REVIEW OF RIA AND LOCA CRITERIA FOR VVER FUEL

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ABSTRACT

The RIA and LOCA fuel safety criteria are under revision in the international community of fuel suppliers, authorities and research organizations. The main criteria will be reviewed in the paper for VVER fuel.

Experimental data on the fuel failure behaviour under reactivity-initiated-accident (RIA) conditions produced in the last decade in French and Japanese test reactors indicated low failure enthalpy for high burnup fuel compared to fresh fuel. However the high burnup was not the only phenomenon influencing the fuel failure. The oxide scale on the external surface of the fuel rod, hydrogen content of the Zr cladding and the local hydriding seemed also be responsible for the failure at low enthalpy. Furthermore differences have been found between Western design fuel and Russian type VVER fuel. The burnup dependence of fuel failure for VVER fuel was found much less, probably due to the low oxidation during normal operational conditions compared to other PWRs. The recently published Vitanza and KAERI correlations for RIA failure enthalpy have been applied to 23 VVER tests. Experimental data from Russian IGR and BIGR reactors have been used. The calculations have shown that both burnup and cladding oxidation effects must be considered, however the pulse width dependence of failure enthalpy has not been confirmed.

During loss of coolant accidents (LOCA) the peak cladding temperature and local oxidation criteria have to be met. The oxidation criterion is under discussion today in many laboratories. The AEKI carried out several experimental series with Zr1%Nb cladding used in VVER reactors. The paper will describe the main results of the tests and present the limit for ductile-brittle transition derived from ring compression test. The behaviour of Zr1%Nb (E110) and Zircaloy-4 claddings under LOCA conditions will be compared as well.

Keywords:
safety criteria, loss of coolant accident (LOCA), reactivity initiated accident (RIA)

1. INTRODUCTION

Experimental data on the fuel failure behaviour under reactivity-initiated-accident (RIA) conditions produced in the last decade in French and Japanese test reactors indicated low failure enthalpy for high burnup fuel compared to fresh fuel [1]. However the high burnup was not the only phenomenon influencing the fuel failure. The oxide scale on the external surface of the fuel rod, hydrogen content of the Zr cladding and the local hydriding seemed also be responsible for the failure at low enthalpy [2]. Furthermore differences have been found between Western design fuel and Russian type VVER fuel. The burnup dependence of fuel failure for VVER fuel was found much less, probably due to the low oxidation during normal operational conditions compared to other PWRs [3].

The fuel criteria for LOCA conditions are almost the same for all zirconium alloy claddings. Recent studies [4] indicated significant differences between the high temperature behaviour of different Zr alloys. There is a special concern about the E110 cladding applied in VVER reactors, that seems to reach significant embrittlement at much lower oxidation rate than that of Zircaloy-4 used in Western PWRs. Furthermore new cladding materials are under development and a need arises for the standardization of test procedures for the investigation of cladding characteristics under accident conditions.

2. RIA CRITERIA

Two criteria are considered here, both are expressed in term of fuel enthalpy:

a. Fuel fragmentation limit. The objective of this criterion is to prevent fuel dispersal from the damaged fuel rod. Its value is 230 cal/g in Hungary. In other countries it varies between 200-280 cal/g.
b. Fuel failure limit. The objective of this criterion is to prevent the loss of fuel integrity. Its value is 140 cal/g in Hungary. In other countries it may be higher and in some countries burnup dependent criteria have been introduced [5]. Taking into account the very low failure of some tests (e.g. HBO-1 and REP Na-1 in Figure 1) the criteria became very conservative and the margin between expected and allowed accidental conditions turned very small. It was understood that beside the burnup dependence other effects influencing fuel failure during RIA must be considered in the criterion as well.

The fragmentation limit is very high, such values as 230 cal/g can be hardly expected in reactor cases.

Concerning the failure limit two similar approaches proposing more general RIA correlations have been published recently.

C. Vitanza, OECD Halden Project derived a correlation on the basis of CABRI experimental data and presented at the IAEA Technical Committee Meeting on Fuel Behaviour Under Transient and LOCA Conditions in Halden, 2001 September [6]. Nam, Jeong and Jung, KAERI applied a statistical approach to various RIA test data from open literature and published in Nuclear

Technology, 2001 November [7]. Both approaches intended to produce a simple correlation using the available experimental data and without the need for additional information on the tested fuel. The produced correlations can be used for the calculation of traditionally applied fuel enthalpy.

2.1 VITANZA CORRELATION

The failure threshold proposed by C.Vitanza is based on cladding deformation. CABRI REP Na data have been used and fuel failure has been considered as the strain level, which can not be tolerated by the cladding. 1% permanent strain was accepted for cladding with ductile mechanical characteristics. The failure threshold of embrittled cladding is the onset of permanent strain (0%). The criterion predicts well the CABRI data and Japanese NSRR tests as well. The proposed correlation has the following form [6]:

$$H_F = \left[200\frac{25+10D}{Bu} + 0.3\Delta\tau\right]\left(1-\frac{0.85OX}{W}\right)^2 \qquad (1)$$

where H_F - fuel enthalpy failure limit, cal/g
Bu - burnup, MWd/kgU
D - hoop strain limit, %
$\Delta\tau$ - pulse width, ms
OX - oxide layer thickness, µm
W - as fabricated cladding thickness, µm

- the calculated failure enthalpy is limited: if H_F>200, H_F=200
- hoop strain is 1% for ductile and 0% for brittle cladding. Two transition functions are proposed, one with spalling oxide and one for cladding without spalling oxide layer. The failure strain drops from 1% to 0% as function of oxide layer thickness. For cladding with oxide scale less then 50 µm in both cases 1% is applied.
- pulse width is also limited: if $\Delta\tau$ > 75 ms, $\Delta\tau$ =75 ms

For generic applications to cases other then the CABRI REP Na tests the effect of initial temperature should be considered according to the following form:

$$\Delta H_F = \left[200\frac{25}{Bu} + 0.3\Delta\tau\right]\left(1-\frac{0.85OX}{W}\right) - c_p(280-T_i) \qquad (2)$$

Correlation (2) predicts the failure threshold in terms of enthalpy increase above the initial instead of total enthalpy. T_i is the initial temperature in ^{o}C.

2.2 KAERI CORRELATION

A statistical regression model has been employed by Nam, Jeong and Jung to predict the failure enthalpy of irradiated PWR type fuel rods based on US, Japanese, French and Russian research reactor results. The failure enthalpy in their correlation is expressed in terms of fuel burnup, oxide thickness and pulse width [7].

$$H_f = 156.6 - 0.774OX - 1.076Bu + 29.41\log(\Delta\tau) \quad (3)$$

where H_F - fuel enthalpy failure limit, cal/g
Bu - burnup, MWd/kgU
$\Delta\tau$ - pulse width, ms
OX - oxide layer thickness, μm

In the development of (3) correlation only the failed fuel data have been used and the peak fuel enthalpy has been considered as failure enthalpy. It must be mentioned, that this approach may cause some problems, as very limited information is known on the precise failure enthalpy in most of the tests. The CABRI facility is capable to measure the failure enthalpy, but in other reactors only the peak enthalpy is determined, which can be much higher than the failure enthalpy.

2.3 VVER RIA TEST RESULTS

Large number of RIA experiments has been performed in Russia on the IGR, GIDRA and BIGR reactors in order to study the behaviour of VVER fuel rods [3,8-11]. Capsule type experiments were carried out with fresh and irradiated fuel, furthermore some refabricated fuel samples were applied with fresh pellets and irradiated cladding. The effects of energy deposition, pulse width, pressurization of fuel rods were tested. In most of the cases water fill was used, but some experiments were conducted in air as well.

According to the test results for highly pressurized fuel rods ballooning was the basic mechanism of cladding failure for both fresh and irradiated fuel. Peak fuel enthalpies, that correspond to the lower failure boundary was found the same (~160 cal/g) for both fresh and irradiated fuel [3]. The conducted tests covered a wide range of pulse width, but showed no effect of this parameter on the failure threshold.

Part of the experiments was collected into a well described database and published in NUREG reports [8]. Recently published experimental data from the ongoing research programme on the BIGR reactor are also available [9-11]. The failure enthalpy was not measured during the tests, these values were calculated with transient fuel behaviour codes.

2.4 APPLICATION OF RIA CORRELATIONS TO VVER TESTS

Both Vitanza and KAERI correlations are based on three parameters: fuel burnup, oxide layer thickness and pulse width. These parameters were available for the above VVER tests and so correlation (1) and (3) were applied for the calculation of failure enthalpy of the listed experiments. The Vitanza correlation was calculated without correction for the temperature, so the second correlation (2) was not used. In the experiments the exact failure enthalpy was not determined, only the peak value is known. So it was not possible to compare directly the calculated and measured failure limits. However checking each test separately the calculated failure enthalpy was compared with the peak fuel enthalpy.

The Vitanza correlation (1) was calculated using 1% hoop strain, 685 µm cladding thickness and 75 ms pulse width for the very long IGR tests. For fresh fuel 1 MWd/kgU burnup was applied. The formula gave very high value for all fresh fuel IGR tests with long pulse width (630-950 ms), the failure enthalpy was limited by the maximum 200 cal/g value. The effect of burnup and oxidation decreased the failure limit to ~150 cal/g for a 50 MWd/kgU burnup fuel [12].

The KAERI correlation (2) was used with the specified experimental data. It gave very high failure enthalpy for fresh IGR fuel, which was much higher than the peak fuel enthalpy of failed fresh rods H6C and H15T. The failure enthalpy was overestimated for high burnup IGR test H5T as well. In case of BIGR tests the formula indicated failure for all fuel rods, while all of them remained intact during the test.

The analysis of results showed that the calculations were too sensitive to the pulse width value. For this reason a constant 75 ms pulse width was selected for all cases and the calculations were repeated [12].

There are several reasons to remove the pulse width from the proposed correlations. First of all the RIA tests (Russian and other as well) showed no significant dependence of the failure enthalpy on the pulse width. Furthermore the peak fuel enthalpy is calculated using the power history over the RIA time, so the peak fuel enthalpy value already includes the information on characteristic pulse width.

The final form of the correlations applied for the VVER tests was the following:

$$H_F = \min\left\{ \left[\frac{7000}{Bu+1} + 22.5\right]\left(1 - \frac{0.85OX}{W}\right)^2, 200 \right\} \tag{4}$$

$$H_f = 211.7 - 0.774OX - 1.076Bu \tag{5}$$

Using constant pulse width the agreement between calculated and experimental values was much better than in the first series of calculations. With this simplification both formula gave higher failure values than the measured peak enthalpy in tests with no fuel failure. In case of fuel failure both correlations indicated lower failure enthalpy than the measured value, except one point H15T, where the difference between measured (195 cal/g) and calculated (200 cal/g and 207.9 cal/g) was small, but the calculated value was higher. The two correlations with constant pulse width produced values very close to each other in most of the analysed cases.

The burnup dependence of VVER fuel failure enthalpy was calculated using correlations (4) and (5) with a constant oxide layers thickness of 10 μm, which is a conservative value for VVER-440 fuel. In Figure 2 beside the two curves the available experimental data are presented and the 140 cal/g limit is also shown. The 140 cal/g value is used in Hungary as fuel failure criteria in RIA accident, and this value does not depend on burnup. Figure 2 shows that the correlations, which proved to be capable to describe the boundary between failed and intact fuels lies above this line and reach the 140 cal/g value at ~60MWd/kgU.

3. LOCA CRITERIA

Several fuel safety criteria exist for LOCA cases [13-14], here only the two criteria will be discussed:

a. The peak cladding temperature (PCT) must remain below 1200 ^{o}C.
b. The local cladding oxidation expressed in equivalent cladding reacted (ECR) can not reach 17%. The calculation must be carried out using conservative correlation for oxidation kinetics.

The LOCA safety criteria (17% ECR and 1200^{o}C PCT) were originally based on ring compression tests [15] (Figure 3). Later thermal shock type tests with water quenching of oxidized fuel rods were used for the experimental support of the above criteria. The thermal shock testing seems to be more representative for LOCA conditions. However it has several disadvantages due to large uncertainties in the simulation of plant conditions [16]. The ring compression tests do not simulate the LOCA scenario, but give direct information on the changes of mechanical behaviour of cladding material due to oxidation. The possibility of the use of ring compression test as a standard procedure for the evaluation of LOCA criteria is discussed today between experts [17]. Furthermore a proposal has been developed on the derivation of LOCA safety limits using ring compression tests [18].

3.1 1200 ^{O}C PCT CRITERION

The peak cladding temperature criterion is applied in order to prevent

- Temperature excursion due to Zr oxidation and
- Cladding embrittlement.

Temperature excursion is illustrated in Figure 4. The tempter histories of a high temperature experiment performed at the CODEX facility are presented. During the test the electrical power of the bundle was linearly increased. The temperatures followed the slope of power increase, however at ~1200 ^{o}C the reaction heat of cladding oxidation became significant and resulted in temperature excursion.

Cladding embrittlement due to oxidation is caused by two mechanisms:

- Formation of α-incursions. Below the oxide layer an oxygen rich α layer exist. Metallographic examinations show that some incursions of α phase can penetrate into the β phase that has low oxygen content and can be described as ductile component.
- Oxygen diffusion. The oxygen can diffuse into the β phase as well and that leads to the embrittlement of the cladding.

Diffusion accelerates at high temperature and so the second mechanism dominates above 1200 °C.

The PCT criterion needs no revision for the currently applied Zr cladding alloys.

3.2 17% ECR CRITERION

The equivalent cladding reacted criterion is applied in order to prevent the embrittlement of Zr cladding.

Returning to the original Hobson ring compression tests one can notice the followings:

- The mechanical tests selected as a basis for criterion were executed at 135 °C temperature.
- Tests of the same series at room temperature indicated brittle behaviour at lower oxidation rate.
- The applied Baker-Just correlation overestimates the oxidation rate.
- Applying a realistic oxidation correlation and using the room temperature tests the ductile-brittle transition of Zircaloy-4 cladding drops to ~10% ECR.

The comparison of Zircaloy-4 and Zr1%Nb (E110) claddings showed significant differences between the two alloys [4]. The E110 cladding becomes brittle at much lower oxidation rate than Zircaloy-4 in LOCA conditions (Figure 5).

In spite of these observations there are no real differences between oxidation criteria for different Zr alloys. Experimental programmes were carried out in different countries on the investigation of oxidation criterion and generally it was concluded that the 17% ECR valid even at room temperature. Recently the criteria are supported by thermal shock tests that simulate the quenching of oxidised fuel samples at high temperature.

The thermal shock testing has several drawbacks, first of all it is not simply to say when the sample fails or remains intact after the test. During the thermal shock tests the steam atmosphere has only limited access to the inner surface of the cladding. However the evaluations of test data always consider two-sided oxidation. So conclusions are drawn on the maximum degree of oxidation in a misleading way: having a sample with low oxidation rate one can conclude that the given type of cladding remains ductile at much higher degree of oxidation.

It is well understood today that the 17 % ECR criterion needs revision for all kinds of Zr cladding. Furthermore different criteria should be applied to different alloys.

3.3 PROPOSAL ON THE REPLACEMENT OF OXIDATION CRITERION

C. Vitanza proposed a new approach for the development of LOCA criteria. He suggested to use mechanical testing (ring compression tests) in order to establish the criterion in terms of oxidation time and temperature [19]. His idea was followed and the following proposal has been developed in the AEKI [18].

The ductility limit curves were determined on the basis of ring compression data [4], using the 50 mJ/mm specific energy threshold for the separation of *intact* and *failed* samples. Their expression determines a relationship between the oxidation time and oxidation temperature. If the oxidation time is less at a given temperature, than the limiting value, no failure can be expected.

The expressions have the following forms:

E110: $T=2\cdot10^{-4}e^{17500/(t+273)}$, T[s] and t[^{o}C] (6)

Zircaloy-4: $T=10^{-4}e^{20000/(t+273)}$ (7)

The comparison of the results for the two cladding shows that Zircaloy-4 alloy can endure longer time at a given temperature than E110 alloy. The two curves show a ~100^{o}C shift, the Zircaloy-4 cladding can be oxidised at higher temperature for the same time to lose ductility (Figure 6).

The above ductility limits indicate lower values for brittle failure of Zr claddings than the currently used 17%ECR. However plant calculations show that the LOCA cases are far from these limits as well (e.g. at 900 ^{o}C E110 cladding can endure 600 s oxidation time and Zircaloy-4 2500 s.)

It must be underlined that the ductile-brittle transition generally is used to characterise material properties. In the Zr oxidation case the oxide layers and the internal layers of the cladding appear in a given scale, which can not be translated into another geometry or sample thickness. For this reason the evaluated criteria can be used for the investigated geometry only. On the other hand the fuel cladding geometry (diameter, thickness) do not differ too much from each other, and the so the ductility limits could have general character for the power plant claddings of the same alloy type.

5. CONCLUSIONS

The following conclusions can be drawn on the basis of the review of RIA criteria for VVER fuel:

- The Vitanza correlation (based on French and Japanese tests) and KAERI correlation (based on US, French, Japanese and Russian data) with slight modification proved to be applicable to VVER tests and provided very similar to each other results.
- The analysis of 23 VVER fuel tests data using the failure enthalpy correlations indicated that this kind of correlation could be successfully used for the calculation of failure threshold during a RIA accident. The formulas reflect the degradation of fuel properties due to burnup and oxidation. The effect of pulse width was not confirmed; furthermore

avoiding this parameter from the correlation gave better agreement with measured data.

- The correlations indicated the decrease of failure enthalpy with fuel burnup and oxide scale growth. The application of typical VVER conditions showed that current RIA fuel safety criteria applied in Hungary (140 cal/g) is satisfied up to ~60 MWd/kgU.

Concerning the LOCA criteria the above review indicated the followings:

- The 1200 ^{o}C PCT criterion is satisfied for Zr claddings, including E110.
- The 17% ECR criterion needs revision. New criterion and standardised test methodology should be developed. Different criteria should be applied to different alloys.
- New criteria have been produced on the basis of ring compression tests. Correlations have been formulated that describe the relation between oxidation time and temperature for Zircaloy-4 and E110 claddings and indicate the limit of ductile-brittle transition of these cladding alloys.

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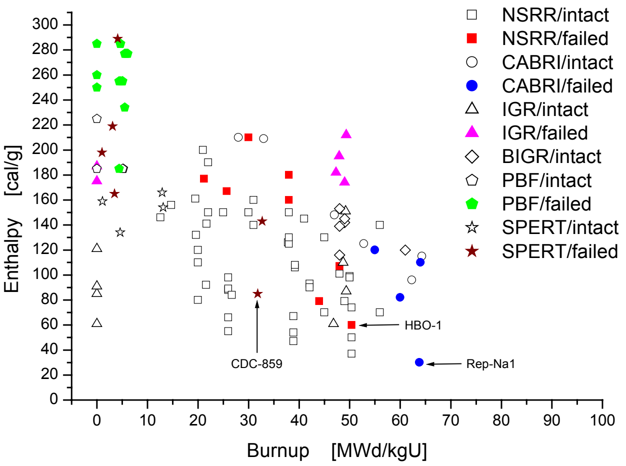

Fig. 1. Summary on fuel failure experimental data

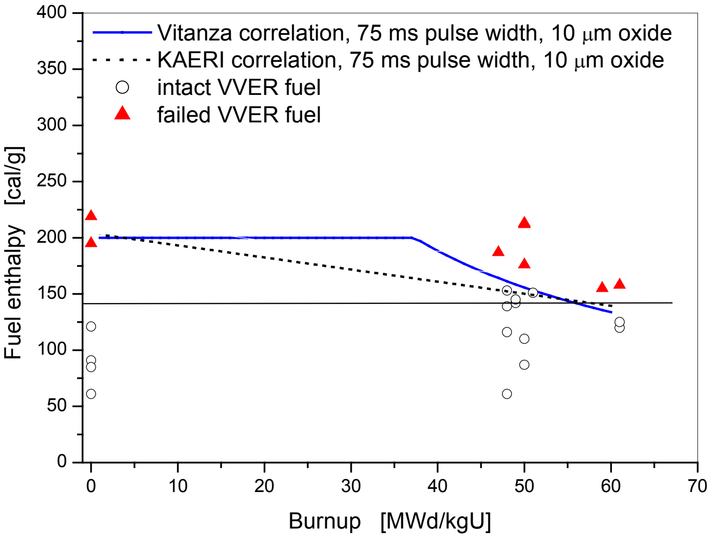

Fig 2. Burnup dependence of VVER fuel failure enthalpy

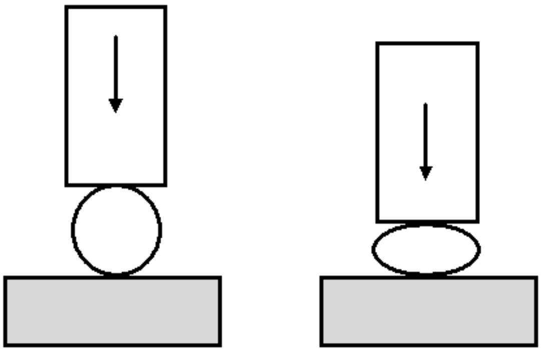

Fig. 4. Scheme of ring compression testing

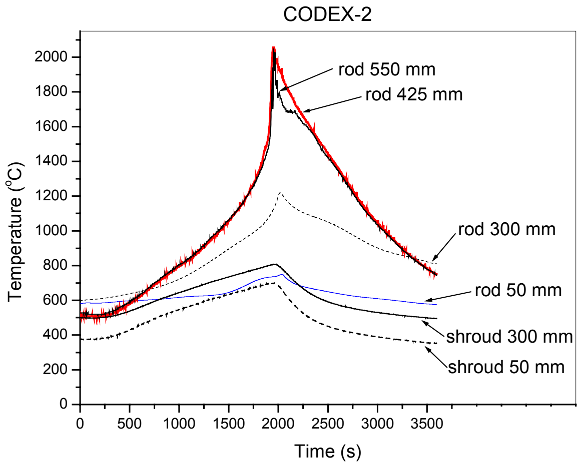

Fig. 3. Measured temperatures in the CODEX-2 test

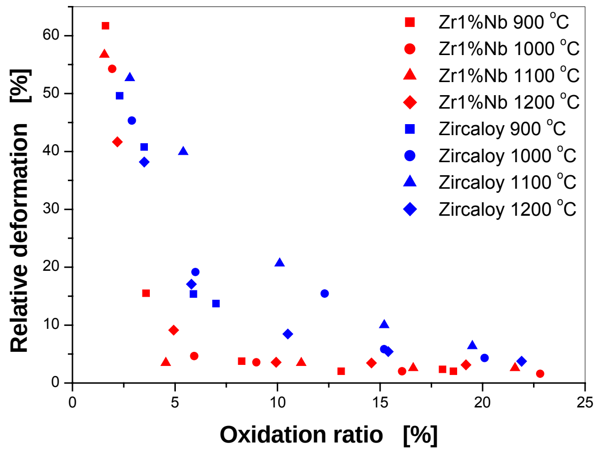

Fig. 5. Results of ring compression tests with Zircaloy-4 and E110 claddings

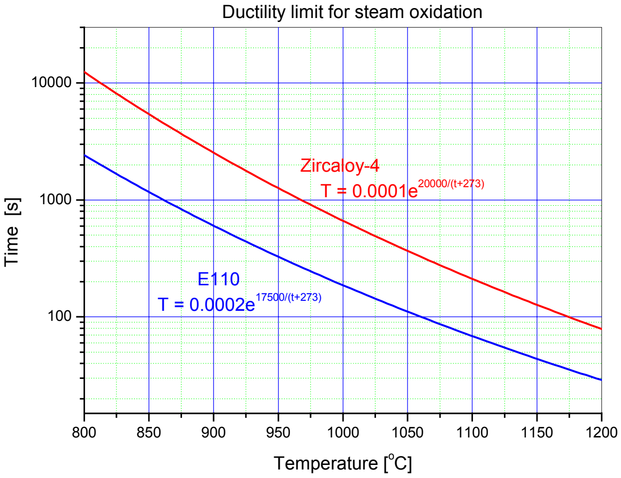

Fig. 6. Ductility limits of Zircaloy-4 and E110 claddings during oxidation in steam