Predictions of Fuel Dispersal During a LOCA

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ABSTRACT: The phenomena of fuel fragmentation, relocation, and dispersal during LOCA have recently been the focus of many large international nuclear safety research programs, and it has been shown that these phenomena can potentially occur during a nominal design-basis LOCA. Consequently, the U.S. NRC is performing analytical research on fuel fragmentation, relocation and dispersal during LOCA. The goal of the research is to determine the safety significance of these phenomena, and to inform the 50.46c rulemaking on ECCS performance. The methodology described at Top Fuel 2013 to predict the amount of fuel dispersed during a LOCA was improved and refined so as to model each assembly in the core individually in FRAPCON/FRAPTRAN and in TRACE under realistic operating conditions. Detailed analyses have been completed at different times in cycle for a Westinghouse 4-loop PWR (LBLOCA), a Combustion Engineering PWR (LBLOCA and SBLOCA), and a General Electric BWR/4 (LBLOCA and SBLOCA). The results of the present study provide detailed core-wide maps of fuel dispersal, where the time and location of fuel rod cladding ruptures is calculated, as well as the mass of fuel dispersed and the particle size distribution of the dispersed fuel, to be used in future consequence analyses.

KEYWORDS: LOCA, Fuel, Fragmentation, Relocation, Dispersal, TRACE, FRAPCON, FRAPTRAN, Cladding, Rupture

I. INTRODUCTION

Fuel fragmentation, relocation, and dispersal (FFRD) during LOCA events have become a major focus of international and regulatory research in recent years. The fuel dispersal phenomenon was submitted to the NRC’s Generic Issues Program in 2011. Since then, the staff received commission direction to evaluate the need for regulatory action related to fuel dispersal within the 10 CFR 50.45c rulemaking effort. The issue was therefore screened out of the Generic Issues program because the program only considers issues that are not being addressed through other regulatory initiatives.

In order to address the question of the safety significance of FFRD during LOCA, and thus determine if and what regulatory actions might be needed, the NRC has been conducting experimental and analytical research in these areas. Many experimental results have been discussed elsewhere, and the results of a preliminary analytical scoping study were presented at ‘Top Fuel 2013’. The present study builds upon the previously presented analytical work, with an improved methodology to perform core-wide fuel rod rupture census calculations and the associated fuel dispersal predictions. The calculations were performed using the NRC’s FRAPCON/FRAPTRAN and TRACE codes, and additional reactor types and transients were modeled using the new and improved methodology. The results of these calculations are presented here.

II. MODELING FRAMEWORK

The overall modeling approach used to generate a core-wide rod rupture census (or rod burst inventory) was as follows. The base irradiation of every single fuel assembly in the core was simulated with the steady-state fuel performance code FRAPCON-3.54. Burnup dependent parameters generated by FRAPCON-3 were then used to initialize the burnup dependent variables for the transient calculation in both the systems thermal-hydraulic code TRACE, as well as the transient fuel performance code FRAPTRAN. The TRACE transient calculation was performed and the cladding surface temperatures as well as coolant conditions in the core were used as boundary conditions for the FRAPTRAN calculation. It is important to note here that all the calculations (fuel performance and systems thermal-hydraulic) performed for this study are nominal calculations, and no added conservatism, with all trains of ECCS operable. Fig. 1 illustrates this scheme, and the following sections describe the models in more detail.

![General modeling scheme for the core-wide rod rupture census.](image-url)
Three different plant types were modeled: W4LP, CE-PWR, and GE-BWR/4. All three cores were modeled after reactors in the US fleet, and all three have obtained a power uprate. The information available in the corresponding Final Safety Analysis Report for each reactor core was of a different nature, so different methods were used in each case to generate the power history of each assembly in the core throughout its life.

Fig. 2: W4LP core: (a) 1st, 2nd, and 3rd-cycle assembly locations (green, yellow, and red, respectively); (b) TRACE core azimuthal sectors and rings.

Fig. 3: Power histories used to model the W4LP core.

For the W4LP, the fuel was typical Westinghouse 17x17 with ZIRLO cladding and the cycles were 18 months long. The power histories were deduced from the known assembly-average peaking factors at BOC, MOC, and EOC. Fig. 2(a) shows a core map for the W4LP modeled. For each assembly, linear interpolation over time between the three known power levels was performed to obtain its power history. Within each group of assemblies (1st-, 2nd-, and 3rd-cycle), those with identical power histories were grouped in power bins. This resulted in 18 first-cycle bins, 22 second-cycle bins, and third-cycle fuel bins. Power histories were generated for each assembly in the core by combining a 1st-cycle power history with a 2nd-cycle power history, and for 25 of the 84 second-cycle assemblies, a 3rd-cycle power history was added. The 59 other 2nd-cycle assemblies were assumed to be discharged after the second cycle. The detailed power history was then reconstituted based on the fact that the core radial peaking factors were known at BOC, MOC, and EOC. For 93 of the 217 assemblies in the core, the process of finding an assembly’s previous location resulted in unrealistic power histories. For these 93 assemblies, the same process used for the W4LP was used to determine the power history. The net result was 19 first-cycle power bins, 27 second-cycle bins, and 33 third-cycle bins. Of the 76 assemblies discharged from the core at each cycle, 11 assemblies only resided 2 cycle in the core, and the other 65 resided 3 cycles. The core-average discharge burnup achieved with the power histories developed was 54.5 GWd/MTU. For the equilibrium core, there were 18 first-cycle power histories, 26 second-cycle power histories, and 11 third-cycle power histories, resulting in 55 power histories required to represent the entire core at any instant (Fig. 3).

Fig. 4: CE-PWR core: (a) 1st, 2nd, and 3rd-cycle assembly locations (green, yellow, and red, respectively); (b) TRACE core azimuthal sectors and rings.

Fig. 5: Power histories used to model the CE-PWR core.

For the CE-PWR, the fuel was typical CE 16x16 with Zircaloy-4 cladding and the cycles were also 18 months long. The power histories were deduced from the known assembly-average peaking factors at BOC, MOC, and EOC, and from a core map with the previous location in the core listed for each assembly. Fig. 4(a) shows a core map for the CE-PWR modeled. For lack of better information, it was assumed that the core map would repeat itself at each new cycle. Each assembly was analyzed by finding its previous location in the core, and repeating this process until a fresh assembly was encountered, which provided the location history of each assembly in the core from BOL to EOL. The detailed power history was then reconstituted based on the fact that the core radial peaking factors were known at BOC, MOC and EOC. For 93 of the 217 assemblies in the core, the process of finding an assembly’s previous location resulted in unrealistic power histories. For these 93 assemblies, the same process used for the W4LP was used to determine the power history. The assemblies with the same BOL to EOL power history were grouped for FRAPCON modeling purposes. The net result was 19 first-cycle power bins, 27 second-cycle bins, and 33 third-cycle bins. Of the 76 assemblies discharged from the core at each cycle, 11 assemblies only resided 2 cycle in the core, and the other 65 resided 3 cycles. The core-average discharge burnup achieved with the power histories developed was 57.8 GWd/MTU. In total, 79 power histories were needed to represent the entire core at any instant (Fig. 5).
5). For the GE-BWR/4, the core contained a mix of 10x10 fuel types, both clad with Zircaloy-2: GE14 (2nd and 3rd-cycle assemblies), and AREVA Atrium10 (1st-cycle assemblies). The burnup and the assembly peaking factor were available at BOC and EOC for each assembly in the core. Fig. 6(a) shows a core map for the GE-BWR/4 modeled. The MOC assembly peaking factor was calculated so as to obtain the correct cycle burnup for each assembly, and the cycle power history for that assembly was obtained by linear interpolation over time between the three known power levels. This provided the current cycle power histories from BOC to the time of the transient, which also corresponds to the power history from BOL to the time of the transient for 1st-cycle assemblies. The previous cycle(s) power history for the 2nd and 3rd-cycle assemblies were developed from the known core average power for 1st, 2nd and 3rd-cycle assemblies and adjusted to match the known BOC burnup for the cycle analyzed. There was no binning for the GE-BWR/4 case: each and every one of the 764 assemblies was modeled individually in FRAPCON (Fig. 7).

![Fig. 6: GE-BWR/4 core: (a) 1st, 2nd, and 3rd-cycle assembly locations (green, yellow, and red, respectively); (b) TRACE core rings.](image)

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3. Steady-State System Thermal Hydraulics

The TRACE code V5.831 with increased stack size was used to perform all the systems thermal hydraulic calculations in this study. The increased stack size was required to handle the large number of heat structures or channels modeled.

For the W4LP and CE-PWR models, the core was modeled in 3D and divided into 2 rings and 14 vertical slabs. The W4LP and CE-PWR models had 8 and 6 azimuthal sectors, respectively (one for each cold and hot leg); see Fig. 2(b) and Fig. 4(b). Each assembly was modeled individually as a heat structure component (HTSTR) with 14 axial cells, and the assemblies that overlapped 2 azimuthal sectors were split into 2 heat structures. The central assembly in the core was split into 8 (W4LP) or 6 (CE-PWR) heat structures to represent the fact that it overlaps all azimuthal sectors. In the CE case, there were two additional assemblies on each side of the central assembly that were divided into 3 heat structures. For both W4LP and CE-PWR, all the azimuthal sectors within the model contained the same number of fuel rods. There were 248 and 260 heat structures in the W4LP and CE-PWR TRACE models, respectively.

For the GE-BWR/4, the core was modeled in 2D, with 4 rings; see Fig. 6(b). Each of the 764 assemblies was modeled individually as a channel component (CHAN) with 28 axial cells, 25 of which corresponded to the active fuel column, the other three being the inlet nozzle and the regions above and below the fuel column.

The burnup dependent parameters required for the heat structures and channels that represented fuel assemblies were extracted from FRAPCON calculations at three different times corresponding to BOC, MOC, and EOC. These parameters were: radial and axial power profile, burnup, rod average oxide layer thickness, rod average cladding creepdown, rod average pellet swelling, rod internal pressure or number of gas moles, and rod gas composition. For each of the three reactors modeled, steady-state calculations were performed at BOC, MOC, and EOC, so as to be able to calculate the LOCA transient response for different times of cycle and assess the impact of cycle time on fuel rod ruptures and fuel dispersal.

4. Transient System Thermal Hydraulics

Several transients were modeled with TRACE as part of this study, and each transient was modeled at BOC, MOC, and EOC to study the differences in plant response for different times of cycle. For the W4LP, the only scenario modeled was a double-ended guillotine cold leg break, which is believed to be the worst design-basis LBLOCA. For the CE-PWR, two scenarios were modeled: (1) LBLOCA consisting of a double ended guillotine cold-leg break at the vessel junction; (2), SBLOCA with the limiting break size of 41.8 cm² at a cold leg nozzle. Finally, for the GE-BWR/4, the two scenarios modeled were (1) LBLOCA consisting of a recirculation loop line break; (2) SBLOCA with a 65.0 cm² break on the recirculation discharge line. The LBLOCA scenarios chosen are believed to be the worst design-basis LBLOCA scenarios, and the SBLOCA scenarios chosen are at the limiting break size for a design basis SBLOCA.

4. Transient Fuel Performance

Although the TRACE code does model the transient behavior of fuel rods, the models used to do this are simplified and do not provide a very detailed thermal-mechanical response of the fuel rods. In particular, the ballooning and rupture models in TRACE do not model the dynamic changes in fuel rod volume, pressure, and strain during the transient in as detailed a manner as the NRC’s transient fuel performance code FRAPTRAN. Consequently,
for cases where the core peak cladding temperatures were above 700°C (973.15 K), and where it is believed that fuel cladding ballooning and burst may occur, the transient fuel rod thermal-mechanical response was calculated with the NRC’s transient fuel performance code FRAPTRAN-1.5.7

The only cases that warranted transient fuel performance modeling with FRAPTRAN were the W4LP LBLOCA cases. For these 3 cases (BOC, MOC, and EOC), the TRACE predicted cladding surface temperatures, as well as coolant conditions in the core, were used as boundary conditions for the FRAPTRAN calculation. This was done by telling FRAPTRAN that the coolant temperature was equal to the TRACE calculated cladding surface temperatures, and by then applying an artificially high heat transfer coefficient between the cladding and the coolant (1.0E+9 W/m²K), so as to effectively impose the cladding surface temperature. The detailed rod plenum temperature model was used in FRAPTRAN, and the ballooning model was turned on so as to capture any potential fuel rod ballooning and rupture events. It is important to point out that in addition to the number of fuel rods predicted to rupture, the FRAPTRAN calculation also provided local burnup (imported from the FRAPCON calculations), strain along the entire length of the fuel rods, and time and axial location of rupture, among other parameters. These parameters are of prime importance to be able to predict the amount of fuel dispersed associated with each fuel rod rupture prediction, as is described in section IV.

III. MODELING RESULTS AND DISCUSSION

For each reactor type and transient modeled, the following paragraphs describe the results obtained from the systems thermal-hydraulic code TRACE, as well the results from the FRAPTRAN calculations, when applicable.

1. Westinghouse 4-Loop PWR LBLOCA

The LBOCA peak cladding temperatures predicted by TRACE for the W4LP at BOC, MOC, and EOC are shown in Fig. 8. The core-wide PCT was 1110 K at BOC, 1090 K at MOC, and 1095 K at EOC. The BOC transient had not only the highest PCT, but also the latest full-core quench time. However, the core-wide PCT only varied by 20 K for all three cases, and the quench time only varied by 20 seconds, such that all three transients were very similar. The core-wide PCT was above 973.15 K in all cases, thus FRAPTRAN analyses were performed to obtain the core-wide fuel rod rupture census used in fuel dispersal analysis.

The results of the FRAPTRAN analyses are shown in Fig. 9, where the number of fuel rod ruptures is displayed as a function of time for each group of assemblies in the core (1st, 2nd, and 3rd-cycle), at BOC, MOC, and EOC. A core map indicating the location of fuel assemblies with ruptured rods is also shown.

At BOC and MOC, the results were almost identical, with 21,252 out of 50,952 fuel rods that ruptured (~42% of the core). The ruptures were confined to the inner region of the core, with at BOC and MOC respectively, 9,372 and 9,504 first-cycle rod ruptures (~42% of 1st-cycle rods), 11,616 and 11,484 second-cycle rod ruptures (~52% of 2nd-cycle rods), and 264 third-cycle rod ruptures in both cases (corresponding to the assembly in the very center of the core). There were two different times in the transient when many ruptures occurred. First between 60 and 150 seconds, when the temperatures were near PCT for a prolonged period of time, all the 1st-cycle rod ruptures occurred, as well as a majority of the 2nd-cycle ruptures (77% of 2nd-cycle ruptures at BOC and 56% at MOC) and of the 3rd-cycle ruptures (63% of 3rd-cycle ruptures at BOC and 75% at MOC). Then between 255 and 280 seconds, during the quench phase of the transient, the remainder of the 2nd and 3rd-cycle rod ruptures occurred. In the BOC case, the 2nd-cycle rods ruptured on average about 15 to 20 seconds earlier than in the MOC case, likely because of the higher temperatures experience in the BOC case. The rods that ruptured when the core-wide temperature was near the PCT (including all 1st-cycle ruptured rods) had a balloon strain equal to the rod pitch (~38% strain, indicating contact with neighboring rods). The 2nd and 3rd-cycle rods that did not balloon all the way to the rod pitch were the ones that ruptured during the quench. They typically had balloon strains between 9% and 10% at BOC, and between 6% and 11% at MOC, likely because the BOC temperatures were slightly higher than the MOC temperatures, resulting in higher plastic strains.

At EOC, a total of 27,852 rods ruptured (~55% of the core), which was significantly more than at BOC and MOC. There were 14,256 first-cycle rod ruptures (~64% of 1st-cycle rods), 13,332 second-cycle rod ruptures (~60% of 2nd-cycle rods), and 264 third-cycle rod ruptures in both cases (corresponding to the assembly in the very center of the core). There were two different times in the transient when many ruptures occurred. First between 30 and 150 seconds, when the temperatures were near PCT for a prolonged period of time, all the 3rd-cycle rod ruptures occurred, as well as a majority of the 1st and the 2nd-cycle ruptures (70% and 92% of 1st and 2nd-cycle ruptures, respectively). Then between 210 and 265 seconds, during the quench phase of the transient, the remainder of the 1st and 2nd-cycle rod ruptures occurred. The fact that the ruptures occurred sooner at EOC than at MOC despite similar temperatures is a result of the higher rod internal pressures at EOC compared to both BOC and MOC. The rods that ruptured when the core-wide temperature was near the PCT (including all 3rd-cycle ruptured rods) had a balloon strain equal to the rod pitch (~38% strain, indicating contact with neighboring rods). The 2nd and 3rd-cycle rods that did not balloon all the way to the rod pitch were the ones that ruptured during the quench. They typically had balloon strains between 9% and 10% at BOC, and between 6% and 11% at MOC, likely because the BOC temperatures were slightly higher than the MOC temperatures, resulting in higher plastic strains.

Fig. 8: W4LP core-wide peak cladding temperature versus time for a LBLOCA at BOC, MOC, and EOC

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contact with neighboring rods). The 1st and 2nd-cycle rods that did not balloon all the way to the rod pitch were the ones that ruptured during the quench. They typically had balloon strains between 5% and 8% at EOC, compared to 6% and 11% at MOC despite very similar temperatures, likely because the EOC rod internal pressures were often significantly higher than at MOC, resulting in a higher strain rate prior to rupture, and leading to ruptures with less strain.

2. Combustion Engineering PWR LBLOCA

The LBLOCA peak cladding temperatures predicted by TRACE for the CE-PWR at BOC, MOC, and EOC are shown in Fig. 10. The core-wide PCT was 975 K at BOC, 970 K at MOC, and 951 K at EOC. It is believed that these temperatures are too low to result in fuel rod ruptures, meaning no fuel dispersal is possible for this particular transient in this particular reactor. Consequently, a FRAPTRAN analysis to obtain a core-wide rod rupture census was not performed. The BOC transient had the highest initial temperature by 5 K during the blowdown phase of the LBLOCA (first 50 seconds), which is expected with the higher power and higher stored energy of fresh fuel assemblies. The reflood peak cladding temperatures (between 50 and 150 seconds) also decreased as the time of cycle increased, such that the BOC reflood PCT was ~50 K higher than the MOC reflood PCT, which itself was 59 K higher than the EOC reflood PCT. However, the increased decay heat at EOC resulted in a later core quench by about 35 seconds compared to MOC.

3. Combustion Engineering PWR SBLOCA

The SBLOCA peak cladding temperatures predicted by TRACE for the CE-PWR at BOC, MOC, and EOC were lower than those predicted for the same plant under LBLOCA conditions, and are shown in Fig. 11. The core-wide PCT was 785 K at BOC, 789 K at MOC, and 768 K at EOC. It is believed that these temperatures are too low to result in fuel rod ruptures, meaning no fuel dispersal is possible for this particular transient in this particular reactor. Consequently, a FRAPTRAN analysis to obtain a core-wide rod rupture census was not performed. For all three times of cycle, the PCT response was identical until around 1700 seconds, which
is when part of the core becomes uncovered. The results show that the core was uncovered a few seconds earlier at MOC than at BOC, but was also quenched a few seconds earlier. In contrast, at EOC, the core was uncovered about 40 seconds later than at BOC and MOC, and the quench occurred about 20 seconds later than at BOC and MOC, meaning the core was uncovered for 20 seconds less at EOC when compared to BOC and MOC.

4. General Electric BWR/4 LBLOCA

The LBLOCA peak cladding temperatures predicted by TRACE for the GE-BWR/4 at BOC, MOC, and EOC were lower than the PCT predicted for LBLOCA for the W4LP and the CE-PWR. As shown in Fig. 12, the core-wide PCT was 743 K at BOC and MOC, and 777 K at EOC. It is believed that these temperatures are too low to result in fuel rod ruptures, meaning no fuel dispersal is possible for this particular transient in this particular reactor. Consequently, a FRAPTRAN analysis to obtain a core-wide rod rupture census was not performed. Unlike for the PWR LBLOCA cases, the blowdown did not result in an immediate temperature increase in the core, and the heat removal was sufficient to remove the fuel rod stored energy. After about 25 seconds, the temperature began to increase as a result of core uncover, and the temperature excursions was driven by decay heat, which explains the higher PCT at EOC by 34 K, as well as the delayed quench by about 5 seconds. The BOC and MOC PCT were almost identical.

![Fig. 12: GE-BWR/4 core-wide peak cladding temperature versus time for a LBLOCA at BOC, MOC, and EOC](image)

5. General Electric BWR/4 SBLOCA

The SBLOCA peak cladding temperatures predicted by TRACE for the GE-BWR/4 at BOC, MOC, and EOC were higher than those predicted for the GE-PWR/4 for LBLOCA, which is the opposite of what was observed for the CE-PWR. As shown in Fig. 13, the core-wide PCT was 764 K at BOC, 783 K at MOC, and 812 K at EOC. It is believed that these temperatures are too low to result in fuel rod ruptures, meaning no fuel dispersal is possible for this particular transient in this particular reactor. Consequently, a FRAPTRAN analysis to obtain a core-wide rod rupture census was not performed. For all three times of cycle, the PCT response was identical until around 255 seconds. After 255 seconds, the PCT increases that were observed were driven by decay heat, such that the temperatures rose faster in the MOC and EOC cases than in the BOC case. Furthermore, the local maxima achieved increased with time of cycle, because of the higher decay heat due to the higher burnup of the core. This explains why the PCT at EOC is about 29 K higher than at MOC, and why the PCT at MOC is about 29 K higher than at BOC. Finally, the BOC case resulted in quench being predicted about 10 seconds earlier than in the MOC and EOC cases.

![Fig. 13: GE-BWR/4 core-wide peak cladding temperature versus time for a LBLOCA at BOC, MOC, and EOC](image)

IV. FUEL DISPERSAL PREDICTIONS

The overall goal of this study was to predict how much fuel might be dispersed into the core from the ruptured fuel rods during a LOCA transient. To achieve this objective, the first step was to determine if fuel rods ruptured, how many, and when. In addition, for the ruptured fuel rods, the characteristics of fuel and cladding near the rupture location are key pieces of information to predict amounts of dispersed fuel. The following sections briefly present empirically derived conditions that are required for fuel dispersal to occur, and provide a discussion on dispersed fuel mass estimates for the transient scenario that resulted in cladding ruptures: the large-break LOCA in the Westinghouse 4-loop PWR.

1. Empirical Thresholds

The conditions required for fuel dispersal to occur have been studied experimentally and have previously been discussed elsewhere, but they are summarized here for convenience:

- Fuel rod rupture must have occurred.
- Fuel fragments must be smaller than the rupture opening: very difficult to analyze for because predicting fuel rod rupture opening size with any reliability remains a major challenge, thus it is assumed all the fine fuel fragments will be able to escape from the rod, but that coarse fragments cannot escape. This assumption is generally supported by many experimental observations during LOCA tests. All fuel particles with a particle size of 1 mm and below are assumed to be fine fuel particles for the purpose of this study.
- A local pellet average burnup threshold exists at which point the fuel fragment size distribution begins to transition from a coarse particle distribution to a fine particle distribution. This burnup threshold is believed to
occur between 55 and 70 GWd/MTU. Furthermore, it is assumed that a fuel pellet with zero burnup will not produce any fine fragments, but that the fraction of fine fragments increases linearly (for lack of better data) between the assumed fragment size distribution at zero burnup (no fines, only coarse fragments) and the assumed particle size distribution at the burnup corresponding to the beginning of the transition from coarse to fine particle size distribution (variations for this burnup were investigated, but the particle distribution was that of 55 GWd/MTU fuel analyzed as part of the NRC Studsvik LOCA tests).

- A given amount of cladding strain is required for fuel particles to be axially mobile within the cladding. This axial mobility strain threshold is believed to be 5% permanent cladding strain.

Based on these assumptions, estimates of fuel dispersal based on variations of the burnup threshold (beginning of the transition from coarse to fine particle distributions) are provided.

2. Dispersed Fuel Masses and Characteristics

The dispersed fuel masses discussed in this section assume that all particles with a size below 1mm are fine particles that can and will be dispersed from the regions of the fuel rod near the rupture node if the cladding hoop strain is above 5%, which is assumed to be the threshold for fuel axial mobility and dispersal. Only the LBLOCA scenario for the W4LP produced fuel rod ruptures, thus the fuel dispersal estimates are presented for that particular scenario, at BOC, MOC, and EOC.

At BOC and MOC, the dispersed fuel quantities are relatively insensitive to the chosen burnup threshold, mainly because there are no fuel rods in the core that have reached burnups above the threshold. The increase in dispersed fuel mass as the burnup threshold is reduced, from 28.3 kg to 33.5 kg at BOC and from 45 kg to 53.2 kg at MOC, is related to the linear interpolation between zero burnup and the threshold for the beginning of the transition to fine fragmentation. The increase in fuel mass for a given threshold between BOC and MOC is moderate (~17 kg to 20 kg depending on the chosen threshold), and is directly related to the increase in assembly burnup between BOC and MOC. Importantly, all the fuel dispersed at BOC and MOC came from low burnup assemblies, where ruptured fuel rods are only expected release very small amounts of fine fuel, but the very large number of fuel rod ruptures nonetheless resulted in 30 kg to 50 kg of predicted fuel dispersal.

At EOC, in contrast with BOC and MOC, the choice of the burnup threshold results in very large variations in the predictions of dispersed fuel mass. This is a result of the fact that at EOC, a relatively large number of rods have peak local pellet burnups above 55 GWd/MTU, 60 GWd/MTU, or even 65 GWd/MTU, and that the burst node is in most cases at or near the peak power and peak burnup nodes. As a result, the dispersed fuel mass predictions vary between 105 kg and 622 kg at EOC depending on the choice of a high or low threshold. Finally, the increase in fuel mass for a given threshold between MOC and EOC is significantly larger than between BOC and MOC (~60 kg to 569 kg depending on the chosen threshold). This large difference is due to the fact that regardless of the chosen threshold, many rupture nodes at EOC have a high burnup that is above the threshold for coarse to fine particle size distribution, thus resulting in much larger dispersed fuel masses.

3. Perspectives, Limitations, and Future Work

This study is part of an ongoing effort to assess fuel dispersal from a regulatory perspective. The work presented in this paper is an analytical scoping study aimed at producing detailed fuel dispersal estimates for LOCA transients, for several different types of reactors in the US fleet. The results presented here should not be generalized. The results of this study are not believed to be valid for all reactors similar to those analyzed here, nor for all transients similar to those analyzed here. In fact, it is very important to point out that predictions of fuel dispersal vary by large amounts depending on the detailed reactor design, and on the transient being analyzed, as well as the modeling assumptions. As a results, accurate fuel dispersal estimates require plant-specific calculations. The 5 cases presented here are simply case studies used to develop methods to produce fuel dispersal estimates for scoping analyses of safety implications of fuel dispersal. The calculations performed for this study are all "nominal" calculations, meaning there are no added conservatisms and no effort to statistically quantify uncertainties, as might be done in some licensing analyses. A systematic statistical treatment of the uncertainties related to modeling assumptions and uncertainties, fuel design, and plant design would be a logical next step, although likely to be very computationally intensive. Of the 5 nominal
calculations performed, only one led to temperatures high enough to produce fuel rod ruptures and dispersed fuel. In that case, it was shown that the assumptions used to predict dispersed fuel amounts could have large impacts on the results of the analyses.

The calculations performed for this study show that as burnup increases, the predicted fuel dispersal also increases. If ruptured assemblies have a local burnup near the rupture that exceeds the assumed fine fragmentation burnup threshold, this increase in dispersed fuel is significantly larger, on the order of a factor of 30 times more dispersed fuel per ruptured fuel rod whose burnup is above the fine fragmentation threshold. It was also observed for the W4LP that resulted in fuel rod ruptures, that none of the fuel rods on the periphery of the core ruptured. This implies that locating high burnup assemblies only on the periphery of the core, and avoiding placing them in the central regions of the core, could result in very significant reductions in fuel dispersal for LOCA scenarios where fuel rod ruptures are expected.

To further increase the precision of fuel dispersal studies, more detailed modeling could be performed for the assemblies whose PCT lies within 10% of the lowest temperature at which cladding ruptures are predicted, to capture intra-assembly variations between fuel rods and thus obtain a more detailed census of the fuel rod rupture populations. This would require sub-assembly binning of fuel rods for the assemblies of interest, and would increase the number of assemblies modeled in TRACE as well as FRAPCON/FRAPTRAN.

Finally, it is foreseen that the results from these analyses will be used in the near term to perform consequence analyses and evaluate the safety implications of fuel dispersal. These studies will be one of the pieces of information that will determine how to address fuel dispersal in regulatory space, if needed.

V. CONCLUSIONS

As part of the effort to evaluate the potential impact of fuel dispersal during a LOCA on reactor safety, several analytical studies of core-wide fuel rod ruptures were performed with a very high level of detail, whereby each and every assembly of the core was modeled individually in both the fuel performance codes and the systems thermal hydraulic code. The NRC’s fuel performance codes FRAPCON and FRAPTRAN were used in conjunction with NRC’s systems thermal-hydraulic code TRACE to produce core-wide fuel rod rupture inventories for LBLOCA for a W4LP, a CE-PWR, and a GE-BWR/4. SBLOCA were also analyzed for the CE-PWR and the GE-BWR/4.

Only the LBLOCA for the W4LP resulted in fuel rod ruptures and in fuel dispersal predictions. The fuel dispersal predictions were shown to be highly dependent on the assumptions used to make the prediction, particularly the burnup at which fine fragmentation of the pellets begins to occur.

It is foreseen that the methods developed for the purposes of this study will continue to be refined and used again in the future to produce more estimates for different plant types, fuel designs, and transient scenarios, as well as investigate the impact of uncertainties on the results. The deleterious effects of increased burnup on predicted fuel dispersal constitute a possible reason to limit burnup to current levels until the consequences of fuel dispersal are fully assessed from a safety perspective.

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NOMENCLATURE

BOC: Beginning Of Cycle
BOL: Beginning Of Life
BWR: Boiling Water Reactor
CE: Combustion Engineering
CHAN: Channel component in TRACE
ECCS: Emergency Core Cooling System
EOC: End Of Cycle
EOL: End Of Life
FFRD: Fuel Fragmentation, Relocation, and Dispersal
GE: General Electric
HTSTR: Heat Structure component in TRACE
LBLOCA: Large-Break LOCA
LOCA: Loss-Of-Coolant Accident
MOC: Middle Of Cycle
NRC: Nuclear Regulatory Commission
PCT: Peak Cladding Temperature
PWR: Pressurized Water Reactor
SBLOCA: Small-Break LOCA
W4LP: Westinghouse 4-Loop PWR

REFERENCES