A PWR PCI FAILURE CRITERION TO BURNUPS OF 60GW·d/t U USING THE ENIGMA CODE

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Abstract

A fuel performance modelling code (ENIGMA) has been used to analyse the empirical PCI failure criterion in terms of a clad failure stress as a function of burnup and fast neutron dose. The Studsvik database has been analysed. Results indicate a rising and then saturating failure stress with burnup and fast neutron dose. Using the PCI failure limits, equivalent to 95/95 confidence limits, an ENIGMA stress-based methodology is used to derive PWR PCI failure limits up to 60 GW·d/t U using a conservative assumption that the failure stress does not increase at high burnup and neutron dose. In addition experimental ramp data on gadolinia-doped fuel rods do not indicate any increased susceptibility to PCI failure implying that the UO_2 criterion can be used for gadolinia doped fuel.

1. INTRODUCTION

Power transients in PWRs may lead to fuel failure from strong Pellet Clad Interaction (PCI). In order to limit the possibility of PCI induced failures, restrictions are imposed on the allowable power uprates during normal operation and fault transients. The magnitude of the uprates are defined by a PCI failure criterion which was derived from an experimental database of ramped fuel prototypic for BNFL fuel loaded in Sizewell B. A statistical analysis of the failure/survivor distribution as a function of fuel conditioning power and burnup was performed [1].

The analysis enabled lines to be defined above which 95% of the fuel ramped to this level would survive with 95% confidence (refered to as 95/95 lines). Originally in the safety case for the first and second fuel loadings at Sizewell B this empirical PCI criterion was used. The main limitation of this approach was the burnup range of applicability (<35 GW·d/t U) which was defined by the experimental database used in the criterion derivation. Although the experimental database in Ref. [1] contains survivors at a burnup of 45 GW·d/t U and a failure at 38 GW·d/t U the conservative view was taken to restrict the high burnup limit to 35 GW·d/t U.

The experience of Siemens with fuel, which has been made available to British Energy for the licensing of Siemens fuel for Sizewell B power station, varying in burnup from 35GW·d/t U to about 45GW·d/t U reveals no failures [2]. Further examples include recent PCI tests conducted by Babcock and Wilcox on three rods at 62.3 GW·d/t U [3] and Siemens fuel ramped at 61 GW·d/t U. It is a feature of high burnup ramped fuel that it is difficult to fail through PCI. However, the problem with high burnup survivors is that they cannot be used in isolation to derive a *failure* criterion at high burnup without some failures to help define a failure/survivor boundary.

Using the ENIGMA code [4],[5], which is a fuel performance code principally developed by British Energy, a methodology has been developed for extending the PCI criterion to burnups of 60GW·d/t U by conducting a detailed analysis [6] of the entire Studsvik ramp database, including non-prototypic fuel. Use has also been made of additional data from Siemens. The methodology uses ENIGMA to calculate the clad hoop stress of identified rods in the PCI database.

2. THE EFFECTS OF HIGH BURNUP ON PCI MECHANISMS

A PCI failure is thought to be driven by Stress Corrosion Cracking (SCC) at the pellet ends where clad ridging occurs due to pellet wheatsheafing. The corrodent is assumed to be an aggressive fission product, nominally iodine which has been confirmed by out-of-pile tests [7]. The evidence from the ramp database suggests a survivor/failure boundary that is dependent on the final power reached in the ramp which is consistent with an increase in fission product release from the fuel at high power.

The ENIGMA analysis indicates that the propensity to failure by PCI depends on the clad hoop stress reaching a threshold value. The observation of an increase in threshold stress with fast neutron dose has been explained in terms of crack initiation and rapid propagation at surface flaws whose depth decreases during neutron exposure [6]. This argument is supported qualitatively by SEM observations of fresh and irradiated cladding [8]. Rather than degrade with irradiation, some mechanical properties of Zircaloy tend to improve, in keeping with the anisotropy of the mechanical properties decreasing. However, changes in the pellet/clad chemical environment such as the oxidation of the clad inner bore can also be expected to influence localised stress levels. Thus clad surface smoothing would not be expected to operate in isolation of other phenomena.

The basic underlying mechanisms of SCC and threshold stress established up to 50GW·d/t U can be expected to dominate above 50GW·d/t U also. Differential thermal expansion, pellet wheatsheafing, clad ridging, fuel and clad creep relaxations will still determine the clad hoop stress in the ENIGMA calculations. The most obvious material change to the pellet clad interaction zone at burnups above 50 GW·d/t U is the gradual formation of a rim region at the periphery of the pellet. In LWR fuel, the pellet rim starts to become porous at an average burnup of approximately 50 GW·d/t U as supported by Ref. [9] and reviewed by Ref. [10]. Although potentially detrimental in terms of increased fuel temperatures and enhanced fission gas release, the effect on PCI is probably more benign. The loss of pellet rigidity at the point of clad contact would be expected to reduce the pellet driving strain and hence reduce the induced clad stresses. Furthermore localised straining effects over radial fuel cracks would be significantly reduced as the pellet cracking fissures are smeared out over the rim region. Put simply, the fuel becomes more compliant in the rim region and unable to sustain concentrated stresses in contact with the clad.

3. ANALYSIS OF THE AVAILABLE DATABASES

The Studsvik database has been analysed using the ENIGMA code. The database consists of ramp tests from the OVERRAMP [11], INTERRAMP [12], SUPERRAMP [13] and the TRANSRAMP (II & IV) [14, 15] programs. Ranges of specific parameters, from the above programs, are listed in Table I. The available current Siemens database, which includes PCA-2a, KWU-SUPER & OVERRAMP and gadolinia cases, [2] has been used to extend a range of parameters from the Studsvik database. The extended parameters are listed in Table II. In order to adequately model Siemens clad and gadolinia doped fuel a new version of the ENIGMA code (version 5.10) was developed [16]. ENIGMA 5.10 gives the same results as that of the ENIGMA 5.9 code except in the cases where Siemens clad or gadolinia doped fuel are modelled.

The available data have been used to calculate peak hoop stresses as a function of fast neutron fluence using ENIGMA 5.10. Survivor and failure cases are plotted in FIG. 1. In addition to these cases the figure also includes hoop stress/fast fluence data points determined for four ramped gadolinia doped rods. The figure shows that the peak hoop stresses increase with fast neutron dose to a maximum peak hoop stress calculated at approximatley 750 MPa which occurs at a fast fluence of 8×10^{25} n/m^2.

TABLE I. A TABLE SHOWING THE RANGE OF PARAMETERS AVAILABLE FROM THE STUDSVIK DATABASE

Pellet length L	11.0–15.24mm
Pellet diameter D	8.19–10.71mm
L/D	1.2–1.66
Fuel grain size	4.5–22 μm
Fuel density	10.27–10.47 g/cm^3
Enrichment	2.82–8.26 %
Burnup	9.4–41.6 GW·d/t U
Clad type	Zircaloy 2 & 4, CW-SR, RX & PRX.
Clad yield stress	363–610 MPa
Clad Temperatures	291–363°C
Fast fluence	1.16–6.94 × 10^{25} n/m^3 (E>1MeV)

TABLE II. A TABLE SHOWING THE INCREASED RANGE OF PARAMETERS WHEN THE SIEMENS DATABASE IS INCLUDED

Pellet length L	10.62–15.24mm
L/D	1.1–1.64
Burnup	9.4–62.5 GW·d/t U
Clad Temperatures	291–372°C
Fast fluence	1.16–11.3 × 10^{25} n/m^3 (E>1MeV)
Gadolinia fuel	0–8wt%

The observation of a rising threshold failure stress with fast neutron dose using ENIGMA was instrumental in forming an alternative perception of the PCI failure criterion. This approach was developed in Ref. [6] where the rising threshold failure stress was associated with the smoothing of incipient clad inner bore surface flaws by processes stimulated by fast neutron bombardment.

Equally plausible as a mechanism to promote surface smoothing during irradiation is the effect of fission damage. Here the relevant parameter is burnup rather than fast neutron dose. FIG. 8.2 shows the variation of threshold stress as a function of burnup and a similar trend to that seen with fast neutron dose is apparent although discrimination between failures and survivors appears not so distinct. On this evidence there is a broader-based root cause associated with the observation of an increasing hoop stress for failure with burnup and/or fluence irrespective of any proposed mechanism. Fission damage could play a major role in enhancing surface smoothing processes.

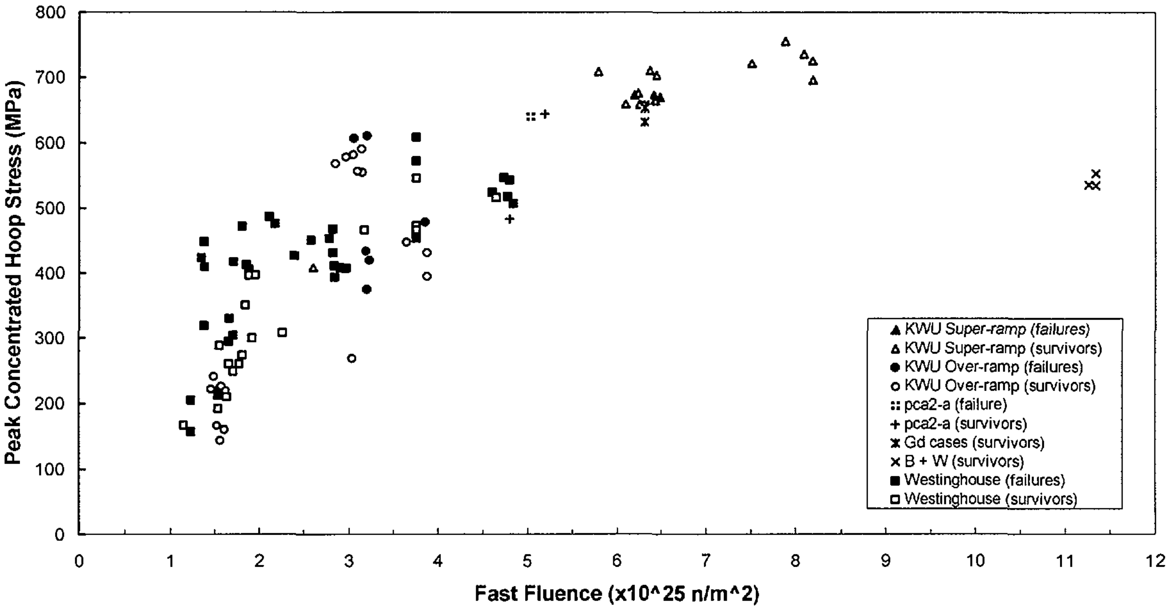

FIG. 1. Peak concentrated hoop stress as a function of fast fluence using ENIGMA 5.10.

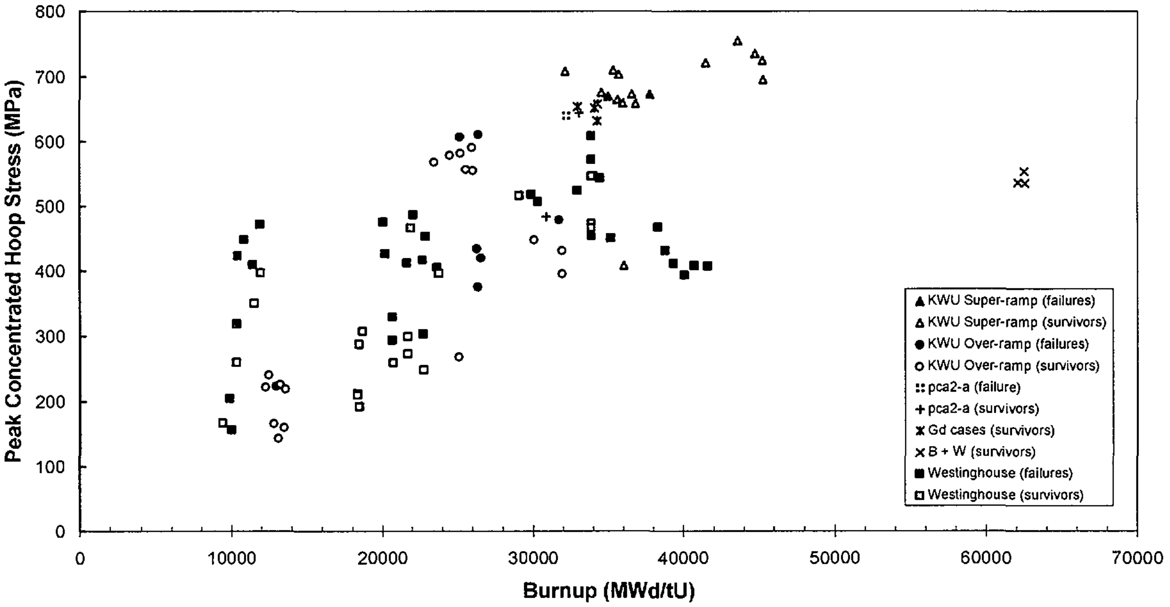

FIG. 2. Peak concentrated hoop stress versus burnup using ENIGMA 5.10.

4. METHODOLOGY AND RESULTS

4.1. Conditioning period

The methodology used to extend the PWR PCI failure criterion to higher burnups utilised power histories that modelled the irradiation conditions experienced by fuel rods in the Sizewell B reactor. The methodology ensures that PCI has occurred and that the pellet and clad are fully conditioned prior to the transient by imposing the following condition: the hoop stress is positive and approximately constant:-

$$\frac{d\sigma_\theta}{dt} \sim 0 \qquad (1)$$

where σ_θ is the hoop stress.

Typically, when equation (1) is satisfied the hoop stress is of order 50±20 MPa.

4.2. Hoop stress calculation of the 95/95 criterion

In order to determine concentrated hoop stresses for the empirical failure criterion, power histories were constructed for fuel rods with burnups of 15, 25 and 35GW·d/t U and conditioning powers of 20, 25 and 30kW/m. The power histories consisted of three parts:

a long base irradiation period at 24kW/m (peak average)
a conditioning period (such that equation 1 is satisfied)
a final ramp at a rate of 30kW/m/min.

A ramp rate of 30 kW/m/min was chosen so that clad stresses are influenced by pellet strains and not primary creep of the clad. The allowable power uprate, from the 95/95 failure lines, is then used to derive a stress due to the uprate, the results of which can be seen in Table III. It can be seen that the criterion relates to a lower hoop stress at the higher conditioned powers. More interestingly the implied 'failure' stresses (implied since the 95/95 lines are assumed in the safety case to define failure) are largely insensitive to burnup. When these stress levels are plotted on the stress-fluence plot of the actual fuel failure database in FIG. 9 it can be seen that they fall some way below the experimental rod failure stresses. By conservatively assuming that the 95/95 stress levels remain constant at higher burnups it is possible to reverse the ENIGMA calculational route and derive allowable uprates.

4.3. Extensions to higher burnups

The extension of the PWR PCI failure criterion to burnups above 35GW·d/t U involves calculating a stress at each of the conditioned powers (20, 25 and 30kW/m) from the 95/95 lines at 15, 25 and 35 GW·d/t U and averaging the stresses over the three burn ups. The derived hoop stresses are listed in Table IV. Due to the hoop stress being relatively insensitive to burnup an average of the hoop stresses at each conditioned power is used to set a failure stress for burnups above 35GW·d/t U. These failure stresses are approximately 418, 332 and 216 MPa for conditioning powers of 20, 25 and 30kW/m respectively (Table IV). In order to determine a power uprate from a transient above 35GW·d/t U power histories were constructed as described in Section 4.2. The power at which the failure stress is reached (E_f) is defined as the failure power equivalent to a new point on a high burnup 95/95 line. The power uprate (ΔP) is defined as:

$$\Delta P = E_f - P_c \qquad (2)$$

where P_c is the conditioned power. Results are listed in Table IV. Figure 4 shows the PWR PCI failure criterion up to burnups of 60GW·d/t U. Note, if the stresses are not averaged over burnup but are linearly extrapolated the results would change by only about 0.7kW/m at 60GW·d/t U.

TABLE III. A TABLE CONTAINING FUEL BURNUPS (15 TO 35GW·D/T U), CONDITIONING POWERS AND POWER UPRATES USED TO DETERMINE CONCENTRATED HOOP STRESSES

Burnup (GW·d/t U)	Conditioned Power (kW/m)	Power Uprate (kW/m)	Hoop stress (MPa)
15	20	15.0	419.8
	25	11.5	341.6
	30	8.0	226.4
25	20	14.0	428.4
	25	10.5	329.4
	30	7.0	223.8
35	20	13.0	406.1
	25	9.5	323.8
	30	6.0	198.2

TABLE IV. A TABLE CONTAINING FUEL BURNUPS (40 TO 60GW·D/T U), CONDITIONING POWERS AND POWER UPRATES THAT WERE DETERMINED FROM AVERAGES OF CONCENTRATED HOOP STRESSES, AT GIVEN CONDITIONED POWERS, FROM TABLE III

Burnup (GW·d/t U)	Conditioned Power (kW/m)	Power Uprate (kW/m)	Hoop stress (MPa)
40	20	11.9	418.1
	25	8.9	331.6
	30	6.0	216.1
50	20	11.0	418.1
	25	8.3	331.6
	30	5.9	216.1
55	20	10.6	418.1
	25	8.1	331.6
	30	5.4	216.1
60	20	10.0	418.1
	25	7.9	331.6
	30	5.4	216.1

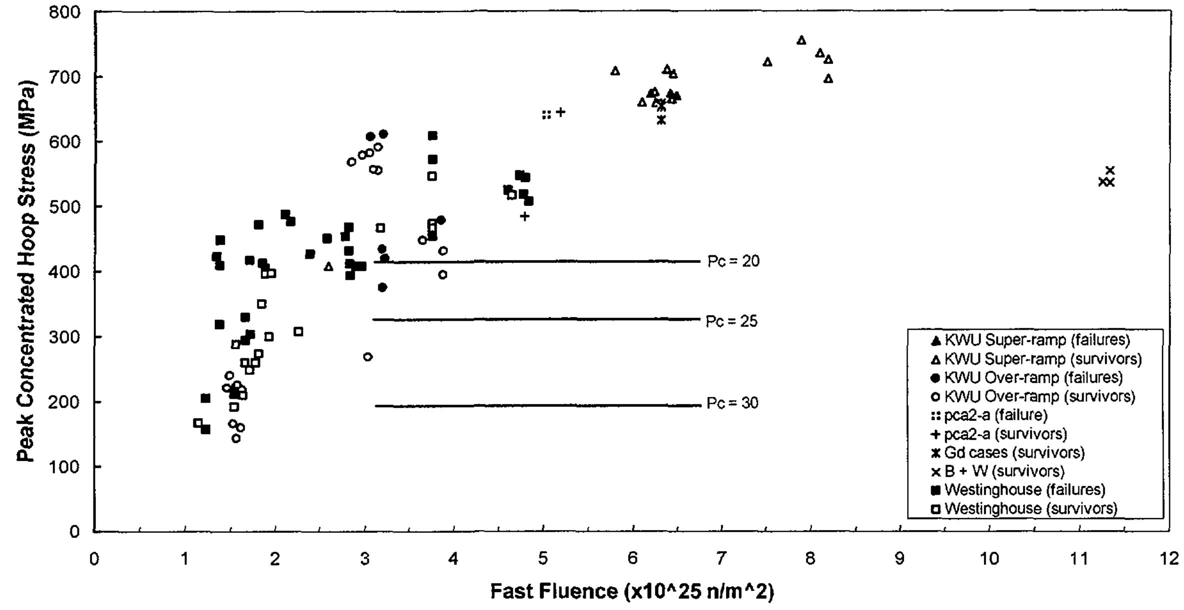

FIG. 3. Peak concentrated hoop stress as a function of fast fluence using ENIGMA 5.10 with conditioned powers indicated.

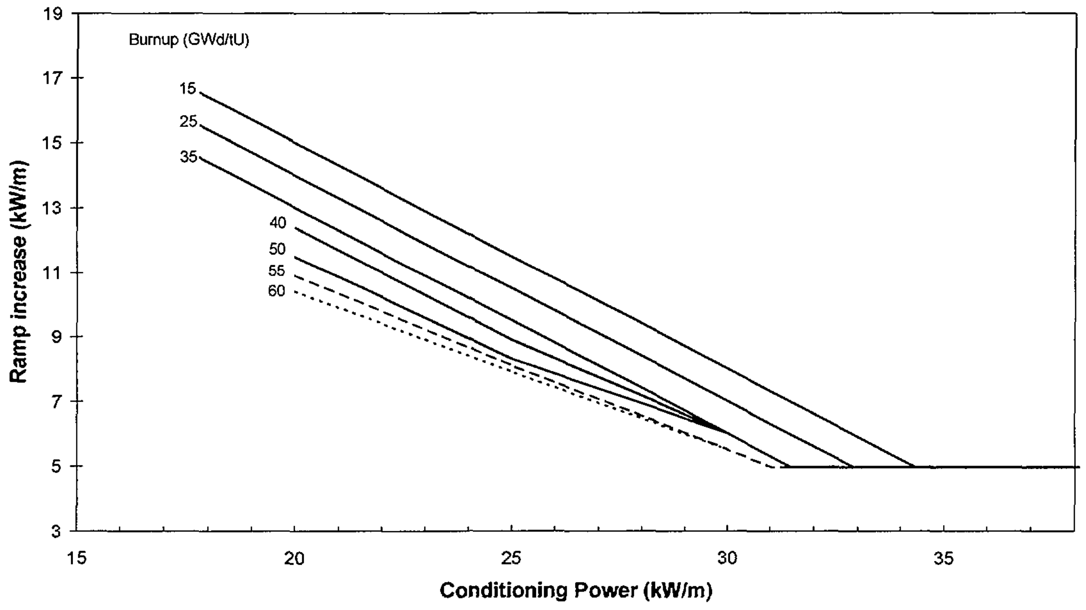

FIG. 4. The PWR PCI failure criterion to 60GW·d/t U.

The trend of decreasing uprate with conditioning power for burnups of 40GW·d/t U and above is similar to that for burnups ≤35GW·d/t U between conditioning powers of 20 and 30kW/m. Also the power uprates, calculated using the ENIGMA code up to a conditioning power of 30kW/m, decrease with burnup above 35 GW·d/t U in a manner similar to the decrease seen in the empirical criterion between 15 and 35 GW·d/t U. Above a conditioning power of 30kW/m the ENIGMA high burnup lines converge to meet the burnup independent portion of the criterion above 31 kW/m.

Above conditioned powers of 30kW/m, the 55GW·d/t U failure threshold has been linearly extrapolated to higher conditioned powers until the high conditioned power 95/95 criterion limit of 4.97kW/m is reached. Because the 55 and 60 GW·d/t U lines are coincident at 30 kW/m they have been conservatively extrapolated to be coincident at the point of the intersection of the 55GW·d/t U line with the 4.97kW/m horizontal line.

4.4. Lower conditioning powers

In order to extend the failure criterion to lower conditioned powers Murfin, Rippon and Turnbull [17] considered the criterion as a final power criterion independent of conditioned power. They argued that as there is no change in the mechanisms that induce/relax stresses in the clad as a function of conditioned power that the empirical best estimate failure lines can be extrapolated, without modification, to lower conditioning powers. By similar reasoning, therefore, as the 95/95 PCI failure lines are derived from the best estimate criterion, they can also be extrapolated below 20kW/m.

4.5. Sensitivity investigations and conservatisms

A sensitivity study has been made of the effect of changes in the power history on conditioned stresses and the choice of concentrated or mean calculated clad stress. Results indicate that if the current methodology is adopted, i.e. the concentrated hoop stress is approximately constant and is between 30 and 70 MPa prior to the final transient, then the derived failure limit lines at burnups above 35 GW·d/t U are relatively insensitive to these parameters.

To check the sensitivity of the ramp rate chosen (30kW/m/min) an investigation of ramp rate at 60 kW/m/min and 10 kW/m/min was performed. This produced an increase of only 10 MPa and a decrease of 30 MPa respectively in a threshold stress of 425 MPa for a conditioned power of 20 kW/m implying that the sensitivity is very low.

The proposed criterion extension can be regarded as conservative in 3 respects as follows:
the 95/95% confidence level PCI criterion on which the extrapolation is based
the threshold stresses to failure for conditioned powers above 20 kW/m are chosen conservatively with respect to the stress versus fluence trend derived from the ramp tests
it is observed that fuel above 35 GW·d/t U is difficult to fail through PCI

5. HIGH BURNUP AND GADOLINIA DATA

5.1. PCI ramp data at high burnup

Additional high burnup data (29 rods at burnups above 35 GW·d/t U) from the Siemens database are presented in FIG. 11. Eleven rods were ramped at a burnup in excess of 40GW·d/t U (highest 61.0GW·d/t U) and did not fail. All survivors and the one failure at 36.7GW·d/t U lie comfortably above the 35 GW·d/t U 95/95 line. The highest burnup rods subjected to PCI ramp tests were Babcock and Wilcox rods which were ramp tested in the Studsvik R2 test reactor at 62.3GW·d/t U [3]. Again none of these rods failed even though they were ramped well in excess of the 95/95 line.

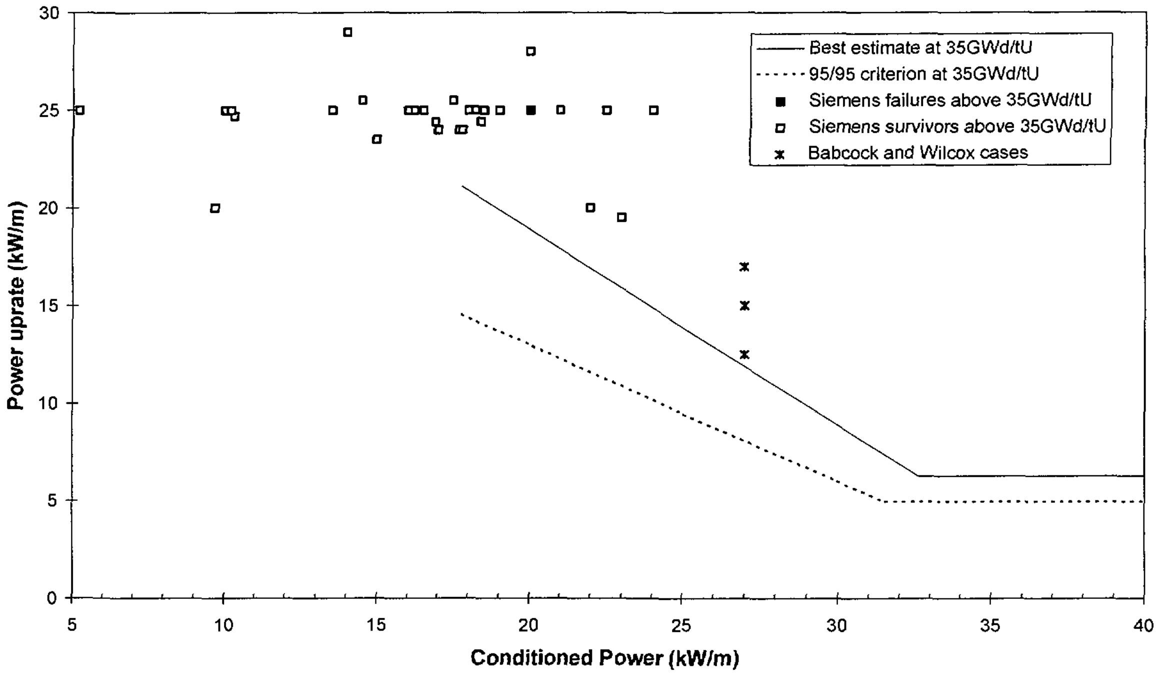

FIG. 5. High burnup cases above 35GW·d/t U with the PWR PCI best estimate and the 95/95 failure line indicated.

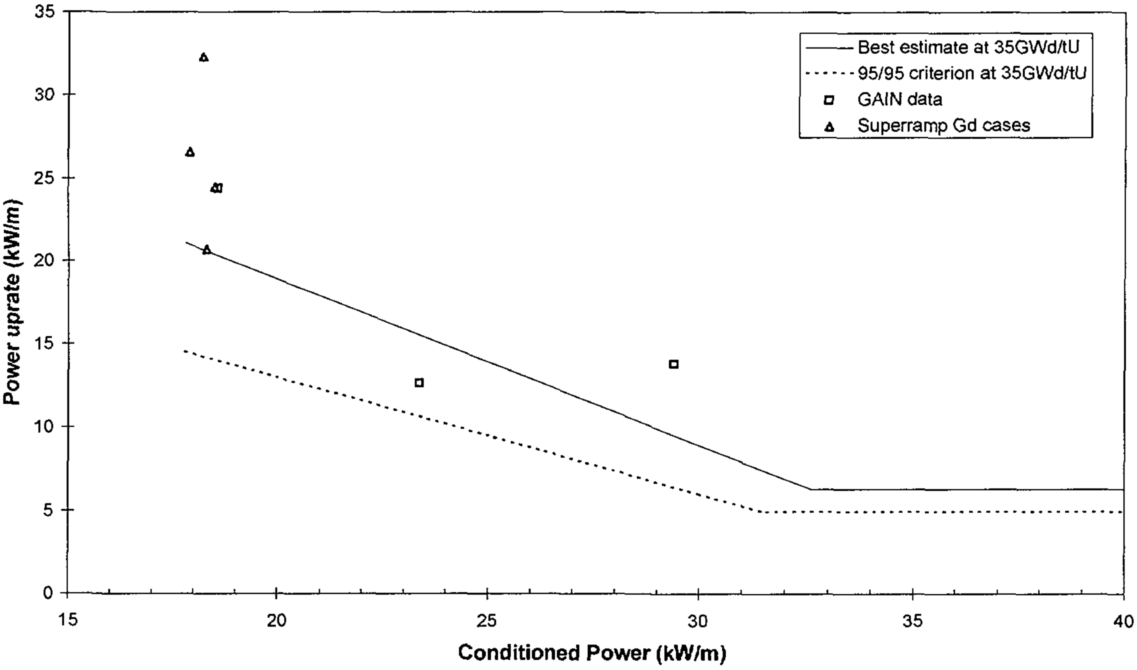

FIG. 6. Gadolinia cases with the best estimate and the 95/95 failure line at 35GW·d/t U indicated.

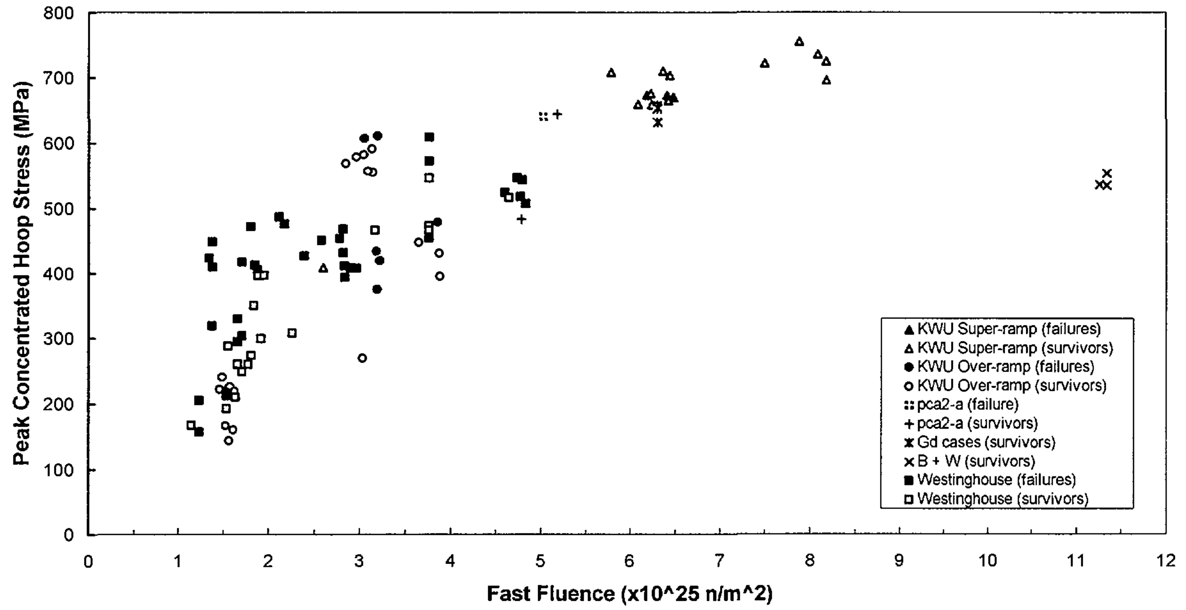

FIG. 7. Peak concentrated hoop stress as a function of fast fluence using ENIGMA 5.10.

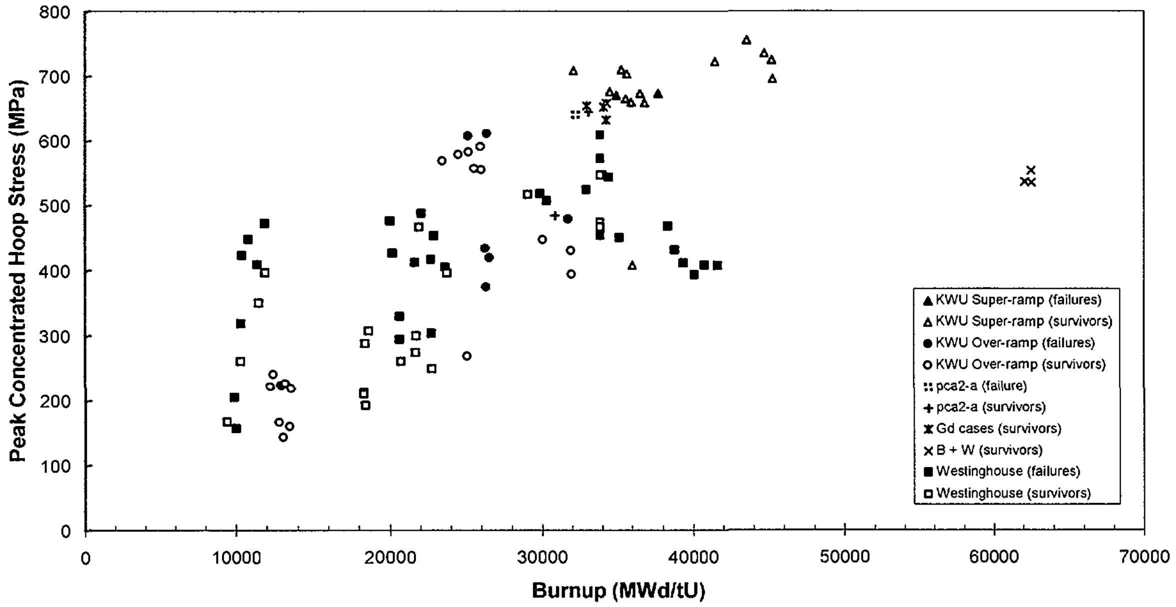

FIG. 8. Peak concentrated hoop stress versus burnup using ENIGMA 5.10.

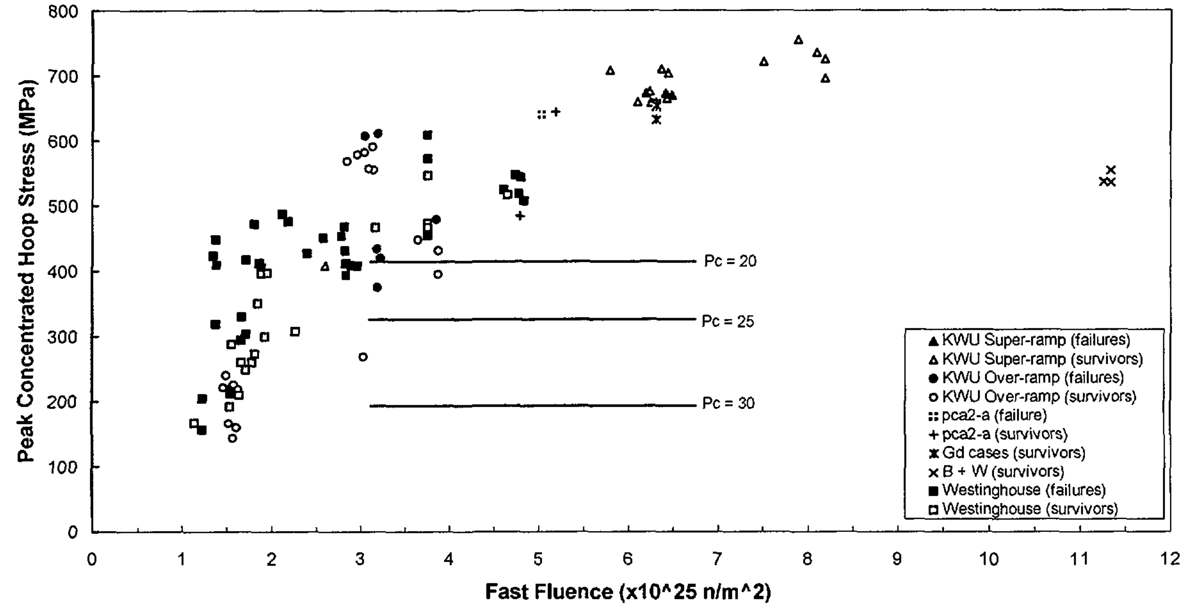

FIG. 9. Peak concentrated hoop stress as a function of fast fluence using ENIGMA 5.10 with conditioned powers indicated.

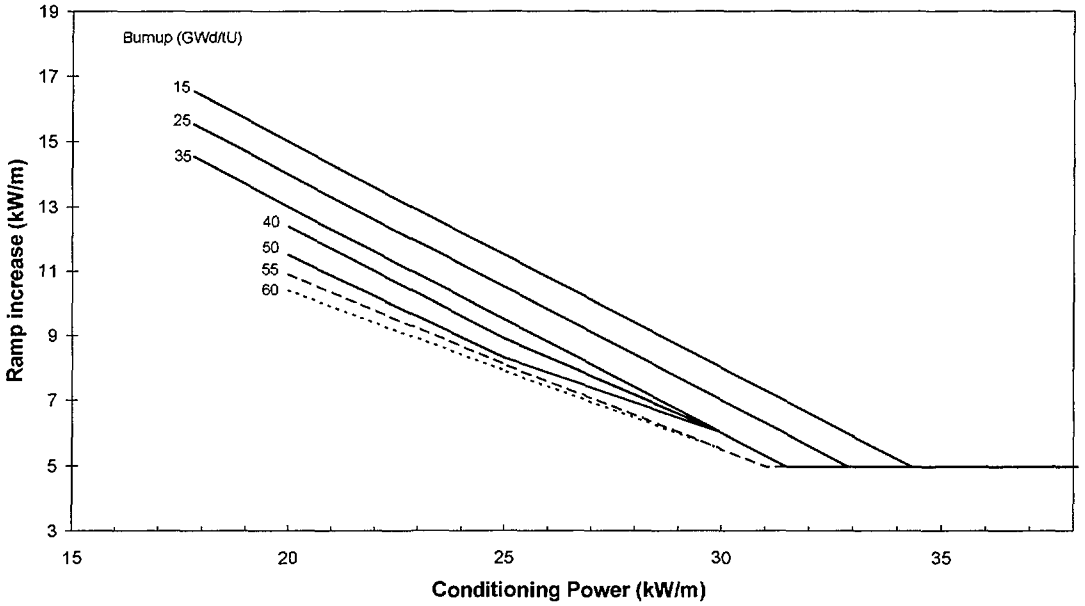

FIG. 10. The PWR PCI failure criterion to 60GW·d/t U.

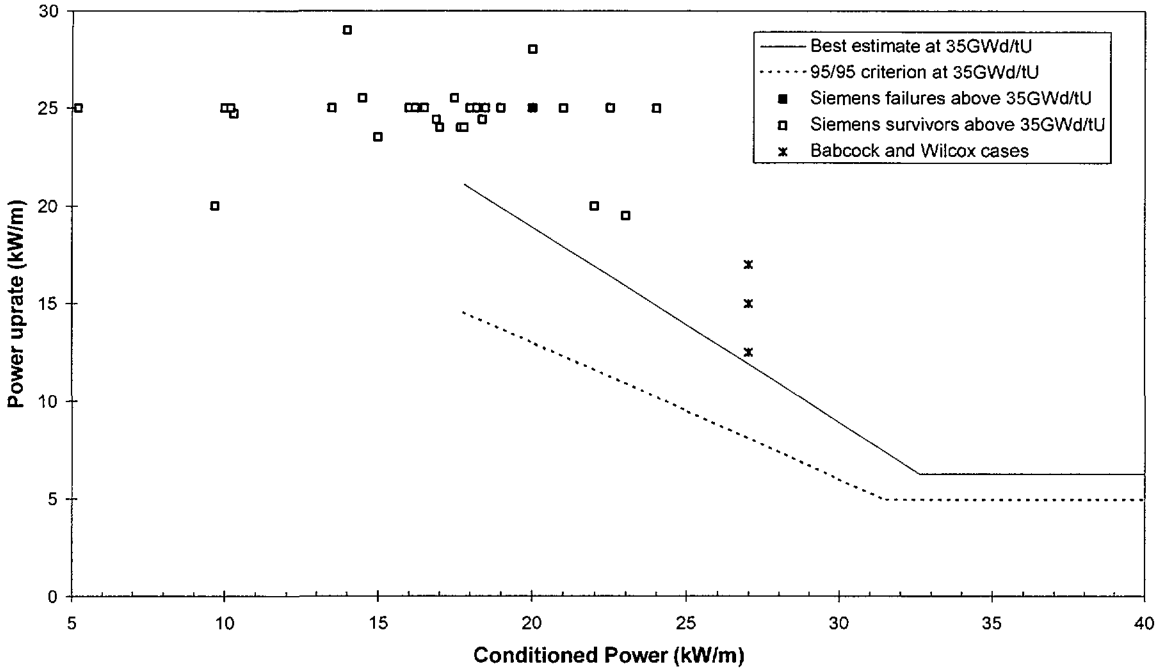

FIG. 11. High burnup cases above 35GW·d/t U with the PWR PCI best estimate and the 95/95 failure line indicated.

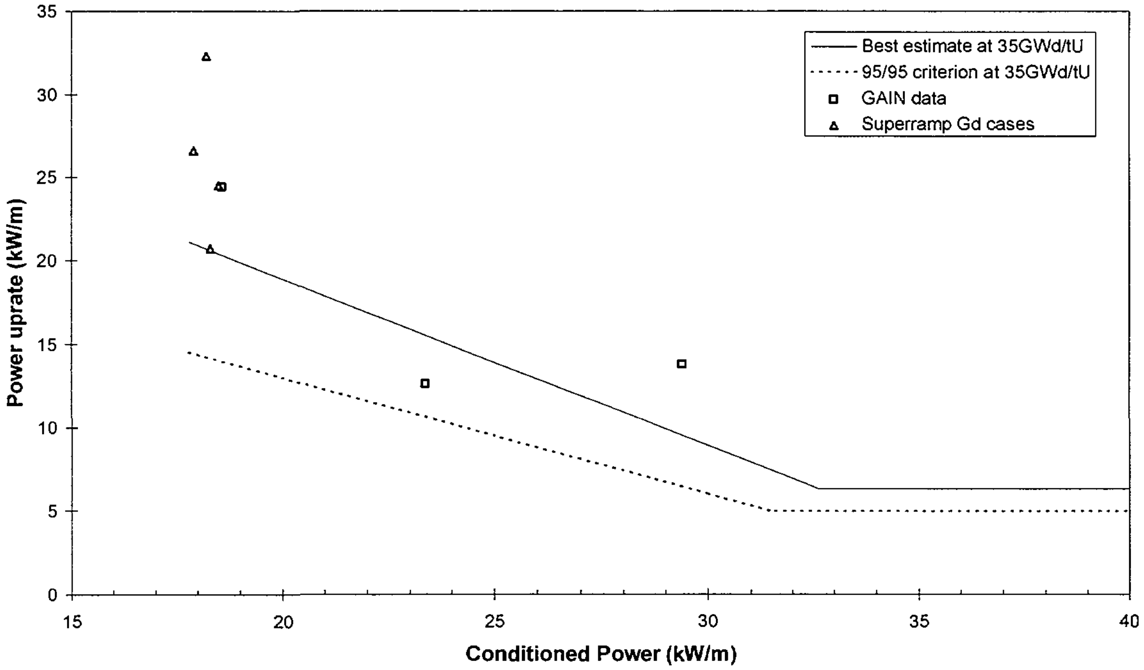

FIG. 12. Gadolinia cases with the best estimate and the 95/95 failure line at 35GW·d/t U indicated.

The difficulty in failing rods at high burnup is reflected in the data, the highest burnup failure occurring at 38 GW·d/t U for Westinghouse clad fuel and 37 GW·d/t U for Siemens clad fuel.

5.2. PCI ramp data on gadolinia - doped fuel

Since PCI induced clad stress is driven primarily by differential thermal expansion between the pellet and the clad, it might be expected that gadolinia-doped fuel (because of its reduced thermal conductivity) would be more susceptible to PCI failure than standard fuel when ramped from the same conditioning power for the same uprate. The data for Siemens fuel and from the GAIN programme [2], however, although limited to seven rods, does not reveal any vulnerability of the fuel to PCI failure. FIG. 12 shows the data for the seven rods, none of which failed. The burnup range covered by the Siemens rods is around 33–34 GW·d/t U and the GAIN rods 20–40GW·d/t U. The Siemens data covered very high final powers as high as 50 kW/m and yet did not fail. Interestingly these rods reached a fast neutron dose of 6.3×10^{25} n/m^2 which would imply a low probability to failure according to the stress-fluence plot in FIG. 7.

As there are data for only seven gadolinia doped rods and none of them failed it is not possible to derive a PCI criterion specifically for gadolinia rods. However, as none of the gadolinia rods failed despite being ramped above failure thresholds defined by the UO_2 rod PCI criterion, the UO_2 criterion can be used for gadolinia doped fuel.

6. CONCLUSIONS

- An ENIGMA based analysis of an enlarged experimental PCI ramp database including additional data from Siemens rods has shown that there is a threshold peak clad stress to failure which increases with fast neutron dose and burnup.
- The conservative assumption that the failure stress does not increase at high burnup has been used to derive PCI limits at high burnups using the ENIGMA methodology.
- PCI failure limits equivalent to 95/95 confidence limits have been derived for burnups up to 60 GW·d/t U.
- Experimental ramp data on gadolinia-doped fuel rods do not indicate any increased susceptibility to PCI failure implying that the UO_2 criterion can be used for gadolinia doped fuel.

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