On PWR Fuel Failure Thresholds and Core Coolability Limits

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1. Introduction

The current fuel failure thresholds and core coolability limits were established in early 70s, based on test data of unirradiated rods or low burnup rods below 40 GWd/t with Zr-based cladding materials. However, since 90s the fuel average burnup has been gradually increased, and new types of fuel and cladding materials also introduced. The initial results from Reactivity Initiated Accident (RIA)-simulation tests on fuel rod segments with burnup levels above 50 GWd/tU, namely CABRI REP Na-1 (1993) and NSRR HBO-1 (1994), raised concerns that the existing licensing criteria may be inappropriate beyond a certain burnup level. As a consequence, the nuclear community has conducted extensive studies of the observed behavior of high burnup fuel under LOCA (Loss of Coolant Accident) as well as RIA conditions [1, 2].

With deliberate consideration of the international research trend, it is needed to review the technical bases of the current fuel failure thresholds and coolability limits applied for PWR transients and accidents, and to examine the fuel burnup effect on them in RIA and LOCA conditions.

2. Fuel Criteria for Accident Conditions

The fuel failure is defined as a loss of cladding integrity on retention of radioactive material, so a radioactive release to the coolant is expected over its threshold. Core coolability refers to maintenance of the coolable geometry with adequate coolant channels to permit removal of decay heat. The fuel failure itself is not considered a safety concern but rather a prerequisite for loss of coolable geometry.

Most nuclear reactor accidents are attributed to an imbalance between the heat generation rate of the nuclear core and heat removal capacity of the coolant. Two extreme cases have commonly been designated as the LOCA in which all or part of the coolant inventory is rapidly lost, and the RIA in which a sudden power increase is initiated within the nuclear core. Between these two extremes lies a wide range of off-normal power-cooling conditions commonly referred to as the power-to-cooling mismatch (PCM) accidents. Safety analyses include compliance with safety requirements related to the fuel cladding in such PCM accidents, in a way that radioactive material release to the atmosphere is controlled at the acceptable level, and core coolability is maintained. Figure 1 illustrates the relationship between the load to fuel rods and its related licensing limits during the PCM accidents.

The fuel cladding is continuously subjected to the thermal and mechanical loads during reactor operation, while its strength changing by irradiation time. In the

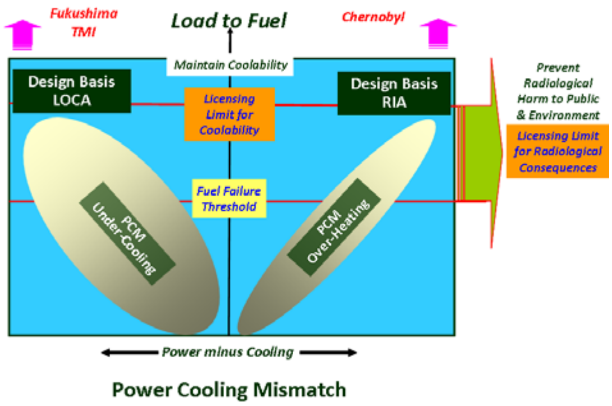

Figure 1 Relationship between load to fuel clad and licensing limits during PCM accidents

PCM accidents the fuel cladding can fail by various mechanisms, which can be represented by two failure modes, high cladding temperature and PCMI. The former can lead to fuel failure by two mechanisms: (1) embrittlement due to oxidation, and then perforation, (2) ballooning due to differential pressure between rod internal and coolant, and then burst. In the latter, the clad can fail by (1) fission gas bubble and differential fuel-to-clad thermal expansion, (2) fuel overheating and (3) rapid excessive fuel enthalpy deposition, which are mainly initiated by reactivity anomaly in the core.

The PWR is normally operated in a subcooled nucleate boiling (NB) condition; if departure from NB (DNB) occurs, heat transfer to coolant deteriorates, quickly increasing clad temperature. Studies showed that sufficiently long time should be taken to reach clad failure at post-DNB condition [3], while there is large uncertainty in irradiation and power history, crud, oxidation etc., not all possible for experimental simulation. In addition, rods which have experienced DNB and then return to nucleate boiling are likely to more embrittle, and more susceptible to failure during additional operation. Traditional practice considers DNB occurrence as one of the fuel failure thresholds.

If the load far exceeding the fuel failure threshold is exerted to the clad, the coolability is threatened by the effects of loss of clad ductility before cooling, violent fuel expulsion, or ballooning, burst and blockage, etc. In particular, loss of clad ductility largely penalizes fuel rod integrity for the accident with a wide range of temperature fluctuation.

3. Reactivity Initiated Accident

The RIA is an unplanned positive reactivity insertion to the core, resulting in an undesirable increase of fission rate and reactor power. Ejection of one single control rod assembly (CRE) is postulated as the worst RIA in PWRs, the main characteristics of which are deposition of considerable amount of energy in the fuel in a brief period, and rapid thermal expansion of the fuel pellet against the cladding.

Studies showed that the RIA pulse and width, response in the fuel pellet rim region, and cladding corrosion and hydride have important effects on high burnup fuel behavior during RIA. In the recent USNRC interim criteria as summarized in Fig. 2, PCMI becomes more important in high fuel burnup than in low burnup. Notice should be taken that there are some arguments on the efficacy of the dispersal of non-molten material in converting the thermal energy in the fuel particles to mechanical energy in the coolant.

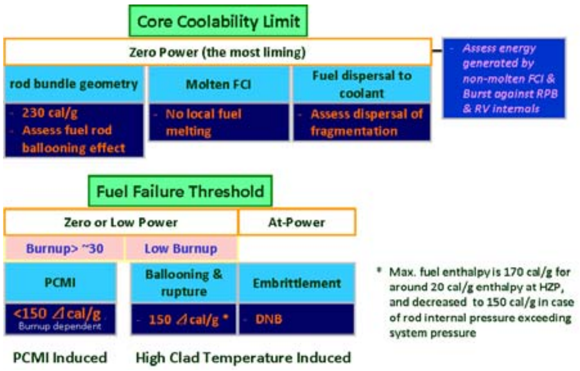

Figure 2 Summary of USNRC RIA Interim Criteria

4. Loss of Coolant Accident

The current LOCA safety criteria, still in use in most countries, are derived from the ECCS acceptance criteria issued by USAEC in December 1973 (10 CFR 50, part 50.46). The criteria are composed of three prescriptive and two qualitative criteria: the first two related to clad embrittlement, the third to minimize hydrogen in containment, and the last two for coolable geometry and long term cooling. Most of attention, at that time, focused on retention of ductility up to the time that cladding would be cooled to a temperature of 300°F or less, while the last two criteria were added by considering the conclusion of the Ergen Task Force in 1967 that a basic objective of the criteria is to maintain core coolability until the heat generation decays to an insignificant level. This implies that understating of the fuel behavior during LOCA was not complete.

The procedure used to determine the embrittlement criteria are: a) LOCA scenarios at ORNL LOCA tests (heat up to 1700-2400˚F, quenched by coolant of 73-302˚F, then slow and fast ring compression test), b) determination of β-layer thickness ratio corresponding to Nil-Ductility, in heat up to clad temperature $\leq$~2200 ˚F, quenching temperature $\geq$275 ˚F and slow ring compression test, c) use of Baker-Just correlation to draw the ECR versus time for thermal shock test, other ring compression tests, and d) determination of constant ECR line (17%) by failed and non-failed boundary.

The recent ANL LOCA tests identified the major six embrittlement mechanisms as seen in Table 1, which is being considered in the USNRC proposed rule [4].

Table 1 LOCA Embrittlement Mechanisms

Embrittlement Mechanisms	**Effect on Rule Change**
Beta-layer embrittlement by oxygen	Maintain max. clad temperature
Beta-layer thinning	Change ECR
Localized hydrogen-induced embrittlement in the balloon region	Serious effect on ECR limit, but not directly considered in rule
Hydrogen-enhanced beta-layer embrittlement by oxygen	Change ECR by corrosion level (related to BU)
General hydrogen-induced embrittlement from breakaway oxidation	Confirm time at elevated temp. against breakaway oxidation (depending on fabrication)
Oxygen pickup from the cladding inner surface	Calculate ECR by additional effect of inner corrosion and fuel clad bonding (BU-dependent)

This ANL study revealed that the ECR margin can be significantly decreased by burnup. The third mechanism in the table is attributed to hydrogen trapped within the balloon region and absorbed in the metal. It challenges a basic USNRC approach on retention of ductility, because it would be difficult to find an ECR low enough to guarantee ductility in the balloon region.

One of the issues found in French IRSN study [5] is that the NUREG-0630 strain correlation, used to derive the blockage ratio in many LOCA analyses, does not reflect the data reported after its publication. According to IRSN study, blockage in a ballooning region with fuel relocation can threaten coolability by blockage ratio, its axial extension and heat flux redistribution.

The current LOCA methodology is based on the assumption that the conditions at earlier lifetime are more limiting. It seems clear that the assumption is not always valid even for moderate burnup, although some pending issues remain for LOCA coolability criteria.

5. Conclusion and Recommendation

Fuel failure thresholds and coolability limits applied for the current safety analyses were reviewed, including the recently proposed RIA and LOCA criteria. Many RIA and LOCA fuel phenomena were investigated by international efforts on how the fuel of high burnup and zircaloy based cladding responds to these conditions, however, further study is needed in relation to RIA non-molten FCI and LOCA ballooning and fuel relocation.

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