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# The Behaviors of the Material Parameters Affecting PCI Induced-Fuel Failure

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# 핵연료봉의 PCI 파손에 영향을 미치는 인자들의 거동분석

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**Abstract**

It is very important to investigate the behaviors of the material parameters governing PCI fuel failure during power ramp because PCI fuel failure is considered to be related to the operationg limits of power reactors. In this study, the behavior characteristics of the material parameters such as hoop stress, hoop strain, ridge height, creep strain rate and strain energy in cladding were studied as a function of the operating paramters such as power shock and ramp rate. The FEMAXI-Ⅳ fuel rod performance analysis code was used for this study.

**요 약**

핵연료봉의 PCI 파손은 원자로의 운전제한과 밀접한 관계가 있기 때문에, 출력급증 조건에서 핵연료봉의 PCI 파손을 지배하는 파손인자들의 거동을 검토하는 것은 매우 중요하다. 본 연구에서는 피복관에서의 원주방향 응력, 원주방향 변형도, 원주방향 주름 높이, 크립 변형율 및 변형도 에너지등의 파손인자들에 대한 거동특성을 핵연료봉 성능해석용 전산코드인 FEMAXI-Ⅳ를 이용하여 출력급증량 및 출력증가율의 운전인자들의 함수로 검토하였다.

## 1. Introduction

Many in-reactor power ramp tests have been performed [1] to investigate the PCI (Pellet-Cladding Interaction) mechanism and its failure criteria. This is because the PCI fuel failure is considered to be related to the operating limits of power reactors. Many investigators have also performed [2] out-of-pile tests to determine the PCI fuel failure criteria, which are, for the most part, given in terms of material parameters such as stress, strain rate and the corrosive element concentration. The out-of-pile test results, however, cannot be applied directly in analyzing in-reactor test results because there is no way, in the out-of-pile tests, to reflect the neutron irradiation effects and the instantaneous stress changes imposed on fuel cladding due to power changes. In reality, most fuel designers use empirical correlations statistically developed as a function of operating parameters such as power shock, ramp rate, burnup and ramp terminal level to predict the PCI fuel failure in ractors [3-7]. These empirical correlations have some restrictions in their application to various fuel and irradiation conditions. For instance, the empirical correlations statistically developed using in-reactor test results for the PCI fuel failure cannot be extended to mechanistic analysis on the effect of fuel design parameters on the PCI fuel failure. This description points out that PCI fuel failure should be analyzed by means of material parameters rather than operating parameters. Nakajima and Sim [8] showed in their analysis on Studsvik Power-Ramp Test results by the FEMAXI-Ⅳ fuel rod performance analysis code that PCI fuel failure was explained much better by material parameters than by operating parameters. The use of the material parameters to predict PCI fuel failure in reactors requires the threshold value of each parameter; above the threshold value PCI fuel failure is considered to occur. Much effort was concentrated on the determination of the threshold values. However, they cannot be applied directly as mentioned above because most of them were found through out-of-pile tests. It seems to us that for adequate use of the out-of-pile test results in the determination of the threshold values of the material parameters, the relation between the material parameters and the operating paramters under power ramp conditions should be investigated.

## 2. The Behaviors of the Material Parameters

According to Nakajima and Sim [8], the material parameters governing PCI fuel failure are hoop stress, creep strain rate, strain energy and corrosive element concentration at the cladding ridge. A sensitivity study was performed using the FEMAXI-Ⅳ computer code to investigate the behavior characteristics of these parameters as a function of the operating parameters under power ramp condition. The FEMAXI-Ⅳ code had been proven to be a reasonable one for the analysis of fuel behaviors under fast transient conditions like power ramp by the comparison of its prediction with Studsvik power Ramp Test results [8-9]. For the sensitivity study, a typical PWR fuel rod was chosen (refer to Table 1), which was assumed to be base irradiated to the burnup of 24,700 MWD/MTU with the average linear heat rating of 23kW/m. since Sim [2] revealed in his analysis of in-reactor power ramp test results that the PCI fuel failure was significantly affected by the fuel rod conditions prior to power ramp-for example, cladding ridge height and ovality, etc - power shock was defined in this study as ramp terminal level minus contact power to reflect the influence of the previous fuel rod conditions. The contact power is considered to be the linear heat rating at the beginning of fuel-cladding contact during power ramp.

**Table 1 Data used in the sensitivity study**

| | |
|---|---|
| Fuel rod data | |
| fuel rod type | PWR |
| fuel outer diameter | 9.15mm |
| fuel grain size | 6.0 μm |
| cladding type | stress-relieved Zry-4 |
| cladding outer diameter | 10.75 mm |
| diametral clearance | 150 μm |
| stack length | 320 mm |
| plenum length | 32 mm |
| initial pressure | 2.25 MPa |
| Irradiation data | |
| coolant pressure | 14.5 Mpa |
| coolant temperature | 300 ℃ |
| average linear heat rating | 23 kW/m |
| burnup prior to ramping | 24,700 MWD/MTU |

Fig.1 shows the variations of increments in maximum cladding hoop stress, maximum cladding hoop strain and cladding ridge hight as a function of the power shock and ramp rate. As shown in Fig. 1, the increments in the maximum cladding hoop stress and strain increase rapidly with the power up to 24kW/m and cease from increase with the power shock higher than 24kW/m. The increment in the cladding ridge height also increases with the power shock up to to 24kW/m, but decreases with the power shock higher than 24kW/m, as shown in Fig.1. The cease from increase in the cladding hoop stress and strain at the higher power shock indicates that the thermal expansion in fuel pellet and the relocation of fuel crack fragments occurred maximally, and stress relaxation in cladding occurred. Fig. 1 also shows that the ramp rate hardly affects the cladding hoop stress and strain. Fig.2 shows the variations of increments in the creep strain rate and strain energy at the cladding ridge as a function of the power shock and the ramp rate. As shown in Fig.2, the increment in the creep strain rate at the cladding ridge increases with the power shock up to 16kW/m, decreases with the power shock higher than 30kW/m. The increment in the strain energy at the cladding ridge gradually increases with the power shock uo to 16kW/m. This corresponds to the power shock range showing the first increase in the cladding creep strain rate. The increment rapidly increases with the power shock in the range of 16-24kW/m. This corresponds to the power shock range showing the decrease in the cladding creep strain rate. This decrement again gradually increases with the power shock higher than 24kW/m. This corresponds to the power shock range showing the saturation of the cladding hoop stress and strain. Fig.2 also shows that the ramp rate significantly affects the cladding creep strain rate and strain energy.

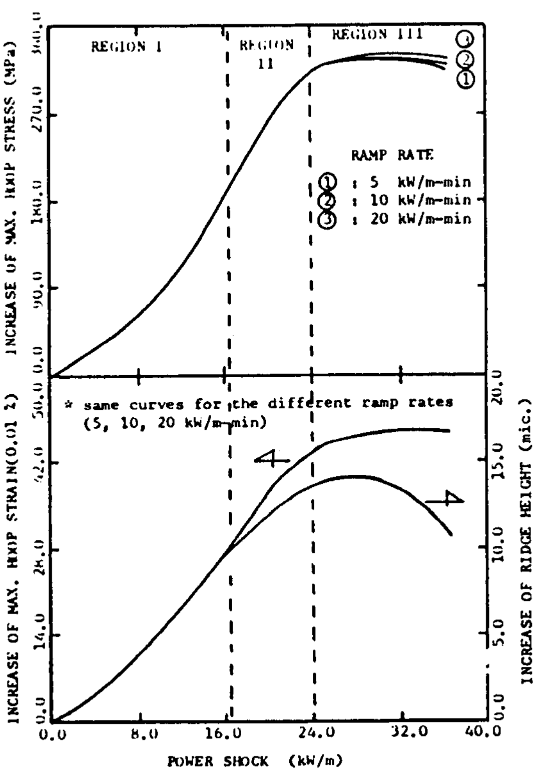


**Fig. 1** Effect of Power Shock and Ramp Rate on Cladding Maximum Hoop Stress, Maximum Hoop Strain and Ridge Heght during Power Ramp

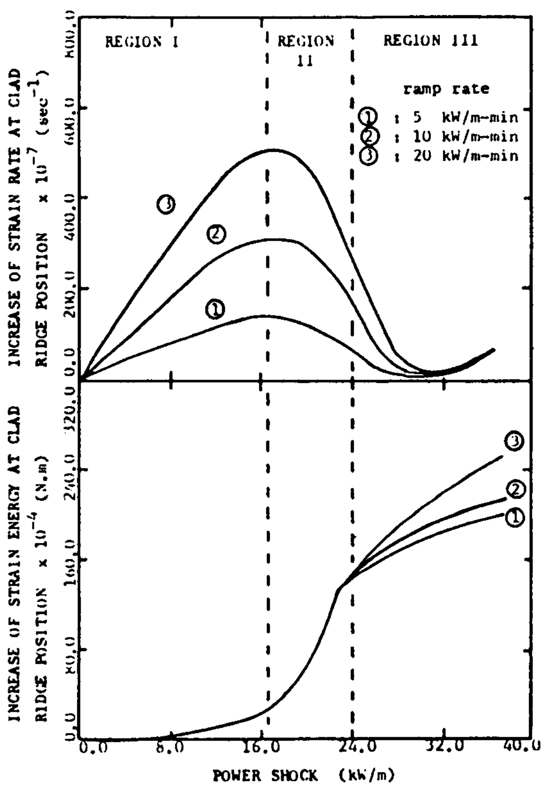


**Fig. 2** Effect of Power Shock and Ramp Rate on Cladding Creep Strain Rate and Strain Energy at Ridge Position during Power Ramp

## 3. Discussion

The sensitivity study described in Chapter 2 indicates that the operating parameters affect the material parameters in three regions as follows. Region 1 (power shock in the range of 0 to 16kW/m in Figs 1 and 2) is characterized by rapid increases in the hoop stress, hoop strain and creep strain rate at the cladding ridge, by rapid increase in the cladding ridge height, and by the gradual increase in the strain energy at the cladding ridge. This region is considered to be governed by the differences in thermal expansion between $UO_2$ pellet and Zircaloy cladding, and by the relocation of the cracked pellet fragments. Region II (power shock in the range of 16 to 24kW/m in Figs 1 and 2) is characterized by rapid increases in hoop stress, hoop strain and strain energy at the cladding ridge, by rapid increase in cladding ridge height, and by decrease in creep strain rate at the cladding ridge. This region is considered to be governed by the phenomena related to Region I and also governed by the swelling difference along the $UO_2$ pellet due to thermal feedback. The thermal migration of fission gas release from intragrain to grain boundary and the growth of fission gas bubbles on grain boundary of the fuel pellet are accelerated by higher temperatures due to poor heat transfer at the middle height of the pellet, leading to a higher swelling rate at the middle height of the pellet as a consequence. It is noted here that the ends of the fuel pellet keep the hard contact with the cladding more than the mid-points of the fuel pellet, because of the hourglassing of the pellet ends. This hard contact at the pellet ends increases local gap conductance, and therefore, lowers the temperature level at the pellet ends more than that at middle height of the pellet, where relatively soft contact is kept with the cladding. Due to this difference in the temperature level along the pellet length, the local swelling rate at the pellet ends appears to be lower than at the middle height of the pellet. The decrease in the creep strain rate at cladding ridge in Region II stems from the lower swelling rate at the pellet ends.

Region III (power shock higher than 24kW/m in Figs 1 and 2) is characterized by saturation in hoop stress and strain at the cladding ridge, by decrease in cladding ridge height, by decrease and increase in creep strain rate at the cladding ridge and by the decelerated strain energy at the cladding ridge. The increase in creep strain rate at the cladding ridge means that the thermal feedback effect, discussed above, is eliminated at much higher powers because the contact between the middle points of the pellet and the cladding becomes harder. This almost equivalent swelling rate along the fuel pellet makes the cladding ridge height lower. This lowered ridge height suppresses the stress and the strain concentration at the cladding ridge. From this fact Region III is considered to be governed by the accelerated thermal expansion difference between $UO_2$ pellet and Zircaloy cladding, and also by stress relaxation.

In Chapter 2, the ramp rate was described not to affect the cladding hoop stress and strain. This is in accord with the previus result [2] of the author. After re-examination of Studsvik Power Ramp Test results, the author concluded that PCI fuel failure strongly depends on both the condition of fuel rods prior to power ramp and power shock and that ramp rate affects PCI fuel failure less than power shock. This description may give background on the use of the threshold stress concept for the analysis of PCI fuel failure during power ramp.

## 4. Conclusion

The behaviors of the material paramters affecting the PCI fuel failure during power ramp was investigated as a function of the operating parameters by FEMAXI-IV fuel rod performance analysis code. This study indicates that the power shock greatly affects the material parameters such as hoop stress, hoop strain, creep strain rate, ridge height and strain energy in cladding. The ramp rate hardly affects the hoop stress hoop strain and ridge height, but affect is made on the creep strain rate and strain energy. This description was found to be consistent with the experimental results. Ths sensitivity study also indicates that the operating parameters affect the material parameters in three regions; a region (Region Ⅰ) goverened by the different thermal expansion between $UO_2$ pellet and Zircaloy cladding and the relocation of the cracked pellet fragments, a region (Region Ⅱ) governed by the effects described above and also by the swelling difference along the $UO_2$ pellet due to thermal feedback, and a region (Region Ⅲ) governed by the accelerated thermal expansion difference between $UO_2$ pellet and Zircaloy cladding and also by stress relaxation.

## References


1. H.Knaab, P.M.Lang and H.Mograd, "Overview on International Experimental Programmes on Power Ramping and Fission Gas Release", Res Mechanica 14, 87-16(1985).
2. K-S. Sim, "Study on PCI Induced-PWR Fuel Failure and Its Remedies," KAERI, May 1988.
3. P.J.Pankaskie, "Mechanistic Considerations Used in the Development of the PROFIT PCI Failure Model", NUREG/CR-1462(1980).
4. R.Rolstad, "Model for Prediction of Fuel Failures", Trans. ANS 24, 163 (1976).
5. W.J.Penn, R.K.Lo and J.C.Wood, "CANDU Fuel - Power Ramp Performance Criteria", Nucl. Technology 34, 249-268(1977).
6. S.G.McDonald, R.D.Fardo, P.J.Sipush and R.S.Kaiser, "A Statistical Analysis of Pellet-Clad Interaction Failures in Water Reactor Fuel", paper presented at the IAEA Specialists Meeting on Pellet-Cladding Interaction in Water Reactors, Riso National Lab., Denmark, Sept. 1980.
7. "SPEAR-BETA Fuel Performance Code System", Vol. 1:General Description, EPRI/NP-2291 vol. 1 (1982).
8. T.Nakajima and K-S. Sim, "Analysis of Fuel Behavior in Power-Ramp Tests by FEMAXI-Ⅳ Code", Res Mechanica 25, 101-128(1988).
9. T. Nakajima and H.Saito, "A Comparison between Fission Gas Release Data and FEMAXI-Ⅳ Code Calculations", Nucl. Eng. Des. 101, 267-279(1987).