A RIA Failure Criterion based on Cladding Strain

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Paper to be presented at the IAEA Technical Committee Meeting on Fuel Behaviour under Transient and LOCA Conditions

This note intends to contribute to the interpretation of the RIA tests that have been performed during the last decade on high burn-up PWR and BWR rods and that have been reported in the open literature. A failure threshold based on cladding deformation is proposed. This criterion predicts well all CABRI data with the exception of one. NSRR fuel failures are also reasonably well predicted by the proposed criterion. Further MOX tests are needed in order to clarify differences between MOX and UO₂. For what concerns mechanisms, fuel swelling is important and FGR less important for the failure mechanism at high burnup (~60 MWd/kg).

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Paris, August 2001

(1) Currently at the OECD-Nuclear Energy Agency
1. Introduction and summary

The RIA test data available in the literature, and in particular the CABRI REP Na test data (Table 1), provide a very consistent basis for the assessment of fuel behaviour mechanisms relevant for RIA transients. For the CABRI REP Na rods that did not fail, valuable information on fission gas release and especially on cladding deformation have been generated in the test programme. REP Na cladding strain data have been used as a start point for deriving an admittedly simple RIA failure criterion. This is based on a maximum strain which can be tolerated by the cladding, i.e. failure can occur only when this strain level is exceeded.

- For cladding that still retains ductility, failure at high burn-up (50-60 MWd/kg) is predicted beyond a 1% (permanent) diameter strain.

- For cladding that has been embrittled due to e.g. large corrosion, spalling and hydriding, a zero ductility is assumed, i.e. the failure threshold is at onset (0%) of permanent strain.

The conditions under which the ductility decreases from 1% to zero are provisionally set in the paper, taking into account the evidence from the CABRI tests and from ANL laboratory tests. Based on the above, one derives that the lowest failure limit at 60 MWd/kg is \( \approx 65-70 \text{ cal/g} \), which applies to heavily corroded/hydrided fuel, i.e. for oxide thickness of \( \approx 80 \mu\text{m} \) and in presence of oxide spalling. For corrosion resistant fuel, i.e. for oxide thickness well below 80 \( \mu\text{m} \) and in absence of spalling, the failure threshold at the same burnup is \( \approx 100 \text{ cal/g} \).

This failure criterion predicts well three of the four failed REP Na tests, but not the REP Na-1 test. For this, the predicted failure threshold is 63 cal/g, whereas the reported experimental value is 30 cal/g. For CABRI unfailed rods, the predicted failure limit is very close to the enthalpy achieved during the test. When used at its higher degree of conservatism (i.e. ductility = 0), the proposed failure threshold predicts reasonably well also the failed NSRR PWR and BWR rods. In general, more data at prototypical conditions are needed in order to arrive to comprehensive, best-estimate failure predictions.

The PIE data of unfailed REP Na rods show a remarkable similarity between the trend exhibited by the cladding strain and by the fission gas release. This is briefly discussed in this paper with regard to a possible FGR mechanism (i.e. it is implied that the gas may mostly be released upon cooling, when cladding constraints are reduced). In any case, it appears that FGR as such has little to do with the mechanism of failure when this occurs at low enthalpy.

A comparison MOX versus UO\(_2\) fuel based on the REP Na tests is also attempted. The data do indicate possible differences between the two fuels at low burnup (~30 MWd/kg). However, at higher burnup the difference between MOX and UO\(_2\) fuel is not so clear (possibly except for fuel ejection), at least on the basis of the limited MOX data available so far.

In conclusion, the REP Na test series have proven to constitute a very valuable and consistent data set. The information on cladding strain fits very well together and has enabled to derive a failure criterion, which predicts reasonably well three out of four REP Na failures and the NSRR failures. However, the reported failure level of the REP Na-1 test cannot be explained based on the present analysis, a point which is discussed in the paper.
2. Cladding strain, CABRI REP Na tests with UO₂ fuel

Unfailed UO₂ fuel rods tested in the REP Na series have been examined in hot cells after the tests in the CABRI reactor. Through the post-test diameter profilometry one can determine how the diameter permanent strain at a given axial position depends on the fuel enthalpy deposited at that position during the transient. This has been done for the UO₂ fuel rods and the outcome is shown in Fig. 1.

The burnup effect on cladding strain can be seen in Fig. 1 by comparing curve 2, which refers to a fuel rod of 33 MWd/kg, with curves 3 and 5, which are for 53 and 64 MWd/kg respectively. One can also discern a slight difference between 3 and 5, which is attributed to the burnup difference between these two fuel rods.

The cladding strain as derived in Fig. 1 is substantially greater than what it would be expected from fuel thermal expansion only, typically 2 to 4 times greater. In fact, fuel swelling is believed to be the most important contributor to cladding strain.

The plots in Fig. 1 show that for the high burnup fuel the slope of the strain vs. energy curve tends to increase gradually, indicating that the fuel swelling might become progressively more pronounced (see curve 3 and 5). The difference between curve 4 and 5 is ascribed to the difference of pulse width, which was larger in test 4 (75 ms versus 9.5 ms).

3. Cladding strain as basis of a failure criterion

Regardless of the details on the mechanisms involved, the ability of the fuel to withstand a RIA transient depends on its capability to accommodate cladding strain. The criterion suggested here reflects this, as it is based on a maximum tolerable cladding strain, i.e. failure can occur for cladding strain exceeding a given limit.

- For cladding that has not been embrittled by hydrogen, the (permanent) strain limit at 50-60 MWd/kg is set at 1%. This is certainly a conservative value, since REP Na tests show that fuel rods with burnup from 53 to 64 MWd/kg could tolerate cladding strains in the range 1 to 2% without failing (See REP Na-3 and -5, Fig. 1).

- The REP Na tests provide evidence that large cladding oxidation and presence of oxide spalling may reduce the cladding ductility due to hydrogen embrittlement, making the cladding more prone to failure. In this case the threshold of cladding failure is set at onset of permanent strain (i.e. permanent strain = 0).

The enthalpy failure limits corresponding to the 1% and 0% ductility threshold are derived from Fig. 1 in a straightforward manner. The resulting enthalpy failure limit when the above strain limit is set over the entire burn-up range, is shown in Fig. 2. It can be seen that the enthalpy limit decreases with burnup. At 60 MWd/kg the threshold is as low as ~70 cal/g for embrittled cladding and ~110 cal/g for cladding which has no hydrogen embrittlement. As Fig. 2 shows, an upper limit of 200 cal/g is set on the curves in the low burnup range, since failure mechanisms other than PCMI prevail for high energy depositions.
4. Inference of a RIA failure threshold

4.1 Correlation for the RIA failure threshold

A correlation for the fuel failure limit has been derived based on the consideration made in the previous sections and on a closer analysis of the data, taking into account that larger strains can be accommodated at lower burn-up. The correlation is as follows

\[ H_F = \left[ 200 \cdot \frac{25 + 10D}{B_{u}} + 0.3\Delta\tau \right] \left[ 1 - \frac{0.85 \cdot OX}{W} \right]^2 \]

where
- \( H_F \) is the fuel enthalpy failure limit, cal/g
- If \( H_F \) from (1) is > 200, set \( H_F = 200 \)
- \( B_u \) is burnup in MWd/kg
- \( D \) is the (ductility or) hoop strain limit at high burn-up (1% for cladding with residual ductility and 0% for embrittled cladding), in percent
- \( \Delta\tau \) is the pulse width in ms (\( \leq 75 \text{ ms, use 75 ms beyond that} \))
- \( OX \) is the oxide thickness in \( \mu m \)
- \( W \) is the as-fabricated wall thickness as-fabricated in \( \mu m \) (576 \( \mu m \) for the REP Na rods)

The parameter \( D \) varies from 1 for ductile cladding to 0 for embrittled cladding. Embrittlement occurs for large oxide and in presence of spalling. The REP Na tests indicate that for cladding having an oxide thickness of 80 \( \mu m \), embrittlement (\( D=0 \)) occurs for spalled cladding oxide, whereas ductility is maintained (\( D=1 \)) for un-spalled cladding. Recently published ANL data indicate that cladding ductility can gradually decrease to zero also for uniform oxides [1]. These data show that ductility decreases with increasing thickness of the peripheral hydride layer, approaching zero when this thickness goes beyond \( \sim 100 \mu m \). For the purpose of this analysis, these findings have been provisionally converted in decreasing ductility vs. oxide thickness. The resulting picture is given in Fig.3, which shows how ductility drops to zero for spalled oxide (inferred from the failed REP Na rods) and for un-spalled oxide (inferred from [1]). One should notice that in most practical cases one does not know a-priori if the cladding is spalled or not, except that spalling may occur for thick oxide. For such cases, the use of the left curve of Fig. 3 is conservatively recommended.

![Fig. 3. Suggested dependency of the term D on cladding oxide](image)

Fig. 3. Suggested dependency of the term D on cladding oxide
The oxide thickness in equation /1/ is important not only because it affects the ductility term D. Oxidation causes also a reduction of cladding metal wall thickness and an increase of hydride formation at the cladding periphery, which both lower the constraint posed by the cladding on the swelling fuel. This is accounted for by the last term of equation /1/. In practice, the above means that low or moderately oxidised fuel will fail at appreciably higher enthalpy than heavily oxidised fuel.

In addition to oxide thickness, burnup is very important. Swelling both during normal operation and during a RIA transient become more pronounced with burnup, causing larger cladding strains. This is acknowledged in equation /1/ by the inverse relation between failure enthalpy and burnup.

Since the oxide thickness is also a function of burnup, at the end of the day the failure threshold can be expressed only in terms of burnup, once the relation between oxide thickness and burnup can be anticipated. Two practical examples are shown in Fig. 4, which gives the failure limits for two types of fuel cladding, one having significant corrosion and spalling, the other one having moderate corrosion. The predictions give a threshold that is ~40 cal/g lower for the more oxidised/spalled cladding. (The cases of Fig. 4 are only meant as examples, as oxide dependency on burnup may be different for different reactors/materials). For cladding having oxide thickness larger than 130 µm, the predicted failure threshold at 60 MWd/kg is lower than ~55 cal/g.

In this evaluation, burnup and oxide thickness are kept as independent, separate variables that affect failure levels in the way expressed by Eq. /1/. They are considered as separate variables because the corrosion-burnup relation may vary substantially from case to case, depending on cladding alloy, water chemistry and fuel duty during service in a commercial reactor. It is possible that some sort of duty index can be used as better parameter to predict fuel failure enthalpy, but such refinements are beyond the purpose of this note. Burnup and oxide thickness are used here simply because they are parameters of common use which have a direct physical meaning— in other words, everyone knows what these parameters represent.

Equation /1/ acknowledges only a moderate effect of pulse width (Δτ). In fact, the predicted failure threshold increases by only ~5 cal/g when the pulse width increases from 9 to 30 ms. Since in the REP Na series the Δτ ranged between 9 and 75 ms, a maximum value Δτ = 75 ms should be used when the pulse width exceeds 75 ms.

4.2 Predictability of the REP Na tests

The calculated enthalpy to failure based on equation /1/ for the various REP Na tests is given in Table 2.

For the rods that had failed, the comparison between predicted and actual failure enthalpy is shown in Fig. 5. Three tests are well predicted by Eq. /1/, but REP Na-1 is not. In this case the failure is predicted at 63 cal/g, whereas the quoted enthalpy to failure is a factor of 2 lower.

A prediction of the failure limit has been done also for the REP Na tests that did not fail. The results are shown in the diagram of Fig. 6. One can observe that all data points lay rather close
to the 1:1 diagonal, typically ~5-10 cal/g above it. This confirms that, with reference to the REP Na-1 database, the proposed correlation is conservative by ~5-10 cal/g, i.e. it is not an "unreasonably" conservative one. One should observe that all the three failed UO₂ fuel rods had spalled oxide, where none of the rods with un-spalled oxide failed. This implies that for the latter category of rods, i.e. those with un-spalled oxide, the failure threshold given by Eq. /1/ contains an inherent conservatism in that the database has only unfailed rods. As shown in Fig. 6, the failure predictions are only 5-10 cal/g away from the actually achieved enthalpy, but we do not know how far this is from the actual failure level - simply because none of such rods failed. In other words, one knows that (for rods with un-spalled oxide) Eq. /1/ provides failure limits which are conservative by at least 5-10 cal/g, but the actual conservatism (or margin to failure) can be greater than that.

Returning to the discrepancy of the REP Na-1 test (calculated failure at 63 cal/g versus a reported experimental value of 30 cal/g), one should notice that the transient started at a steady temperature of 280°C, corresponding to ~20 cal/g. The tests, which was to achieve 110 cal/g, resulted in a fuel failure that reportedly occurred when the transient had just started (see figure on the right side). At that point-in-time, only 8.9 cal/g had been injected onto the fuel, bringing the total enthalpy to (~20 + 8.9) = ~30 cal/g. Fuel failure at such conditions is difficult to explain and to reconcile with the experimental evidence from other tests, in CABRI and elsewhere.

A ΔH = 8.9 cal/g means an average fuel temperature of ~400°C. Fuels are not expected to fail at such conditions, also considering that in this case the fuel was likely exposed to more challenging conditions for a long time during service in the power reactor. The fact that the temperature was higher than 400°C in the pellet rim does not change the substance of this observation. The REP Na-1 test will remain unexplained unless an effort is made to re-examine the details of the test or fuel specimens condition that might have led to such a low failure enthalpy.

4.3 Generic failure threshold, application to the NSRR tests

While Eq. /1/ already contains a reasonable degree of conservatism, the correct setting of the parameter D must be considered further for cases different than the REP Na tests. As said earlier, in REP Na tests it is apparent that an inverse relation does exist between oxide thickness/spalling and cladding ductility. However, other factors than oxide morphology may also contribute to ductility degradation for fuel and conditions different than the ones of the REP Na tests. Changes of cladding type may result in different residual ductility at high
burnup, as affected by irradiation as well as by hydrogen content and distribution in the cladding. The coolant temperature during irradiation at normal conditions as well as during the transient may also affect the residual ductility in that it affects the balance between irradiation induced embrittlement and temperature induced annealing.

If well-characterised cladding ductility data are available, the value of the parameter D can be set on the basis of such data. In lack of this information, the most conservative setting, i.e. D=0, should be used for failure prediction based on Eq. /1/.

For applications to other cases than the REP Na tests, another point to consider is the temperature or enthalpy at the start of the test. In Eq. /1/, \( H_F \) is the total enthalpy to failure, with a start enthalpy level of \[ [C_p \cdot 280{^\circ}C] = 20 \text{ cal/g} \] (1). For generic applications to a lower (or different) initial temperature, such as in the NSRR tests, the failure threshold should be expressed in terms of enthalpy increase above the initial value. Thus for those generic applications to cases other than the REP Na ones, the failure threshold should be expressed by

\[
\Delta H_F = \left[ 200 \cdot \frac{25}{\beta_{th}} + 0.3 \Delta \tau \right] \left( 1 - \frac{0.85 \cdot \Delta X}{W} \right)^2 - C_p \cdot (280 - T_i) /2/
\]

which is equivalent to Eq. /1/ except that D is set D=0 and the enthalpy increase \( \Delta H_F \) above the initial instead of total enthalpy. The terms \( T_i \) is the test initial temperature (which was 280\(^{\circ}\)C in the REP Na tests).

The performance of Eq. /2/ is predicting the NSRR PWR and BWR tests where failure occurred is shown in Table 3.

### 5. Fission gas release, tests with \( \text{UO}_2 \) fuel

An evaluation has been made in order to derive the dependency of FGR on enthalpy, on the reasonable assumption that the release depends mainly on fuel enthalpy and burnup. The resulting FGR versus enthalpy curves for REP Na rods having different burnup are shown in Fig. 7. Not surprisingly, one can observe that the release increases with fuel burnup and enthalpy. By comparing this figure with Fig. 1, one can also note that the onset of FGR is very close to the onset of permanent deformations.

As an additional exercise, the enthalpy at 5% FGR has been derived for the four curves given in Fig. 7, and then plotted as function of the corresponding fuel burnup, as shown in Fig. 8. In the same figure, the onset of cladding permanent strain curve has also been plotted. One can again note that the 5% FGR curve is remarkably close to the onset of cladding strain curve, which was derived in Fig. 2.

Fig. 8 basically says that appreciable fission gas release is observed beyond the onset of permanent cladding strain. Since the latter is also the failure threshold for brittle cladding, it

(1) \( C_p = 0.30 \text{ J/g^{\circ}C} \) or \( C_p = 0.072 \text{ cal/g^{\circ}C} \)
follows that FGR "occurs" beyond the low-enthalpy failures (i.e. those related to brittle cladding). Said in other terms, while fission gas induced fuel swelling is important, FGR has little to do with the failure mechanism for these low enthalpy failures. Fission gas release - more than the cause of clad diameter deformation - seems to be the consequence of it. This can be rationalised, for instance, if the gas release takes place mainly in the cooling phase, i.e. after the cladding has been deformed and, upon cooling, does not provide any more constraint to the fuel.

6. MOX fuel

The diameter strain for the two unfailed MOX tests are compared with the diameter stain of the unfailed UO₂ tests in the diagram of Fig. 9. Although this is only an indicative comparison, one can observe that the diameter strain observed in REP Na-6 are comparable with the ones observed for UO₂ fuel at high burnup. Instead, REP Na-9 gave larger deformations than the UO₂ test at corresponding burnup (REP Na-2). It should be noted, however, that the REP Na-2 fuel was of quite different source than the rest of the REP Na series. Fig. 10, where the FGR of MOX and UO₂ fuel are compared, gives approximately the same picture, i.e. the MOX REP Na-6 FGR is compatible with UO₂ fuel, whereas the REP Na-9 gives higher release than REP Na-2.

In conclusion, the high burnup MOX data (REP Na-6) on cladding strain and FGR are comparable with UO₂ high burnup data. Whether the differences observed at lower burnup between REP Na-9 and 2 are due to the MOX vs. UO₂ fuel differences or to other factors (e.g., the REP Na-2 had BR-3 fuel), cannot be concluded at this time.

Based on the microstructural differences between MOX and UO₂ fuel, one would expect that appreciable differences exist in the failure behaviour of the two types of fuel. However, the data available on MOX, shown in Fig. 5 and Fig. 6, are too few to ascertain clear differences between MOX and UO₂ failure propensity, at least in terms of failure predictability based on Eq. /1/, and more data are needed in order to draw firm conclusions.

Reference

## Table 1. The CABRI REP Na tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Rod</th>
<th>Pulse (ms)</th>
<th>Energy end of peak (cal/g)</th>
<th>Corrosion (µ)</th>
<th>RIM (µ)</th>
<th>Results and observations</th>
</tr>
</thead>
</table>
| Na-1 (11/93) | GRA 5 4.5% U 64 GWD/t | 9.5 | 110 (at 0.4 s) | 80 initial spalling | 200 | - Failure, brittle type for \( H_F = 30 \) cal/g.  
- Hydride accumulation  
- Fuel dispersion 6 g., including fuel fragments outside RIM (>40 µ)  
- Pressure peaks in Na of 9-10 bars |
| Na-2 (6/94) | BR3 6.85% U 33 GWD/t | 9.1 | 211 (at 0.4 s) | 4 | | No failure  
\( H_{MAX} = 210 \) cal/g  
Max. strain: 3.5% average, 3.1% mid-pellet, FGR: 5.5% |
| Na-3 (10/94) | GRA 5 4.5% 53 GWD/t | 9.5 | 120 (at 0.4 s) | 40 | 100 | No failure  
\( H_{MAX} = 125 \) cal/g  
Max. strain: 2%  
FGR: 13.7% |
| Na-4 (7/95) | GRA 5 4.5% U 62 GWD/t | #75 | 95 (at 1.2 s) | 80 no initial spalling | 200 | No failure  
H_{MAX} = 99 cal/g  
Cladding spalling under transient  
Max. strain: 0.4%  
FGR: 8.3% |
| Na-5 (5/95) | GRA 5 4.5% U 64 GWD/t | 9.5 | 105 (at 0.4 s) | 20 | 200 | No failure  
H_{MAX} = 115 cal/g  
Max. strain: 1%  
FGR: 15.1% |
| Na-8 (07/97) | GRA 5 4.5% 60 GWD/t | 75 | 106 (at 0.4 s) | 130 lim. initial spalling | 200 | Failure  
\( H_F \leq 82 \) cal/g,  
\( H_{MAX} = 110 \) cal/g  
no fuel dispersion  
Examinations to be performed |
| Na-10 (07/98) | GRA 5 4.5% U 62 GWD/t | 31 | 107 (st 1.2 s) | 80 important initial spalling | 200 | Failure at \( H_F = 79 \) cal/g,  
\( H_{MAX} = 110 \) cal/g  
no fuel dispersal  
Examinations to be performed |
| Na-9 (04/97) | MOX 2 cycles 28 GWD/t | 34 | 197 at 0.5 s 241 at 1.2 s | <20 | | No failure  
\( H_{MAX} = 210 \) cal/g  
Max. strain: 7.4% average  
FGR: ~34% |
| Na-6 (03/96) | MOX 3 cycles 47 GWD/t | 35 | 125 at 0.66s 165 at 1.2 s | 35 | | No failure  
\( H_{MAX} = 148 \) cal/g  
Max. strain: 3.2% (2.5% average)  
FGR: 21.6% |
| Na-7 (1/97) | MOX 4 cycles 55 GWD/t | 40 | 125 at 0.48s 175 at 1.20s | 50 | | Failure  
\( H_F = 120 \) cal/g  
(t=0.452 s)  
Strong flow ejection, pressure peaks of 200-110b, fuel motion in the lower half zone |
Table 2. Failure predictions of REP Na tests based on Eq. /1/

<table>
<thead>
<tr>
<th>Test</th>
<th>$\Delta\tau$</th>
<th>Bu</th>
<th>OX</th>
<th>D</th>
<th>Experiment fuel enthalpy</th>
<th>$H_F$ (Eq. 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REP Na-1</td>
<td>9.5</td>
<td>64</td>
<td>80 (spalled)</td>
<td>0</td>
<td>$H_{\text{Fail}} = 30$</td>
<td>63</td>
</tr>
<tr>
<td>REP Na-2</td>
<td>9.1</td>
<td>33</td>
<td>4</td>
<td>1</td>
<td>$H_{\text{MAX}} = 210$</td>
<td>200</td>
</tr>
<tr>
<td>REP Na-3</td>
<td>9.5</td>
<td>53</td>
<td>40</td>
<td>1</td>
<td>$H_{\text{MAX}} = 125$</td>
<td>119</td>
</tr>
<tr>
<td>REP Na-4</td>
<td>75</td>
<td>62</td>
<td>80</td>
<td>1</td>
<td>$H_{\text{MAX}} = 99$</td>
<td>105</td>
</tr>
<tr>
<td>REP Na-5</td>
<td>9.5</td>
<td>64</td>
<td>20</td>
<td>1</td>
<td>$H_{\text{MAX}} = 115$</td>
<td>107</td>
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<tr>
<td>REP Na-6</td>
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<td>47</td>
<td>35</td>
<td>1</td>
<td>$H_{\text{MAX}} = 148$</td>
<td>142</td>
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<tr>
<td>REP Na-7</td>
<td>40</td>
<td>55</td>
<td>50</td>
<td>1</td>
<td>$H_{\text{Fail}} = 120$</td>
<td>120</td>
</tr>
<tr>
<td>REP Na-8</td>
<td>75</td>
<td>60</td>
<td>130 (spalled)</td>
<td>0</td>
<td>$H_{\text{Fail}} \leq 82$</td>
<td>70</td>
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<tr>
<td>REP Na-9</td>
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<td>20</td>
<td>1</td>
<td>$H_{\text{MAX}} = 210$</td>
<td>200</td>
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<tr>
<td>REP Na-10</td>
<td>31</td>
<td>62</td>
<td>80 (spalled)</td>
<td>0</td>
<td>$H_{\text{Fail}} = 79$</td>
<td>71</td>
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Table 3. Comparison of the NSRR PWR/BWR Experimental Enthalpy at Failure with the Values Predicted by Eq. /2/

<table>
<thead>
<tr>
<th>Test</th>
<th>$\Delta\tau$</th>
<th>Bu</th>
<th>OX</th>
<th>Exp. $\Delta H$ at failure</th>
<th>$\Delta H_F$ (Eq. 2)</th>
<th>Fuel type</th>
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<tbody>
<tr>
<td>NSRR</td>
<td></td>
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<td>HBO-1</td>
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<td>67</td>
<td>PWR</td>
</tr>
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<td>HBO-5</td>
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<td>44</td>
<td>60$^{(1)}$</td>
<td>77</td>
<td>75</td>
<td>PWR</td>
</tr>
<tr>
<td>TK-2</td>
<td>5</td>
<td>48</td>
<td>35</td>
<td>60</td>
<td>73</td>
<td>PWR</td>
</tr>
<tr>
<td>TK-7</td>
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<td>86</td>
<td>73</td>
<td>PWR</td>
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<td>NSRR/BWR</td>
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<td></td>
<td></td>
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<td>FK-6</td>
<td>5</td>
<td>61</td>
<td>$\sim 20$</td>
<td>70</td>
<td>59</td>
<td>BWR</td>
</tr>
<tr>
<td>FK-7</td>
<td>5</td>
<td>61</td>
<td>$\sim 20$</td>
<td>62</td>
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<td>BWR</td>
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<td>FK-9</td>
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<td>61</td>
<td>$\sim 20$</td>
<td>86</td>
<td>59</td>
<td>BWR</td>
</tr>
</tbody>
</table>

(1) Maximum value
Fig. 1. Permanent diameter strain versus enthalpy as derived from the post-test rod profilometry of the four REP Na UO₂ fuels that did not fail. One can see that the curves tend to shift towards left at increasing burn-up. The pulse width also has an effect as shown by the comparison of curve 4 and 5.

Fig. 2. Failure threshold derived from the experimental cladding strain plots (in Fig.1). The upper curve is the failure limit for cladding that still retains ductility (1% $\Delta D/D$ permanent). The lower curve is for embrittled cladding (0% $\Delta D/D$). For fuel at burnup of 60 MWd/kg, the lowest failure threshold is approximately 65-70 cal/g.
Fig. 4. RIA failure threshold as predicted by Eq./l/in the case of a cladding exhibiting significant oxidation and spalling (curve 1) and in case of a corrosion resistant cladding (curve 2). At 60 MWd/kg, the predicted enthalpy-to-failure threshold is ~40 cal/gr higher for the corrosion resistant cladding (70 vs. 110 cal/gr).

Fig. 5. Comparison of calculated vs experimental enthalpy to failure for the four REP Na tests that failed. Three tests, including a MOX test, are well predicted. The REP Na-1 test cannot be predicted by the proposed correlation (Eq./l/).
Fig. 6. Comparison between the calculated enthalpy to failure and the actually achieved fuel enthalpy for the REP Na tests that did not result in fuel failure.

Fig. 7. Fission gas release (FGR) data, plotted as function of the fuel enthalpy, for the UO₂ REP Na tests.
Fig. 8. Plot of the 5% FGR threshold derived from the previous figure (Fig. 7). Together with it, the curve for onset of cladding plastic deformation is also plotted. The latter is identical to (the lower curve of) Fig. 2 and is derived from the cladding strain data shown in Fig. 1. The trend of the two curves is remarkably similar.

Fig. 9. Comparison of the percent diameter strain in UO₂ and MOX fuel. The REP Na-6 test gave strains comparable with the UO₂ tests at high burnup. The REP Na-9 MOX test strains appreciably greater than the REP Na-2 UO₂ (test at comparable burnup). Note however that the REP Na-2 was a "special" fuel.
Fig. 10. Comparison of the fission gas release UO$_2$ and MOX fuel. The REP Na-6 MOX test (47 MWd/kg) gave FGR compatible with the REP Na-3 UO$_2$ test (53 MWd/kg). The REP Na-9 MOX test (28 MWd/kg) gave much higher gas release than the REP Na-2 UO$_2$ test (33 MWd/kg). Note however that the latter has a “special” type of fuel.