A Model for Asymmetric Ballooning and Analyses of Ballooning Behaviour of Single Rods with Probabilistic Methods

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Summary

Plastic deformation behaviour of zircaloy cladding is extensively examined during past and can be described best with a model for asymmetric deformation. Asymetric deformation behaviour of the cladding is explained by the fact, that slight displacement between the pellet and cladding will always exist and this will lead to the formation of azimuthal temperature differences. The ballooning process is strongly temperature dependent and as a result of the built up temperature differences, differing deformation behaviour along the circumference of the cladding results.

Calculated ballooning of cladding is mainly influenced by its temperature, applied burst criterion and the parameters used in the deformation model. All of these influencing parameters possess uncertainties, leading ultimately to deviations and representation of the results by bands. In order to quantify these uncertainties and to estimate distribution functions of important parameters like temperature and deformation the Response Surface Method was applied. For a hot rod the calculated standard deviation of cladding temperature amounts to 50 K. From this high value the large influence of the external cooling conditions on the deformation and burst behaviour of cladding can be estimated.

In an additional statistical examination the parameters of deformation and burst models have been included and their influence on the deformation of rod has been studied. It is shown that the deformation is excessively influenced by external cooling conditions than by those other parameters. Out of these results it can be concluded that so long thermohydraulic boundary conditions are not better known, a further refinement of deformation and burst model is not required. With the help of statistical methods and by considering all the uncertainties, analyses on the probable extents of deformation, the number of burst claddings and that of mutual contacts can be made. The likelihood for higher damages can also be quantified.

1. Introduction

During a loss-of-coolant accident (LOCA) with a large break in a recirculation loop of a PWR the thermal and mechanical behaviour of the fuel rods are very important, because changes in their geometry can sufficiently influence the coolability of the core. Additionally, the loss of the integrity of the fuel rods will lead to partial release of the radioactive inventory of the rods.

In order to calculate the cladding deformations during LOCA a deformation and burst model is introduced by F. Erbacher et. al./1/. This model is based on concentric circumferential expansion of the cladding without considering the existing azimuthal temperature differences in the cladding. The empirical model considers heating rate, temperature, internal pressure and the oxidation of the zircaloy claddings.

However, this model appears to be limited in its application to determine the behaviour of the fuel rods or their simulators, as the azimuthal temperature differences are continuously formed due to slight displacements of the fuel pellets from their concentric positions. These displacements are caused by anisotropic behaviour of cladding like rod bowing, fuel fragmentation, and relocation or are simply due to vibration of fuel pellets during reactor operations. As the ballooning process is strongly dependent on temperature, differing circumferential expansions along the cross section of the cladding result due to the temperature distributions. This phenomen is called asymetric deformation.

Fuel rod behaviour is influenced both by thermohydraulic and fuel rod parameters. All of these influencing parameters possess uncertainties leading ultimately to deviatians and representation of the results within error bands. So there is a necessity of a core-wide analysis including statistical uncertainties and using probabilistic methods.

With a regression analysis the output of the complex fuel behaviour code is replaced by a simple function of the input values (response surface). With the established and tested response surface few computing time consuming statistical calculations (e.g. Monte-Carlo calculations) could be done. A result of these calculations are distribution functions for maximum strain, burst strain and number of ruptured rods.

2. The Asymetric Deformation Model

Figure 1 illustrates the typical deformation behaviour of the fuel rod cladding. Due to an existing eccentricity or relocation of the fuel pellet a local hotspot will develop at one side of the rod. The anisotropy of the zircaloy material will cause a bowing of the cladding, if temperatures are high enough for plastic deformation. The hotspot is forced into the fuel and the opposite side is lifted away from the fuel.

The azimuthal temperature difference along the circumference will increase as the hotspot heats up and the opposite side cools. As the deformation is very sensitive to temperature, the cladding circumferential strain and wall thinning become functions of the prevailing temperatures at different segments of the circumference. Once the transition from secondary to tertiary creep has occured, the deformation process proceeds rapidly. Thus the positive temperature difference at the hotspot leads to maximum deformation and wall thinning at that location leading to ultimate rupture.

In order to model the cladding deformation behaviour the concentric deformation model /1/ is extended. The cladding cross section will be divided into segments and the deformations of each segment resulting from the existing temperature distribution will be calculated. The average circumferential elongation is thus calculated from the deformations of each segment. It will be assumed in this model that the change in azimuthal temperature and rate of deformation is small in the regions of hot and cold spots.

For comparison a micrograph of a burst cladding and its calculated cross sections are presented in Figure 2. For this experiment the measured temperature is about 64 K and the circumferential elongation amounts to 38 %. The calculated temperature gradient appears to be slightly higher than the measured values, but the measured temperature has uncertainties in the determination of the locations for maximum and minimum temperatures, convection due to thermocouple etc. The graphical representation of calculated deformations does not show the wide burst opening as such behaviour is not modelled.

For the verification of the asymetric deformation model, the fuel rod simulations experiments performed within the frame work of Project Nuclear Safety (PNS), Karlsruhe, Germany are used /2/. The deformation calculated with the asymetric deformation model agrees well with the measured values.

3. The Probabilistic Approach

All codes calculating fuel rod cladding temperatures, strain and cooling conditions use certain models and input data sets. The input data and the output data are deterministic values, either conservative or best-estimate (Figure 3).

As these programs do not consider statistical deviations (e.g. geometrical properties) and physical uncertainties (e.g. decay heat), probabilistic methods are developed in order to calculate the output parameter distributions according to the given distributions of the input parameters. These methods give the connection between the best-estimate result (the most probable one) and the conservative result, which is most unlikely.

In order to consider the statistical deviations and uncertainties of important parameters, various methods, for example Monte-Carlo-Method or the Response-Surface Method, can be applied. The application of direct simulation processes on complex codes results in such a numerical expense, which mostly can not be dealt with. For these reasons the Response-Surface Method is developed.

With a regression analysis the considered output of the complex code is replaced by a simple function of the input values. Various types of functions can be given and their coefficients are determined by a regression code. This code uses data points, which are to be calculated with the complex code. The input data are selected by a random number generator (experimental design). With the established and tested response surface few computing time consuming statistical investigations (e.g. Monte-Carlo calculations) could be done.

So for example a response-surface was generated for the maximum fuel rod cladding temperature. In order to perform Monte-Carlo calculations with this function not only the uncertainty bands of the input parameters, but also their distribution functions had to be determined. This was done by applying the knowledge gained by sensitivity studies.

The result of the Monte-Carlo calculation was the cladding temperature distribution (Figure 4). The standard deviation amounts to 50 K. Because the cladding temperature is dominating the strain rate, this value gives a feeling of the large influence of the external cooling conditions on the deformation and burst behaviour of fuel rods.

4. Analyses and Results

Calculations were performed for a 1300 MW PWR. For the analyses 32 variables in total were considered. The table gives the list of the 12 most important influential parameters, divided into general, thermohydraulic and creep model parameters. The table also contains the minimum and maximum values, mostly related to the design values. Between the extreme values the distribution is given by beta-functions. The creep equation stands for the time derivation de/dt of the strain.

$$de/dt = A \cdot s^n \cdot \exp(-Q/RT)$$

A = empirical constant value

s = hoop stress

n = stress exponent

Q = activation energy

R = constant of gas

T = temperature of cladding

All thermohydraulic parameters have influence on the temperature T of cladding, whereas stress exponent n and activation energy Q are the important factors for the creep velocity.

The four dominating influential parameters (marked with numbers within parenthesis in the table) are

- the maximum power factor of the single rod,
- the activation energy in the creep equation,
- the internal gas pressure of the single rod,
- the heat transfer coefficient during flooding.

The maximum power factor is valid for the level with the highest axial peaking factor. For the calculated example nearly 15 % of the rods have maximum power factors above 1.8.

Figure 5 shows the results of two regression analyses, one for the broken and the other for the unbroken rods. The compilation of their probability density functions (pdf) to one valid for all rods is given in the right part of the figure. The broken rods show higher strains than the unbroken rods, naturally.

Because the analyses were done for single rods, two limitations ought to be mentioned. For strains above 33 % contact can occur and for strains above 66 % contact must occur between neighbouring rods. That means that high strains might be only theoretical values in core bundle geometry.

Figure 6 shows again the pdf of the strain for all rods and additionally gives the fraction of the broken rods. For strains greater than 10 % nearly 80 % of all rods are broken. This fraction remains constant for all the higher strains.

Figure 7 shows the cumulative distribution function (cdf) of all rods, both broken and unbroken, and the fraction of the broken rods. Nearly 50% of the rods considered (with peaking factors above 1.8) are broken, related to the total number of rods nearly 7 %. In detail one can get the following results (percentage of all rods):

- strain above 10 %	7,3 %
- possible contact (strain above 33 %)	3,3 %
- mutual contact (strain above 66 %)	1,2 %

These percentages seem relatively high due to the high maximum peaking factor of 2.5.

Monte-Carlo calculations with the response surface are useful tools to show the influence of different types of input data and model parameter. So for the category of unbroken rods curve 1 in figure 8 shows the pdf of strain like figure 5. The two additional curves are the result of Monte-Carlo calculations, where only a) the thermohydraulic parameters in curve 2 and b) in curve 3 the creep model parameters as listed in the table are used with their input distribution functions. All other parameters are used with their best-estimate values.

The figure shows, that curve 2 is nearly equal to curve 1. That means, the thermohydraulic parameters are dominating the strain distribution. So the pdf for only the variation of the creep model parameters has a much lower standard deviation. If only the 4 most important parameters (marked as 1 to 4 in the table) are used, the relations are similar. These 4 parameters are dominating the fuel rod behaviour.

Figure 9 shows the influence of the power factor. The curve with the square symbols has a maximum peaking factor of 2.5 and was already shown in figure 7. For the curve with the circular symbols the distribution function of the power factors was limited by 2.2. For both distribution functions the number of rods with peaking factors above 1.8 is the same. For these lower peaking factors the result is:

- strain above 10 %	3,3 %
- possible contact (strain above 33 %)	1,4 %
- mutual contact (strain above 66%)	0,5 %

Compared to the results for higher peaking factors the number of rods with high strains is reduced to 42 %. These numerical results are restricted to the analysed type of reactor. In general one can say, that a small increase in power factor will have enormous effect on strains and on the number of failed rods.

Conclusion

Probabilistic methods were successfully tested to calculate fuel rod behaviour. The most influencing parameters have been identified. They are power factor, activation energy of the zircaloy material, internal pressure and flooding heat transfer coefficient. Furthermore it is shown that the deformation is excessively influenced by external cooling conditions. So long thermohydraulic boundary conditions are not better known, a further refinement of deformation and burst model is not required. Inspite of such uncertainties with the help of statistical methods reasonable results for the extent of deformation and the number of burst claddings or mutual contacts could be obtained.

References

/1/ ERBACHER, F.J., NEITZEL, H.J., ROSINGER, H., WIEHR, K., "Burst Criterion of Zircaloy Fuel", ASTM 5. International Conference on Zirconium in the Nuclear Industry, Boston, USA August 4 - 7, 1980

/2/ ERBACHER, F.J., "LWR Zircaloy Cladding Deformation and Future Needs", Enlarged Halden Project Group Meeting on Water Reactor Fuel Performance, Hankö, Norway, June 14 - 18, 1981

TABLE of the most important influential parameters and uncertainty bands

Parameter	Minimum Value	Maximum Value
<u>General Parameters</u>		
Internal pressure, psi (3)	652	1305
Pellet diameter, inch	0,354	0,368
<u>Thermohydraulic Parameters</u>		
Power factor (1)	1,8	2,5
Coolant temperature multiplier	1,0	1,1
Steam quality multiplier	0,8	1,2
Multiplier of flooding heat transfer coefficient (4)	0,7	1,3
Refill - time, s	5	25
Decay heat multiplier	0,8	1,2
Blowdown mass flow multiplier	0,7	1,3
Coolant pressure multiplier	0,95	1,05
<u>Creep Model Parameters</u>		
Stress exponent multiplier	0,9	1,1
Activation energy multiplier (2)	0,9	1,2

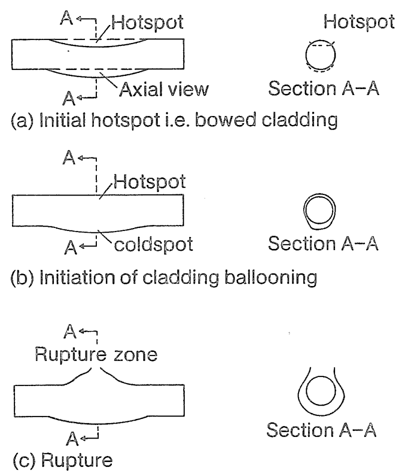

FIGURE 1

SCHEMATIC REPRESENTATION OF CLADDING DEFORMATION PROCESS

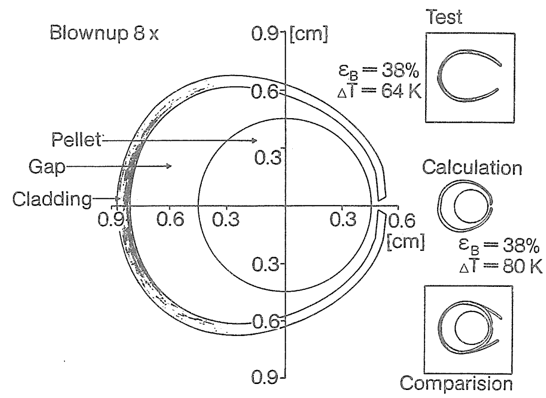

FIGURE 2

COMPARISION OF ASYMETRIC DEFORMATION MODEL WITH THE MICROGRAPH OF A REAL FUEL ROD SIMULATOR

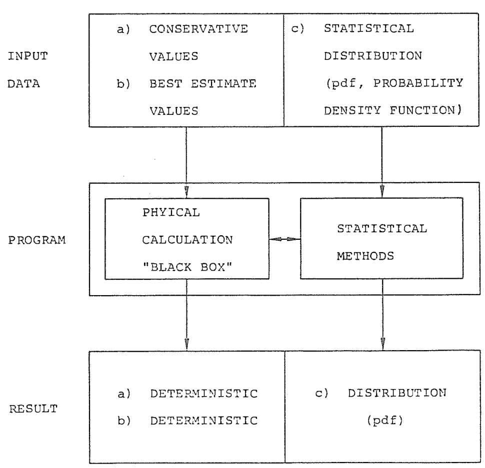

FIGURE 3

DETERMINISTIC AND PROBABILISTIC CALCULATION

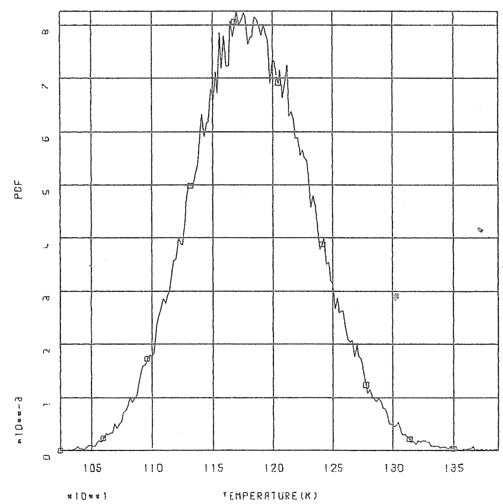

FIGURE 4

PROBABILITY DENSITY FUNCTION (PDF) OF THE MAXIMUM HOT ROD CLADDING TEMPERATURE

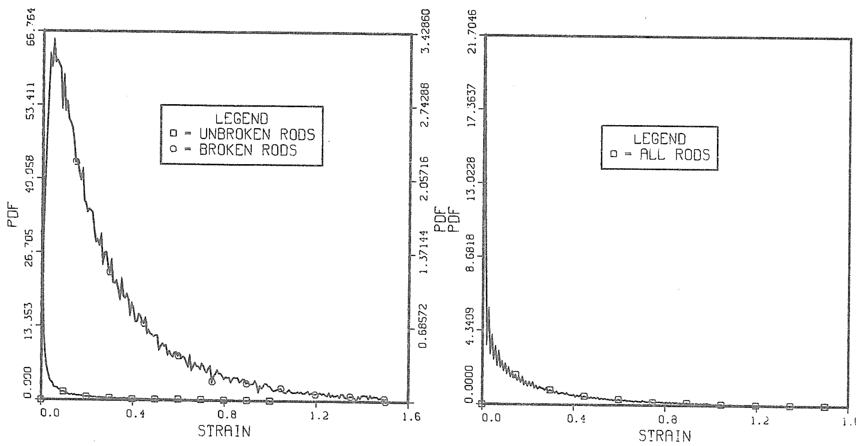

FIGURE 5

PDF OF THE CIRCUMFERENTIAL STRAIN

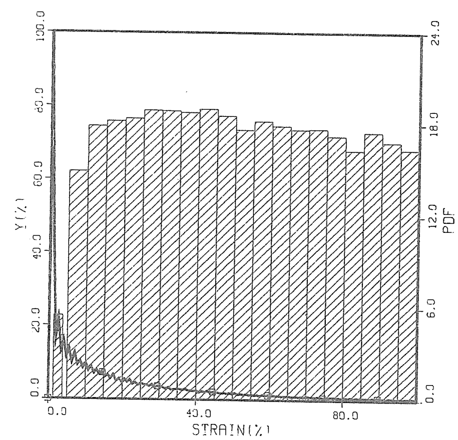

FIGURE 6

PDF OF CIRCUMFERENTIAL STRAIN AND FRACTION OF BROKEN RODS

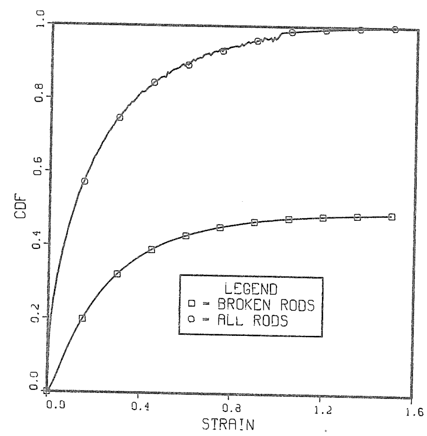

FIGURE 7

CUMULATIVE DISTRIBUTION FUNCTION (CDF) OF CIRCUMFERENTIAL STRAIN AND FRACTION OF BROKEN RODS

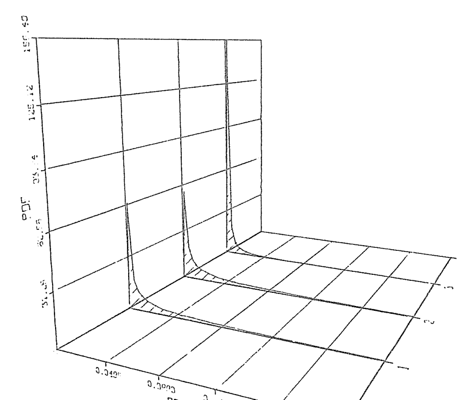

FIGURE 8

INFLUENCE OF THE THERMOHYDRAULIC AND THE CREEP MODEL PARAMETERS FOR THE UNBROKEN RODS

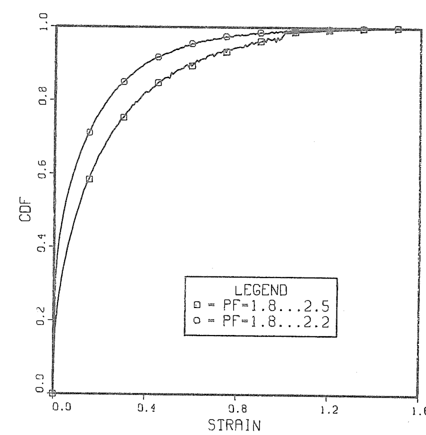

FIGURE 9

CDF OF CIRCUMFERENTIAL STRAIN FOR DIFFERENT MAXIMUM POWER FACTORS