WCAP-14204-A, Addendum 1, Revision 1

Addendum 1 to WCAP-14204-A

Revision to Design Criteria

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Introduction

The purpose of this submittal is to update one fuel licensing criterion that is applied to Westinghouse fuel. This criterion pre-dates NUREG-0800(1) and is inconsistent with other Westinghouse business units and industry guidelines. The proposed criterion replaces an indirect performance correlation with a direct performance correlation that is more readily measured and provides direct feedback to design. Both the current and proposed criterion is shown below. In this addendum, the term zircaloy is used in a generic sense and applies to both Zircaloy-4 and ZIRLO™ material.

Parameter:	Fuel Structural Hydrogen Content
Current Criteria:	The hydrogen content of zircaloy structural components shall be less than [ ]^{a,c}.
Proposed Criteria:	The zircaloy structural component stresses will be consistent with ASME Code Section III requirements after accounting for thinning due to corrosion.

The following sections give the bases for justifying the change to the design criterion.

Structural Hydrogen Criteria

The Westinghouse imposed hydrogen criteria for both cladding and structural components is defined(2) as:

> "The clad and structural component hydrogen pickup is limited to [ ]^{a,c} at end of life to preclude loss of ductility due to hydrogen embrittlement by the formation of zirconium hydride platelets."

The criterion is based on historical data for unirradiated zircaloy which showed that hydrogen levels of [ ]^{a,c} were acceptable. No differentiation was made between heated (cladding) and unheated (structural) surfaces.

Recent data for zircaloy material shows that ductility does not suddenly decrease and that some ductility remains at hydrogen concentrations well in excess of [ ]^{a,c}. Unheated structural components are not susceptible to hydrogen redistribution due to temperature gradients within the components.

Thus, high local hydrogen concentrations do not exist. Irradiation reduces the material ductility and increases the material yield and ultimate strengths. Thus, any analysis of irradiated components should account for changes in ductility and material strength due to both irradiation and hydrogen pickup.

Effects of Hydrogen Content on Zircaloy Structural Material Properties

Westinghouse has conducted programs to collect material property data on both unirradiated and irradiated zircaloy. Tensile test results for grid strap material and assembly thimble tubes are described below.

Tensile tests were performed on unirradiated ZIRLO^{TM} strip material that is used to manufacture grid straps. Tests were conducted at room and elevated [ ]$^{a, b, c}$ temperatures. Hydrogen charging was used to give material hydrogen concentrations up to [ ]$^{a, b, c}$. The ductility, defined as plastic strain or the total strain minus the elastic strain, is plotted versus hydrogen content in Figure 1. The plot shows a [ ]$^{a, b, c}$. Significant ductility exists for hydrogen concentrations up to [ ]$^{a, b, c}$.

Projections of the data indicate that ductility will still exist for hydrogen concentrations [ ]$^{a, b, c}$.

Yield strength of the strip material is plotted versus hydrogen content in Figure 2. There is [ ]$^{a, b, c}$. The ultimate strength is plotted versus the hydrogen content in Figure 3. There is [ ]$^{a, b, c}$.

Tensile tests were also conducted on hydrogen charged unirradiated thimble tubes. The room temperature ductility is plotted versus the hydrogen content in Figure 4. There is [ ]$^{a, b, c}$. The ductility at elevated temperatures is plotted in Figure 5. These tests were conducted [ ]$^{a, c}$ shown in

Figure 5. These data illustrate that at elevated temperatures, [ ] a, b, c for the unirradiated ZIRLO™ thimble tubes for hydrogen concentrations [ ] a, b, c.

Yield and ultimate strength of the unirradiated ZIRLO™ thimble tubes are plotted versus the hydrogen content in Figures 6 and 7. There are [ ] a, b, c with the hydrogen content. There is [ ] a, b, c as the hydrogen content increases.

Material property data have also been obtained from irradiated Zircaloy-4 and ZIRLO™ thimble tubes. These tubes were irradiated to burnups of about [ ] a, c. Sample hydrogen concentrations were [ ] a, b, c. The room and elevated temperature ductility are shown in Figures 8 and 9. The trends for [ ] a, b, c. The minimum ductility at elevated temperatures [ ] a, b, c.

The yield and ultimate strength at room and elevated temperatures are shown in Figures 10 and 11. There are [ ] a, b, c. Comparisons of the data for unirradiated and irradiated ZIRLO™ thimble tubes shows that [ ] a, b, c.

Comparisons of the ductility of irradiated and unirradiated Westinghouse thimble tubes at elevated temperature are shown in Figure 12. Irradiation reduces the ductility [ ] a, b, c.

A survey of the literature indicates that other fuel vendors have published similar data. General Electric reports(3) that the total and uniform elongation of irradiated Zircaloy-2 at operating temperatures are independent of the hydrogen content in the range of 0 to 815 ppm. Siemens has published(4) data for the elongation after fracture of irradiated zircaloy with hydrogen contents up to 2000 ppm and concludes that the influence of irradiation on the ductility and strength of zircaloy is dominant at both room and operating temperatures. They further conclude that even high hydrogen contents do not add to the effects of irradiation and do not have an additional influence on reducing the ductility.

The third Nuclear Fuel Industry Research Program (NFIR) sponsored a program to gather data on the properties of irradiated cladding and guide tubes. A specific objective of the program was to evaluate the decrease in ductility of Zircaloy-4 materials due to reactor irradiation and increasing hydrogen content. Both cladding and guide tube materials were included in the studies. The results of the material property measurements are reported in References 5 and 6.

Data in Reference 5 (page 4-18) illustrates that the total plastic elongation of the irradiated guide tubes decreases from about 8 % with no hydrogen present to about 0.3 % at a hydrogen concentration of about 1300 ppm. This sensitivity of ductility to the hydrogen content is somewhat greater than determined by Westinghouse, General Electric, and Siemens. Tensile strength was found to increase with the hydrogen content. Hydrogen charging was performed on unirradiated archive samples and the tensile properties were determined. The hydrogen contents of the archive samples was higher than the irradiated samples, and there was a large scatter in the data. However, it is still clear that irradiation had a much greater impact on reducing the ductility than did the hydrogen charging.

Tensile strains for both irradiated and unirradiated guide tube material at operating temperature is shown in Figure 3-15 of Reference 6. Irradiation has a much larger effect on reducing the ductility than does the hydrogen content. There is a weak dependence of ductility on the hydrogen content. Tensile strengths increase slightly with the hydrogen content.

In summary, the Westinghouse and other industry data show that:

- The ductility of unirradiated zircaloy does not abruptly decrease above hydrogen concentrations of [ ] ^{a,c}. There is a gradual decrease in ductility with increases in hydrogen concentrations up to [ ] ^{a,c}. At operating temperatures, significant ductility still exists for hydrogen concentrations up to [ ] ^{a,c}.

- The ductility of irradiated zircaloy is primarily affected by irradiation.

- While hydrides contribute to the embrittlement of irradiated zircaloy, the [ ] ^{a,c}.

- Hydrogen content has little effect on the tensile strength of irradiated zircaloy at either room or operating temperatures.

- The yield strength of irradiated recrystallized zircaloy at operating temperatures is [ ]$^{a, b, c}$. The value is [ ]$^{a, b, c}$ at room temperature.

Impacts of Hydrogen Content on Grids

Irradiation, corrosion, and hydrogen uptake could potentially impact the strength of grids. The seismic capability of grids is performed by testing them under simulated conditions. NUREG-0800(1) specifies that grid crush tests should be performed on unirradiated production grids at, or corrected to, operating temperature. A number of phenomena associated with irradiation could impact the seismic/LOCA capability. Westinghouse has conducted tests to verify that unirradiated production grids would continue to demonstrate the minimum seismic/LOCA capability when accounting for corrosion, wall thinning due to corrosion, hydrogen uptake, and enlargement of the grid cell size.

A series of tests were conducted on unirradiated 5x5 grid sections with oxidation, wall thinning, hydrogen pickup, and enlargement of the grid cell size. The test sections were conditioned by oxidizing them in autoclaves in steam and steam/lithium mixtures. Hydrogen uptake was due to oxidation of the zircaloy material.

- One-sided oxide thickness ranged from [ ]$^{a, b, c}$.
- Hydrogen content was up to [ ]$^{a, b, c}$.
- Wall thinning varied from [ ]$^{a, b, c}$.
- Grid spring-to-rod gaps varied from [ ]$^{a, b, c}$.

The test results are illustrated in Figure 13 where the grid section crush strength is plotted versus the hydrogen content. The figure illustrates that the crush strength, P, is [ ]$^{a, b, c}$. The data also show that [ ]$^{a, b, c}$. Additional evaluations showed that the crush strength and seismic capability factor were [ ]$^{a, b, c}$.

Tests were also conducted on full size grids which had been oxidized in air to give internal strap thinning values of [ ]$^{a, b, c}$. The cell sizes were adjusted to give [ ]$^{a, b, c}$. Grid crush strength and stiffness data were compared to production grids with no wall thinning and with both open and closed rod-to-grid gaps. The seismic capability factor is plotted versus the percent of internal strap thinning in Figure 14. There is [ ]$^{a, b, c}$.

These data from the grid crush tests indicate that [ ]$^{a, b, c}$.

Evaluation of Thimble Tube Stresses

Thimble tube stresses are evaluated using Westinghouse design procedures that follow the ASME Code Section III guidelines. An evaluation was performed that considered both unirradiated beginning-of-life conditions with no wall thinning and with wall thinning and irradiation strengthening of the thimble tube material. The evaluation was performed for a limiting design and considered shipping/handling loads and Condition I – IV events. It was concluded that [ ]$^{a, b, c}$. Since [ ]$^{a, c}$.

Revised Westinghouse Design Criteria for Hydrogen

A review of material property data for Westinghouse zircaloy structural material indicates that [ ]$^{a, b, c}$. There is no decrease of yield or ultimate strength with the hydrogen content. Ductility is primarily affected by irradiation, and [ ]$^{a, c}$. The impact of irradiation on thimble tube stresses has also been evaluated. It was concluded that [ ]$^{a, b, c}$. Thus, the ductility of thimble tubes is not an issue with present designs. Crush tests on 5x5grid sections showed that the seismic capability factor [ ]$^{a, b, c}$. Crush tests on full size production grids showed that there was [

] ^{a,b,c}.

All of these results support the conclusion that the current Westinghouse imposed hydrogen criteria for structural components is inappropriate. The desirable characteristics of a design criterion are:

- Related to a physical criteria,
- There is a basis for quantifying the criteria, and
- The criterion can be readily verified by measurements.

The data and discussions provided previously show that the first two characteristics are not met by the current Westinghouse structural hydrogen content limit. Verification of the hydrogen content is difficult in that it requires sending a structural section to a hot cell for analysis, and there can be large uncertainties associated with the measurement methods. The difficulties in performing such measurements severely limit the amount of data available for verification. It is thus concluded that the current structural hydrogen criterion possesses none of the desired characteristics of a design criterion.

A more appropriate criterion that has all of the desired characteristics is a wall thinning criteria. It is proposed that Westinghouse eliminate the current hydrogen content criteria and replace it with the following criteria:

> "The zircaloy structural component stresses will be consistent with ASME Code Section III requirements after accounting for thinning due to corrosion."

Conclusions

The current criteria applied to Westinghouse fuel pre-date NUREG-0800(1) and do not conform completely to NUREG-0800(1), to industry guidelines(7), and to those criteria in use at other Westinghouse business units. The proposed updated criteria conform to both NUREG-0800(1) and to industry guidelines(7). These updated criteria are sufficient to preclude fuel damage and will also promote convergence between Westinghouse business units.

References

1. U. S. NRC, "USNRC Standard Review Plan, Section 4.2, Fuel System Design," NUREG-0800, July 1981.

2. Davidson, S. L. (Ed.), et al., "VANTAGE + Fuel Assembly Reference Core Report," WCAP-12610-P-A, April 1995, pg. 12.

3. S. Wisner and R. B. Adamson, "G E Nuclear Energy," 1996 , Vol. 3, pg. 1.

4. W. Jahreib, R. Manzel and E. Ortlieb, "Annual Meeting on Nuclear Technology," Cologne, 1993 pg. 303.

5. A. Hermann, et. al., "Fuel Cladding Integrity at High Burnups (Part I)," NFIR-III/EPRI, DRAFT TR-108753-P1, July 1999, pg. 4-18.

6. R. C. Kuo, et al., "Fuel Cladding Integrity at High Burnups (Part II)," NFIR-III/EPRI, TR-108753 P2, August 1999, pg. 3-47.

7. EPRI, "Robust Fuel Program Technical Requirements for Nuclear Fuel Performance," TR-110689, November 1999.

Figure 1. Ductility vs Hydrogen Content for Unirradiated ZIRLO™ Strip Material

a, b, c

Figure 2. Yield Strength vs Hydrogen Content for Unirradiated ZIRLO™ Strip Material

a, b, c

Figure 3. Ultimate Strength vs Hydrogen Content for Unirradiated ZIRLO™ Strip Material

a, b, c

Figure 4. Room Temperature Ductility vs Hydrogen Content for Unirradiated ZIRLO™ Thimble Tubes

a, b, c

Figure 5. Elevated Temperature Ductility vs Hydrogen Content for Unirradiated ZIRLO™ Thimble Tubes

a, b, c

Figure 6. Room Temperature Strength vs Hydrogen Content for ZIRLO™ Thimble Tubes

a, b, c

Figure 7. Elevated Temperature Strength vs Hydrogen Content for Unirradiated ZIRLO™ Thimble Tubes

a, b, c

Figure 8. Room Temperature Ductility of Irradiated Thimble Tubes

a, b, c

Figure 9. Elevated Temperature Ductility of Irradiated Thimble Tubes

a, b, c

Figure 10. Room Temperature Strength of Irradiated Thimble Tubes

a, b, c

Figure 11. Elevated Temperature Strength of Irradiated Thimble Tubes

a, b, c

Figure 12. Elevated Temperature Ductility of Unirradiated and Irradiated Westinghouse Thimble Tubes

a, b, c

Figure 13. Crush Strength vs Hydrogen Content for Unirradiated 5x5 Grid Sections

a, b, c

Figure 14. Seismic Capability Factor vs Grid Strap Thinning for Production Grids

a, b, c