Session II

PRESENT OPERATIONAL RECOMMENDATIONS AND THEIR ECONOMIC IMPACT

Chairman

R. TRACCUCCI
FRAMATOME

INFLUENCE OF SOME FABRICATION PARAMETERS AND OPERATING CONDITIONS ON THE PCI FAILURE OCCURRENCE IN LWR FUEL RODS

P. BOUFFIOUX
Belgonucléaire S.A.,
Brussels, Belgium

ABSTRACT.

In recent LWR designs, the fuel rod failures are induced by a chemically assisted mechanical process, i.e. stress corrosion cracking.

The analytical approach towards the analysis of PCI - SCC failures is mainly based on the predictions of the COMETHE code.

The failure criteria rely on the concept of a stress threshold together with fission product availability.

In the present paper, the use of the COMETHE code to minimize PCI induced clad failure occurrences is illustrated by parametric studies to define acceptable fuel specifications and reactor operating conditions (steady and transient).

1. INTRODUCTION.

Nowadays, most of the fuel rod failures in LWR can be attributed to PCI - SCC of Zircaloy claddings. These failures are correlated to the characteristics of the fuel rod as well as to the operating conditions. The analytical approach of fuel rod failure by PCI - SCC is mainly based on the predictions of the integral fuel rod modelling code COMETHE. Its utilization to minimize PCI induced clad failure occurrences is illustrated by parametric studies performed to define acceptable fuel specifications and reactor operating conditions (steady and transients). The effect of various fuel characteristics have been reported previously [1] [2] [3] [4] ; this paper will concentrate on the impact of the fuel rod pre-pressurization coupled with the power history, related to the in-core fuel management, on the PCI failure occurrence.

2. PCI FAILURE CRITERIA.

Out-of-pile experiments on unirradiated and irradiated Zircaloy claddings and post-irradiation examinations of failed rods led to the conclusion that crack formation is the key event in Zircaloy clad PCI - SCC failure. A crack can initiate if the hoop stress at the cladding inner surface exceeds a critical level (stress threshold for SCC) in the presence of a significant amount of corrosive fission products (mainly iodine) [4]. The COMETHE III-J version presently utilized by BELGONUCLEAIRE for its design and licensing calculations does not include any clad failure model. Therefore, the criteria as adopted by BELGONUCLEAIRE for PCI are quite conservative.:

(a) the hoop stress at the clad inner surface cannot exceed the minimum stress threshold for SCC. The threshold stress is expressed as a fraction of the yield stress. It enables to take into account the effect of the irradiation (irradiation hardening). The adopted criterion for stress threshold is about 30 % of the yield stress. It means that once the ratio of the hoop stress at the clad i.d. to the yield stress exceeds 30 %, the cladding is supposed to be severely damaged, provided the amount of fission products is sufficiently high. This concerns the second criterion.;

(b) the amount of corrosive fission products which have been released from the hot fuel and have deposited on the colder inner clad surface, must be low. The way by which the corrosive fission products are made available at the clad inner surface is not yet clearly established. Likely mechanisms have been discussed elsewhere [5]. In the absence of any model, it is assumed that the amount of corrosive fission products susceptible to induce SCC is proportional to the fission gas release. It has been reported that a quantity as low as 5 10^{-3} mg/cm^2 of free iodine would be largely sufficient to induce SCC [6] [7] [8]. It corresponds for a 15 x 15 typical fuel rod (like TIHANGE) to 0.6 % of the iodine inventory at 20,000 MWd/tU burn-up. In fact, a significant amount of iodine is bonded to the cesium. We will assume that 50 % of the iodine is free and 50 % bonded and that the release of free iodine follows the same mechanisms as fission gases. From this, we deduce a critical fission gas release limit of 1.2 % at 20,000 MWd/tU.

3. PARAMETRIC STUDY.

The performance of a 15 x 15 typical LWR fuel rod has been evaluated for three different power histories (Fig. 1), related to the in-core fuel management :

① with no power ramp at BOC ;
② with a power ramp at BOC 2, and
③ with a power ramp at BOC 3.

In addition, the influence of the rod pre-pressurization has been investigated for fuel considered power histories.

The calculations have been performed for an unpressurized rod (initial pressure, 1 kg/cm^2) and for a fuel rod pre-pressurized at 30 kg/cm^2. The characteristics of the fuel rod are summarized in Table I below.

- TABLE I -

FUEL ROD CHARACTERISTICS

Array	15 x 15
Clad OD	10.72 mm
Clad thickness	0.62 mm
Diametral gap	190 μm
Fuel bulk density	93.5 % TD
Active length	3642 mm

The results are illustrated in Figs. 2 to 7. For each power history, the evolution versus the irradiation time of the following variables have been plotted and the effect of pre-pressurization is compared ;

- peak pellet linear power (q'_{max}), fuel central temperature (T_c), integral fractional fission gas release (f), pellet - clad gap heat transfer coefficient (h) and the radial pellet - clad gap at ridge location (δ_r) in Fig. 2 (power history ①), Fig. 4 (power history ②) and Fig. 6 (power history ③) ;
- peak pellet linear power (q'_{max}), radial pellet - clad gap at ridge location (δ_r) and contact pressure at ridge location (P_c) in Figs. 3, 5 and 7 respectively for power histories ①, ② and ③.

4. DISCUSSION AND CONCLUDING REMARKS.

Before starting the discussion, it is good to insist on the fact that the specifications of the evaluated fuel rod (i.e. density, fuel grain size, ...) have been unchanged in all cases.

As the goal of the present study is to investigate the impact of fuel rod pre-pressurization and operating conditions on the PCI - SCC failure occurrence, the discussion will concentrate on the predictions at the time where the pellet - clad mechanical interaction is maximum. As it is illustrated in Fig. 1, that time is very different according to the power history.

Although it is generally thought that pre-pressurization of fuel rod leads to less fission gas release - and therefore, lower corrosive fission product availability at the cladding i.d. - than in the case of unpressurization, the present calculation would seem to demonstrate the contrary. Indeed, as it is shown in Figs. 2, 4 and 6, the pre-pressurized fuel rod releases more fission gases than the unpressurized one, whatever may be the power history. That phenomenon is a matter of the pellet - clad gap heat transfer coefficient variation during the irradiation. The heat transfer through the gap mainly depends upon two components : the gas mixture conductivity (directly proportional) and the gap thickness (inversely proportional). That latter decreases during the irradiation as a result of the following effects acting simultaneously : the fuel thermal expansion, the fuel swelling and the cladding creep down. In the unpressurized fuel rods, that latter is the leading effect in the gap closure. Indeed, in those rods, the inner gas pressure (less than 3 bar at B O L) is negligible compared to the system pressure (about 157 bar). High compressive stresses are generated in the cladding resulting in a very fast gap closure both by thermal creep (acting at B O L) and irradiation creep. The more the gap size is decreasing, the more the heat transfer through the gap is improving. As a result, the fuel temperatures fall down. As for the fission gas release, the release of corrosive fission products such as iodine is very sensitive to the fuel temperature. In the pre-pressurized fuel rods, because of the higher inner gas pressure (about 80 bar at B O L in fuel rod pre-pressurized at 30 bar), the compressive stresses in the cladding are strongly reduced. For instance, the magnitude of the compressive stress at B O L is about -16 kg/mm^2 in an unpressurized rod and about a factor 2 less in a pre-pressurized one. The cladding creep down rate is reduced and the gap closure is slowed down. As long as the gap thickness remains significant (> 10 μm), the heat transfer between the gap and the clad is bad, which leads to higher fuel temperatures and therefore to a more important fission gas release. Once the gap is closed and the pellet - clad interaction is onset, the heat transfer through the pellet - clad gap is highly better in the case of the pre-pressurized rod - as it is mainly attributed to the gas mixture conductivity - which decreases the fuel temperatures. Therefore, due to the gap closure kinetics, more fission products would be made available on the clad inner surface at the moment when the pellet - clad interaction is maximum in the pre-pressurized fuel rods.

However, a benefit consequence of the rod pre-pressurization is to delay the onset of the pellet clad interaction and to reduce the magnitude of that interaction as shown in Figs. 3, 5 and 7. The Table II below gives the burn-up at which the PCMI starts (at ridge location) as a function of the power history and the rod pre-pressurization.

It can be noticed that the time when the pellet - clad interaction starts up is very dependent upon the type of the power history. Apparently, the power history ③ would be the ideal one, the time required for the gap to close being the longest. Nevertheless, it is premature to conclude on the basis of the results presented here above. The Table III summarizes the most important results on the basis of which constructive conclusions and recommendations will be retrieved. That table gives for each power history and rod pressurization, the following results : the time when the pellet - clad interaction is maximum in terms of burn-up, the associated fission gas release, contact pressure, inner gas pressure and the ratio of the hoop stress at the clad i.d. to the yield stress. That latter is calculated from the creep correlation at ordinary strain rate, taking into the irradiation hardening.

From the results displayed in the figures and tables presented here above, it may be concluded :

- TABLE II -

ONSET OF PCMI AT RIDGE LOCATION AS A FUNCTION OF THE ROD PRE-PRESSURIZATION

Power history	Fuel rod pre-pressurization	Onset of PCMI - burn-up (MWd/tU)
①	No Yes	940 11,730
②	No Yes	4260 14,900
③	No Yes	7690 18,040

- the fuel rod pressurization is benefit as it delays the onset of mechanical interaction and reduces the magnitude of that interaction. Nevertheless, due to the slower creep down, the fuel temperatures decrease very slowly which leads to an increased fission product release ;
- the PCI failure is unlikely in the considered cases, which are representative of peak rated rods for this type of power plant. Some cases provide more maneuver margins than others. In this frame, the fuel management policy must be chosen in order to minimize the rating during the last irradiation cycle of each rod. That compromise is achieved by power histories of the types ① or ②. However, a power history of the type ③ could be acceptable whether a power ramp is imposed at the beginning of the cycle 3, as shown in Fig. 8. These limitations on power maneuvrability will reduce the plant capacity and lead to an important loss of energy production.

Finally, an economical compromise must be reached between the conflicting requirements of core reactivity, power map, fuel rod specification and fuel rod behaviour at high burn-up : this alone will allow an increasing load follow capability without any significant rod failure detrimental effect.

These conclusions are valid for the characteristics of the evaluated fuel rod and might be different for fuel presenting other specifications. Therefore, it would be recommended to gather as many as possible data related to the effect of pre-pressurization and operating conditions.

REFERENCES.

[1] H. BAIRIOT, P. BOUFFIOUX, M. GAUBE, Cl. VANDENBERG, Influence of Fuel Rod Characteristics on Performance, International Symposium on Water Reactor Fuel Element Fabrication with Special Emphasis on its Effect on Fuel Performance, Prague, CSSR, November 6-10, 1978.

[2] E. DE MEULEMEESTER, P. DERAMAIX, Sensitivity of Fuel Rod Behaviour on As-Fabricated Characteristics, Conference on Characterization and Quality Control of Nuclear Fuels, Karlsruhe (Germany), June 13-15, 1978.

[3] P. BOUFFIOUX, P. DERAMAIX, Sensitivity of Fuel Rod Behaviour on As-Fabricated Characteristics and on Operating Conditions, A N S Topical Meeting on Light Water Reactor Fuel Performance, Portland (U S A), April 29 to May 2, 1979.

[4] P. BOUFFIOUX, J. VAN VLIET, P. DERAMAIX, M. LIPPENS, Potential Causes of Failures Associated with Power Changes in L WR's, KTG/ENS/JRC Meeting, Petten (Holland), November 30 - December 1, 1978.

[5] P. BOUFFIOUX, J. VAN VLIET, Fission Product Release during Reactor Operation, A N S Topical Meeting, Portland (U S A), April 29 to May 2, 1979.

[6] J.T.A. ROBERTS, R.L. JONES, E. SMITH, D. CUBICCIOTTI, A.K. MILLER, H.F. WACHOB, F.L. YAGEE, A SCC Model for PCI Failures in L WR Fuel Rods, 4th International Conference on Zirconium in the Nuclear Industry, Stratford-upon-Avon (UK), June 1978.

[7] D.O. PICKMAN, J.A. GITTUS & al, Zircaloy Performance in Water Reactors, Review of the 4th International Conference on Zirconium in the Nuclear Industry, Stratford-upon-Avon (UK), June 1978.

[8] KATSUMI UNE, Stress Corrosion Cracking of Zircaloy-2 in Iodine Vapour, Journal of Nuclear Science and Technology, 14 [6], pp. 443-451, June 1977.

- T A B L E III -

DETERMINISTIC RESULTS FOR PCI FAILURE OCCURRENCE

Power history	Burn-up at maximum interaction (ridge location) (MWd/tU)*	$f_{crit.}$ (%)	Unpressurized rod				Pre-pressurized rod			
			f (%)	P_c (kg/cm^2)	P_g (kg/cm^2)	σ_θ/σ_y (-)	f (%)	P_c (kg/cm^2)	P_g (kg/cm^2)	σ_θ/σ_y (-)
①	36,720 (E O C 3)	0.65	(0.51)	142	7.8	- 0.04	[0.92]	63	128	0.014
②	12,000 (B O C 2)	2	0.37	326	4.7	(0.26)	0.91	89.5	100	0.044
③	22,090 (B O C 3)	1.1	0.29	337	5.4	(0.275)	0.69	265	115	[0.324]
			System pressure : 157 kg/cm^2 - $(\sigma_\theta/\sigma_y)_{crit}$ = 0.30							

<u>Nomenclature</u> :
f = rod integral fractional fission gas release
P_c = contact pressure at ridge location
P_g = inner gas pressure
σ_θ = clad i.d. hoop stress at ridge location
σ_y = yield stress
$f_{crit.}$ = critical fission gas release limit for SCC at the considered burn-up

* Average burn-up
[ ] means that the threshold for SCC is exceeded
( ) means that the threshold for SCC would be exceeded if an overpower even occurred (e.g. the oscillation).

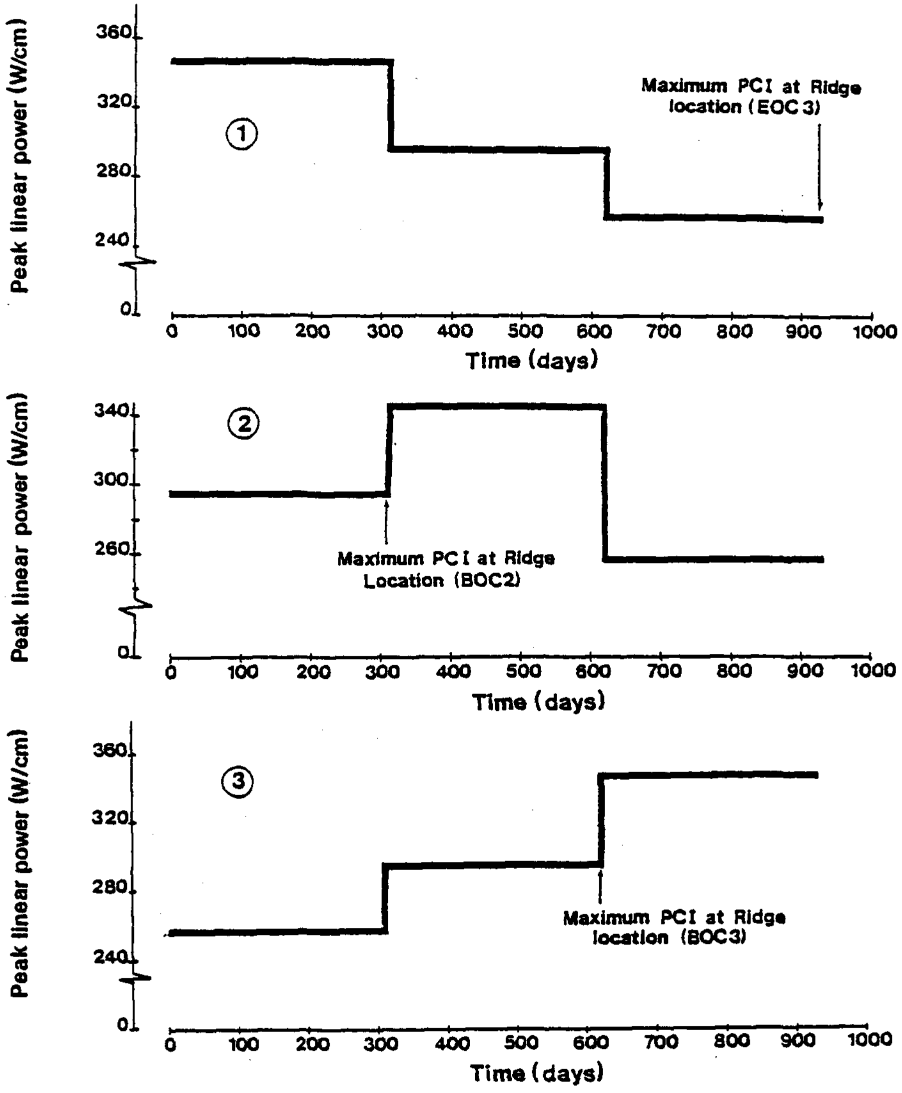
Peak linear power (W/cm)
360
320
280
240
0
①
Maximum PCI at Ridge location (EOC 3)
0
100
200
300
400
500
600
700
800
900
1000
Time (days)
340
300
260
②
Maximum PCI at Ridge Location (BOC2)
③
Maximum PCI at Ridge location (BOC3)

FIG.1

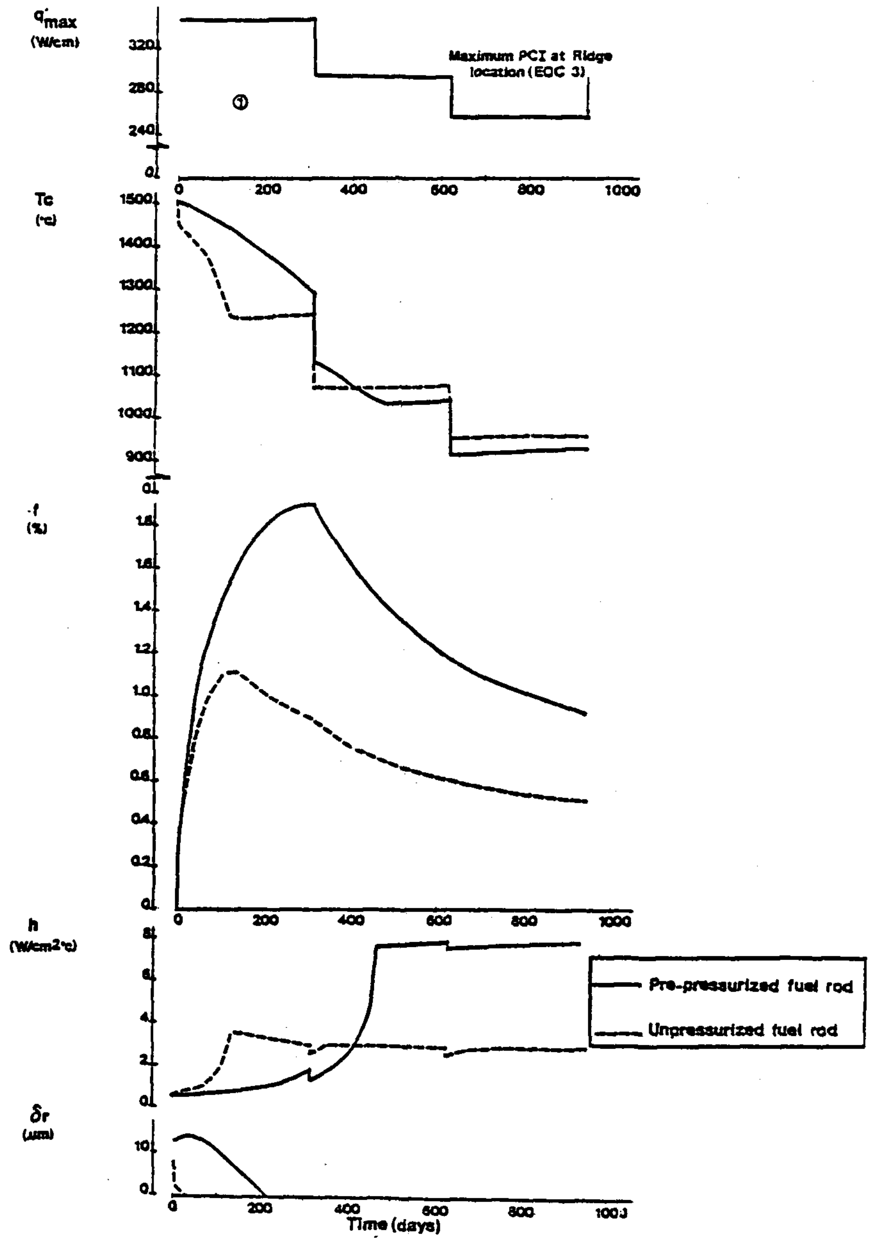
q'max (W/cm)
320
280
240
0
①
Maximum PCI at Ridge location (EOC 3)
0
200
400
600
800
1000
Tc (°c)
1500
1400
1300
1200
1100
1000
900
0
f (%)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
h (W/cm²°c)
8
6
4
2
0
Pre-pressurized fuel rod
Unpressurized fuel rod
δr (µm)
10
0
Time (days)

FIG. 2

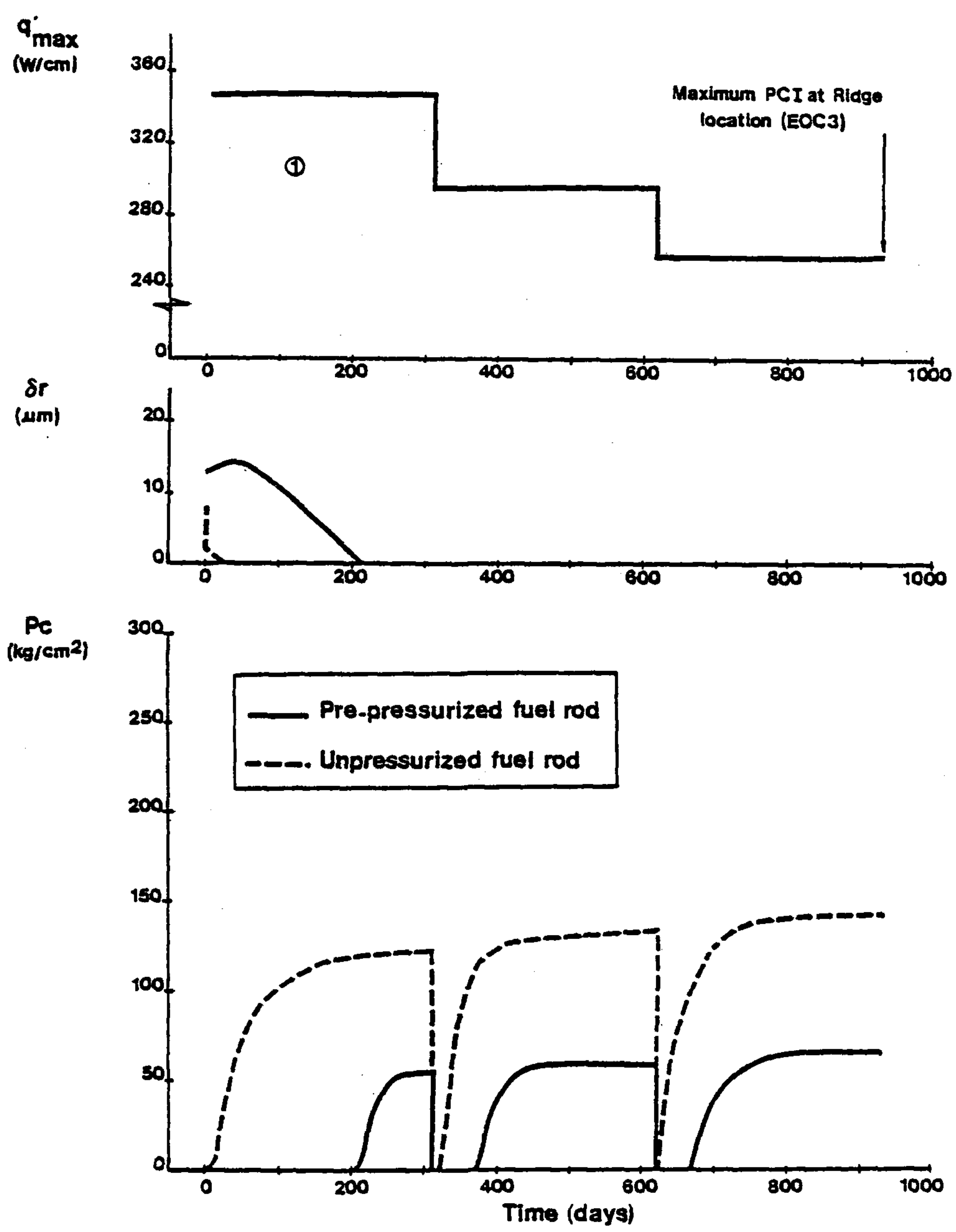
q'_{max}
(W/cm)
360
320
280
240
0
①
Maximum PCI at Ridge location (EOC3)
0
200
400
600
800
1000
δr
(μm)
20
10
0
0
200
400
600
800
1000
Pc
(kg/cm2)
300
250
200
150
100
50
0
Pre-pressurized fuel rod
Unpressurized fuel rod
0
200
400
600
800
1000
Time (days)

FIG. 3

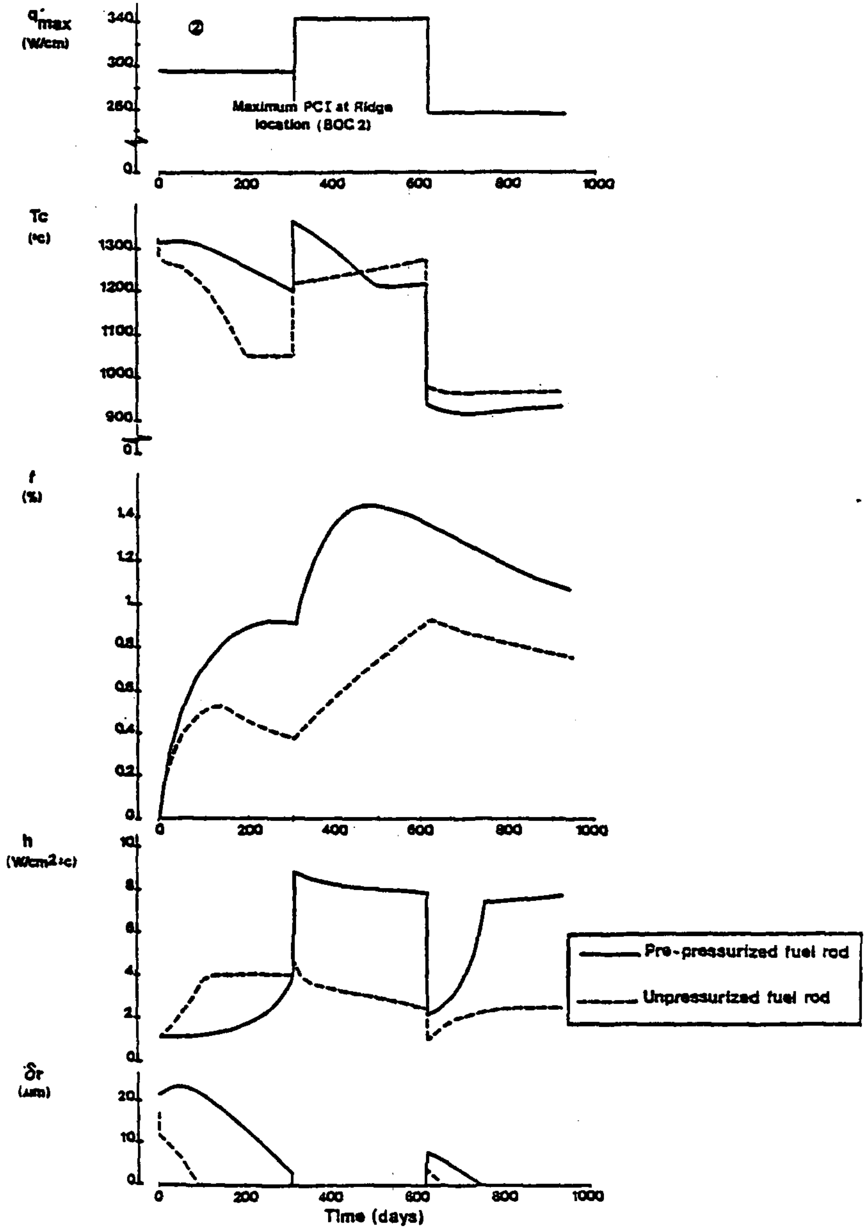
q'_{max}
(W/cm)
340
300
260
0
②
Maximum PCI at Ridge location (BOC 2)
0
200
400
600
800
1000
Tc
(°c)
1300
1200
1100
1000
900
0
f
(%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
h
(W/cm2·c)
10
8
6
4
2
0
Pre-pressurized fuel rod
Unpressurized fuel rod
δr
(μm)
20
10
0
0
200
400
600
800
1000
Time (days)

FIG. 4

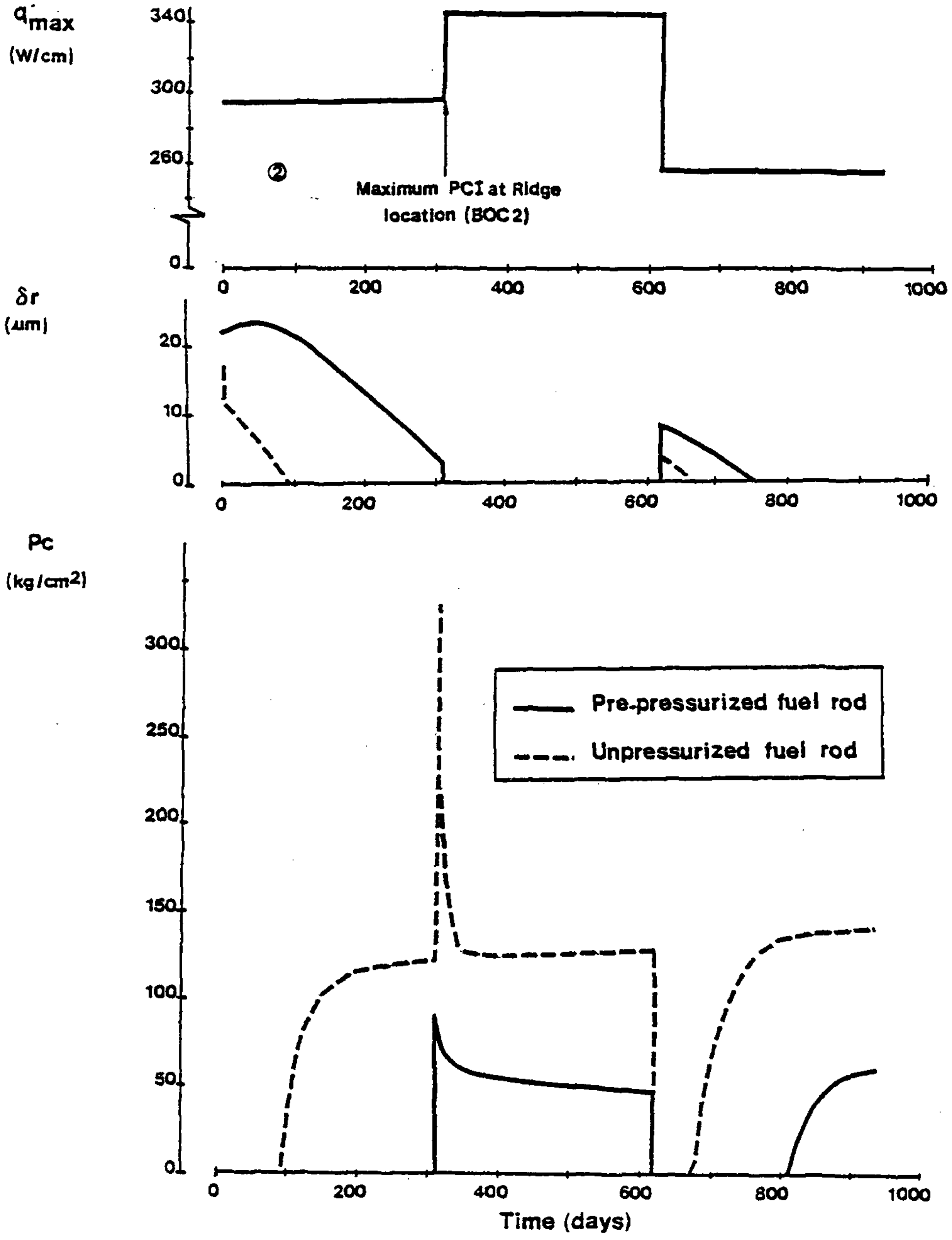
q'max
(W/cm)
340
300
260
0
②
Maximum PCI at Ridge location (BOC 2)
0
200
400
600
800
1000
δr
(μm)
20
10
0
0
200
400
600
800
1000
Pc
(kg/cm2)
300
250
200
150
100
50
0
Pre-pressurized fuel rod
Unpressurized fuel rod
0
200
400
600
800
1000
Time (days)

FIG.5

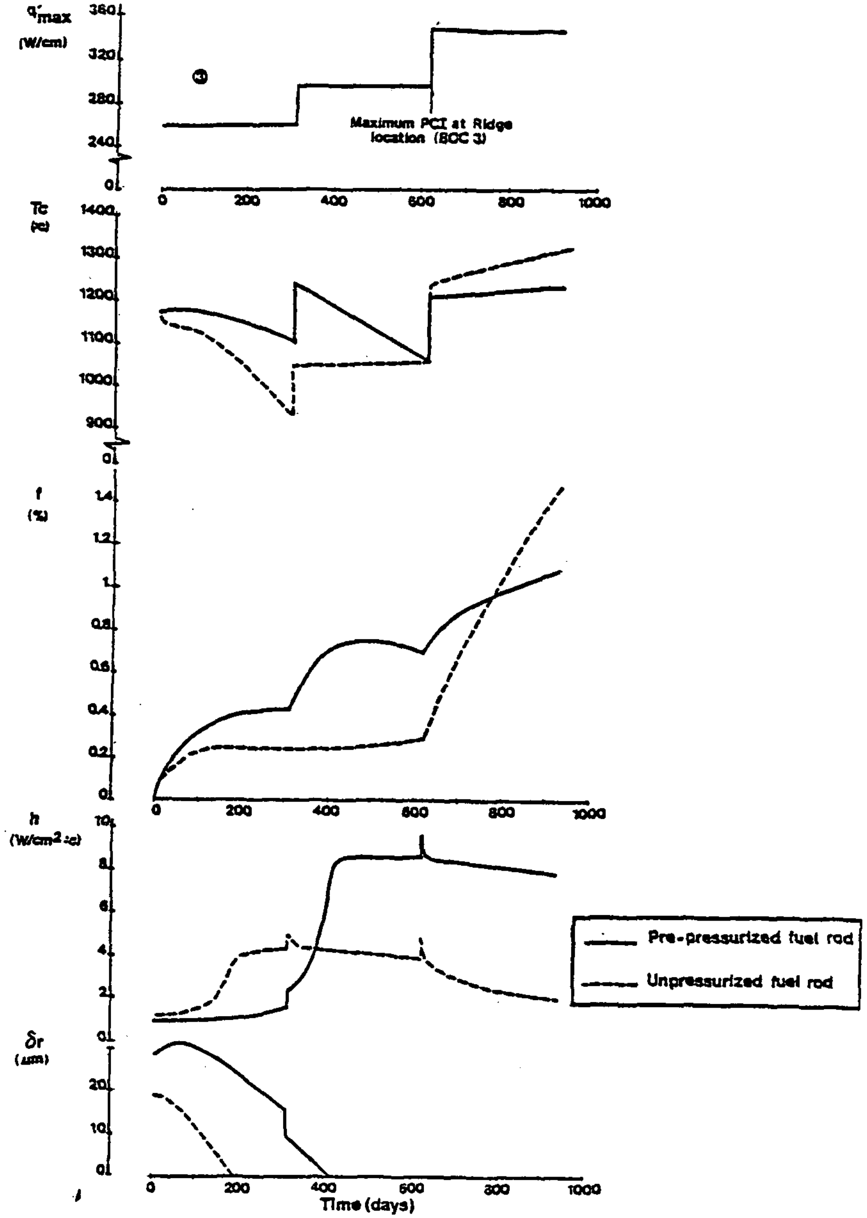
q'max
(W/cm)
360
320
280
240
0
③
Maximum PCI at Ridge location (BOC 3)
0
200
400
600
800
1000
Tc
(c)
1400
1300
1200
1100
1000
900
0
f
(%)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
200
400
600
800
1000
h
(W/cm2·c)
10
8
6
4
2
0
Pre-pressurized fuel rod
Unpressurized fuel rod
δr
(μm)
20
10
0
0
200
400
600
800
1000
Time (days)

FIG.6

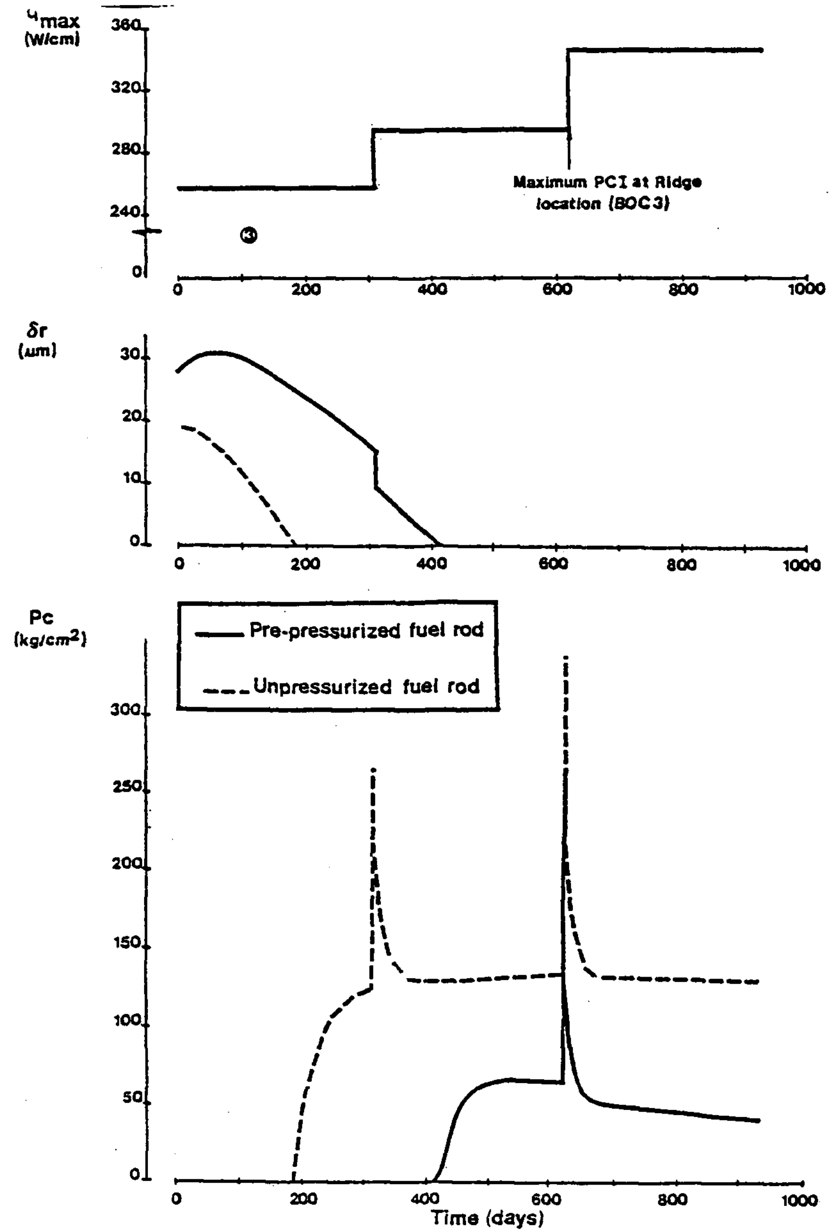
q max (W/cm)
360
320
280
240
0
③
Maximum PCI at Ridge location (BOC3)
0
200
400
600
800
1000
δr (μm)
30
20
10
0
0
200
400
600
800
1000
Pc (kg/cm²)
Pre-pressurized fuel rod
Unpressurized fuel rod
300
250
200
150
100
50
0
0
200
400
600
800
1000
Time (days)

FIG. 7

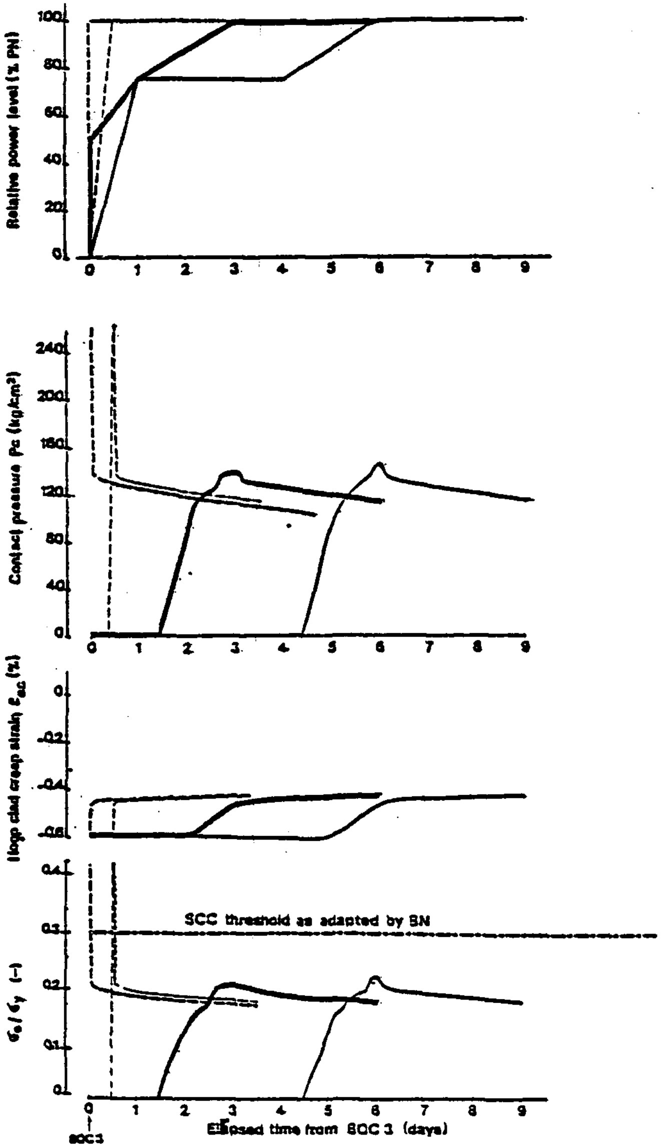
Relative power level (% PN)
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
9
Contact pressure Pc (kg/cm²)
240
200
160
120
80
40
0
0
1
2
3
4
5
6
7
8
9
Hoop clad creep strain ε_θc (%)
0
-0.2
-0.4
-0.6
0.4
0.3
0.2
0.1
0
SCC threshold as adapted by SN
σθ / σy (–)
0
1
2
3
4
5
6
7
8
9
BOC3
Elapsed time from BOC 3 (days)

FIG. 8