference D-4 provides a fuel assembly handling requirement that a test or analysis of the assembly must not [

].

Of more significance to safety performance is that the tie structure maintains an acceptable dimensional configuration in the core during normal operation and anticipated operational occurrences (AOO). The design loads are small and consist mostly of component weight, friction forces transmitted through spacer grids, and hydraulic differential pressure. These loads are analyzed against the strength requirements listed in Table D-3. In addition, a dimensional analysis must be performed to ensure the deformation caused by these loads (including the effects of thermal expansion, growth, and creep) do not significantly affect design engagements and clearances. There are no significant cyclic loads so a break due to fatigue is not a concern.

Analytical Methods

The mechanical analytical methods have been described in Section 4 of this topical report. Section 4.1.1 describes the general strength evaluations which include those performed for the water channel assembly to demonstrate that the stress, strain, and loading limit criteria (including fuel handling) defined above in Table D-3 are met. The use of Z4B™ material has no significant impact on either the method or calculated margins for these evaluations.

As discussed in Section 2 of this topical report, the composition of Z4B™ differs from ASTM Zry-4 only by slight increases in Fe and Cr. Both alloys are composed of about 98 wt% zirconium and have a hexagonal crystal structure at room and service temperatures. Based on these considerations, there are negligible differences in basic material properties (e.g., elastic moduli, heat capacity, thermal expansion, thermal conductivity, density, etc.) between Z4B™ and Zry-4. The minimum specified strengths are used in the analyses. As shown in Table D-4, the minimum mechanical property requirements for Z4B™ water channel strip are the same as or higher than those for Zry-4 water channel strip. There is no difference in the specification limits for end plug barstock. Therefore, the use of Z4B™ in place of Zry-4 for these components will not result in a reduction in strength margins. The strength analyses are also dependent on corrosion and related wall thinning. As discussed in Section 2, the compositional increases in Fe and Cr result in superior corrosion resistance and lower hydrogen uptake of Z4B™ relative to Zry-4. Therefore, the corrosion and hydrogen embrittlement behavior of Z4B™ components will be bounded by that of Zry-4 components.

Table D-4 Unirradiated Strength Specifications for Zry-4 and Z4B™

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General fit-up and deformation analyses are performed at BOL and EOL conditions to demonstrate that adequate engagements and clearances are maintained throughout the fuel assembly lifetime as described in Section 4.1.5. The methodology for axial growth is described in Section 4.1.5.2 which demonstrates that the criteria for axial irradiation

growth defined in Table D-3 are met. The assembly growth correlation with Z4B™ water channels is documented in Appendix C.

Testing of unirradiated, recrystallized Zry-2, Zry-4, and Z4B™ has shown that differences in alloy composition between these materials have no significant effect on creep rate. [

]. Overall, the difference is not judged to be significant, and it remains conservative to use the creep rate already defined for Zry-2 and Zry-4 fuel channel material in Reference D-5.

APPENDIX D REFERENCES

D-1. ASTM B352/B352M, *Standard Specification for Zirconium and Zirconium Alloy Sheet, Strip, and Plate for Nuclear Application.*

D-2. Rudling, P., Zr Alloy Corrosion and Hydrogen Pickup. A.N.T. International. NRC Accession Number: ML15253A227. 2013.

D-3. ANP-10336P-A, Revision 0, "Z4B™ Fuel Channel Irradiation Program," AREVA NP, July 2017.

D-4. ANF-89-98(P)(A) Revision 1 and Supplement 1, "Generic Mechanical Design Criteria for BWR Fuel Designs," Advanced Nuclear Fuels, April 1995.

D-5. EMF-93-177 Revision 1 Supplement 1(P)(A), "Mechanical Design for BWR Fuel Channels, Supplement 1: Advanced Methods for New Channel Designs," AREVA NP, September 2013.