MODELLING OF FISSION GAS RELEASE IN RODS FROM THE INTERNATIONAL DEMO-RAMP-II PROJECT AT STUDSVIK

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ABSTRACT

The DEMO-RAMP-II rods had a burn-up of 25-30 MWd/kg U. They were ramped to powers in the range 40-50 kW/m with hold times between 10 s and 4.5 minutes. In spite of the short hold times the fission gas release at the higher powers was more than 1 %. With these short hold times it is natural to assume that mixing of released gas with plenum gas is limited.

Modelling has been performed using GAPCONSV (a modified GAPCON-THERMAL-2) both with and without mixing of released gas with plenum gas. In particular for the high power-short duration ramps only the "no mixing" modelling yields release fractions comparable to the experimental values.

1 INTRODUCTION

Calculation of high temperature fission gas release requires both a fission gas release model and a temperature prediction. It is well known that fission gas contamination of the helium fill gas leads to substantial reduction in gas thermal conductivity and thus increased fuel temperature. In a transient situation, for instance a sudden power increase, the fission gas concentration will not be in equilibrium in the rod. In most fuel behaviour codes the fission gas concentration in the gap is taken to be the rod average concentration. It is important to know under what conditions the local concentration is substantially larger than the average concentration so as not to tune the fission gas release model if it is the temperature model that should be changed.

In this paper the mixing of released fission gas with the plenum gas is studied using the code GASMIX (Appendix A). The experimental situation of concern is the relatively short Demo Ramp II transients.

2. GASMIX CALCULATIONS

In the International Demo Ramp II (DRII) experiments performed at STUDSVIK (1) power ramps with hold times in the range 10 s to 5 min were studied. Data used here are shown in Table 1.

The relatively high burn-up of the rods (25 - 30 MWd/kg U) makes the gas release prediction sensitive to modelling assumptions due to the feed-back of gap gas contamination on temperature.

Calculations with the code GASMIX have been performed for DRII-rods with given release fractions in a given time using a square root of time dependence of the amount released.

We first studied the DRII-rod S30H ramped in a more "normal" fashion. This rod experienced two ramps. First a ramp to 38.5 kW/m (axial maximum powers are reported here and in the following) for 24 h and then a re-ramp with conditioning at 38 kW/m for 24 h and a final ramp to 43.5 kW/m for one hour. The total xenon-release was 7.5%. Neutron radiography after the first ramp showed substantial dish filling and it is thus supposed that a large part of the fission gas release occured during this ramp.

For the GASMIX-calculation we used the assumption 3% release in 24 h. The final Xe/He-ratio with this release is 1.0.

Fig 1 shows the time dependence of the Xe/He-ratio at the rod mid position (maximum power). As an illustration of the influence of the gap gas composition the temperature jump across a 4.7 μm wide gap at a power of 38.5 kW/m is shown in Fig 2.

As can be seen from these figures the release rate is so slow that diffusion gives a relatively good mixing of released xenon and plenum helium. In particular the influence on temperature of slow mixing is in this case small.

The DRII rod S38H was held for almost five minutes at 42 kW/m. The final xenon release was 0.8%. The pre-ramp release is not known. The ANS 5:4 low release model (2) gives 0.2% at the burn-up 28 MWd/kg U.

For the GASMIX calculation 0.5% release in 5 min was assumed. This leads to a final Xe/He-ratio of 0.2. The maximum value during the transient according to GASMIX is 1.5 (Fig 3) so that slow gas mixing has an influence. The temperature jump across a 4.7 μm wide gap (Fig 4) is, for a Xe/He-ratio of 1.5, 120 K at 42 kW/m to be compared with the value of 50 K for the final Xe/He-ratio of 0.2.

The DRII rod S35H experienced a shorter but higher ramp, only 36 s at 48 kW/m. The final xenon release was 2.6%. For the GASMIX calculation 2.5% release in 36 s was assumed. In this case the influence of slow mixing is substantial. The final Xe/He-ratio is 0.8 but the local concentration goes up to a value of 35 according to GASMIX (Fig 5). This corresponds to a temperature jump across a 4.7 μm gap (Fig 6) at 48 kW/m of 500 K to be compared with a jump of 100 K at a Xe/He-ratio of 0.8.

3. RELEASE MODELLING FOR DRII RODS WITH GAPCONSV.

These GASMIX results show that for the DRII rod S30H (3% - 24 h) mixing can be assumed for the calculation of fission gas release. The average temperature used during the ramp should, however, be rather close to the final temperature (Fig 2).

The other extreme studied is the short (36 s) transient seen by DRII rod S35H. In this case almost no mixing occurs during the ramp and a high overtemperature is predicted (Fig 6).

The DRII rod S38H experienced a transient in the intermediate range (270 s). In this case some mixing occurs but an average temperature during the ramp above the final must be assumed (Fig 4).

The GAPCONSV-code is based on GAPCON-THERMAL 2 (GT2) (3). A time dependent fission gas release model has been introduced. This is a diffusion model adapted to the logic of GT2. The dependence of release on temperature, time and grain size is given in Table 2.

When the gas composition substantially reduces the gas conductivity this, in combination with the feedback temperature-gas release, gives a strong sensitivity of the final gas release on the model used for gap conductivity. This means that roughness and contact pressure are very important parameters. With GAPCONSV it was easy to obtain values in the range 1.5 - 25% for rod S30H with minor changes in the assumptions.

One aspect of GT2 is that relocation is completely reversible. Our interpretation is that relocation represents radial movement of fuel fragments. (In practice, however, relocation modelling in GT2 means tuning of center-line temperature). Obviously pushing the fragments back can not be made without force due to "drawer effect" and crack roughness. This leads to the concept of cracked pellet stiffness. A contact pressure between fuel and clad must be assumed even when relocation is used to fill the gap.

For the DRII-rods the experiments show (ridging) that there is a contact pressure at 40 kW/m although the code only predicts contact with relocation. A contact pressure has been introduced in GAPCONSV proportional to the amount of "overrelocation" that is the amount of relocation predicted which exceeds what is necessary to produce contact. The magnitude of the contact pressure is left as a tuning parameter.

This model reduces the influence of slow mixing when there is contact between fuel and clad. It also reduces the great sensitivity to roughness. At present this model, however, is an improvement of the gap conductivity model and not a true model for radial clad deformation.

Results from some GAPCONSV-calculations are given in Table 3. Notice that a factor of two in fission gas release corresponds to a temperature change of about 100 K (Table 2).

For rod S30H use of reported roughness (previously this was divided by 3.6 to obtain reasonable temperature and gas release) and a contact pressure leads to an overestimate of the fission gas release which decreases when higher contact pressure is assumed.

For rod S30H the experimental release lies between the GAPCONSV-calculated values for the assumptions of total mixing and no mixing of released gas during the ramp. This was expected since the GASMIX-calculations predicted relatively much mixing.

For rod S35H the GAPCONSV-calculation assuming total mixing greatly undetestimates the ramp fission gas release. Actually also the no mixing calculation underestimates the fission gas release in particular for the higher assumed contact pressure.

There are only two mixing options used in GAPCONSV at present. The original one assumes total mixing of all gas in the rod. The new no mixing option assumes that all gas released during a time step remains at the axial segment from which it was released. After the time step total mixing of gas is assumed but during a time step released gas is only mixed with local gas present after the previous time step.

These simplified GAPCONSV-calculations show, in particular in combination with the GASMIX-calculations, that only for the very short ramps (here represented by rod S35H) is the assumption of slow mixing necessary in order to explain the measured fission gas release.

The calculations also show that the sensitivity of fission gas release to temperature, and of temperature to fission gas concentration and contact pressure, means that a release prediction within less than a factor of two for the DRII rods requires further model tuning.

4. SOME CONSIDERATIONS ON MIXING EFFECTS IN OTHER SITUATIONS

Of interest is of course the effect of fill gas pressure and rod length. The diffusion coefficient is inversely proportional to pressure (Appendix A). This leads to slower diffusion in a prepressurized rod but the amount of helium is larger. A GASMIX calculation has been performed for the case 2.5% release in 36 s (i.e. DRII rod S35H) but with 10 times larger fill gas pressure. The result is shown in Figures 7 and 8. There is definitely an influence of slow mixing but it is smaller than for the unpressurized rod.

Also for the case of 3% release in 24 h (S30H) with ten times larger fill gas pressure the reduction of the diffusion constant with pressure does not compensate for the large amount of helium present (Fig 9 and 10). The temperature jump across a 4.7 μm gap is smaller than for the unpressurized rod (Fig 2).

For a power reactor rod the distance to the plenum is much larger than for the DRII-rods which leads to longer mixing times. Since the average diffusion distance is proportional to the square root of time, a tenfold length increase leads to a 100-fold increase in diffusion time. The critical time for the DRII-rods with a UO_2 pellet column length of 0.3 m was about one minute. The corresponding time for a power reactor rod with a stack length of 3.6 m would be about two hours. A GASMIX calculation has been performed for an unpressurized power reactor rod. The release was assumed to come from one segment (here a tenth of the stack length). The releasing segment was the third from the bottom. The total release during a 12 h period was such that the final Xe/He-ratio was 0.3. The concentration and the temperature jump across a 4.7 μm gap at a power of 25 kW/m are shown in Figures 11 and 12.

5 CONCLUSIONS

Slow mixing of released fission gas with plenum gas is a concern for short test reactor rods (stack length 0.3m) in transients with a duration of minutes or less. For power reactor rods slow mixing is of concern for transients with duration of hours or less. Further, a fuel-to-clad contact pressure reduces the influence of a xenon overconcentration and the strongest influence of the effect should thus be found in a rod releasing gas with the gap still open. Finally, prepressurization is beneficial since the increased amount of fill gas more than compensates for the decrease of the diffusion constant with pressure.

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Table 1 Results used here from the International Demo Ramp II project performed at STUDSVIK (1).

Rod	Burn-up MWd/kgU	Ramp terminal level kW/m	Hold time s	Xenon release %
S30H First ramp	27	38.5	86400	-
Second conditioning		38.0	86400	-
Second ramp		43.5	3600	7.5
S38H	28	41.8	270	0.8
S35H	29	48.0	36	2.6

Table 2. Fission gas release model used in GAPCONSV.

The fission gas release model used in GAPCONSV is in principle:

$$F = 2.85 \cdot 10^4 \exp(-19000/T)\, t^{0.5}/D_G$$

where

F = fractional release
T = temperature (K)
t = time (h)
D_G = grain size (μm)

When F > 1 then F = 1 is assumed.

This model has been adopted to the logic of the code.

Rod	GAPCONSV calculated gas release %					Experimental Xe-release %
	Preramp	With mixing		No mixing		
		I*	II*	I*	II*	
S30H	0.34	13.5	9.3	-	-	7.5
S38H	0.51	-	0.59	-	2.0	0.8
S35H	0.36	-	0.58	2.2	1.4	2.6

* Case I with one relocation contact pressure relation and case II with twice that contact pressure.

Table 3 CAPCONSV-results for the rods S30H, S38H and S35H from the International Demo-Ramp II project performed at STUDSVIK (1).

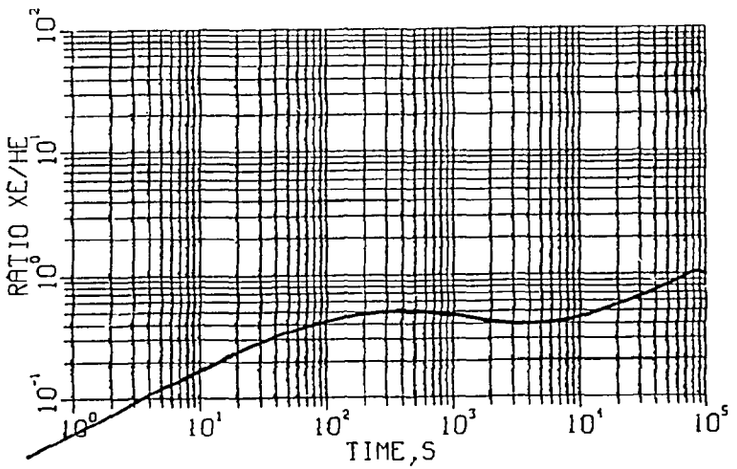

Fig 1. 3% release at 30 MWd/kg U in 24 h (DRII-rod S30H). Local Xe/He-ratio at maximum power position.

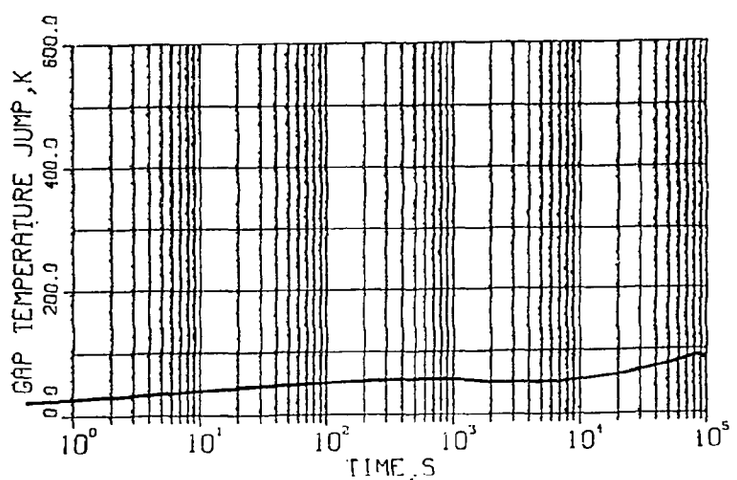

Fig 2. Same conditions as in Fig 1. Temperature jump across a 4.7 μm gap for a local power at 38.5 kW/m.

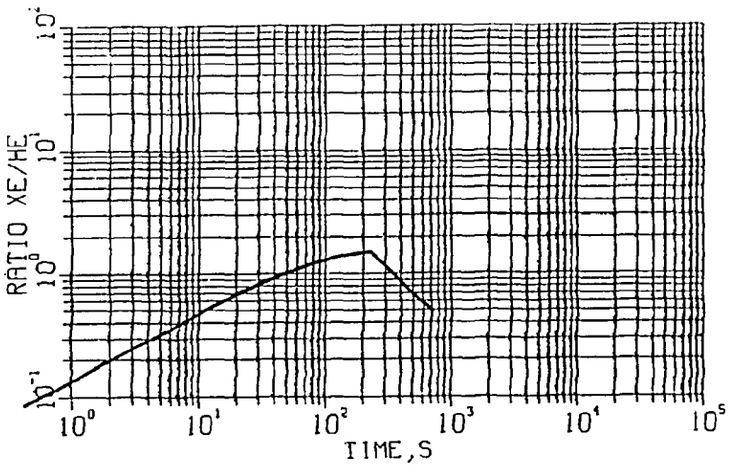

Fig 3. 0.5% release at 30 MWd/kg U in 300 s (DRII-rod S38H). Local Xe/He-ratio at maximum power position.

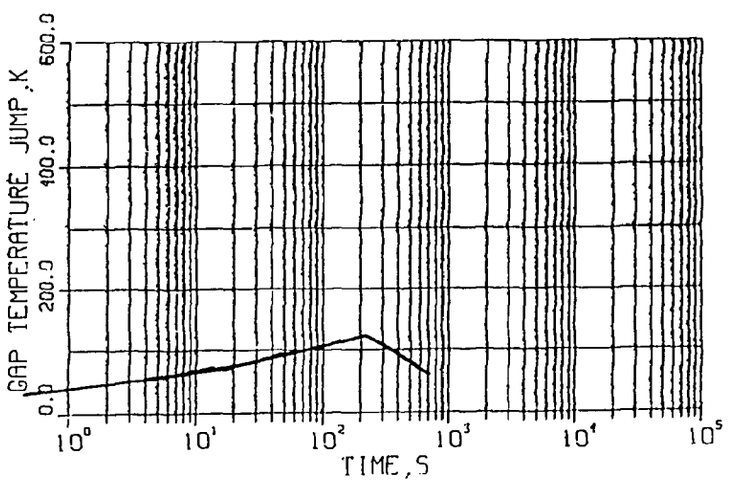

Fig 4. Same conditions as in Fig 3. Temperature jump across a 4.7 μm gap for a local power of 42 kW/m.

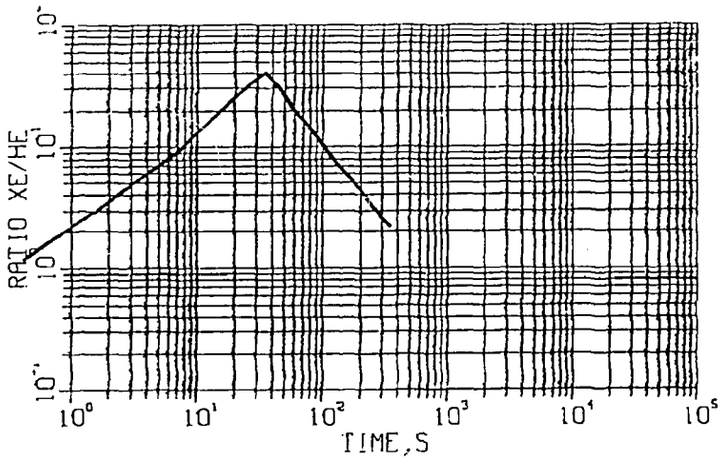

Fig 5. 2.5% release at 30 MWd/kg U in 36 s (DRII-rod S35H). Local Xe/He-ratio at maximum power position.

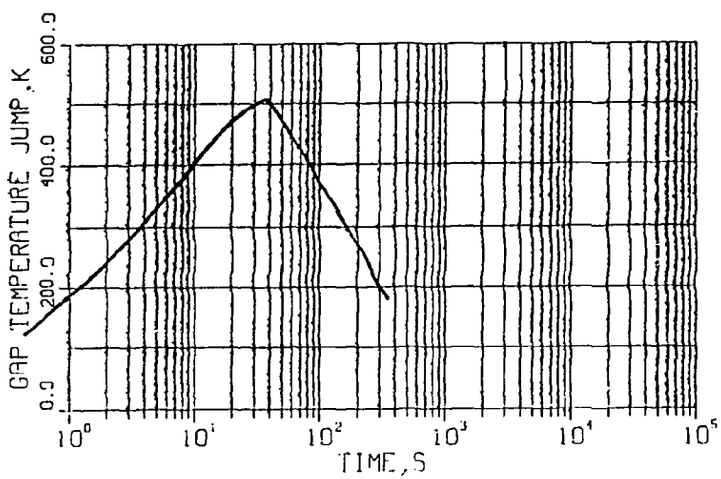

Fig 6. Same conditions as in Fig 5. Temperature jump across a 4.7 µm gap for a local power of 48 kW/m.

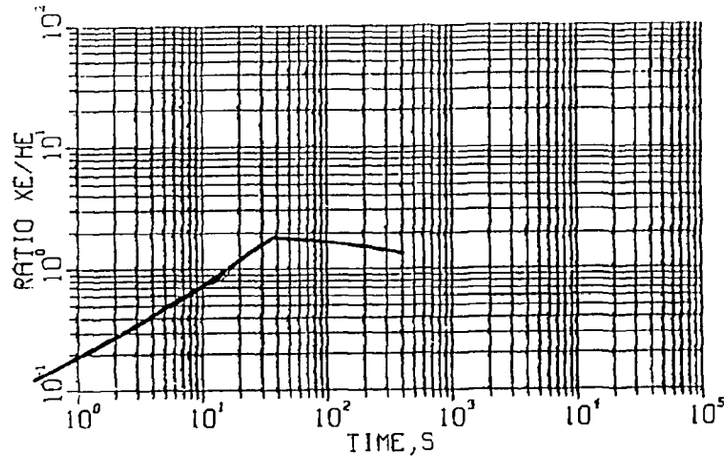

Fig 7. Same as Fig 5 but with ten times higher fill gas pressure.

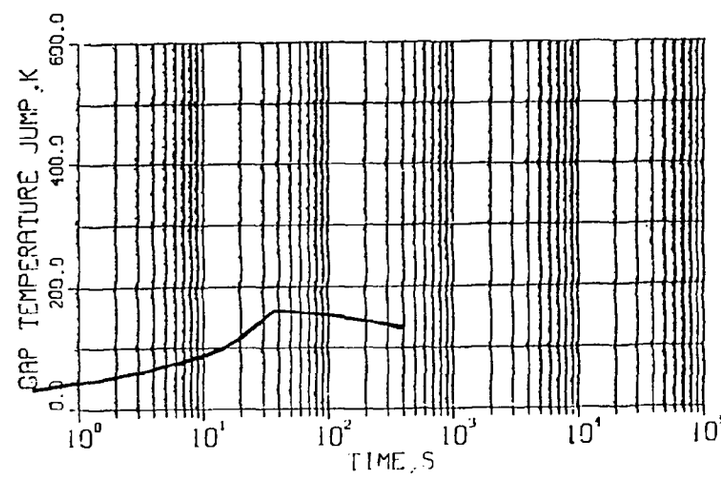

Fig 8. Same as Fig 6 but with ten times higher fill gas pressure.

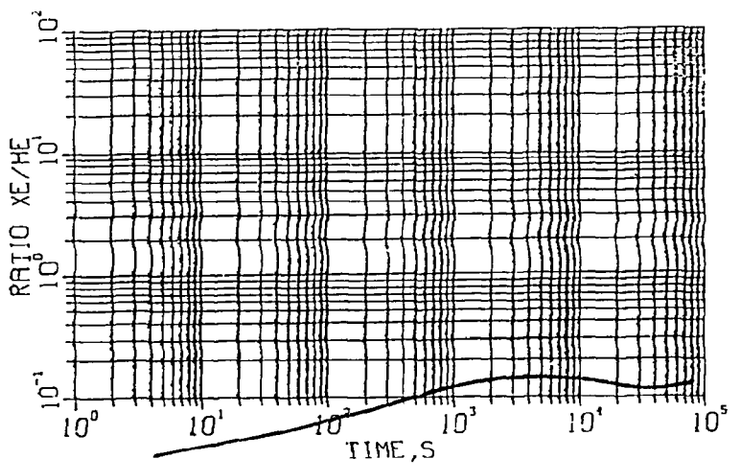

Fig 9. Same as Fig 1 but with ten times higher fill gas pressure.

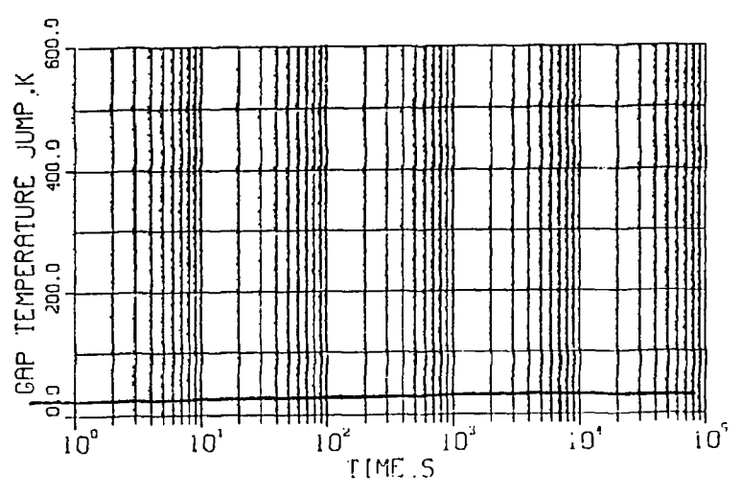

Fig 10. Same as Fig 2 but with ten times higher fill gas pressure.

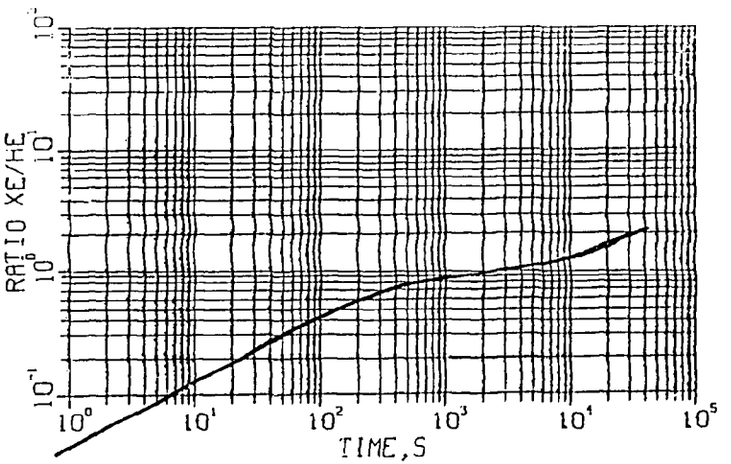

Fig 11. 0.3% release at 30 MWd/kg U in 12 h in an unpressurized BWR power reactor rod. Local Xe/He-ratio at release position.

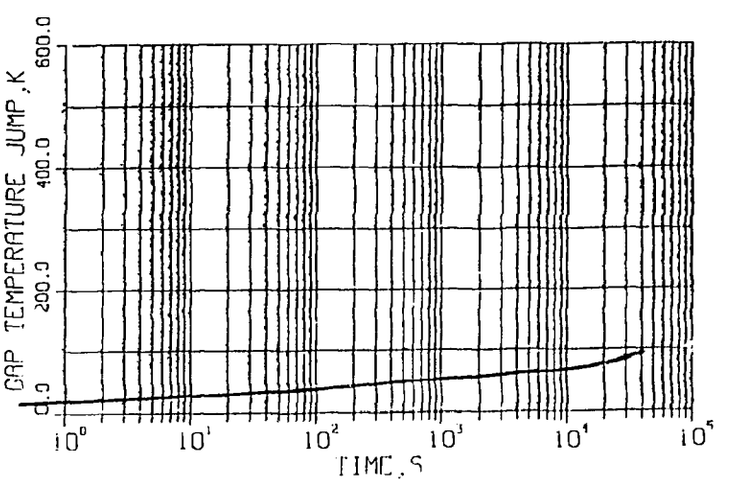

Fig 12. Same conditions as in Fig 11. Temperature jump across a 4.7 μm gap for a local power of 25 kW/m.

APPENDIX A

GASMIX-code description

The GASMIX code considers gas flow in a fuel rod gap due to pressure differences and diffusion due to concentration gradients. This is done in essentially the same way as in the LINUS code by Kinoshita (4) with minor differences in the details.

The rod is divided in axial segments. Laminar flow between the midpoints of the segments in assumed with

$$\dot{m} = \frac{\pi (p_2^2 - p_1^2) D_R t^3}{24 RT \mu L} \qquad (A1)$$

Here
- $\dot{m}$ = gas flow rate (mol/s)
- p_1, p_2 = pressure (Pa) at the end points of the flow path
- D_R = rod diameter (m) (at the gap position)
- t = gap width - radial (m)
- R = gas constant (8.314 J/mol, K)
- T = temperature in the gap (K)
- μ = gas viscosity (Kg/m,s) - taken from MATPRO (5)
- L = length of flow path (m)

The composition of the gas flowing is assumed to be that of the point from where the gas flows. With the assumptions used (e.g. gap width) pressure equilibration is relatively fast (seconds to tens of seconds). Important is however that continuous release of fission gas leads to continous flow from the release point to the plenum.

Release is input at segment midpoints with the total amount released proportional to the square root of time.

Diffusion is calculated separately for xenon and helium using for concentration the absolute concentration, that is the number of moles of the species per unit volume (moles/m^3). The diffusion constant is the "first approximation" binary diffusion constant without influence of mixture composition (6).

$$D_{12} = 2.66 \cdot 10^{-2} \frac{T^{1.5}}{p \cdot \sqrt{M_{12}}\, \sigma_{12}^2} \qquad (A2)$$

with $$M_{12} = \frac{2 M_1 M_2}{M_1 + M_2} \qquad (A3)$$

and $$\sigma_{12} = \left(\frac{\sigma_1 + \sigma_2}{2} \right)^{0.5} \qquad (A4)$$

Here M_1 and M_2 are the molecular weights of the species (g/mol) and σ_1 and σ_2 are the colllision diameters (Å). These values are taken from the data base for the MATPRO (5) viscosity calculation. Further T is temperature in K and p is pressure in Pa.

For p = 0.1 MPa and T = 673 K one finds D_{12} (Xe, He) = $1.5 \cdot 10^{-4}$ m^2/s

This can be compared to what Kinoshita (4) uses

$$D = 0.496 \left(\frac{T}{273.15} \right)^{1.7} \cdot \frac{1}{p} \qquad (A5)$$

This gives D in cm^2/s with T in K and p in atm.

For T = 673 K and p = 1 atm (0.1 MPa) this gives D ≈ $2.3 \cdot 10^{-4}$ m^2/s which is in fair agreement with our estimate.