Recommended Modifications to the NRC White Paper:

Technical and Regulatory Basis: Interim Acceptance Criteria and Guidance for the Reactivity-Initiated Accident (Appendix 4B of NUREG-0800 Standard Review Plan).

3.1 Fuel Cladding Failure Criteria

1. It is recommended that the failure criterion #1 for the peak radial average fuel enthalpy be restored to the current value of 170 cal/gm on the total enthalpy, independent of the initial enthalpy conditions.

   Rationale
   The draft specifies failure criterion #1 as a threshold on the peak radial average fuel enthalpy (H_{max}) to account for non-PCMI fuel failure and to be applied only to RIA events that initiate at hot or cold zero power conditions. It appears that this criterion is based on experimental data on low burnup fuel failures due to clad swelling and burst processes that occur above 170 cal/gm. The 170 cal/gm criterion was reviewed in 1980 by MacDonald et. al., and found to be adequate. Similar conclusions were reached by Ishikawa and Shiozawa. Since these reviews, no new data have been generated that would indicate a need for lowering of the non-PCMI failure criterion. Failure criterion #2, which accounts for PCMI fuel failure and limits the peak radial fuel enthalpy change (ΔH_{max}) as a function of either oxide thickness to clad thickness ratio or cladding hydrogen content to less than 150 cal/gm, takes over and becomes more limiting at points where the oxide thicknesses (or cladding hydrogen content) become significant. Reducing criterion #1 to 150 cal/gm (total fuel enthalpy) effectively reduces criterion #2 to ~135 cal/gm (fuel enthalpy rise) for events that initiate above cold-zero power events and therefore supersedes failure criterion #2 for HZP conditions. Such a situation results in some confusion on the definition of the failure threshold.

2. It is recommended that that definition of the zero enthalpy temperature of 20°C (68°F) be provided in the document.

   Rationale
   Specifying a consistent definition of the zero enthalpy temperature will eliminate the ambiguity in defining the total fuel enthalpy.

3. It is recommended that the option to provide technical justification for the use of alternative failure PCMI failure criteria be included in the description of 3.1.1 Interim Criteria.

   Rationale
   The RIA test results used to develop the PCMI failure criteria shown in Figure 3.1-3 and 3.1-7 are based primarily on older Zr-4 and Zr-2 cladding alloys. Improvements in alloy composition and fabrication can have an important effect on the oxidation kinetics and hydrogen uptake rates, which would impact cladding mechanical properties and possibly the fuel rod performance under RIA conditions. Recognizing that several factors, including the hydrogen concentration, can influence cladding performance during an RIA and allowing

that with sufficient technical justification the failure criteria can be other than those shown in Figure 3.1-4 and 3.1-7 will permit licensees to take advantage of advanced cladding alloys.

4. It is recommended that the MOX test CABRI REP Na-7 used in Figure 3.1-3 to define the PCMI fuel cladding failure criterion for PWR fuel be removed from consideration.

Rationale
The MOX test CABRI REP Na-7 result in Figure 3.1-3 is not applicable to UO_2 fuel because the fuel enthalpy at failure in irradiated MOX rods is not representative of UO_2 rods. Consideration of REP Na-7 is the primary cause of the excessive reduction (lower than RIL 0401) in the values given for criterion #2 at oxide ratios near 0.8.

A review of the experimental data has shown that the pellet expansion process in irradiated MOX fuel is larger than for irradiated UO_2 fuel for a given radial average enthalpy level. The result is that the PCMI forces in MOX fuel produce a cladding strain that can be approximately twice that in UO_2 fuel for highly irradiated rods.

Experimental data from both the CABRI and NSRR RIA tests show that irradiated MOX fuel behavior is different from irradiated UO_2 fuel under RIA conditions at similar burnup and fuel enthalpy levels. Post-test ceramography examinations and measurements of cladding permanent hoop strain and fission gas release reported in the literature finds that irradiated MOX fuel experiences stronger pellet-cladding mechanical interaction (PCMI), larger amount of pellet swelling, and higher fission gas release during rapid energy deposition events as compared to UO_2 fuel. These post-test observations are supported by in-pile measurements of dynamic fuel rod volume changes during the CABRI experiments.

An important indication of the enhanced PCMI due to pellet swelling in the MOX rods comes from the dynamic rod volume changes measured in the CABRI reactor. The effect of MOX pellets on the fuel rod expansion process is shown clearly in Figure 1 which contains a plot of the displaced sodium volume from the flow channel at an injected energy of 70 cal/gm as a function of test rod burnup in the UO2 and MOX rods tested in CABRI. The amount of sodium displaced from the flow channel is determined by integrating the difference between the channel outlet and inlet flowmeter measurements. The sodium expelled from the flow channel consists of two parts; the prompt part caused by fuel rod volume expansion and the delayed part caused by sodium dilation. The sodium volume displacement from the flow channel that is of interest is that caused by the radial and axial expansion of the test rod during the early energy deposition phase of the RIA tests in CABRI. Early time measurements of the displaced sodium volume represent mostly `the fuel rod volume change due to PCMI. In the later portion of the transient, rod to coolant heat conduction causes dilation of the sodium, leading to a further increase in displaced sodium volume beyond that caused by PCMI. The results shown in Figure 1 are at an injected energy of 70 cal/gm, which is early enough in the power pulse for the different tests to minimize the effect of rod to coolant heat conduction on sodium dilation and clearly show the effect of fuel rod expansion due to PCMI.

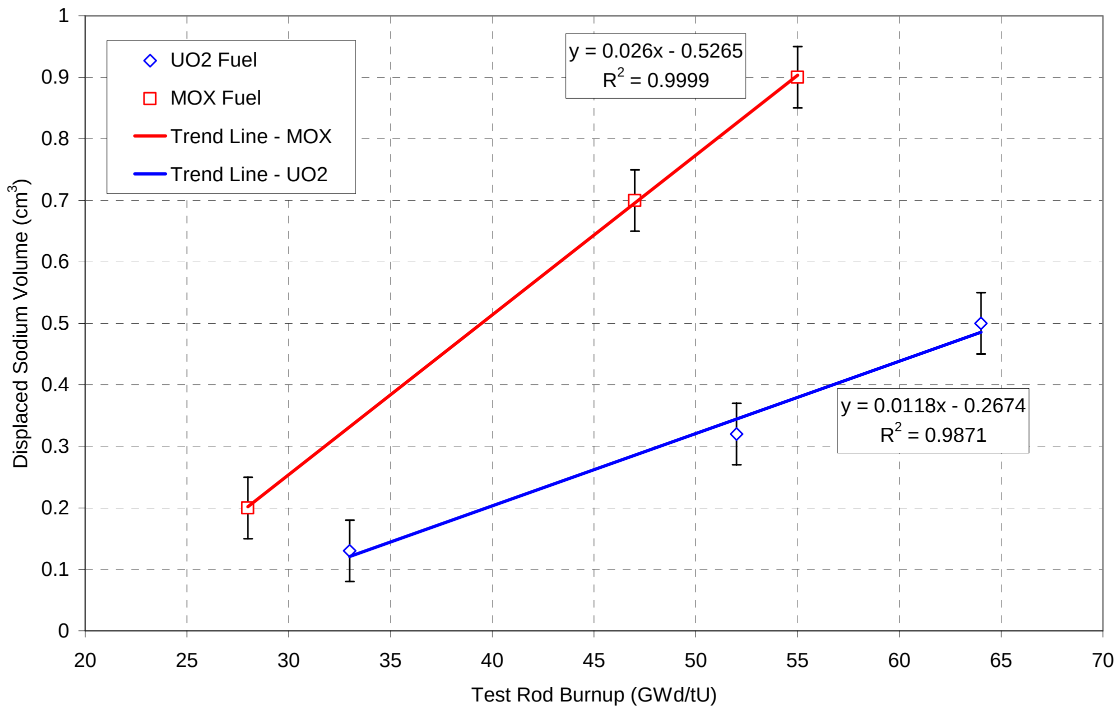

Figure 1. Displaced sodium volume at an injected energy of 70 cal/gm as a function of test rod burnup for both MOX and UO_2 rods tested in the CABRI facility.

In general, both UO_2 and MOX fuel rods show a tendency of larger fuel rod expansion with an increase in burnup. Such behavior is caused by the progressively smaller residual pellet-cladding gap from fuel swelling and cladding creep during the base irradiation for the higher burnup rods. More importantly, the measured values shown in Figure 1 demonstrate that the fuel rod volume increases at a faster rate in the highly irradiated MOX rods as compared to the UO_2 rods during the energy deposition phase of the experiments. For the UO_2 rods, the displaced sodium volume results shown in Figure 1 reflect the amount of fuel rod volume change caused by thermal expansion of the UO_2 pellet column. This has been confirmed by analysis. Such is not the case for the MOX rods, where the increase in fuel rod volume is much higher than expected based only on pellet thermal expansion. From the linear trend of the data shown in Figure 1, the effect of burnup on the fuel rod expansion rate is about 2 times higher in MOX fuel than a UO_2 fuel. The larger pellet expansion process in MOX fuel pellets increases the PCMI forces on the cladding, thus increasing cladding deformations in MOX fuel rods. As a result, the failure of CABRI REP Na-7 at a radial average peak fuel enthalpy of 113 cal/gm does not represent a UO_2 fuel rod at the same fuel enthalpy. Based on this assessment, a separate failure threshold is required for MOX fuel that accounts for the increase in PCMI forces as burnup increases.

5. It is recommended that the NSRR tests rod failures for oxide thickness/clad thickness ratios below 0.12 used to define the PCMI failure criterion for PWR fuel be removed from consideration.

   Rationale

   The NSRR RIA tests used in Figure 3.1-3 were performed at initial coolant temperatures of ~20°C, whereas, the initial coolant temperature in a PWR at HZP conditions is typically around 280°C. Mechanical property tests show that the ductility of irradiated cladding material containing zirconium hydrides increases by a factor between 2 and 4 when the temperature is increased from 20°C to 280°C. Since the PCMI failure process is controlled by the cladding ductility, the improved ductility at representative HZP temperature conditions means that fuel rods with similar oxide thickness conditions would fail at fuel enthalpy levels above those observed in NSRR. In RIL 0401, the NSRR tests were evaluated to determine both a pulse width adjustment factor and a coolant temperature adjustment factor. In the final analysis, the NSRR adjustment factors in RIL 0401 only included a pulse width effect and an initial pellet-cladding gap effect. No consideration was given to an improvement in material ductility at elevated temperatures. The subsequent adjusted fuel enthalpy rise values for the NSRR tests shown in Figure 3.1-3 are conservatively low and unduly bias the failure criterion at oxide thickness values below ~60 microns (0.11 ratio). A comparison of tests performed in CABRI and NSRR at similar burnup and oxide/wall thickness values are shown in Table 1. These results highlight the effect of temperature on cladding failure during an RIA event. Recently published results for the REP Na-12 test further support the need to consider the impact of initial coolant temperature on material ductility in applying the NSRR test results to PWR HZP conditions.

   Table 1. Comparison of NSRR and CABRI Tests at Equivalent Burnup and Oxide/Wall Thickness Values (Bold – Failed, Italic – Non-failed)

Test	Material	Burnup (GWd/MT)	Test Temperature (ºC)	Pulse Width (ms)	Oxide/wall Thickness	Failure Enthalpy Rise (RIL adj.) (cal/g)
VA-2	Zirlo	79	20	4.4	0.12	**55 (80)**
CIP-01	Zirlo	75	280	32	0.14	*>75*
HBO-1	Zr-4	50.4	20	4.4	0.075	**60 (85)**
REP-Na3	Zr-4	54	280	9.5	0.08	*>109*
TK-2	Zr-4	48	20	4.4	0.055	**60 (85)**
REP-Na6	Zr-4	47	280	32	0.06	*>118*
TK-7	Zr-4	50	20	4.4	0.047	**86 (111)**
REP-Na5	Zr-4	64	280	8.8	0.044	*>93*

   Based on these observations, the use of the NSRR data (either raw or RIL adjusted) is inappropriate for developing fuel rod failure criteria for PWR control rod ejection accidents.

6. It is recommended that the rationale for using the ratio of oxide thickness to cladding thickness to capture the wide variation in fuel rod design in the empirical database be changed from "*cladding stress is proportional to wall thickness*" to "*hydrogen concentration is proportional to wall thickness. By correlating the RIA experimental results to this parameter, it is recognized that cladding hydrogen concentration is a key factor in the cladding failure process and using the oxide thickness to cladding thickness ratio serves as a surrogate for cladding hydrogen concentration*".

   <u>Rationale</u>
   One of the important factors that influence PCMI-related cladding failure during an RIA event is the hydrogen concentration within the cladding. The main reason for normalizing the oxide thickness by the wall thickness is to account for the hydrogen concentration in PWR cladding. Simply using oxide thickness may not be sufficient because the hydrogen concentration for a given oxide thickness is dependent on the cladding wall thickness. For example, a 50 micron oxide layer on a 1000 micron thick cladding tube will have a lower wall-average hydrogen content than a 500 micron thick cladding tube for the same hydrogen pickup fraction (15% of the total hydrogen produced is absorbed in the cladding). This is because the total amount of hydrogen that is produced from creating a 50 micron oxide layer is about the same in both cases, but for the same pickup fraction the hydrogen concentration in the cladding will be higher for the thinner wall case. Since accurate cladding hydrogen measurements may not be available for some of the experiments in the RIA data, it is reasonable to use the oxide thickness/wall thickness ratio as a surrogate for hydrogen concentration.

7. It is recommended that the cladding thickness used in determining the oxide-to-wall thickness parameter be defined as the nominal as-fabricated cladding thickness.

   <u>Rationale</u>
   As used in the paper, it is unclear if the oxide thickness to cladding thickness ratio is based on the nominal as-manufactured cladding thickness or the as-irradiated cladding thickness.

8. It is recommended that the fuel enthalpy rise in failure criterion #2 for PCMI failure shown in Figures 3.1-3 and 3.1-7 be changed to the prompt fuel enthalpy rise and that the use of failure criterion #2 be restricted to the prompt fuel enthalpy rise for both BWRs and PWRs. The prompt fuel enthalpy rise is defined as the radial average fuel enthalpy rise at the time corresponding to one pulse with after the peak of the prompt pulse as shown in Figure 2. Failure criterion #1 for non-PCMI failure should be applied to the total fuel enthalpy (prompt + delayed) to evaluate failure by non-PCMI processes.

   <u>Rationale</u>
   Because of the power pulse characteristics of both the BWR control rod drop accident and the PWR control rod ejection accident, the fuel enthalpy rise consists of two parts; (1) the prompt part during which limited clad heating occurs, and (2) the delayed part during which significant clad heating has occurred. The total fuel enthalpy rise is the sum of the two parts. Cladding failure by PCMI is only possible during the prompt part of the power pulse when the pellet thermal expansion rate exceeds the heat conduction rate across the pellet-cladding

gap to the cladding. During the later delayed part of the fuel enthalpy rise, significant clad heating occurs with a corresponding improvement in material ductility, which precludes failure by PCMI. Failure by high temperature processes (ballooning/burst or oxidation embrittlement) is still possible during the delayed fuel enthalpy rise, depending on the maximum cladding temperature and the pressure differential across the cladding. In a commercial LWR, the prompt part of the fuel enthalpy rise is 70% to 90% of the total enthalpy rise. In developing a failure criterion for PCMI, the enthalpy rise to failure from the PCMI-related failures in NSRR and CABRI only applies to the prompt part of the total enthalpy rise.

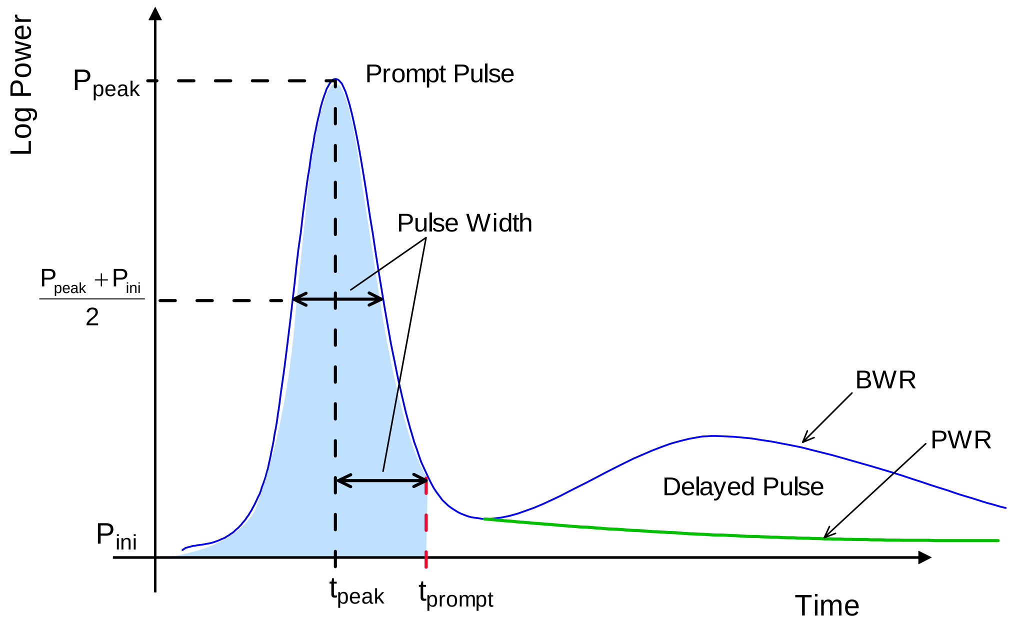

Figure 2. Definition of time of maximum prompt fuel enthalpy rise

9. It is recommended that the abscissa in Figure 3.1-7 be changed to excess hydrogen content in order to be applicable to elevated temperature (>20°C) conditions and extended to 300 ppm.

<u>Rationale</u>
The enthalpy rise curve shown in Figure 3.1-7 is based on tests performed at cold conditions (~20°C) in which all the hydrogen in the cladding has precipitated to zirconium hydrides. Zirconium hydrides have been shown to be a factor in decreasing irradiated cladding material ductility. Upon heating above 20°C, some fraction of the zirconium hydrides will dissolve into the zirconium alloy matrix, following the hydrogen solubility curve. Mechanical property tests have shown an improvement at elevated temperature for material containing zirconium hydrides. A part of this improvement has been attributed to the resolution of zirconium hydrides upon heating. As a result, the material ductility of the cladding, which controls cladding failure, should be a function of the excess hydrogen above the terminal solubility available to form zirconium hydrides.

10. It is recommended that the NSRR FK tests that failed by PCMI shown in Figure 3.1-7 be adjusted upward to account for the differences in power pulse shape between the NSRR reactor and BWR control rod drop accidents in a similar manner as the adjustments developed in RIL 0401 for the PWR NSRR tests.

    Rationale
    It seems appropriate that pulse width effect considerations for the NSRR FK tests should be included in developing the PCMI failure threshold for BWRs, similar to the adjustments developed in RIL 0401 for the PWR NSRR. The much wider prompt pulse width and the significant fraction of delayed energy deposition in a BWR CRDA power pulse results in less demanding PCMI forces on the cladding compared to the 4 millisecond power pulse used in the NSRR experiments. As a result, the use of the NSRR FK test rod failures without adjustment for the pulse width effects is overly conservative when used to develop a lower bound failure threshold as a function of hydrogen content.

11. It is recommended that a statement be added that allows the use of the curves shown in Figures 3.1-3 and 3.1-7 beyond the oxide-to-wall thickness ratio or excess hydrogen contents shown in the figures. One approach to facilitate this would be to provide mathematical expressions (or slopes) for the failure threshold curves shown in Figures 3.1-3 and 3.1-7 which define the fuel enthalpy rise as a function of oxide thickness to clad thickness ratio or excess hydrogen content.

    Rationale
    Without clarification of the fuel enthalpy rise curves shown in Figures 3.1-3 and 3.1-7, the upper value of the independent variables used in the figures could be misunderstood to represent limits on either the oxide-to-wall thickness ratio or the excess hydrogen content. However, upper limits on the cladding oxide thickness or hydrogen content are defined separately from the values shown in Figures 3.1-3 and 3.1-7. The range of independent variables used in Figures 3.1-3 and 3.1-7 could then be identified as an example for purposes of illustration. Providing the slopes of the different portions of the curves or some mathematical expressions would allow the use of these curves beyond the limits shown in Figures 3.1-3 and 3.1-7.

12. It is recommended that additional clarification be provided in section 3.1.1 to state that for at-power conditions only failure criterion #3 should be applied. Further, it is recommended that the reference to ≥ 5% rated thermal power be removed from the definition for failure criterion #3.

    Rationale
    For at-power conditions, the occurrence of the local heat flux exceeding the fuel thermal design limits (e.g. DNBR or CPR) will be more limiting than either failure criterion #1 or failure criterion #2. As a result, application of failure criteria #1 and #2 to at-power RIA events adds unnecessary burden in the licensing analysis methodology.

3.2 Coolable Core Geometry

1. It is recommended that the description of Path 2 for demonstrating compliance with the coolability criteria given in Section 3.2.2, subsection on Fuel dispersal, be modified to allow industry to develop the technical position that PCMI failures are possible without fuel fragmentation and dispersal.

   Rationale
   As written, the description of Path 2 appears to preclude the possibility to provide a technical argument that demonstrates that PCMI failure may occur without fuel dispersal. The part in question is; "*Demonstrate via improved physics methods and/or fuel management techniques that the characteristics of the power pulse and/or change in fuel enthalpy will not yield fuel fragmentation and PCMI fuel cladding failure.*" The industry would like the opportunity to demonstrate that PCMI failure may occur without fuel dispersal, e.g. for situations where the power pulse width will be larger than 10 milliseconds, as part of the technical disposition of fuel dispersal consequences.

2. It is recommended that the term "*fuel relocation*" used in the description of Path 3 for demonstrating compliance with the coolability criteria given in Section 3.2.2, subsection on Fuel Dispersal, be replaced or defined as "*the transport of dispersed fuel fragments within the primary coolant system*".

   Rationale
   The term fuel relocation is used to describe fuel column movement into the ballooned region during of a Loss-of-Coolant Accident (LOCA) or for the movement of molten fuel during a severe core accident. To minimize confuse with these other accidents, it would be desirable to use the term "*transport of dispersed fuel fragments within the primary coolant system*" to describe the phenomena associated with the movement (or relocation) of the fuel fragments following dispersal during a reactivity initiated accident.

3. It is recommended that the term "*improved physics methods and or fuel management techniques*" referenced in the description of Path 1 and Path 2 for demonstrating compliance with the coolability criteria given in Section 3.2.2, subsection on Fuel Dispersal, be changed to "*approved methods*".