SENSITIVITY OF FUEL PERFORMANCE CODE ANALYSIS TO DESIGN AND PROPERTY ASSUMPTION

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SUMMARY

The code COMETHE III-J was used to demonstrate the sensitivity of fuel performance codes to input properties, assumed models and small changes in design parameters. For this study the Maine Yankee Core 1 rods were chosen, because of the unexpected phenomenon which was observed during a very complete PIE of these rods. The examination showed, that a group of almost identical rods, which underwent similar power history could be separated into two populations of fractional gas release (less than 1% and 11.3 to 13.5%). Low gas release rods showed no fuel restructuring whereas the high gas release rods showed equiaxed grain growth in the fuel along almost the total fuel column.

The rods with extended equiaxed grain growth and the high fractional fission gas release rates could be simulated by the COMETHE code, using the actual power history and fuel pin design data. The fuel centerline temperature of this case showed the unexpected trends. Axial segments with lower axial peaking factors showed higher central fuel temperatures than segments with higher axial peaking factors for end of like condition. The normally expected relationship between power and temperature existed at BOL.

The reversed trends of the fuel centerline temperatures were caused by a combination of gap closure, fission gas release behavior and relocation due to fission gas bubble swelling.

A parametric study was performed for this case to study the sensitivity of the code to design variably, property assumptions and model changes, specifically the following variables were examined:

Fuel pin power level
Amount of fuel densification
As fabricated Gap
Cladding creep rates
Initial pressurization level
Amount of sorbed gases
Clad Thickness
Relocation model

A small change in some of the above mentioned parameters such as, increase in cladding creep rates, prepressurization of the fuel pin or smaller as fabricated gap caused or considerable change in the thermal behavior of the fuel pin. Changes in these input parameters eliminated restructuring, and reduced predicted fission gas release, similar to the "low gas release rods" population of the Maine Yankee rods.

It appears that for some specific power histories the thermal behavior of the fuel pin is very sensitive to small design and property changes. The parameter, which seems to be responsible for the unstable behavior is the effective cold gap and its axial variation.

It appears that for a specific power-gap combination the fission gas release rate changes suddenly. This "instability" in fission gas release was triggered by some of the examined parameters. The phenomenon seems also to be very sensitive to the power history the rods had experienced.

1. INTRODUCTION

The thermal-mechanical fuel performance code COMETHE was used to demonstrate sensitivity of the analytical results by this code to material properties, changes in the fuel rod design parameters, and changes in power level. Some of the design parameter changes were small, within the typical tolerance range of LWR fuel. The effect of these changes on the predicted fuel rod performance was analyzed. For this study the Maine Yankee core 1 rods were selected, because of the unsual phenomenon which were observed during a very complete post-irradiation examination of these rods [1, 2]. The examination showed, that a group of almost identical rods, which underwent similar power history could be separated into two populations of fractional gas release (less than 1 % and 11 to 16 %). Low gas release rods showed no fuel restructuring whereas the high gas release rods showed the same equiaxed grain growth in the fuel along almost the total fuel column, in spite of a factor of two different linear heat generation rates between fuel rod ends and peak power location. The power history in the Maine Yankee core 1 was somewhat unique, showing a rapid increase in power by a factor of almost 3 at a burnup of about 5200 MWD/MTU, which might have caused the observed instability in fission gas release rates. However it is likely that other power histories could trigger similar fuel rod behavior.

2. DESCRIPTION OF THE SENSITIVITY STUDY

The fuel rod, selected for this sensitivity study, is identified as JBY097 from Batch B of Maine Yankee Core 1. The description of the rods has been published before [3] and the most important design parameters are listed below in Table 1.

The significance of the design was that the rod was unpressurized and contained relatively low density fuel pellets densifying to about 96.8 % theoretical density.

TABLE 1 - Fuel Rod Design Parameters for the Base Cases

	Case # 1	Case # 2
Cladding Outer Diameter	0.4405 inches	0.4405 inches
Cladding Thickness	0.026 inches	0.026 inches
Diametral Gap	0.009 inches	0.007 inches
Active Fuel Length	136.7 inches	136.7 inches
Plenum Length	9.5 inches	9.5 inches
Fuel Density	92.8 % TD	92.8 % TD
In Reactor Fuel Densification	4.0 %	4.0 %
Fill Gas Composition	88 % He/12 % N	88 % He/12 % N
Fill Gas Pressure	15 psia	15 psia
Fuel Grain Size	4 microns	4 microns

The assumed power history for the peak power location and several other locations is given in Figure 1.

A parameter study was performed for this case to study the sensitivity of the code to design variables, variations in properties and models, and power levels. Specifically the following variables were examined :

- Fuel pin power level ;
- Amount of fuel densification ;
- As fabricated fuel-clad gap ;
- Cladding creep rates ;
- Initial pressurization level ;
- Amount of sorbed gases ;
- Clad thickness ;
- Relocation model ;
- Fuel open porosity.

Only one design variable was changed from case to case, so that the effect of a single parameter on the fission gas instability could be studied.

3. DESCRIPTION OF THE COMETHE CODE

The code COMETHE is devoted to the prediction of the mechanical and thermal behavior of a complete fuel rod with oxide fuel in metallic cladding. It has been described in details in a number of papers or reports, the latest one being reference [4]. Only the latest implemented modifications are reported here, they correspond to the version COMETHE III-J [5].

3.1. Zircaloy

- Anisotropic creep with time or strain hardening
- Anisotropic growth

3.2. Equiaxed Grain Growth Model

The irradiation effect in the previous model has been modified to account for variable power and temperature history. It is now assumed that the growth is inhibited by a threshold amount of fission gas bubbles at grain boundaries. The parameter determining that amount is empirically deduced from the fission gas bubble swelling model.

3.3. Fission Gas Release Model

One aspect of the irradiation effects has also been modified in this model. It still considers diffusion, trapping and re-solution in the matrix of a sphere. The size of that sphere is correlated, at begining of the irradiation, to the specific surface or open porosity of the as-fabricated fuel and, later on, to the grain size when fission gas bubbles are present at grain boundaries, creating new open porosity. The threshold criteria is the same as in the equiaxed grain growth model. From these models results that the fission gas release rate increases significantly when fuel is heated up at restructuring temperatures, i.e., to a regime of fission gas bubble swelling or equiaxed grain growth.

3.4. Ridging Effects

The ends of the pellets expand more than the center (hour glassing effect). This behavior is simulated by the code in special axial slices : a correction factor is applied to the fuel thermal expansion so that the code evaluates the resulting effects, higher tangential stresses and higher local straining in the clad when fuel interacts with the clad. The correction factor depends on the fuel geometry (length to diameter ratio, dishing, central hole and chamfering mainly) and has, of course, to be tuned with the support of an experimental data base.

The first cases using that approach have been very encouraging. The main advantages of the method are its simplicity and the very low additional cost.

3.5. Relocation Effects

The code has proven to possess a build in capacity of pellet relocation due to cycling. That model results in fact in a natural way from all the modeling features of the code (cracking, pivot concept, crack healing, ...) as described in reference [6].

3.6. Prediction Capabilities

The latest modifications reported here are in fact a last major step of series of modifications initiated in 1974 when the fuel in-pile densification has been implemented in the code. The whole set of modifications allow to follow the various phenomenons occuring in a fuel rod particularly when the rod is subjected to a variable power history. The restructuring models take into account the major physical mechanisms which are important for the fuel behavior, they also allow to make reasonable comparison with experimental results on end of life pattern by interpreting the kinetics effects (e.g. active or inactive columnar grains) as illustrated in reference [7].

Further improvements are, of course, still possible and are indeed foreseen.

4. RESULTS OF THE SENSITIVITY STUDY

4.1. Modeling Details and Assumptions

The 147 inch long PWR rod was axially modeled by seven fuel segments and a top fission gas plenum. Radially each pellet was divided into 10 zones and the surrounding Zircaloy-4 cladding into 4 zones.

Cladding outer diameter temperatures were analyzed using standard heat transfer correlations and a heat balance along the length of the fuel rod. The assumed flux depression factors as calculated by COMETHE were the same for all cases ; the normalized heat generation rate was 0.973 at the center and 1.027 at the surface of the pellet.

4.2. Discussion of the Results

A total of 14 cases were run to simulate and study the effect of fuel rod design parameters, property assumptions and model changes on the fuel rod behavior.

Table 2 shows the examined parameters and the corresponding run identities. Cases 1 and 2 are considered the base cases, to which all other runs are compared. The two base cases represent the as built variation in the fuel-clad gap. Case # 1 has a 0.009 in. gap, generally representing the high fission gas release population, and Case # 2 has a 0.007 in. gap generally representing the lower fission gas release population.

The most important results of base case 1 are summarized in Figure 2, showing the power history, fuel centerline temperature, and the hot radial gap at the peak power location of the rod versus time. Included in the same plot is also the fractional fission gas release rate for the total fuel pin. Worthwhile mentioning is the opening of the hot gap during the first 100 days due to fuel densification. The fission gas release rate in this time period is very low, less than 1 %. After 224 days of irradiation, when the power is increased from 85 to 232 W/cm, the higher fuel temperatures triggered a sudden fission gas release, thereby diluting the helium in the gap and driving up the fuel temperatures.

The fuel central temperature in the hottest region exceeded some threshold temperatures (i.e., fission gas bubble swelling), and the fuel clad gap started to decrease at the peak power location. Since the large gap did not close down in the axial segments with lower heat generation rates, the pellet clad gap conductances became worse and the fuel centerline temperatures increased. In the peak axial segments, however, the effect of reduction in gap size is greater than the effect of poorer gas conductance, and, therefore, the fuel centerline temperature goes down. This thermal behavior caused the following two observed phenomena :

. About the same EOL equiaxed grain growth radius was predicted in the fuel along almost the total fuel column, independent of the axial power peaking.

. A "fuel centerline temperature inversion" was predicted at EOL condition i.e. fuel centerline temperature at the high power locations were lower than fuel centerline temperature at axial locations with lower heat generation rates. At BOL, however, the fuel centerline temperatures were proportional to the heat generation rates. This behavior is shown in Figure 3.

In the following parameter study the sensitivity of the code to the change of a single variable was examined.

The most important results are summarized in Table 2 and 3. The sensitivity study was set up in such a way that the change of a single parameter changes the predicted thermal performance of the rod from the expected performance of the base case.

COMETHE showed significant sensitivity to the as fabricated diametral gap (Cases 1, 2 and 3). Fabricated diametral gaps of 9 mils and more caused significant EOL gas release rates of more than 13 %, which were triggered by the sudden power increase, as described before for the base case. For all cases with gaps below 7 mils this fission gas instability was not predicted. A comparison of the most important parameters, i.e. fission gas release rate and hot diametral gap, versus time for cases 1 and 2 is given in Figure 4. The fuel pin behavior was very similar for both cases up to 224 days. The fuel centerline temperature was slightly lower for case 2 due to a 2 mils smaller diametral gap. However, case 2 did not show the sudden increase in fission gas release in the following cycle, as discussed before for case 1.

Comparing reduction of the in-pile fuel densification from 4 % to 0 % (Case 1 vs. Case 6) had the same effect of fission gas release rate as the reduction of the fuel-clad gap. The EOL fission gas release rate dropped from 19.5 % to 0.5 %.

The same sensitivity was also observed for the two Zircaloy creep correlations that were compared. The more applicable, standard COMETHE creep correlation in Base Case 1 predicted 19.5 % fission gas release, while the creep correlation of ref. 3, which overpredicts creepdown by a factor of two, reduced the fission gas release to 2.2 % (Case 1 vs. Case 11). However, changing the clad thickness by 2 mils from 26 to 24 or 28 mils, using the standard COMETHE creep correlation, did not cause a significant change in the predicted performance (Cases 1 and 2 vs. 9, 10 and 13).

All the previously discussed parameters affect the thermal behavior of the fuel rod directly by their effect of the size of the hot diametral gap. Figure 5 shows the hot gap versus all fuel rod axial locations for Cases 1 and 2, at 224 days of irradiation just after the power ramp. Included in the plot are the hot gaps of all other cases at one peak and one low power axial location. The upper curve represents all cases with fission gas release rates above the instability point, the lower one below the instability point. Figure 6 shows the two populations of EOL fission gas release as a function of the hot gap at the peak power location just after the critical power increase after 224 days of irradiation.

The effect of the hot gap on the two populations of fuel restructuring diameter ratios is given in Figure 7.

A difference in the hot gap of less than 1 mil at a burnup of 5,200 MWD/MT is responsible for the large difference in fission gas release rates and the fuel restructuring at EOL.

Other parameters or models not explicitly studied here, that increase the hot gap to the critical size, will have the same effect on the fission gas release rate. An accelerated empirical pellet relocation mode, for example, will tend to close the hot gap more rapidly. The effect will be the same as discussed for reduced initial gap size or increased cladding creep rate.

In the following section the sensitivity of the code to other design and performance parameters were performed.

Two runs were made to determine the sensitivity to power change. A reduction of the large gap (9 mils) rod power by 20 % (Case 1 vs. 5) reduced the fission gas release to the lower level. A 20 % power increase in the small gap (7 mils) rod (Case 2 vs. 4) increased the fission gas release to the higher level.

The sensitivity to initial prepressurization and fill gas composition was examined in Cases 7 and 8. The prepressurization of the fuel pin to 350 psi of helium reduced the predicted fission gas release rate from 19.5 % to 1.1 %. However, the elimination of nitrogen in the fill gas (representing release of sorbed gases, or initial air atmosphere) had no significant effect on the thermal behavior.

The last parameter, which was examined, was the fuel pellet morphology. A change in the open porosity from 2.2 % to 0.7 % (Cases 1 vs. 12 and 2 vs. 14) caused a considerable reduction in the predicted fission gas release rates. For the 9 mil gap case the predicted gas release dropped from 19.5 % to 13.4 % and for the 7 mil gap case form 7.6 % to 0.8 %. The lower release rates agree much better with the measured release rates of the Maine Yankee rods. However the change in the open porosity did not cause the predicted fission gas release rate to shift to the other side of the instability point.

5. SUMMARY AND CONCLUSION

The code COMETHE III-J was used to demonstrate the sensitivity of fuel performance codes to input properties, assumed models and small changes in design parameters. Changes in parameters such as, increase in cladding creep rates, prepressurization of the fuel pin or smaller as fabricated gap caused a considerable change in the thermal behavior of the fuel pin.

It appears that for a specific combination of power history and hot gap, the fission gas release rate changes suddenly. This "instability" in fission gas release was triggered by most of the sensitivity runs considered by this study. The results show, most cases studied can be separated into two groups, one with low fission gas release rates and one with high fission gas release rates.

For rods with low gas release insignificant or no fuel restructuring was predicted, whereas for rods with high gas release significant equiaxed grain growth was predicted for almost the entire fuel column. The most important parameters separating these two groups for a given power history were :

. the hot radial gap and its axial variation ;
. the linear heat generation rate ;
. prepressurization of the fuel rod.

The COMETHE code predicted that for various combinations of power level and hot gap the instability in fission gas release rate could be triggered in an unpressurized rod. In a pressurized rod the instability could not be triggered. It also appears possible that this instability might occur for other power histories and is not limited to the observed one from Maine Yankee.

The main driving force for the thermal instability is the release of a large fission gas inventory, caused by a sudden power increase. However the instability can only be triggered if pellet and clad are not yet in contact and the hot gap is large enough, so that the dilution of helium by fission gas has a significant effect on gap conductance. Since the inventory of fission gas is increasing with burnup, similar instability could also be postulated for higher burnups, even with slightly smaller hot gaps or smaller power changes.

A good prediction of this thermal instability is only possible with a well balanced computer code, which models all important thermal and mechanical phenomena, such as COMETHE.

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TABLE 3

Case	EOL, Fission Gas Release Rate %	Ratio of Equiaxed Grain Growth Cross Section to Pellet Cross Section at Axiál Location 6.5 in	82 in
1	19.5	0.77	0.54
2	7.6	0.18	0.37
3	27.8	0.94	0.64
4	16.6	0.64	0.41
5	1.1	0.0	0.0
6	0.5	0.0	0.0
7	1.1	0.0	0.0
8	20.8	0.61	0.43
9	20.8	0.59	0.45
10	20.3	0.62	0.42
11	2.2	0.0	0.10
12	13.4	0.45	0.41
13	8.3	0.02	0.27
14	0.8	0.0	0.0

TABLE 2

	Base Cases													
Run Identity	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Case to be Compared to			1	2	1	1	1	1	1	1	1	1	2	2
As Fabricated Diametral Gap, mils	9.	7	11	7	9	9	9	9	9	9	9	9	7	7
Relative Power	1.	1.	1.	1.2	0.8	1.	1.	1.	1.	1.	1.	1.	1.	1.
Fuel Densification , % TD	4.	4.	4.	4.	4.	0.	4.	4.	4.	4.	4.	4.	4.	4.
Prepressurization, psia	15.	15.	15.	15.	15.	15.	350.	15.	15.	15.	15.	15.	15.	15.
Partial Pressure of Nitrogen Fill Gas, psia	1.8	1.8	1.8	1.8	1.8	1.8	1.8	0.	1.8	1.8	1.8	1.8	1.8	1.8
Clad Thickness, mils	26.	26.	26.	26.	26.	26.	26.	26.	28.	24.	26.	26.	28.	26.
Fuel Open Porosity, %	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	0.7	2.2	0.7
Clad Creep Model (1)	1	1	1	1	1	1	1	1	1	1	2	1	1	1
EOL Fission Gas Release Rate, %	19.5	7.6	27.8	16.6	1.1	0.5	1.1	20.8	20.8	20.3	2.2	13.4	8.3	0.8

(1) Model 1 is the standard COMETHE Zircaloy creep correlation
2 is the Zircaloy creep correlation from Reference [3], Appendix A.

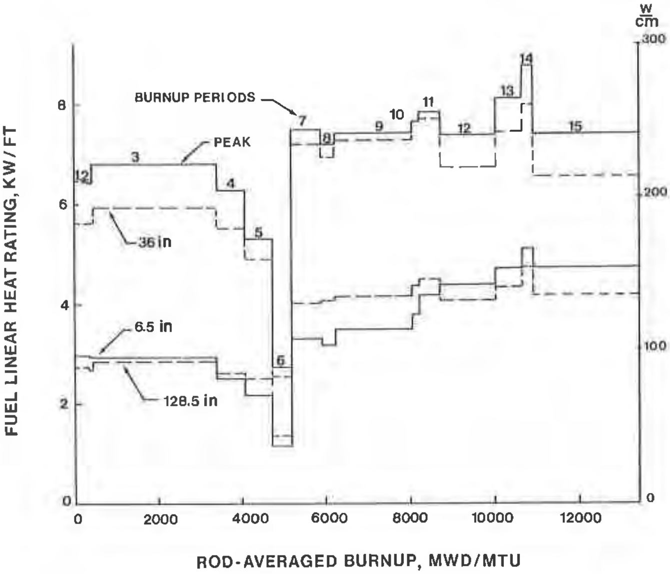

Fig. 1 Fuel linear heat rating vs. burnup

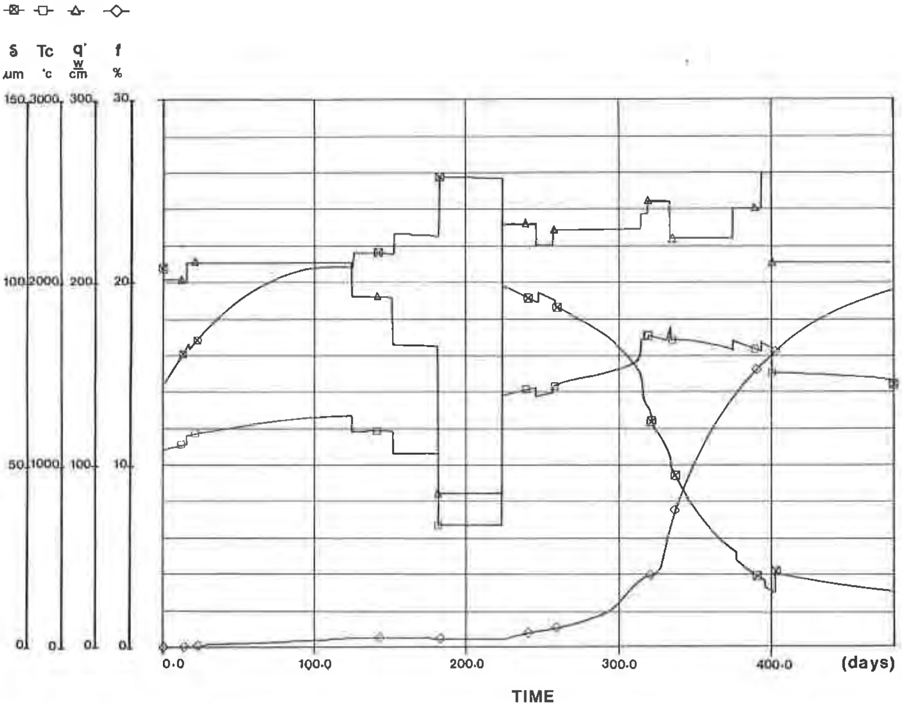

Fig. 2 COMETHE results for base case 1

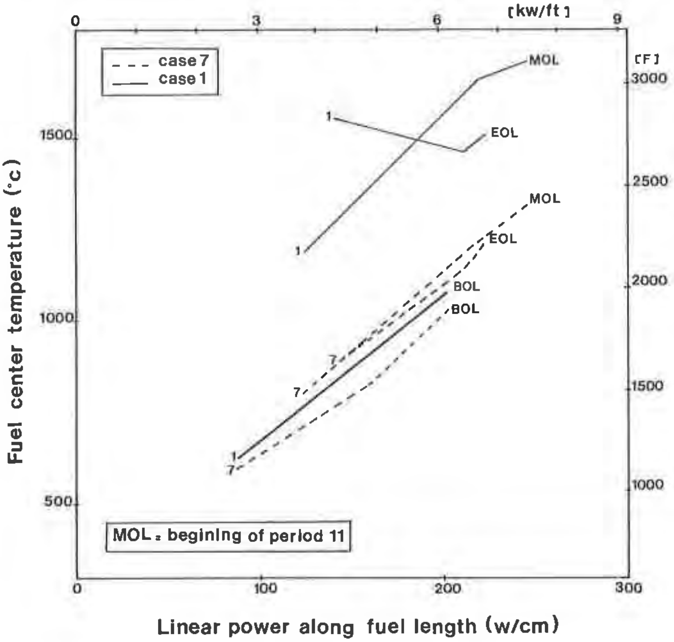

Fig. 3 Fuel center temperature vs. linear power

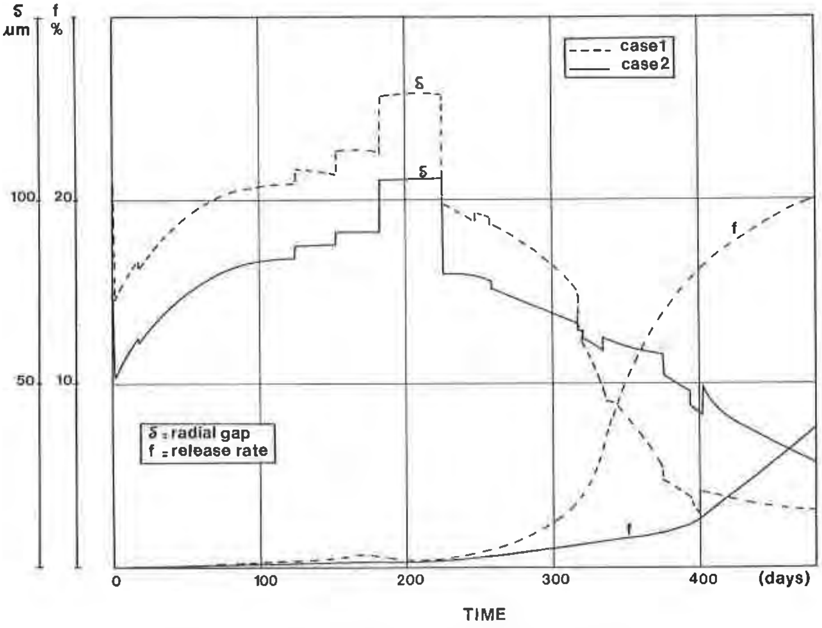

Fig. 4 Hot gap and release rate versus time for cases 1 and 2

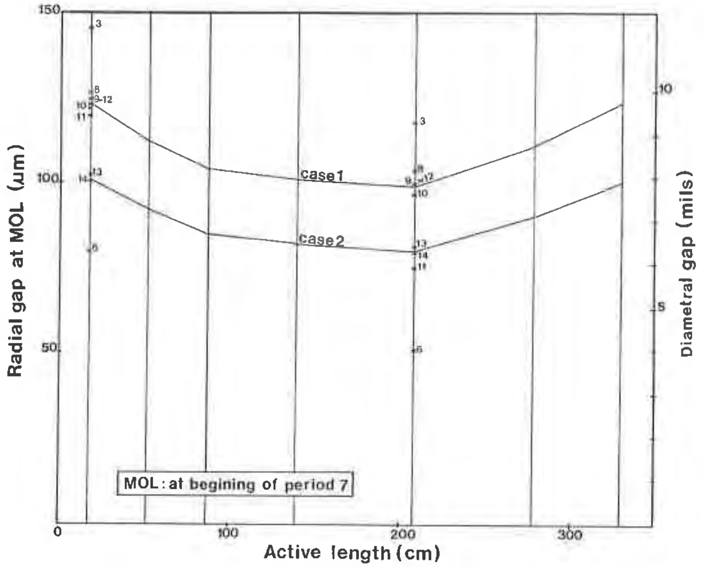

Fig. 5 Hot gap vs. axial location

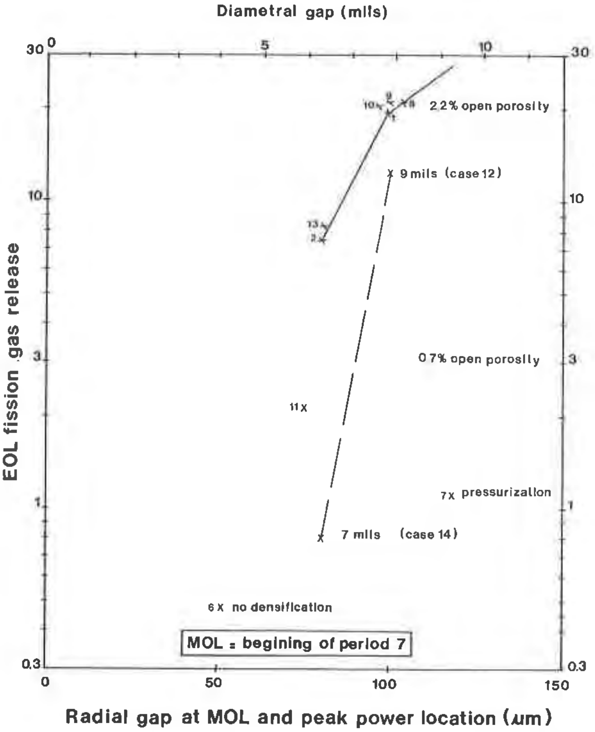

Fig. 6 EOL Fission gas release vs. hot gap

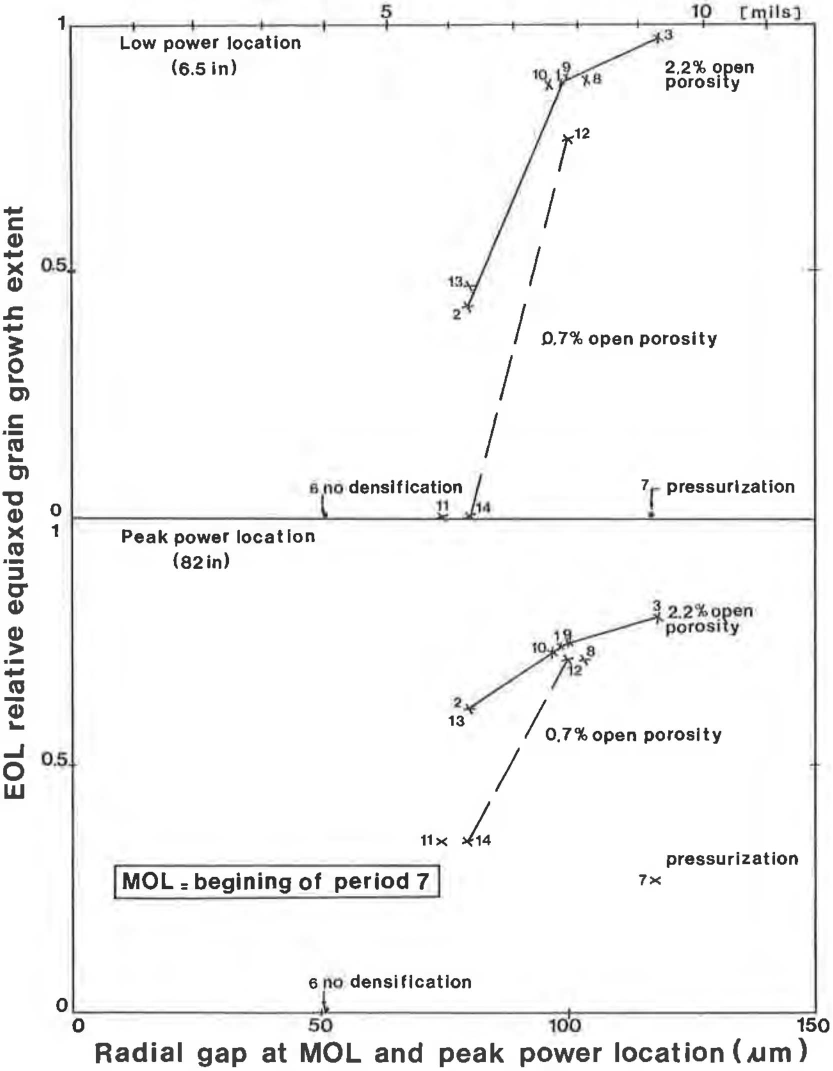

Fig. 7 Fuel restructuring vs. hot gap