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Prediction of the Onset of Fission Gas Release from Fuel in Generic BWR

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EXECUTIVE SUMMARY

An analysis was performed to determine the minimum time to fuel perforation given a Design Basis Accident (DBA) Recirculation Line Break with no Emergency Core Cooling System (ECCS) injection assumed.

This analysis is intended to be generic for BWR plants. Therefore, the limiting plant configuration was selected to minimize reactor vessel inventory and maximize the recirculation break flow. The limiting fuel type was selected which had the highest Peak Linear Heat Generation Rate (PLHGR) and highest internal stored energy. Previous analyses of Peak Clad Temperature (PCT) achieved during Loss-of-Coolant Accident (LOCA) analyses were used to validate the limiting plant configuration and fuel type.

Based on thermal-hydraulic calculations using the computer code SAFER[1], the limiting plant/fuel configurations were found to be the BWR/4 product line with a reactor pressure vessel internal diameter of 205 or 213 inches using GE11 fuel. The heat transfer profile developed for the limiting plant/fuel configuration in SAFER was input into the CHASTE[2] code to determine the minimum time to fuel perforation. A minimum time of 121 seconds was obtained.

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[1] GE code which calculates the long-term system response of the reactor over a complete spectrum of hypothetical break sizes and locations.

[2] GE code which performs fuel rod heatup and perforation calculations.

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1.0 INTRODUCTION

1.1 Background

Nuclear Steam Supply System vendors applying for advanced reactor design licensing approvals have used a more realistic application of source terms compared to TID-14844 and Regulatory Guides 1.3 and 1.4. This methodology includes consideration of different accident phases, including blowdown, gap release, and core melt. NUREG-1465 included a review of current plant Final Safety Analysis Reports (FSAR) to identify all Design Basis Accidents (DBA) in which licensees had identified the potential for fuel failure. The class of accidents that had the shortest time from the onset of a DBA until the first fuel rod was postulated to fail was the design basis Loss of Coolant Accident (LOCA). This is consistent with GE experience. If the design basis LOCA is combined with the assumed failure to inject water through the Emergency Core Cooling System (ECCS), the minimum time to postulated fuel rod failure will result.

A Control Rod Drop, or reactivity insertion event, does not apply to this analysis. Isolation is never credited in such an event, so valve closure times are not a consideration for this type of transient.

The minimum time before postulated fuel rod failure is very sensitive to the plant and reactor configuration, the type of accident assumed and the fuel rod design. In particular, the Maximum Linear Heat Generation Rate (MLHGR), the internal fuel rod pressure and the stored energy in the fuel rod are all significant considerations. NUREG-1465 notes that review of BWR FSARs indicates that fuel failures may occur significantly later in the accident sequence (compared to PWRs), but that no specific calculations were performed to substantiate that perception. NUREG-1465, therefore, assumes a BWR time of 30 seconds based solely on PWR analyses. In order to not unduly penalize BWRs, NUREG-1465 allows BWRs to submit different release timing supported by BWR-specific analyses.

1.2 Purpose

The minimum time to BWR fuel failure is an important parameter in determining the necessary response time during a LOCA to prevent radiological releases. Once fuel failure is assumed, radioactive gases contained in the fuel gap are assumed to be released. The purpose of performing BWR-specific gap release timing analyses is to justify very little source term released during the NUREG-1465 described "Coolant Activity Release" phase (Reference 5). This would permit extended duration for the initiation of LOCA radiological response functions (e.g., primary containment isolation, and secondary containment establishment {drawdown times}). Such gap release timing modeling will be beneficial to all BWR owners, for not only timing-related future Revised

Source Term (RST) applications, but for future full-scope RST applications as well. Other non-LOCA events, such as the control rod drop accident and fuel handling accident, also release source terms to the environment. Relaxing the performance of radiological mitigation functions requires the consideration of all analyses that credit these functions, including non-LOCA scenarios.

2.0 BWR PLANT SELECTION

In order to minimize the number of analyses, the most limiting plant for this study was chosen. Since this analysis involves the worst case LOCA scenario, the limiting break is a recirculation suction line break with GE LOCA methodology. Assuming no ECCS flow, the plant configuration that will lead to the earliest fuel failure will have the smallest vessel water inventory combined with the largest break flow rate. The combination of these two parameters leads to the fastest vessel inventory depletion time with commensurate earliest core uncovery time. Geometry ratios were used to compare the amount of water present at the time of the break (vessel water inventory) with the amount of water exiting the break. Plants with smaller RPV ID^2 to recirc pipe ID^2 ratios will have a smaller vessel inventory to break flow ratio, and thus will tend to have the earliest core uncovery times.

Two classes of plants were considered: jet-pump and non jet-pump plants. Based upon the above geometry ratios alone, the non jet-pump plants are most limiting. However, the time to fuel perforation for these plants is longer than for the jet-pump product line due to lower internal fuel gas pressure and lower Peak Linear Heat Generation Rates (PLHGR) for the fuel. Sensitivity studies performed with the SAFER code showed that the non-jet pump plants were not limiting for this analysis. Therefore, the rest of this analysis deals with jet-pump plants only.

For the jet-pump plants, a comparison of the two geometry parameters shows the BWR/4 product line, with a RPV I.D. of 205 inches and a recirculation pipe I.D. of 28 inches, to be the most limiting geometry for early core uncovery time with no ECCS flow. Previous analyses to determine Peak Cladding Temperature (PCT) during LOCAs validate that the geometry of this type of BWR/4 plant leads to the fastest fuel heatup for all BWR/3, 4, 5, and 6 product lines.

The BWR/4 product line with a RPV I.D. of 218 inches and a recirculation pipe I.D. of 28 inches is also quite close to the limiting geometry. This geometry was investigated as a sensitivity study. In each case, the plant operating at the highest power for each geometry type was used.

3.0 BWR FUEL SELECTION

Several different types of fuel were investigated to determine which would be the most limiting for the DBA LOCA with no ECCS injection scenario. GE fuel types 8, 9 10, 11, and 12 were considered as well as Siemens 8x8 and 9x9 fuel. The limiting fuel has the highest internal stored energy response. Based upon previous analyses involving PCT, the GE11 fuel type was determined to be most limiting.

Fuels were compared using the peak linear heat generation rate (PLHGR), which is the power limit for the highest powered location on the highest powered rod. PLHGR is related to the Maximum Average Planar Heat Generation Rate (MAPLHGR), which is the power limit for the highest powered location in the bundle, and is always lower than the PLHGR. The PLHGR is lower for GE10 than for GE8 and GE11. The PLHGR for the Siemens fuel investigated is also lower than for GE8 and GE11. GE12 has similar bundle power to GE11, but it also has more rod footage, therefore, the kW/ft ratio is lower. Analyses were performed for the DBA LOCA with no ECCS injection scenario with GE11 fuel. Sensitivity studies were performed using GE10, GE8 and Siemens fuel. Results given in Section 4 show that the GE11 fuel type is limiting.

Another consideration in fuel selection is the fuel exposure time. LOCA analyses are normally run at the exposure vs. power curve "knee", i.e., the point at which the power starts to decrease with increasing exposure. However, fuel perforation time is dependent upon the internal pressure of the fuel pellet. The internal pressure due to gas buildup of the fuel pellet will continue to increase with increasing exposure. A set of analyses were performed at different points on the exposure vs. power curve, to investigate the effect of increasing gas pressure. The limiting exposure vs. power point is given in the results in Section 4.

4.0 ANALYSIS RESULTS

Several GE computer codes qualified for LOCA analyses were used to determine the minimum time to fuel rod failure. The SAFER code was used to select the limiting BWR plant/fuel configuration. This was done by running SAFER with the combinations selected in an initial screen (Sections 2 and 3) to calculate the time to fuel perforation, and finding the combination with the minimum perforation time. The fuel perforation model in the CHASTE code is more accurate than the fuel perforation model in the SAFER code, so the CHASTE code was used with the limiting heat transfer values obtained from SAFER to determine an accurate time to fuel perforation. This analysis was performed using nominal methodology, and not Appendix K methodology.

Fuel perforation occurs when the metal clad heats up and softens. As the temperature rises the clad will balloon out at a soft spot until it bursts. This analysis uses the hoop stress resulting from fill gas pressure, the clad temperature and an empirical correlation to determine a perforation temperature. Plastic yielding is assumed to occur at 200°F below the perforation temperature.

4.1 Description of Models

Five GE Nuclear Energy qualified computer models were used to determine the plant and fuel response for this analysis. These models are LAMB, SCAT/TASC, SAFER, GESTR-LOCA, and CHASTE (References 1, 2, and 3). Together, these models evaluate the short-term and long-term reactor vessel blowdown response to a pipe rupture, the subsequent core flooding by ECCS (not used in this analysis), and the final fuel rod heatup and perforation. The purpose of each model is described in the following subsections.

4.1.1 LAMB

This model analyzes the short-term blowdown phenomena for postulated large pipe breaks in which nucleate boiling is lost before the water level drops sufficiently to uncover the active fuel. The LAMB output (most importantly, core flow as a function of time) is used in the SCAT model for calculating blowdown heat transfer and fuel dryout time. LAMB results from previous LOCA studies were used in this analysis.

4.1.2 SCAT/TASC

This model completes the transient short-term thermal-hydraulic calculation for large recirculation line breaks. The time and location of boiling transition is predicted during the period of recirculation pump coastdown. When the core inlet flow is low, SCAT also predicts the resulting bundle dryout time and location. The calculated fuel dryout time is an input to the long-term thermal-hydraulic transient model, SAFER. For GE11 and later fuel, an improved SCAT model (designated TASC) is used to predict the time and location of boiling transition and dryout. This model explicitly models the axially varying flow areas and heat transfer surface resulting from the GE11 part length fuel rods, and incorporates the critical power correlation for GE11. SCAT/TASC results from previous LOCA studies were used in this analysis.

4.1.3 SAFER

This model calculates the long-term system response of the reactor over a complete spectrum of hypothetical break sizes and locations. SAFER is compatible with the GESTR-LOCA fuel rod model for gap conductance and fission gas release. SAFER calculates the core and vessel water levels, system pressure response, ECCS performance, and other primary thermal-hydraulic phenomena occurring in the reactor as a function of time. SAFER realistically models all regimes of heat transfer which occur inside the core, and provides the PCT and the heat transfer coefficients (which determine the severity of the temperature change) as a function of time. For GE11 and later fuel analysis with the SAFER code, the part length fuel rods are treated as full-length rods, which conservatively overestimates the hot bundle power.

4.1.4 GESTR-LOCA

This model provides the parameters to initialize the fuel stored energy and fuel rod fission gas inventory at the onset of a postulated LOCA for input to SAFER. GESTR-LOCA also establishes the transient pellet-cladding gap conductance for input to both SAFER and SCAT-TASC. GESTR-LOCA results from previous LOCA studies were used in this analysis.

4.1.5 CHASTE

The CHASTE model solves the transient heat transfer equations for the highest power axial plane of the highest power assembly during the entire LOCA transient. Fuel rod heatup calculations are performed using the GESTR08 gap conductance model (Reference 4).

4.2 SAFER Results

SAFER runs were made for several different plants for the DBA recirculation line break with no ECCS injection. The results are given in Table 4.1. The minimum SAFER time to fuel perforation was found to be 145.4 seconds.

Plant Type	Plant Dimensions (inches)	Fuel Type	Exposure (Mwd/MTU) / PLHGR (kW/ft)	First Time of Fuel Rod Perforation (s)
BWR/4	RPV ID - 205 Recirc line ID - 28	GE11	14600.0 / 13.8	147.4
BWR/4	RPV ID - 218 Recirc line ID - 28	GE11	14600.0 / 13.8	145.4
BWR/4	RPV ID - 205 Recirc line ID - 28	GE10	16603.4 / 13.3	195.0
BWR/4	RPV ID - 205 Recirc line ID - 28	GE8	16603.4 / 13.8	189.2
BWR/4	RPV ID - 251 Recirc line ID - 28	GE11	21822.0 / 12.8	162.2
BWR/4	RPV ID - 251 Recirc line ID - 24	Siemens	20000.0 / 12.52	175.4

Table 4.1: Results of SAFER Time to Fuel Perforation Analyses

The time to reach fuel perforation is dependent on the internal pressure of the fuel rod. The internal pressure of fuel rods continues to increase over the lifetime of the fuel. However, as fuel exposure increases, the fuel power eventually hits a "knee" point and the power begins to decrease. SAFER code runs are normally made at this "knee" on the exposure-power curve, at the maximum exposure before the power starts to decrease, because this maximizes PCT.

Because of the importance of internal rod pressure on the fuel perforation time, a sensitivity study was performed to determine the limiting point on the fuel's exposure-power curve. The results are shown in Figure 4.1. The "knee" of the exposure-power curve was confirmed to be the limiting point for this analysis.

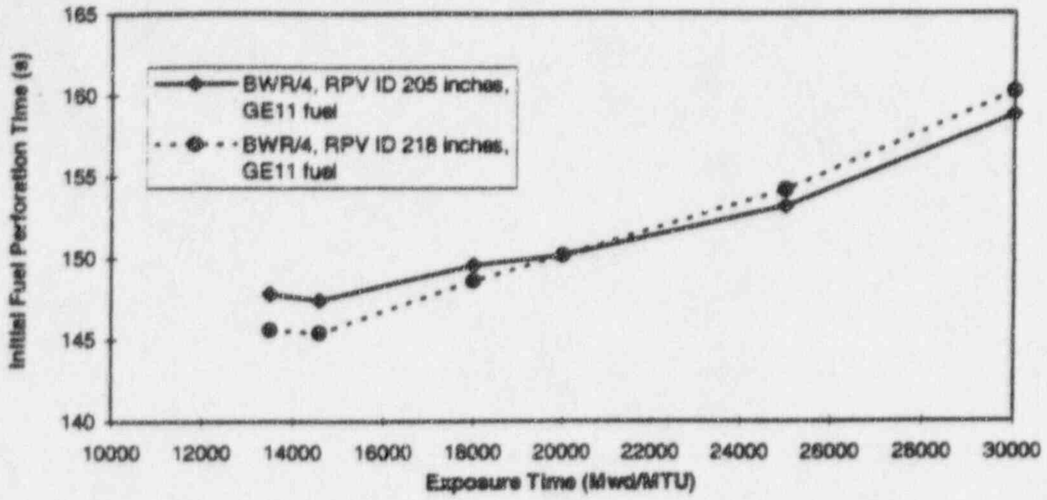

Figure 4.1: Relationship Between Fuel Exposure Time and Initial Fuel Perforation Time

Another parameter to consider when using SAFER is what peak linear heat generation rate (PLHGR) to use. Normally, the Tech Spec PLHGR is scaled down slightly to account for statistical variations that will occur in PLHGR between bundles. On this basis, the Tech Spec PLHGR was credited in this analysis. However, the effect of assuming that all of the fuel bundles were at exactly the PLHGR rate was investigated. The results are shown in Figures 4.2 and 4.3. Results vary slightly among fuel types, but for GE11 fuel it was found that the time to fuel perforation decreases by approximately nine seconds for this type of sensitivity analysis. The results for GE8 fuel show a decrease in fuel perforation time of approximately 17 seconds.

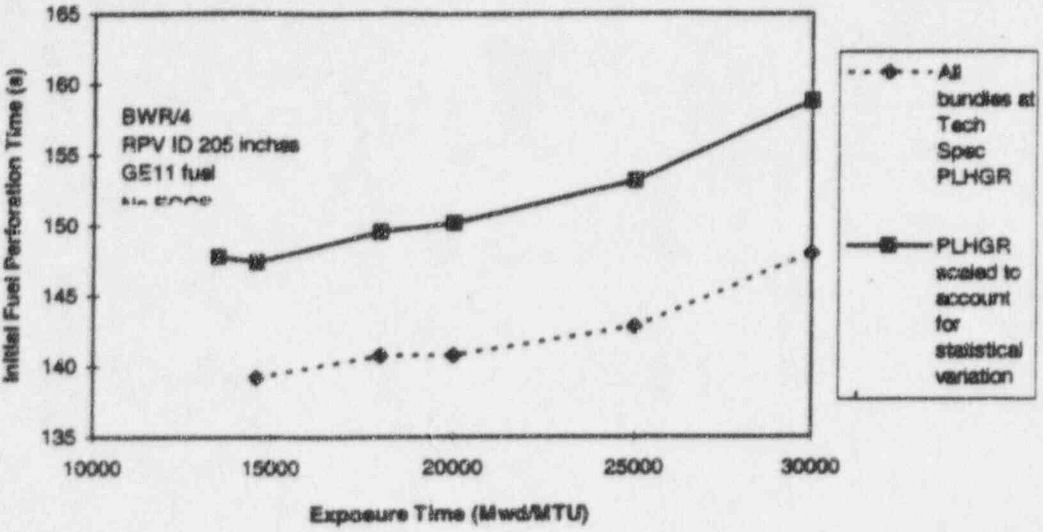

Figure 4.2: Effect of Assuming All Fuel Bundles are at PLHGR (GE11)

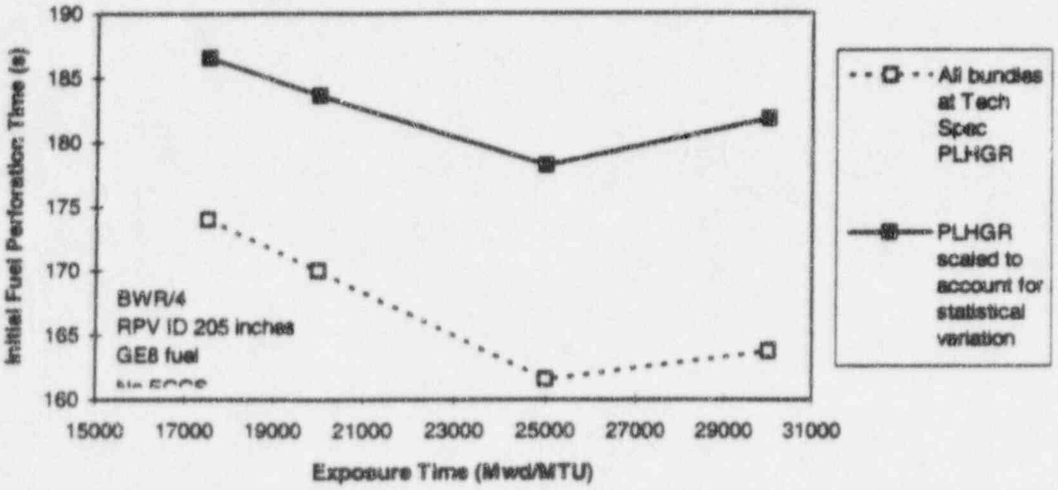

Figure 4.3: Effect of Assuming All Fuel Bundles are at PLHGR (GE8)

4.3 CHASTE Results

The CHASTE code was used to more accurately determine the minimum time to fuel perforation by inputting the limiting heat transfer values determined in the SAFER analysis into CHASTE. The limiting SAFER heat transfer values were calculated for the BWR/4 product line with an RPV ID of 205 inches and a recirculation line ID of 28 inches. A CHASTE model of a GE11 fuel bundle with no ECCS injection was used.

CHASTE results show a minimum time to fuel perforation of 121 seconds. As a sensitivity study, the exposure time was varied between 15000 Mwd and 25000 Mwd. Different exposure times did not produce perforation times lower than this minimum.

5.0 REFERENCES

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2. "General Electric Company Analytical Model for Loss-of-Coolant Analysis in Accordance with 10CFR50 Appendix K", NEDO-20566A, General Electric Company, September 1986.

3. "CHAST07 User's Manual", NEDE-30306, General Electric Company, November 1983.

4. EB Johansson, et. al., "GESTR08 - A Model for the Prediction of Fuel Rod Thermal Performance", NEDE-22092, General Electric Company, March 1982.

5. NUREG-1465, "Accident Source Terms for Light-Water Nuclear Power Plants", U.S. Nuclear Regulatory Commission, February 1995.

APPENDIX A

List of BWROG Participating Utilities

Carolina Power & Light Company
ComEd Company
Detroit Edison Company
Entergy Operations, Inc.
GPU Nuclear Corporation
Illinois Power
IES Utilities Inc.
Nebraska Public Power District
New York Power Authority
Niagara Mohawk Power Corporation
Northeast Utilities Service Company
Northern States Power Company
PECO Energy
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