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Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis (Departure from Nucleate Boiling Mechanistic Propagation Methodology)

Westinghouse

WCAP-8964-A Addendum 1

Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis (Departure from Nucleate Boiling Mechanistic Propagation Methodology)

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Abstract

WCAP-8964-A, "Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis" (Reference 1), defines the approach currently employed by Westinghouse Electric Company LLC (Westinghouse) to assess Departure from Nucleate Boiling (DNB) Propagation for its various fuel rod designs. The approach described therein is statistically based. This addendum promotes the best practices of all other Westinghouse business segments and is part of the overall Westinghouse integration process. This addendum to WCAP-8964-A describes an alternate approach for assessing DNB propagation which has been previously licensed by CE for its fuel designs. This alternative, which is mechanistically based, is described in topical report CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure" (Reference 3) and revalidated in CENPD-404-P-A, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs" (Reference 5) for its applicability to ZIRLO™ cladding material. Westinghouse intends to adopt the mechanistic approach without change from its licensed form. Westinghouse has demonstrated, herein, that the previously licensed mechanistic approach is applicable to Westinghouse specific fuel design features which are principally geometric differences in fuel dimensions. As with the CE licensed application, this approach applies to both Zircaloy-4 and ZIRLO™ fuel designs. (ZIRLO™ as stated herein refers to the current licensed ZIRLO™ and Optimized ZIRLO™ as justified in WCAP-12610-P-A/CENPD-404-P-A, Addendum 1, Reference 7).

This addendum justifies the applicability of the previously licensed mechanistic DNB propagation approach to Westinghouse fuel designs including the range of applicability and the acceptance criteria values relevant to Westinghouse fuel designs. Typical example analyses of the mechanistic approach applied to Westinghouse designs are also provided.

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Acronyms

CE	Combustion Engineering
DNB	Departure from Nucleate Boiling
DNBR	Departure from Nucleate Boiling Ratio
GAD or Gd	Gadolinia
IFBA	Integrated Fuel Burnable Absorber
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RIP	Rod Internal Pressure
SAFDL	Specified Acceptable Fuel Design Limit
SRP	Standard Review Plan (NUREG-0800)
Westinghouse	Westinghouse Electric Company LLC

Definitions

Condition I: **Normal Operation**. Condition I occurrences are those that are expected to occur frequently or regularly in the course of power operation, refueling, maintenance, or maneuvering of the plant. As such, Condition I occurrences are accommodated with margin between any plant parameter and the value of that parameter which would require either automatic or manual protective action. Since Condition I events occur frequently, they must be considered from the point of view of their effect on the consequences of fault conditions (Conditions II, III, and IV). In this regard, analysis of each fault condition described is generally based on a conservative set of initial conditions corresponding to adverse conditions which can occur during Condition I operation.

Condition II: **Faults of Moderate Frequency**. These faults, at worst, result in the reactor trip with the plant being capable of returning to operation. By definition, these faults (or events) do not propagate to cause a more serious fault, i.e., Condition III or IV events. In addition, Condition II events are not expected to result in fuel rod failures, reactor coolant system failures, or secondary system overpressurization.

Condition III: **Infrequent Faults**. Condition III events are faults which may occur infrequently during the life of the plant. They may result in the failure of only a small fraction of the fuel rods. The release of radioactivity will not be sufficient to interrupt or restrict public use of those areas beyond the exclusion area boundary, in accordance with the guidelines of 10 CFR 100. A Condition III event alone will not generate a Condition IV event or result in a consequential loss of function of the reactor coolant system or containment barriers.

Condition IV: **Limiting Faults**. Condition IV events are faults which are not expected to take place but are postulated because their consequences would include the potential of the release of significant amounts of radioactive material. They are the most drastic faults which must be designed against and they represent limiting design cases. Condition IV faults are not to cause a fission product release to the environment resulting in doses in excess of guideline values of 10 CFR 100. A single Condition IV event is not to cause a consequential loss of required functions of systems needed to cope with the fault, including those of the ECCS and the containment.

1.0 Introduction

The purpose of this submittal is to obtain generic approval for an alternative approach for evaluating Departure from Nucleate Boiling (DNB) propagation in Westinghouse Electric Company LLC (Westinghouse) fuel designs.

WCAP-8964-A, "Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis" (Reference 1), defines the approach currently employed by Westinghouse to assess DNB propagation for its various fuel rod designs. The approach described therein is statistically based. This addendum promotes the best practices of all other Westinghouse business segments and is part of the overall Westinghouse integration process. This addendum to WCAP-8964-A describes an alternate approach for assessing DNB propagation which has been previously licensed by CE for its fuel designs. This alternative, which is mechanistically based, is described in topical report CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure" (Reference 3) and revalidated in CENPD-404-P-A, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs" (Reference 5) for its applicability to ZIRLO™ cladding material. Westinghouse intends to adopt the mechanistic approach without alteration from its previously licensed form, except where necessary to account for Westinghouse specific fuel design features which are principally geometric differences in fuel dimensions. As with the CE licensed application, this approach is applicable to both Zircaloy-4 and ZIRLO™ fuel designs. (ZIRLO™ as stated herein refers to the current licensed ZIRLO™ and Optimized ZIRLO™ as justified in WCAP-12610-P-A/ CENPD-404-P-A, Addendum 1, Reference 7).

The current accepted practice is to assume that rods predicted to be in DNB fail. Consequently, if DNB is predicted to occur, fuel failure is assumed and the consequences of the radiological dose are considered. DNB is not allowed during normal operation or anticipated operational occurrences (i.e., Condition I and II events). During normal operation there is a potential for some portion of the fuel rods to achieve internal gas pressures that are in excess of the external RCS pressure. During a postulated DNB transient, the surface temperature of a fuel rod may increase significantly, resulting in a potentially significant increase in creep rate. If the fuel rod experiences both DNB and high internal pressure conditions, the potential exists for clad ballooning to occur, thereby degrading heat transfer from adjacent fuel rods. Under such conditions, the adjacent fuel rods are assumed to experience DNB as well and the DNB propagation phenomenon is initiated.

This addendum justifies the applicability of the previously licensed mechanistic DNB propagation approach to Westinghouse fuel designs including the range of applicability and the acceptance criteria values relevant to Westinghouse fuel designs. Typical example analyses of the mechanistic approach applied to Westinghouse designs are also provided.

1.1 Assumptions and Range of Applicability

The assumptions and range of applicability of this mechanistic DNB propagation approach to Westinghouse designs are as follows:

- Applicable for any transient conditions falling within the licensed range of applicability of the cladding high temperature creep and burst models,
- Applicable for Westinghouse rod and lattice geometries ranging from rod diameters of [ ] a, b, c, and rod pitches from [ ] a, b, c,
- Applicable to calculated cladding ballooning strains up to [ ] a, c,
- Applicable to current licensed codes and methods, and
- Applicable to Zircaloy-4 and ZIRLO™ fuel designs.

2.0 Current Criterion

The DNB propagation criterion has been established in WCAP-8964-A to address the NRC criterion in the Standard Review Plan (SRP) Section 4.2.II.A.1.(f),

> "Fuel and burnable poison rod internal gas pressures should remain below the nominal system pressure during normal operation unless otherwise justified."

In WCAP-8964-A, a pressure design criterion has been justified and accepted by the NRC under which the fuel rod internal pressure is permitted to exceed system pressure. The pressure design criterion that has been established states that RIP will not cause extensive DNB propagation to occur. This criterion will not change based on the alternate approach to analyze DNB propagation.

3.0 Current Approach

The current approach in WCAP-8964-A, used for analyzing the potential for DNB propagation, is based on a statistical convolution of probabilities of a fuel rod simultaneously experiencing DNB and an elevated internal pressure greater than system pressure. Specifically, the analysis assumes that if [

] a, c, during a

Condition III or IV transient. If [

] a, c, thus,

propagating the DNB process.

4.0 Mechanistic Approach

A mechanistic DNB propagation methodology has been previously developed and licensed (References 3 and 5). The mechanistic high temperature creep and rupture correlations described in Sections 5.1 and 5.2 are used to determine total accumulated strain during a DNB transient. If the strain exceeds the strain criterion defined in Section 5.3, DNB propagation to the adjacent fuel rods is assumed to occur.

Incremental cladding high temperature creep strain is calculated using [

]^{a,c}. The time-dependent DNB transient local properties are obtained from the appropriate licensed transient analysis methodology for any given plant. These inputs include time, heat flux, quality, mass flow, system pressure, rod internal pressure, and fuel rod initial geometry.

The input heat flux, rod internal pressure and flow conditions are utilized to calculate the local cladding temperature and differential cladding stress. The temperature and stress are then input to the high temperature creep model. The calculated [

]^{a,c} of the DNB transient. The resultant output is the [ ]^{a,c} strain incurred by the rod.

To evaluate the potential for DNB propagation against the design criteria, the plant's limiting Condition III and IV transients are used. The transients inputs are generated using NRC licensed codes and methods. In general, the most limiting transients would be ones which occur for the longest duration, highest heat flux, lowest flow, highest rod internal pressure, lowest system pressure, and lowest DNBR, or some combination thereof.

For Condition I and II events, DNB propagation is precluded by meeting the DNB design limits. Condition I and Condition II events are limited to a steady state and transient strain value. The Condition I and Condition II strain limits are significantly less than the allowable clad strain specified herein for a Condition III or Condition IV transient. In conclusion, only Condition III and IV events need to be analyzed.

5.0 Application to Westinghouse Fuel Designs

The application of the mechanistic DNB propagation approach to Westinghouse designs is nearly identical to that licensed for CE designs in References 3 and 5. The only differences exist in supplying the transient inputs and application of the appropriate cladding creep models.

[

]^{a,c} be supplied from a plant specific licensed methodology. There is no feedback from the output of this analysis into any other design calculations or safety analyses, unless it is shown that the limits cannot be met in which case, additional radiological analyses may be required.

The Westinghouse specific high temperature creep model for ZIRLO™ has already been used in this approach in CE designs (Reference 5). Therefore, the only difference in creep models would apply to Zr-4. Both CE and Westinghouse have licensed similar high-temperature creep models for Zr-4 (References 1 and 3), therefore, when using this approach on Westinghouse designs with Zr-4, the appropriate licensed creep model (Reference 10) will be used.

The following sections summarize the application of the mechanistic approach to Westinghouse fuel designs.

5.1 High Temperature Creep Models

For the example discussion, the details of the high temperature creep behavior of ZIRLO™ cladding are included below. However, the application of this approach may be used with any cladding material given that the appropriate licensed high temperature creep model is used.

The high temperature creep behavior of ZIRLO™, used in mechanistic DNB propagation evaluations is based on the licensed model for Westinghouse in Reference 6 and is based on the licensed model for CE in Reference 3. The following describes the details and implementation of the model.

High temperature creep strains have been modeled as a function of [

]^{a,c}.

Strain rate is given by

$$\frac{de}{dt} = A' \exp(-\frac{Q}{RT})S^n = AS^n \tag{5.1}$$

where:

S = hoop stress, MPa
e = true strain, in/in
t = time, seconds
T = temperature, K

and

$$A = A' \exp(\frac{-Q}{RT}) \tag{5.2}$$

$$A = A(S, T) \tag{5.3}$$

$$n = n(S, T) \tag{5.4}$$

The coefficients are obtained directly from Reference 6.

The accumulated true strain e is obtained from the numerical integration of Equation 5.1 and can be converted into engineering strain by the relationship:

$$e = \ln(1 + \varepsilon) \tag{5.5}$$

or

$$\varepsilon = \exp(e) - 1 \tag{5.6}$$

where:

ε = engineering strain, in/in

Since large deformations occur, the effect of an increasing diameter and a decreasing wall thickness is included. Dimensional changes for large deformations are given by:

$$D = D_o(1 + \varepsilon) \tag{5.7}$$

$$w = \frac{w_o}{(1 + \varepsilon)} \tag{5.8}$$

and the stress is given by

$$S = \Delta P \frac{D}{2w} \tag{5.9}$$

where:

ΔP = pressure difference across wall, MPa
D_o = initial tube diameter, inches
w_o = initial wall thickness, inches
D = deformed diameter, inches
w = deformed wall thickness, inches

An additional empirical correction to the calculated strain increment during a given time increment is required [

] a, c. The correction is provided in terms of the engineering strain.

The engineering strain increment is adjusted to an effective engineering strain increment by the following equation.

[ ] a, c (5.10)

where:

[ ] a, c

5.2 Cladding Burst Mechanism

Creep of the cladding during a DNB transient stops if the cladding is perforated and the internal pressure is relieved. As an example, Reference 6 provides data on [

] a,c.

[ ] a, b, c

5.3 Strain Criterion versus Channel Blockage

The amount of channel blockage is limited to prevent degradation of the cooling of adjacent fuel rods as described in Reference 3. The strain criterion for channel blockage is primarily based on geometric effects in terms of fuel rod gap closure. Reference 3 provides an NRC approved criterion of [ ] a,c fuel rod diametral strain or less. It is assumed that DNB propagation will not occur if the fuel rod diametral strain is less than or equal to [ ] a,c.

The above [ ] a,c strain has been developed using standard CE geometries. Westinghouse designed lattices have very similar geometries to those used in Reference 3. Table 5.3.1 summarizes the fuel rod diametral strain at a [ ] a,c gap reduction and the % gap reduction at the [ ] a,c strain criterion for typical Westinghouse and CE fuel design lattices.

Table 5.3.1
Comparison of Fuel Rod Strains at % Gap Reduction and % Gap Reduction at % Strain for Typical Westinghouse and CE Fuel

[ ] a, b, c

It can be seen from Table 5.3.1 that the [ ]^{a,c} criterion bounds the strain at [ ]^{a,c} gap reduction for all Westinghouse and CE fuel geometries. There is no effect on DNB as long as gap reductions are less than [ ]^{a,c} based on DNB tests defined in References 3 and 4. The maximum % gap reduction at the [ ]^{a,c} strain limit for the Westinghouse fuel geometries [ ]^{a,c} to the maximum value of the CE fuel geometries [ ]^{a,c}. Therefore, the application of the CE licensed [ ]^{a,c} strain criterion is applicable to Westinghouse designs and will be used in the DNB propagation methodology for all designs.

5.4 Discussion of Conservatism for DNB Propagation

The analysis of DNB propagation is extremely conservative. Reference 3 provides a detailed discussion of the propagation model conservatisms. However, the primary conservatisms are listed below:

1. The DNB rod ballooning is conservatively assumed to occur symmetrically. [ ]^{a,c}.

2. [ ]^{a,c}.

3. [ ]^{a,c}.

4. DNB transients are modeled conservatively assuming the hot rod in DNB when the plant DNB Ratio (DNBR) limit is violated. The DNBR limit is determined based on test data so that there is at least a 95 percent probability at a 95 percent confidence level that DNB will not occur on the hot rod.

5. During the DNB transient, it is conservatively assumed that film boiling heat transfer occurs if the DNBR is below the DNBR limit.

6. The strain criterion of [ ]^{a,c} is less than allowed by the [ ]^{a,c} gap reduction strain (References 3 and 4).

7. [

]^{a,c}.

Therefore, while DNB propagation is conservatively assumed, the physical mechanisms involved do not actually support the occurrence of DNB propagation.

5.5 Examples of Mechanistic Approach Applied to Westinghouse Designs

Typical example analyses have been performed on sample Condition III and IV DNB transients in Westinghouse designs.

A total of five typical example designs have been modeled. These 5 cases represent a cross-section of lattice designs. They also represent 2, 3, and 4 loop plants. The 5 cases include postulated locked rotor, rod ejection, and single rod withdrawal transients. It should be noted that due to the duration and limited flow conditions of the Locked Rotor transients, they are considered limiting in terms of induced clad strain. For comparison, the Rod Ejection and Single Rod Withdrawal are modeled. The Single Rod Withdrawal is considered to bound Rod Ejection due to it's longer time duration.

The transients associated with those designs are not absolutely limiting, but represent relatively severe conditions for Westinghouse designs. For the example analyses herein, all 5 of the cases have been modeled with a conservatively high assumption of [ ]^{a,c}. Typically much lower rod internal pressures are predicted using fuel performance models. In addition to the 5 cases stated, two additional repeats of Case 2 with varying rod internal pressures were made.

The following table gives a brief description of the 5 cases:

Table 5.5.1

Example Cases Analyzed

[ ]a, b, c

The required transient input data has been extracted from a sub-channel thermal-hydraulic code such as VIPRE-01, References 8 and 9. The inputs included: time (s), heat flux (btu/h-ft^2), quality, mass flow (lbm/h-ft^2), and system pressure (psi). The DNBR has been used to select the time steps associated with the transients when the DNBR is below the 95% bounding DNBR limit for each case. The DNBR limits are shown below:

Table 5.5.2
DNBR Limits for Example Cases

[ ]a, c

The sub-set of the total transient when the DNBR limit is violated is what was used to [
]a,c transient creep strain.

Figures 5.1 through 5.5 show the input DNB transients for cases 1 through 5 respectively. [

]a,c. The result produces an increased final transient strain.

Additional inputs required in the analysis include cladding radius, cladding wall thickness, and hydraulic diameter in inches. These values for the example analysis represented herein are in the table below.

Table 5.5.3
Geometric Parameters for Fuel Designs

a, b, c

[ ]

Figure 5.1: Case 1 DNB Transient

a, b, c

[ ]

Figure 5.2: Case 2 DNB Transient

a, b, c

Figure 5.3: Case 3 DNB Transient

a, b, c

Figure 5.4: Case 4 DNB Transient

a, b, c

a, b, c

Figure 5.5: Case 5 DNB Transient

[ ]

The resultant [ ]a,c strains due to the DNB transients for Cases 1 through 5 are shown below in Table 5.5.4.

Table 5.5.4
Cumulative Strains for Cases 1 through 5

[ ]a,c

It can be seen that none of the example transients induced a strain near the limit of [ ]a,c. Case 1 exhibited an insignificant amount of strain. This was due, in part, to the [ ]a,c. The most severe transient is Case 2. This particular transient is a locked rotor, which [ ]a,c.

Plots of the ballooning strain, cladding temperature, and stress as a function of time for each of the 5 cases are shown in Figures 5.6 through 5.10. [ ]a,c.

[ ]a,c.

Figure 5.6: Case 1 Ballooning Strain Results

a, b, c

[ ]

a, b, c

Figure 5.7: Case 2 Ballooning Strain Results

[ ]

a, b, c

Figure 5.8: Case 3 Ballooning Strain Results

a, b, c

Figure 5.9: Case 4 Ballooning Strain Results

[ ]

a, b, c

Figure 5.10: Case 5 Ballooning Strain Results

[ ]

The strains reported in Table 5.5.4 as well as Figures 5.6 through 5.10 have been reported without consideration of the [

]a,c.

[

]a,c.

The above evaluation illustrates the fact that the [

]a,c.

Figure 5.11: Case 2 Burst Stress Analysis

a, b, c

Figure 5.12: Case 2_3000 psi Burst Stress Analysis

a, b, c

Figure 5.13: Case 2_2800 psi Burst Stress Analysis

a, b, c

5.6 Range of Applicability

Westinghouse implementation of the mechanistic approach remains within the range of applicability of the previously licensed approach described in WCAP-8964-A (Reference 1) as well as CEN-372-P-A (Reference 3) and CENPD-404-P-A (Reference 5).

This approach is applicable for any transient conditions falling within the licensed range of applicability of the cladding high temperature and burst models.

This approach is applicable for Westinghouse geometries ranging from rod diameters [ ][a,b,c], and rod pitches from [ ][a,b,c].

This approach is applicable to calculated cladding ballooning strains up to [ ][a,c].

6.0 Conclusion

This evaluation demonstrates that the alternate mechanistic approach can be applied to all Westinghouse fuel designs and this approach does not impact other fuel performance or safety analysis methodologies or evaluations.

7.0 References

1. WCAP-8964-A, "Safety Analysis for the Revised Fuel Rod Internal Pressure Design Basis," August 1978.

2. WCAP-15063-P-A, Revision 1 with Errata, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)," July 2000.

3. CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure," May 1990.

4. Letter from C. O. Thomas (NRC) to E. P. Rahe (Westinghouse), "Acceptance for Referencing of Licensing Topical Report WCAP-8691 (P)/WCAP-8692 (NP)," December 1982.

5. CENPD-404-P-A, Revision 0, "Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs," November, 2001.

6. WCAP-12610-P-A, "VANTAGE+ Fuel Assembly Reference Core Report," April 1995.

7. WCAP-12610-P-A/CENPD-404-P-A, Addendum 1, "Addendum 1 to WCAP-12610-P-A and CENPD-404-P-A Optimized ZIRLO™," February 2003.

8. NP-2511-CCM-A, "VIPRE-01: A Thermal-Hydraulic Code for Reactor Cores," Volumes 1-3 (Revision 3, August 1989), Volume 4 (April 1987), Electric Power Research Institute.

9. WCAP-14565-P-A/WCAP-15306-NP-A, "VIPRE-01 Modeling and Qualification for Pressurized Water Reactor Non-LOCA Thermal-Hydraulic Safety Analysis," October 1999.

10. WCAP-12945-P-A, Volume 1, Revision 2, Sections 1-10, "Code Qualification Document for Best Estimate LOCA Analysis, Volume 1: Models and Correlations," March 1998.