Power ramp and reshuffling analysis for nuclear fuels using the BACO code

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ABSTRACT

Fuel integrity during power ramping depends on many factors: burnup, ramp height, initial Linear Heat Generation Rate and previous time at that power level, ramp rate, etc. Despite the low burnup at which Heavy Water Reactor fuel operates, Stress Corrosion Cracking has been identified as a failure mechanism. Those operation conditions have led CNEA to study the influence of material properties on the fuel behaviour. CNEA develops the BACO code for the simulation of the fuel rod. Power ramp analysis with BACO is presented in this paper.

INTRODUCTION

The improvement of fuel performance under demanding operating conditions requires a good understanding of the properties of fuel rod materials and their in-service performance. Thermal, mechanical and microstructural irradiation effects are strongly interrelated while the fuel is at reactor operating conditions.

At the Argentine Atomic Energy Commission (Comisión Nacional de Energía Atómica, CNEA) the BACO code (for BArre COmbustible, fuel rod) was developed for the simulation of Pressurized Heavy Water Reactor (PHWR) fuel rod behavior under irradiation. However, the code’s structure allows the numerical simulation of almost any cylindrical fuel rod. It is based on a physically sound description of the phenomena taking place in a fuel rod, therefore describing the coupling between stress-strain evolution, thermal field and irradiation induced effects.

Argentina has two nuclear power stations in operation: Atucha-I (a Pressure Vessel PHWR) and Embalse (CANDU 600 type). At both stations, on-power fuel reshuffling produces fast fuel power ramps and also load-following has been successfully tested. Those operation conditions have led CNEA to study the influence of material properties on the fuel behaviour under power ramps and cycling operation at different burnup levels.

Fuel integrity during power ramping depends on many factors: burnup, ramp height, initial Linear Heat Generation Rate (LHGR) and previous time at that power level, ramp rate, etc. Despite the low burnup at which Heavy Water Reactor (HWR) fuel operates, Stress Corrosion Cracking (SCC) has been identified as a failure mechanism. This requires a concentration of corrosive fission products in the fuels, a strain rate above some initial value and tensile stress...
on the cladding during certain time. The threshold values for all these variables are inter-dependent.

The hoop stress predicted by BACO, for a fixed ramp velocity, at the inner surface of the cladding correlates well with the fuel failure probability over a wide range of pre-conditioned powers and power increments during the ramp. The predicted hoop stress at the cladding inner surface is plotted as a function of time for the Atucha fuel rods ramped from the same initial power $q_0$ to the same final power $q_0 + \Delta q$ at different ramp rates. The ramp rates used are those within the power ramp velocities ranging from on-power fuel reshuffling to reactor start-up.

We study the power ramps due to fuel reshuffling from a low power channel to a higher power one in an HWR; Atucha I fuel is used as a basis for the exercise. We assume that operation might be performed within a wide range of burnup levels at the first position, which is not the case for the fuel paths used at the station, where the position shift is performed approximately at mid life. On-power fuel reshuffling is done at Atucha I. Here, we run the BACO code for a typical power input history of Atucha I power plant, where the parameters are $d q$ (refers to the power increase between two reactor channel positions), $q_0$ and $B_0$ (respectively the local power and the final burnup at the axial position of the fuel rod where the maximum power is attained before the ramp). Realistic axial power gradients are also included in the calculation. Fuel integrity under stress corrosion cracking (SCC) is studied.

Stress corrosion cracking of the cladding is a complex function of power history, fission gas release and stress at the cladding. The threshold value for stress relieved Zry is much smaller than the plasticity limit. The critical iodine concentration for SCC depends on the system. However, it appears to be very small in value and it seems to be attained at relatively small burnups. With respect to the stress threshold for SCC, we take this as the critical parameter and adopt a fixed threshold hoop stress ($\sigma_{SCC}$) as a lower limit for initiation and safe operation at burnup values over the 1500 MWD/tonU. The power increase needed for reaching, at the cladding, the limiting value of $\sigma_{SCC}$ during the ramp, will be shown as a function of local power and burnup of the fuel before the ramp. Results are given at various local burnups for reshuffling.

**BACO CODE v.2.30**

CNEA has developed the BACO code for the simulation of a fuel rod behavior under irradiation. The domain of use is for PHWR, but may be extended for particular applications due to its flexibility. It has been used for simulating PWR, CANDU, FBR and experimental fuel rods. The development of the code began in 1976 [1] and the upgrades of the code are continuous [2].

The last version of the code was developed in connection with the CRP FUMEX (Coordinated Research Project on Fuel Modelling at Extended Burnup) of the IAEA (International Atomic Energy Agency) [3]. As results of that international project we originated a conceptual revision of the original code, a set of new tools for the analysis of the outputs, the inclusion of checked capabilities about extended burnup and statistical improvements.

BACO is a code for the simulation of the thermo-mechanical and fission gas behavior of a cylindrical fuel rod under reactor operation conditions. Steady state and transient analysis are included.

The UO$_2$ pellet properties included in the code are as follows: linear thermal expansion, elastic constants, creep laws and fuel cracking stress, creep (alternative model being available), restructuring, thermal conductivity, thermal transmission, swelling, densification, cracks
opening, fission gas release. While, for the Zircaloy cladding linear thermal expansion, elastic constants, plasticity laws, creep, growth under irradiation, thermal conductivity and gap pellet-clad thermal conductance are included.

The numerical model is based on the assumption of cylindrical symmetry. Axial symmetry and modified plane strain (constant axial strain) are assumed. Therefore, the stress-strain problem is reduced to a quasi-two-dimensional problem. Pellet and cladding are divided into circular concentric rings. Mechanical equations are integrated with a finite difference scheme and time integration by subsequent finite time steps.

The mechanical model assumes that during the time interval \( (t_0, t_0 + \delta t) \), the strain-stress increments can be expressed as the linear superposition of the strain-stress increments due to different existing deformation mechanisms. The equations to be integrated are, essentially, the compatibility equation of each ring, the equilibrium equation and the constitutive equation, subject to the appropriate boundary conditions. This is a system of coupled differential equations, that leads to a nonlinear system of algebraic equations linearized through a Taylor expansion.

The temperature distribution conditions is a fixed temperature at the cladding external surface and fuel power.

POWER RAMPS AND FUEL ROD BEHAVIOUR

Basic design of Atucha and CANDU fuel elements are different in the both cases. The Atucha fuel assembly consists of a supporting rod and 36 pre-pressurized, self-standing 600 cm long fuel rods, similar to the PWR rod except for its unusual length. The CANDU fuel bundle has 37 non-pressurized, collapsible, 50 cm long fuel rods. In both cases, a stress-relieved Zry-4 cladding and non-enriched UO₂ pellets are used with a LHGR (Linear Heat Generation Rate) higher than PWR.

At both stations, on-power fuel reshuffling causes fast fuel power ramps and also load-following has been successfully tested. Those operation conditions have led CNEA to study the influence of material properties on the fuel behavior under power ramps and cycling operation at different burnup levels.

Fuel integrity during power ramping depends on many factors: burnup, ramp height, initial LHGR and previous time at that power level, ramp rate, etc.

Despite the low burnup at which Heavy Water Reactor (HWR) fuel operates, Stress Corrosion Cracking (SCC) has been identified as a failure mechanism [4]. This requires a concentration of corrosive fission products in the fuels, a strain rate above some initial value and tensile stress on the cladding during certain time. The threshold values for all these variables are inter-dependent.

![Hoop stresses at power ramps](image)

Figure 1: Hoop stress at the cladding inner surface vs. time for different ramp rates. 

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A previous work [5] showed that, for a fixed ramp velocity, the hoop stress predicted by BACO at the inner surface of the cladding correlates well with the fuel failure probability over a wide range of pre-conditioned powers and power increments during the ramp. The predicted hoop stress at the cladding inner surface is plotted as a function of time for five Atucha fuel rods ramped from the same initial power $q_0$ to the same final power $q_0 + \Delta q$ at five different ramp rates (Figure 1). The ramp rates used for the figure are those within the power ramp velocities ranging from on-power fuel reshuffling to reactor startup. Code calculations predict the maximum tensile stress at the end of the ramp; afterwards, cladding stress relaxes while power is kept at its highest value $q_0 + \Delta q$. This stress relaxation is mainly due to UO$_2$ creep into the pellet dishing and cracks, and to the cladding mechanical relaxation. We find that stress relaxation depends on the initial power $q_0$, the ramped power $q_0 + \Delta q$, and the ramp rate $v$.

We show the hoop stress predicted at the cladding as a consequence of a power ramp; this is calculated as a function of power rate. We determine that slow power ramps result in small stress in the cladding and in large relaxation times for the stress, while on the other side, fast power changes result in large stresses and in small relaxation times. Those effects can be related to mechanical models that realistically reflect materials performance: a small ramp gives time for a stress accommodation via UO$_2$ creep into dishing and pellet cracks; however, the stress is not large enough for permanent mechanical strain of the cladding. On the other hand, for a sudden power change large stresses develop, those imply the possibility of deeper fuel cracking and of mechanical relaxation in the cladding. The latter effects are time independent, except for their synergistic coupling with time dependent phenomena.

ATUCHA I FUEL REShuffling ANALYSIS

We study the power ramps due to fuel reshuffling from a low power channel to a higher power one in an HWR; Atucha I fuel is used as a basis for the exercise. We assume that operation might be performed within a wide range of burnup levels at the first position, which is not the case for the fuel paths used at the station, where the position shift is performed approximately at mid life ($\sim 3700$ MWd/tonU). Here, we run the BACO code for the power input history sketched in Figure 2, where $\Delta q$ refers to the power increase between two reactor channel positions. Hereafter, the parameters $q_0$ and $B_0$ are respectively the local power and the final burnup at the axial position of the fuel rod where the maximum power is attained before the ramp. Realistic axial power gradients are also included in the calculation. Fuel integrity under stress corrosion cracking (SCC) is studied.

SCC of the cladding is a complex function of power history, fission gas release and stress at the cladding. Spino [6] did a careful study of Zry cladding fracture in corrosive media. There, he claims that the threshold value for stress

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**Power History for Reshuffling Analysis**

(CN Atucha I)

![Image of power history graph](image)

Figure 2: Plot for the input data of the power history for reshuffling analysis in Atucha I.
relied Zry is much smaller than the plasticity limit [7, 8]. The critical iodine concentration for SCC depends on the system [9, 10]. However, it appears to be very small in value and it seems to be attained at relatively small burnups [6, 10]. With respect to the stress threshold for SCC, we take this as the critical parameter and adopt a fixed threshold hoop stress ($\sigma_{SCC} = 170 \, \text{MPa}$, [6]) as a lower limit for initiation and safe operation at burnup values over the 1500 MWd/tonU.

**Reshuffling limits due to SCC**
(CN Atucha I)

![Graph](image)

**Figure 3:** Power increase dq needed for reaching, at the cladding, the limiting value of $\sigma_{SCC}$ during the ramp.

**Reshuffling limits due to SCC**
(CN Atucha I)

![Graph](image)

**Figure 4:** Final ramp power needed for reaching, at the cladding, the limiting value of $\sigma_{SCC}$ during the ramp.

In Figure 3, we plot the power increase dq needed for reaching, at the cladding, the above limiting value of $\sigma_{SCC}$ during the ramp. This is shown as a function of local power and burnup of the fuel before the ramp. Results are given at four local burnups for reshuffling: 3000, 4000, 6000 and 9000 MWd/tonU. The same calculation results are used for Figure 4, where the power $Q = (q_0 + dq)$ at the second fuel position is plotted. It can be seen that the designer's recommendation for reshuffling ramps is conservative for reasonably low burnups, as those attained at present by the fuel in the reactor. Better models of SCC would be needed in the code for testing higher burnups (i.e. over 4000 MWd/tonU at the first position).

As the Atucha cladding is self standing at reactor pressure, the rod initiates its stay in the reactor with an open fuel-cladding gap. Depending on power and burnup at the first position, this gap might close during the rod stay at that position or during the reshuffling, reaching a positive hoop stress due to PCI. Therefore, in the case of the initial position corresponding to a low power $q_0$ channel, or relatively

**Cladding hoop stress evolution**

![Graph](image)

**Figure 5:** Tangential stress at the inner surface of the cladding vs. Burnup. $B(0)$: Burnup at reshuffling.
low burnup for the fuel; a larger power in the second fuel position must be reached before the hoop stress is at the threshold value. This can be clearly seen in Figure 4, where, for a larger \( q_0 \), the power increase needed is smaller. In the case of a relatively large power \( q_0 \) at the initial position, the gap might have closed before the power ramp (these cases are in Figures 3 and 4). Therefore, tensile stresses due to PCI have already relaxed at that first fuel position due to \( \text{UO}_2 \) and Zry creep and the stress tends to a saturation value before reshuffling. This effect is illustrated in Figure 5. This, in turn, implies that the increment in power, \( \Delta q \), needed for reaching the fixed SCC hoop stress threshold has a tendency to be constant, as can be seen in Figure 3 and 4.

CANDU FUEL PERFORMANCE ANALYSIS

In CANDU reactors, fuel reshuffling is done under reactor operation. During the reshuffling operation the fuel undergoes a power ramp due to the power distribution along the fuel channel. For this reason, it is interesting to study the behaviour of a CANDU fuel under fast (10-20 min long) power ramps. The linear heat generation rate (LHGR) before the ramp, the burnup at which the ramps occurs \( B_0 \), and the ramp height \( \Delta q \), cover a wide range. Figure 6 schematises the kind of power histories to be analysed: at power \( q_0 \) and burnup \( B_0 \) the fuel is ramped to power \( q_0 + \Delta q \); time for power increment \( \Delta q \) is in the range 10-20 minutes; at the end of reshuffling the fuel stays at a constant power \( q_1 \).

A more quantitative image of the BACO Code capability to describe fuel behaviour under power ramping is given by the analysis of CANDU fuel. Based on actual experience of power ramping due to fuel reshuffling in nuclear power stations, AECL has published bounds for safe operation. Usually [11], the maximum power increase and maximum power such that fuel operation below those values present (statistically) no failures, are given as a function of burnup.

With the purpose of studying susceptibility to SCC, the BACO Code is used to determine - for given initial power \( q_0 \) and reshuffling burnup \( B_0 \) - the power increment at which the hoop stress at the cladding inner surface reaches a fixed value \( \sigma_{SCC} \). Due to the fact that the fuel stays at the peak power \( q_0 + \Delta q \) only for a few minutes, \( \sigma_{SCC} \) is taken as higher than the usually accepted threshold for SCC (170-190 MPa). A threshold hoop stress of \( \sigma_{SCC} = 280 \text{ MPa} \) tensile was adopted [12].

Figures 7 and 8 show the experimental bounds for power increase and maximum power corresponding to the Pickering Stations [4]. Power histories simulating reshuffling were simulated with the BACO code. In the Code, the criterion for safe operation was based on the maximum hoop stress at the cladding inner surface; this is related to susceptibility to stress corrosion cracking. It can be seen in Figures 7 and 8 that BACO results are in good agreement.
with AECL data; even the mispredictions can be explained on a physical basis. At low burnups, BACO overpredicts SCC susceptibility, and at high burnups, it is lightly underpredicting it; that is consistent with an SCC criterion in which threshold stress is burnup independent or, in other words, where the role of dwell time and corrosive products concentration is not included.

**Figure 7:** Power increase $q$ needed for reaching, at the cladding, the limiting value of $\sigma_{SCC}$ during the ramp.

**Figure 8:** Final power needed for reaching, at the cladding, the limiting value of $\sigma_{SCC}$ during the ramp.

**CONCLUSIONS**

The modular structure of the BACO code and its detailed coupling of thermo-mechanical and irradiation-induced phenomena make it a powerful tool for the prediction of the influence of material properties on the fuel rod performance and integrity. The hoop stress predicted by BACO, for a fixed ramp velocity, at the inner surface of the cladding correlates well with the fuel failure probability over a wide range of pre-conditioned powers and power increments during the ramp.

On-power fuel reshuffling was done at Atucha I. For the sake of the exercise, we adopt a hoop stress value at the cladding of 170 MPa as a realistic limiting threshold stress that allows SCC to initiate (though, actually, it only results in a progressive deterioration once the proper atmosphere has been attained inside the rod). We conclude that the designer’s recommendation for reshuffling is conservative at the burnup level used at the station for that operation. In the case of developing a high burnup fuel, that needs to be reshuffled after a larger burnup than those in the present design, better models of SCC could be needed in our code for testing its performance in a realistic way.

A simple rule for fuel failure was included in the calculation of CANDU fuel performance. The SCC criteria for fuel failure used for this calculation is the basis for the developing of a complex model for fuel performance. But, that criteria was enough for the understanding of the fuelgrarms of the Reference [6]. The prosecution of the model include the evaluation of Iodine in the rod and cracks opening.
REFERENCES