POWER RAMPING/CYCLING EXPERIENCE AND OPERATIONAL RECOMMENDATIONS IN KWU POWER PLANTS

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SUMMARY

The power cycling and ramping experience of KWU is based on experiments in test and commercial reactors, and on evaluation of plant operation (PHWR, PWR and BWR). Power cycling of fuel rods did never lead to PCI failures. In ramping experiments, for fast ramps PCI failure thresholds of 480/420 W/cm are obtained at 12/23 GWd/t(U) burnup for pressurized PWR fuel. No failures occurred during limited exceedance of the threshold with reduced ramp rate. Today and in the near future, operational recommendations cannot be derived from mechanistic PCI models because of the lack of knowledge about the many different interacting mechanisms during a power ramp. A useful application of empirical models is limited to the specific design, pre-irradiation and ramping conditions as used for the calibration of the model. Therefore KWU uses operational recommendations which are derived from experiments and plant experience. The effects of ramping considerations on plant operation is discussed. No rate restrictions are required for start-ups during an operating cycle or load follow operation within set limits for the distortion of the local power distribution. In a few situations, e.g. start-up after refueling, ramp rates of 1 to 5 %/h are recommended depending on plant and fuel design.

1. INTRODUCTION

The fuel behaviour during an increase of local rod power is strongly influenced by the preceding power history which determines the conditioned power of a fuel rod. For applications, the conditioned power is normally defined as the maximum steady state power held for a minimum time (12 to 72 h) in some specified burnup interval (typically 1000 MWd/t(U)) before the power increase. "Power cycling" includes all power changes below the conditioned power, "power ramping" means an increase beyond the conditioned power.

In actual plant operation it is essential to distinguish between local power (power density or LHGR) and reactor power, since local power changes are often not proportional to the initiating reactor power change, but may be amplified in height and rate by shifts in the power distribution due to control rod movements and xenon effects. Fuel conditioning relates to the envelope of preceding steady state power distributions rather than to the preceding reactor power.

This paper will briefly summarize the power cycling and ramping experience of KWU which has been published elsewhere /1 - 4/, and assess the present capability of theoretical PCI models. Then the operational recommendations for KWU reactor fuel and the effects on plant operation will be discussed.

2. POWER RAMPING / CYCLING EXPERIENCE

The good fuel behaviour during power cycling has been early demonstrated by experiments in Petten (400 cycles) and Obrigheim (880 cycles) /5/, and has been confirmed by evaluating shut-down/start-up and load follow manoeuvers in KWU reactors: No failures occurred during all fast plant manoeuvers with no or only limited ($\lesssim$ 10 %) transient local power increase beyond the previous steady state power distribution /4/. This implies that not only power cycling is safe, but also repeated fast small ramps beyond the conditioned power.

The KWU ramping investigations include experiments in operating reactors and in test reactors. Consistent results were obtained for pressurized KWU PWR rods /1 - 3/. Failure thresholds are 480 W/cm in the lower burnup range (~ 12 GWd/t(U)) and 420 W/cm in the higher burnup range (~ 23 GWd/t(U)). Fast ramps to powers above the threshold had a non-zero failure probability. Fast ramps to powers below the threshold did not lead to failures, as has been demonstrated by additional experiments in power reactors /2/. Earlier operating experience with BWR fuel has indicated that for unpressurized rods the failure thresholds may be lower. Future evaluation of plant experience and planned ramp tests will provide new data for unpressurized and pressurized BWR rods.

Substantial efforts have been made to determine the allowable ramp rate for safely exceeding the failure threshold during high power ramps. With individual rod testing of PWR rods up to 70 W/cm beyond the threshold /2/, failures could be prevented by reducing the ramp rate above the threshold to values in the range 0.1 - 5 W/cm min (Fig. 1). PWR and BWR plant experience gives a more detailed picture /1,4/: (i) Local ramp rates > 3 W/cm min did lead to failures, (ii) ramp rates ≦ 0.3 W/cm min did not lead to failures with ramps to LHGRs in the range 400 - 450 W/cm, (iii) above 450 W/cm peak LHGR, there is no confirmed PWR plant experience with high and slow ramps, but BWR experience indicates that with unpressurized rods ramp rates < 0.1 W/cm min are required to prevent failures. Therefore one might speculate that the safe ramp rate is not a single number, but may depend on design and peak LHGR.

3. MODELLING CONSIDERATIONS

Today it is generally accepted that PCI failures are caused by a combination of clad stress and chemical attack at the clad inner surface. Nevertheless, at the present time it is not possible to describe the PCI failure mechanism by the aid of first principles. There are too many interacting mechanisms which are not yet fully understood.

In order to predict the clad stress during a power ramp, it is necessary to have full knowledge of the following effects:

- gap size at the start of a ramp (mainly depending on fuel densification, swelling, relocation and thermal expansion, and on clad creepdown, ovalization, and thermal expansion),
- gap conductance (mainly depending on the size of the residual gap due to surface roughness and waviness, on the composition of the gas in the residual gap, and on the contact pressure contribution to the gap conductance),
- fuel relaxation (mainly depending on the reversibility of relocation and the fuel creep properties),
- stress localization at the clad inner surface (opposite to radial fuel cracks and at pellet/pellet interfaces).

The knowledge of the kinetics of transient fission gas release is a pre-requisit for the knowledge of the gap conductance during a power ramp, since it is well known that power ramps up to power levels where PCI failures can occur, are accompanied by large amounts of transiently released fission gas /1/. Due to the fact that the thermal conductivity of the fission gas is about 20 times lower than the thermal conductivity of the fill gas helium, the transient gas release

during a power ramp may significantly influence the gap conductance /6,7/ and thereby fuel thermal expansion and clad strain and stress. Mechanistic modelling of the chemical aspects of PCI is presently even more difficult than calculation of clad stresses because of the lack of basic information (e.g. species of volatile fission products causing stress corrosion cracking, chemical state of the species reacting with the clad, necessary fission product concentrations).

Empirical PCI models as e.g. the CANDU Fuelograms /8/, the POSHO model /9/, or the KWU interference approach /6,10/ can only be valid for the specific fuel design, preirradiation and ramping conditions as used for the calibration of the models. As an example unpressurized CANDU fuel with collapsed clad and pressurized PWR fuel with freestanding clad behave differently /1,4/, since the mentioned design differences have a strong influence on the gap size at the start of a ramp and on the gap conductance during a ramp (increasing gap conductance with increasing prepressurization).

As pointed out in chapter 2, power cycling in contrast to power ramping does not lead to PCI failures. This is understandable because there is practically no clad stress due to mechanical fuel/clad interaction during power cycling: The fuel-to-clad gap and - particularly at high power - cracks within the fuel open during the power decrease and close again during the power increase. Also transient fission product release is not given in the case of power cycling, since the fuel has already released the fission products at previous high power levels.

4. FUEL OPERATING RECOMMENDATIONS

Because of the uncertainties in PCI modeling, it is the general philosophy of KWU that fuel operating guidelines, which are both effective in preventing failures and economic by minimizing availability losses, must presently be based on experience rather than models. Obviously, such guidelines have only to be applied in those operational conditions and power ranges, where local exceedance of the PCI failure threshold is anticipated. The main features of the guidelines for KWU fuel may be summarized as follows.

(i) An optimized operating mode has to be used to limit the distortion of the power distribution during fast plant manoeuvers. In modern KWU PWRs this is done by an operational safety grade limitation system which limits local power density and shifts in power distribution /11/. In KWU-BWRs there are limitations on rod control, and mainly flow control is used in the high power range (Fig. 2). The continuous control rod drive enables to restrict the motion of rods in the high power range (e.g. for burnup compensation) to small steps which do not require preconditioning.

(ii) There is no rate limitation on power cycling, i.e. load changes or start-ups during an operational cycle, within the envelope of the conditioned power or the preceding steady state full power distribution. In BWRs this may require temporary surveillance of in-core detector signals at odd xenon conditions. Experience shows that repeated limited exceedance of the envelope (5 - 10 %) is tolerable. In particular, load follow operation and frequency stabilization seem to be no problem, since the fuel remains conditioned to higher than the steady state local power (schematically shown in Fig. 3).

(iii) A rate limitation to ≤ 5 % P_N/h is recommended only if a conditioned power distribution does not exist or is significantly exceeded in the high power range (ramping beyond the PCI threshold). This mainly applies to the first start-up after refueling, the first start-up after control rod pattern exchange in BWRs, and the first return to full power after extended (> 4 weeks) part load operation. (Additional recommendations and ≤ 1 % P_N/h ramp rate in the above cases are applied for unpressurized BWR fuel, particularly for 7x7 fuel.)

The effect of these guidelines on plant availability is not very significant in standard plants. The optimized operating mode as outlined under (i) has practically negligeable effects. The requirement (ii), that the envelope of the conditioned power distribution is not significantly exceeded, also imposes only small restrictions which are comparable to those resulting from the additional requirement not to exceed design limits (e.g. max. LHGR). The effect of the rate limitations in the particular situations stated under (iii) can easily be estimated. If one conservatively assumes 5 - 10 events per operational cycle (year), which require a 5 %/h rate limitation from 70 to 100 % power, the loss will be less than 10 full power hours or $\lesssim$0.15 %.

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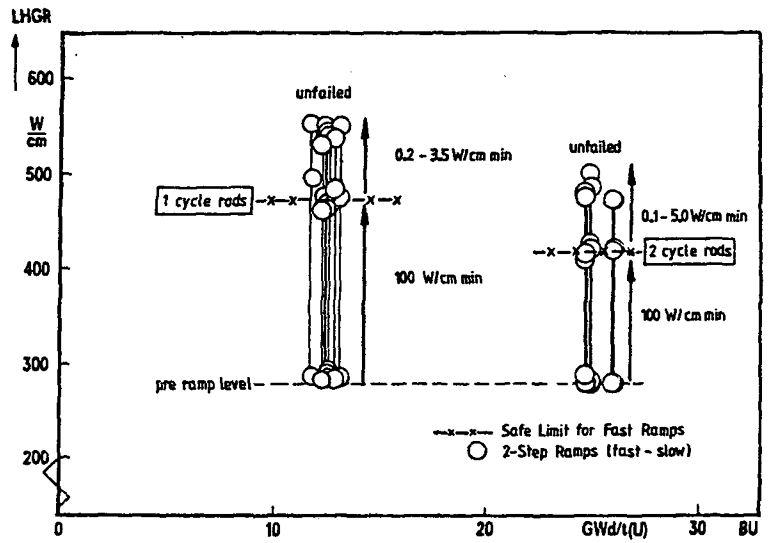

Fig. 1 Ramp Tests in HFR Petten. Ramp Power vs. Burnup (Ref. /2/). (PWR-Rods, prepressurized; Status Jan. 1979)

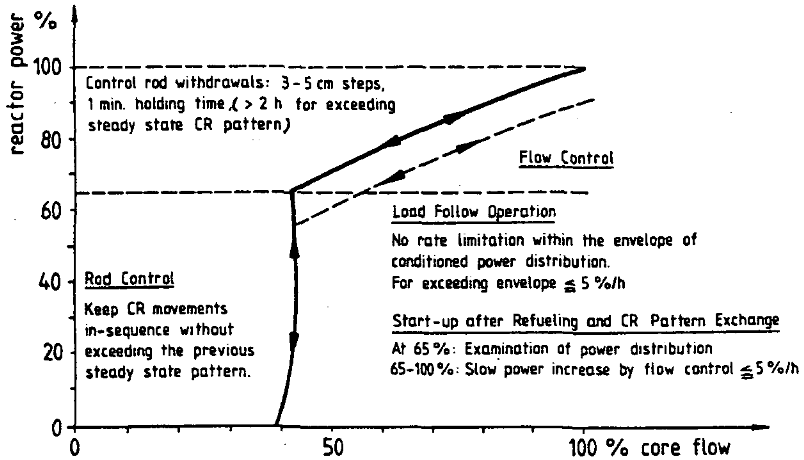

Fig. 2 KWU-BWR Operating Recommendations (prepressurized 8x8 fuel)

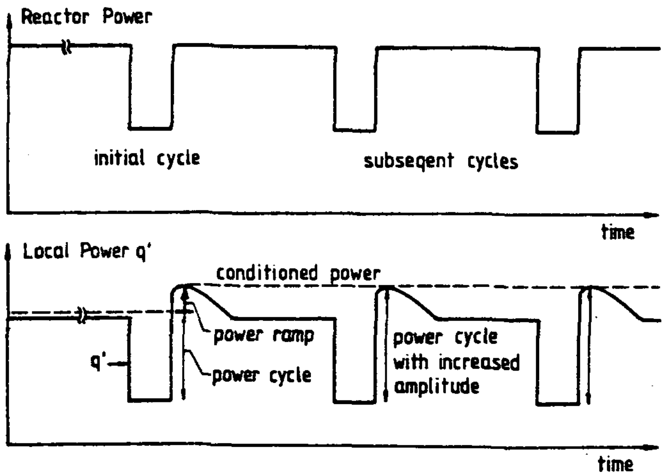

Fig. 3 The Effect of Load Follow Operation on Fuel Duty (daily or weekly cycles)

PCI-OGRAMS: APPLICATION OF CANDU FUELOGRAM METHODOLOGY TO PCI DATA FROM LIGHT-WATER REACTORS

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ABSTRACT

The FUELOGRAM model was derived to predict PCI defect probabilities for CANDU fuel bundles that had experienced power increases after being irradiated to burnups mostly in the range 100 ± 60 MW.h/kg U. It is inappropriate to extrapolate the FUELOGRAM model to predict the performance of differently designed fuels at burnups up to 600 MW.h/kg U. Therefore data obtained from the operation of a Boiling Water Reactor were analyzed using the FUELOGRAM methodology to assess fuel performance criteria at high burnups. The resultant PCI-OGRAMS evaluate defect probabilities in terms of power increase (ΔP), ramped power (P), and the burnup (ω) of the most highly rated rod in a fuel assembly. Defect probability also depends on the dwell time (t) of fuel at the ramped power. The predictions of the PCI-OGRAM, FUELOGRAM and other models are compared in three dimensional sketches of P, ΔP and ω with the dwell time t held constant.

INTRODUCTION

It has been known for about fifteen years [1] that increasing the power of UO_2-fuelled, Zircaloy-clad fuel pins with appreciable burnup can cause fuel defects. The term PCI defects suggests that their origin is from mechanical pellet-clad interaction but the concensus of opinion is that fission product-induced stress corrosion cracking (SCC) is the principal defect mechanism [2-4]. Iodine is an abundant fission product that, when sufficiently concentrated, is capable of inducing SCC of Zircaloy on exceeding a critical stress, sustained for sufficient time [5]. The fuel burnup ω determines the iodine inventory and the ramped power P regulates the UO_2 temperature and hence the release of iodine to the Zircaloy surface. We have noted that fission gas release from UO_2 increases sharply at P = 46 kW/m