WCAP-13988-A

10 CFR 50.46 EVALUATION MODEL REPORT: WCOBRA/TRAC TWO-LOOP UPPER PLENUM INJECTION MODEL UPDATES TO SUPPORT ZIRLO™ CLADDING OPTION

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Westinghouse Energy Systems

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Westinghouse Non-Proprietary Class 3

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February 1994

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ACKNOWLEDGEMENTS

The author would like to thank the following people who assisted in the preparation of this report:

Mitch Nissley
Mike Emery

Their assistance in the analysis efforts and general support aided immensely in the preparatio. of the following topical report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 INTRODUCTION

Westinghouse has developed the WCOBRA/TRAC Best-Estimate Large Break Loss-Of-Coolant Accident (LOCA) Evaluation Model and licensed it for application to Two-Loop Pressurized Water Reactors (PWRs) equipped with Upper Plenum Injection (UPI)[1-5]. [

]a,c

The current Evaluation Model does not have built-in cladding models for zirconium-based alloys other than zircaloy. Although density, thermal conductivity, and specific heat can be input to the code, cladding models for high temperature creep, rod burst, circumferential strain after burst, assembly blockage and clad-water reaction are only available for zircaloy cladding. Therefore, in order to support use of ZIRLO™ clad fuel, an option needs to be added to WCOBRA/TRAC to use ZIRLO™ material properties and select appropriate models for high temperature creep, rod burst, circumferential strain after burst, assembly blockage and clad-water reaction when ZIRLO™ clad is chosen. Similar model updates to incorporate ZIRLO™ fuel cladding have also been prepared for other Westinghouse Emergency Core Cooling System (ECCS) Evaluation Models[6,7].

A series of test programs has been performed in order to determine the behavior of ZIRLO™ cladding during a LOCA. These tests indicate that several of the physical and mechanical properties of ZIRLO™ are similar to those of Zircaloy-4 when the two metals are in the same metallurgical phase. However, the phase changes occur at different temperatures for the two alloys. The difference in the phase change temperatures results in different cladding heat capacities, swelling, and burst behavior.

This WCAP describes all of the changes that were made to the existing WCOBRA/TRAC code version, described in References 1 through 5, to model ZIRLO™ cladding. These changes allow the user to choose the cladding type, ZIRLO™ or Zircaloy-4, and apply the appropriate cladding models within the framework of the existing calculation options for Appendix K, Superbounded, or Nominal computation models as described in Reference 2, and required in Reference 8. The updates include changes to the high temperature creep (swelling) model, burst and blockage model, specific heat model, and metal-water reaction model.

2.0 MODIFICATIONS TO MODEL ZIRLO™ FUEL CLADDING

Several of the ZIRLO™ physical and mechanical properties are similar to those of Zircaloy-4, when the two cladding materials are in the same metallurgical phase. However, the phase changes occur at different temperatures for the two alloys, resulting in different clad specific heat, clad creep, and burst behavior.

The following updates are necessary to model the use of ZIRLO™ cladding in the WCOBRA/TRAC code. As stated above, these updates were implemented with consideration for the appropriate model options required to perform Nominal, Superbounded, and Appendix K calculations. These updates include changes and additions to the high temperature creep (swelling), the burst and blockage, the specific heat and the metal-water reaction models.

2.1 ZIRLO™ Specific Heat

The alpha-to-beta phase change has a significant effect on the cladding specific heat. The phase changes in ZIRLO™ cladding material occur at different temperatures than for the Zircaloy-4 cladding material. Models for the specific heat were developed in Reference 9, Subsection 10-4-3, as a function of temperature for use in the safety analyses. Figure 1 contains a comparison of the specific heat curves of ZIRLO™ cladding and Zircaloy-4 cladding duplicated from Reference 9. The points used are tabulated in Table 1.

This specific heat model is incorporated into the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option.

2.2 ZIRLO™ High Temperature Creep

The high temperature creep behavior of ZIRLO™ cladding was developed based on constant pressure and constant temperature tests for the alpha, mixed, and beta phase regions. [

]a,c

Details of the creep tests and the verification of the creep model for the constant temperature and constant pressure conditions of the tests are given in Reference 6, Appendix C. When applying the creep model in the LOCA analysis, the model must be generalized to allow for varying cladding temperatures and pressure differentials. The generalized creep model used in LOCA analysis evaluation models is described in Reference 6, Subsection 5.2.1. This creep model was incorporated into the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option. This high temperature creep model was previously approved in Reference 7.

2.3 ZIRLO™ Burst Temperature

NUREG-0630[10] describes the burst and blockage models which the USNRC has required to be used in the Appendix K Evaluation Models for pressurized water reactors with zircaloy cladding. Due to the shift in the ZIRLO™ phase change temperatures, these models cannot be directly applied to analyses of the ZIRLO™ cladding.

Single rod burst tests for ZIRLO™ cladding were performed by Westinghouse following the methodology of NUREG-0630. A model was developed to represent the rupture behavior phenomena in the small break LOCA analyses. [

]a,c Details of the burst tests and the development of the burst temperature are given in Reference 6, Appendix D. Figure 2 contains a plot of the burst temperature curve as a function of the engineering hoop stress for both ZIRLO™ and zircaloy. The points used in the analysis are taken from this curve and listed in Table 2.

This burst temperature correlation was incorporated into the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option. This model was implemented in the code in the same fashion as reported in Reference 6, which was previously approved in Reference 7.

2.4 ZIRLO™ Circumferential Strain Following Burst

The maximum circumferential strains at the burst elevation were measured in the ZIRLO™ single rod burst tests. A conservative upper bound curve was developed to generate a correlation of burst strain as a function of burst temperature, which was consistent with the NUREG-0630[10] correlation for Zircaloy. This conservative curve was previously reported in Reference 6, and approved in Reference 7.

[

]a,c

[

]a,c

The ZIRLO™ burst strain correlation is shown in Figure 3, along with the Zircaloy burst strain correlation, with is dependent on the heatup rate. The points for this curve are listed in Table 3. This burst strain correlation for ZIRLO™ was incorporated into the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option.

2.5 ZIRLO™ Assembly Blockage

[

]a,c

The resulting model is shown in Figure 4, which contains a comparison of ZIRLO™, [ ]a,c, and zircaloy, [ ]a,c. The points used for the curve are tabulated in Table 3. This blockage model was implemented in the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option.

This model was implemented in the code in the same fashion as reported in Reference 6, which was previously approved in Reference 7.

2.6 ZIRLO™ Metal-Water Reaction

High temperature oxidation tests were performed to determine the reaction rate for the ZIRLO™ cladding material. Although a best estimate metal-water reaction rate correlation was developed from the test data[11], the WCOBRA/TRAC large break LOCA evaluation model will use the [ ]a,c for the metal-water reaction for the Appendix K LOCA analyses for both ZIRLO™ and Zircaloy-4.

The metal-water reaction rate for the Superbounded LOCA analysis with the ZIRLO™ cladding, however, will be modeled as described in Reference 11, including uncertainties.

These metal-water reaction rate equations, both for the Appendix K analyses and the Superbounded analyses, were incorporated into the WCOBRA/TRAC large break LOCA evaluation model as part of the ZIRLO™ cladding model option.

3.0 WCOBRA/TRAC ZIRLO™ INPUT OPTIONS

[ ]a,c

[ ]a,c

4.0 VERIFICATION

The updates necessary to add the option of ZIRLO™ cladding must be verified. These updates include adding option flags to choose either Zircaloy-4 cladding or ZIRLO™ cladding, and also the physical properties of the ZIRLO™ alloy. The areas that are focused upon in the verification are burst temperature versus engineering hoop stress, high temperature creep, flow blockage, burst strain, specific heat, and metal-water reaction.

4.1 Verification of Burst Temperature vs. Hoop Stress

A verification case was performed using WCOBRA/TRAC to determine when the hot rod would burst. From the output of the run, the burst occured at [ ]^{a,c} seconds. The temperature at this time is [ ]^{a,c}, and the strain reaches [ ]^{a,c} at this time. Figure 5 contains a plot of the burst strain vs. time from the output of the run, showing that the 10 percent strain limit is reached at [ ]^{a,c} seconds.

At 38 seconds into the transient, however, the stress in the rod is nearly [ ]^{a,c}, which is more than enough to burst the rod (see Table 2), [ ]^{a,c}. Figure 6 contains a plot of the engineering hoop stress vs. the burst temperature from the run at three points in time prior to burst. The curve of the ZIRLO™ engineering hoop stress versus the burst temperature is also plotted on the same set of axes. From the plotted points, it is evident that the rod could have burst at or before [ ]^{a,c} seconds as discussed above.

4.2 Verification of High Temperature Creep Model

Details of the creep tests and the verification of the creep model for the constant temperature and constant pressure conditions of the tests are given in Reference 9, Appendix C. Confirmation that the previously verified high temperature creep model was incorporated in the same manner as in Reference 9 was performed.

4.3 Verification of Flow Blockage Model

The output from the verification run performed above is also used to verify the blockage data. At the burst temperature of [ ]^{a,c}, the flow blockage from the output is [ ]^{a,c}.

From a linear interpolation on Table 3, the burst temperature at a flow blockage of [ ]^{a,c} is [ ]^{a,c}. Thus, the value computed in the WCOBRA/TRAC run verifies the flow blockage model.

4.4 Verification of Burst Strain Model

The output from the verification run performed above is also used to verify the burst strain model. At the time of hot rod burst, the burst strain from the output is [ ]^{a,c}.

From NUREG-0630[10], the burst strain is [ ]^{a,c}. From a linear interpolation on Table 3, the burst temperature at a burst strain of [ ]^{a,c} is [ ]^{a,c}.

The NUREG-0630 burst strain versus burst temperature data is being used correctly. If the NUREG-0630 burst strain determined is greater than the critical strain based on 14x14 OFA fuel rod pitch, then the critical strain is used, i.e., the burst strain is [ ]^{a,c}. Thus the burst strain model is being properly applied, and is verified to be correct.

4.5 Verification of Specific Heat Data

In order to verify that the data for the specific heat of ZIRLO™ was being used, temporary printout statements were inserted into the WCOBRA/TRAC code. These printouts provided the values of the temperature verses specific heat curve being used in the code calculations. The values in the output were verified to be identical to the model contained in Reference 9 for ZIRLO™, so the specific heat model is validated.

4.6 Verification of Metal-Water Reaction Model

Similar to the verification for specific heat, it was necessary to insert temporary printout statements in the WCOBRA/TRAC coding to verify the metal-water reaction model. The temporary printout listed the metal-water reaction equation constants being used for the code calculations. These constants were then verified to be identical to those in the references.

5.0 CONCLUSIONS

The differences between ZIRLO™ and Zircaloy-4 behavior under the high temperature conditions typical of a loss-of-coolant accident (LOCA) have been studied in a series of test programs. Revised cladding models have been developed to describe the ZIRLO™ specific heat, high-temperature creep, burst temperature, burst strain, assembly blockage, and metal-water reaction rates. These models have been incorporated into the WCOBRA/TRAC large break LOCA evaluation model.

6.0 REFERENCES

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11. WCAP-12610 (Proprietary) Appendix E, "ZIRLO™ High Temperature Oxidation Tests," Burman, D. L., August 1990.

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Table 1

Points Used in ZIRLO™ Specific Heat Curve

[ ]a,c

Table 2

Points Used in ZIRLO™ Burst Temperature Curve

[ ]a,c

Table 3

Points used in ZIRLO™ Burst Strain and Assembly Blockage Curves

[ ] a,c

Table 4

Parameters of the WCOBRA/TRAC
Metal-Water Reaction and High Temperature Creep Models

[ ] a,c

Figure 1

Comparison of ZIRLO™ and Zircaloy-4 Specific Heat

a,c

Figure 2

Burst Temperature in ZIRLO™ and Zircaloy-4
Appendix K Evaluation Models

a,c

a,c

Figure 3

Burst Strain in ZIRLO™ and Zircaloy-4
Appendix K Evaluation Models

[ ]a,c

Figure 4

Assembly Blockage in ZIRLO™ and Zircaloy-4
Appendix K Evaluation Models

a,c

Figure 5

Test Run Burst Strain vs. Time Curve

[ ]a,c

Figure 6

Test Run Hoop Stress vs. Burst Temperature Curve

a,c