AXIAL TRANSPORT OF FISSION GAS IN LWR FUEL RODS

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Abstract

With regard to fission gas transportation inside fuel rod, following three mechanisms are important: (1) a localized and time dependent fission gas release from UO_2 fuel to pellet/clad gap, (2) the consequent gas pressure difference between the gap and the plenum, and (3), the inter-diffusion of initially filled Helium and released fission gas such as Xenon. Among these three mechanisms, the 2nd mechanism would result in the one dimensional flow through P/C gap in the axial direction, while the 3rd averaging the local fission gas concentration difference.

In this paper, an attempt was made to develop a computerized model, LINUS (LINear flow and diffusion under Un-Steady condition) describing the above two mechanisms, items(2) and (3). The item (1) is treated as an input. The code was applied to analyse short length experimental fuel rods and long length commercial fuel rods. The calculated time evolution of Xe concentration along fuel column shows that the dilution rate of Xe in commercial fuel rods is much slower than that in short experimental fuel rods. Some other sensitivity studies, such as the effect of pre-pressurization, are also presented.

1. Introduction

To use the LWR oxide fuel for the extended burnup, it is most important to prevent fission gas release from fuel pellets. This release is very sensitive to the fuel temperature and it is necessary to keep the temperature low enough to achieve high fission gas retention. But, when a certain amount of fission gas was released in the small gap volume, gap conductance is deteriorated due to a high Xe concentration and results in a stepwise jump of the fuel temperature and induces more release. This is the temperature feedback effect known as the key mechanism of significant fission gas release experienced at power reactor fuels and must be avoided under usual operating conditions. Experiments for burnuped fuels show that some temperature shock can induce a transient of fission gas release which is possibly more significant as the burnup increased [1]. Recently, several in-reactor experiments are proposed aiming to understand the time dependence of the gas release through real time measurements of rod internal-pressure. These data enable us to look into the temperature feedback more in detail. The previous computer models for temperature estimation assumed the instantaneous mixing of the released gas and the stored Helium. This assumption worked well for the un-pressurized rods because the free volume was contaminated by the fission gas immediately after the start of the release. But for the pre-pressurized rods, this treatment is not sufficient to understand the temperature feedback effect. The analysis of the time dependence of this effect is necessary to evaluate the affect of the pre-pressurization and to study the effective improvements for the high burnup fuel design and operation.

For the first stage of this analysis, the increase of the fission gas concentration in the P/C gap must be well simulated. When the transient release was initiated, the gas pressure increases locally in the gap and causes a gas flow in axial direction. The released gas, mainly Xe, will be mixed with the stored Helium in plenum and P/C gap. This axial transport process is the subject of this work and a computerized model, LINUS (LInear flow and diffusion under Un-Steady conditions) was developed. In this code, one dimensional flow and diffusion model was employed. Some parametric studies for commercial reactor fuels are mainly presented.

2. Description of Models

The Basic equations are summarized in Table-1 where ρ is mol density of the mixed gas and C is Xe concentration. The first three equations describe the pressure induced flow. The flow resistance, estimated on the assumption of laminar flow, was calculated using Hagen number by which gas flow experiments were successfully analysed (2,3,4,5). A reflective boundary condition was used at the lower rod end to attain flow stagnation. At the other boundary where fuel stack and plenum is connected, it is assumed that the hot gas from fuel stack is instantaneously cooled down to the plenum temperature. The gradients of pressure and concentration are neglected in the plenum volume. Enthalpy of the fission gas, released from high temperature oxide grains to cold gap, is not considered in this model. The last equation describes composite effect of drift and diffusion on the transport of Xe in He. The released fission gas contains Xe and Kr, but the fraction of Kr is small and neglected in this analysis. The inter-diffusion constant of Xe and He is approximated by the 3-dimensional diffusion theory and measurements.

neglecting the effect of semi-2-dimensional geometry because the mean free path of Xe seems to be fairly shorter than the gap size. From ref. [5], the LINUS uses the following diffusion constant:

$$D=\frac{0.496}{P}\left(\frac{T}{273.15}\right)^{1.7}\quad(\mathrm{cm^2/sec})$$

Here, temperature is in Kelvin and pressure is in Atm. To solve the diffusion equation, normal difference scheme is not applicable because the drift term becomes very large and dominant at the beginning of the gas release and induce numerical instability. In the LINUS code, a newly developed method by Ikeda is adopted, which was applied to the same kind of problems successfully [7,8].

3. Results of Calculation

The power reactor fuel, which has pellet stack of 360cm and a single plenum at the upper end, was analyzed by the LINUS. The fission gas was assumed to be released uniformly along 1/3 of the total stack at a constant rate. The total rod is divided into 31 nodes (30 for pellet stack and 1 for plenum volume). The effective gap for the flow resistance was set as a constant during the transient. The plenum gas temperature was assumed to be the same as the coolant temperature of 300° C.

3.1 Induced flow at the start of release

During the initial stage just after the start of fission gas release, some pressure difference is induced locally around the released region and causes an axial flow which transports the released gas towards the upper plenum. Figs.1 and 2 represent the time dependent behaviour of the Xe concentration and the flow velocity along the fuel stack. The gas is released from 1/3 of the pellet stack at the middle part of the rod into the radial gap of 20um. The total released gas is 12cc (NTP) and the duration of the release is 900sec at a constant rate.

When the release was started, two different flows; one is to the upper plenum and the other is to the lower end of the rod, are induced. After a short seconds, around the bottom of the rod, the shortage of the free volume leads to the increase of pressure and the velocity of the downward flow becomes slower and terminates. In contrast with the bottom side, the velocity of the upward flow becomes faster due to the continuous increase of the pressure difference between the released region and the plenum. The development of the high pressure region toward the plenum causes some velocity excursion around the upper end, which relaxes in a minute. Finally a steady flow is established after two to three minutes from the start of the release. The released gas is transported mainly by the axial flow in this initial stage. The stored He in the P/C gap contributes to dilute the released Xe so that the 100% concentration is achieved only in asymptotic manner.

3.2 Pre-pressurization, Release rate, Fuel stack length

Fig.3 shows the effect of pre-pressurization on the time dependence of fission gas concentration at the centre of the fuel stack. The pressurization increases the density of stored He in the gap and suppresses the increase of the Xe concentration.

The effect of fission gas release rate is shown in Fig.4 where the total volumes of 12, 24 and 36cc (NTP) are released in 20 hours. the increasing rate of the concentration is non-linearly dependent on the release rate as a result of the non-linear dependence of the concentration on the released total volume.

The dilution and mixing is slower at the bottom end due to the long diffusion length to the plenum. Fig.5 shows the Xe concentration at the bottom comparing the effect of fill gas pressure. The small P/C gap of 5μm is assumed so that the gap free volume is much smaller than the previous case and Xe concentration is approximately 100% after the release. The fill gas pressure significantly affects the mixing rate and high Xe concentration is kept for many hours in high pressure rods.

The short rods such as ones used at test reactors may have different behaviour from the power reactor fuels. Fig.6 compares short 40cm rod and long BWR8x8 rod assuming the same asymptotic concentration. The mixing in the short rod completes in some minutes while the BWR rod needs more than ten hours.

4. Discussion

When the gap was widely opened, the temperature feedback induces fuel temperature increase up to several hundred deg.C. In this case, pre-pressurization can confine relatively large amount of He gas in the wide gap and the increase of Xe concentration can be suppressed. The concentration increase at the point where axial flow has negligible effect is approximated by the following;

$$1 - e^{(-Xe/He)}$$

where Xe and He are locally released and locally stored gas volume respectively. This equation approximately reproduces the approaching behaviour of the concentration to the saturation shown in the Fig.2.

In case that the fission gas release was initiated by a certain power shock, the release rate can be somewhat larger and the released amount can be much enough to fill the small volume of the P/C gap. Under these transient release conditions, pre-pressurization cannot suppress the temperature feedback. For example, at the power ramping experiments conducted to investigate the SCC failure thereshold, especially for the rod irradiated at lower heat rating to avoid the gas release untill a certain burnup, significant fission gas release occurs during the power ramping and improving effect to reduce the failure threshold by the pre-pressurization cannot be observed.

For the high burnuped rods, the P/C gap, which was opened until some middle stage of the burnup, closes due to the fission gas and solid product swelling. Especially at a burnup range where the transient release can be easily triggered, this swelling may be significant enough to close the opened gap and we cannot expect the effect of the pre-pressurization. In this case the temperature rise by the feedback may also be small step, but it can be order of 200° C and this ΔT can make a large affect around the threshold temperature of the transient release.

High pre-pressurization suppresses the occurrence of local pressure difference due to gas release and prevents the axial flow. The diffusion constant is inversely proportional to the pressure of the mixed gas so that the transportation by the diffusion is also slow. These two effects make the fission gas localizes around the released region and this local high Xe concentration lasts long, keeping high fuel temperature. Especially at the bottom end, the inter-diffusion mixing takes place very slowly. Simple analytic calculation shows that the mixing rate is inversely proportional to the square of pellet stack length. The analyses of Figs.5 and 6 indicate that the short length rods, such as instrumented fuels in test reactors or segmented fuels in the power reactor experiments, may behave differently from the real full lengh power reactor fuels and careful analyses are necessary to extrapolate the short rod fission gas release data to power reactors fuels.

Diffusion model in the LINUS assumed only atomic inter-diffusion but the turbulent diffusion, which is two dimensional, may exist and accelerate diffusional transport. Furthermore, the P/C gap may vary in oscillatory manner if reactor power or fuel temperature fluctuates inducing reciprocal flow which contributes the mixing significantly. The effect of these additional mechanisms of the transport is so difficult to be estimated that in-reactor experiments are necessary to check the validity of these calculations.

5. Conclusion

A computer model, LINUS, was developed to analyse the axial fission gas transport and some parametric studies revealed the following:

- As far as the atomic diffusion is dominant for the inter-diffusion mechanism in the small P/C gap, the increase of the filled He pressure delays the diffusion mixing of the released fission gas significantly.

- The He pre-pressurization has no effect on the improvement of the failure threshold at the power ramping because the gas release in the burnuped rods is fast enough to contaminate the gap and to induce the temperature feedback instantaneously.

- The short length rods for test reactors and the long length rods for the power reactors are different in the temperature feedback effect so that careful analysis is necessary to extrapolate the results of experiments to the power reactor fuels.

- Once the bottom of the power reactor fuel is contaminated by the fission gas, it takes many hours to dilute the gas by the He stored in upper plenum and the mixing time-constant is proportional to the square of the rod length.

These quantitative analyses by the LINUS code indicate that more careful analysis of the temperature feedback is necessary to assess the operating condition or to propose improvements for extending the burnup of LWR fuels.

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Table 1. Model Equations

Conservation of Mass: $\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho U) = q$

Ideal Gas Law: $P = \rho RT$

Laminar Flow Resistance: $U = -\frac{2D_h^2}{H_s\eta}\frac{\partial P}{\partial x}$

Diffusion with Gas Flow: $\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = \frac{\partial}{\partial x}(D\frac{\partial C}{\partial x}) + \frac{\rho_x q}{\rho^2}$

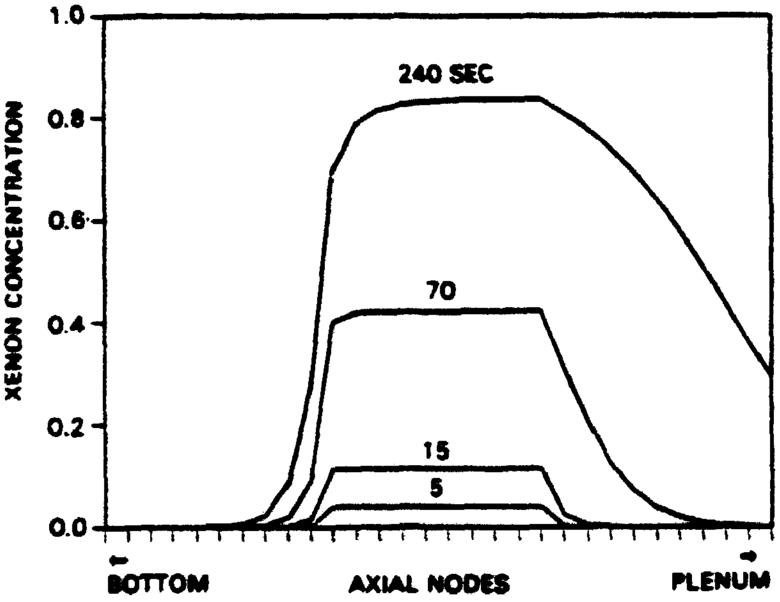

Fig. 1. Calculated Axial Profile of Xe Concentration

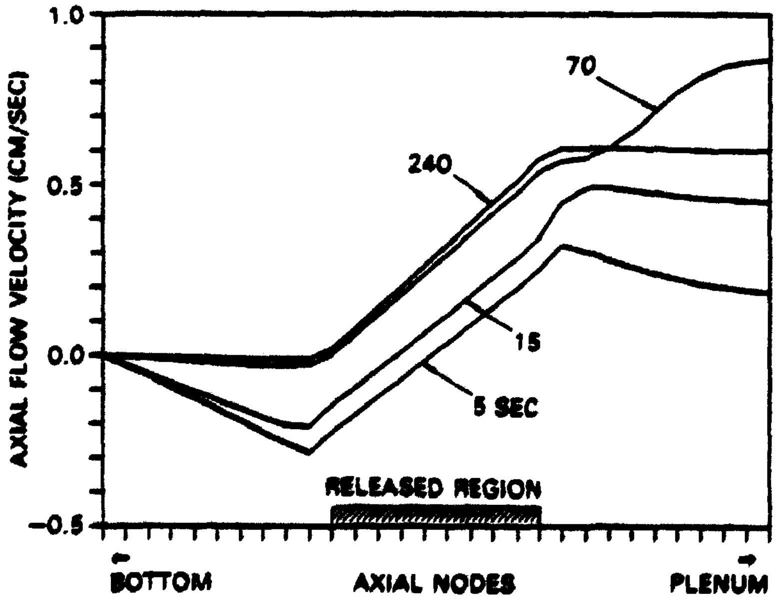

Fig. 2. Calculated Axial Profile of Flow Velocity

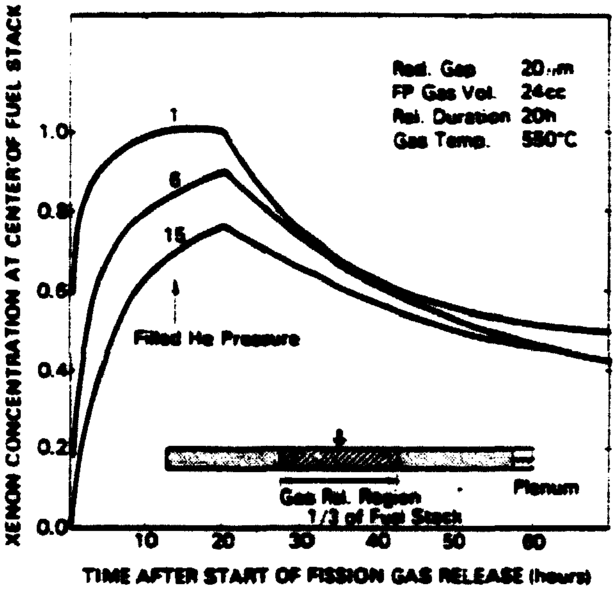

Fig. 3. Effect of Fill Gas Pressure on Evolution of Xe Concentration

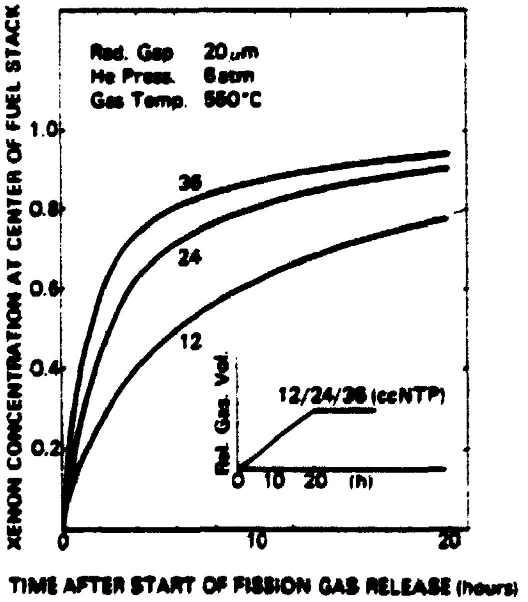

Fig. 4. Effect of Gas Release Rate on Evolution of Xe Concentration

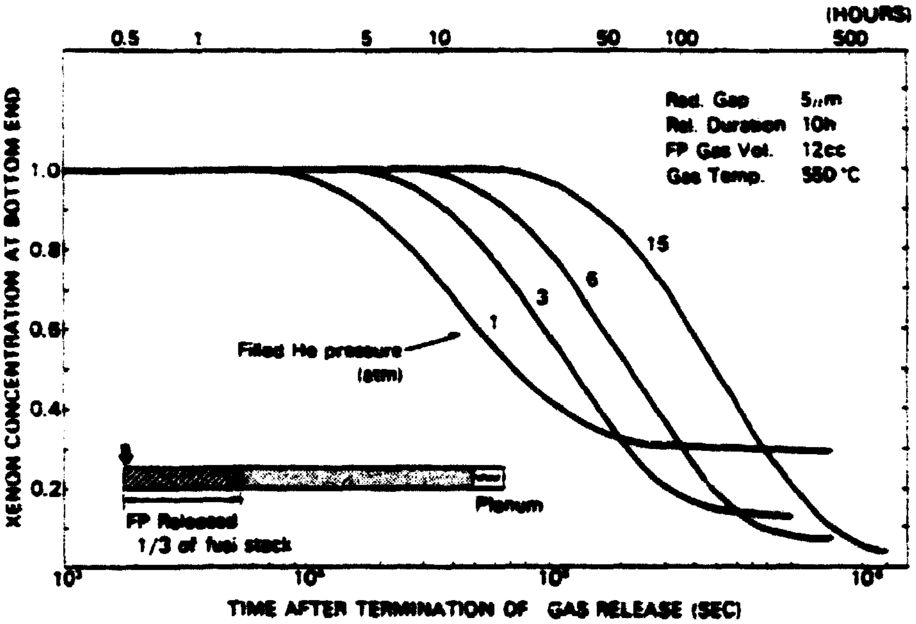

Fig. 5. Xe/He Mixing at Rod Bottom End

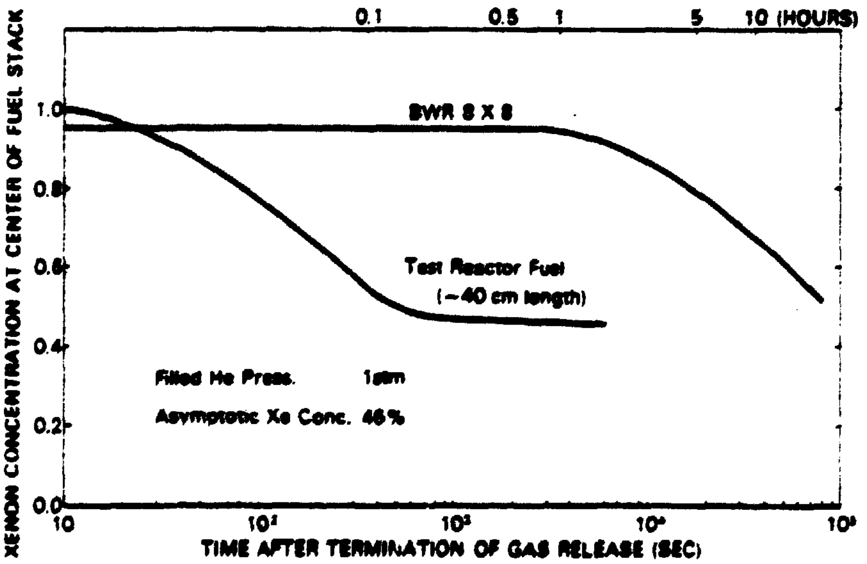

Fig. 6. Xe/He Mixing in Long and Short Rods