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FUEL ROD DESIGN BY STATISTICAL METHODS FOR MOX FUEL

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Abstract

Statistical methods in fuel rod design have received more and more attention during the last years. One of different possible ways to use statistical methods in fuel rod design can be described as follows: Monte Carlo calculations are performed using the fuel rod code CARO. For each run with CARO, the set of input data is modified: parameters de-scribing the design of the fuel rod (geometrical data, density etc.) and modeling parameters are randomly selected according to their individual distributions. Power histories are varied systematically in a way that each power history of the relevant core management calculation is represented in the Monte Carlo calculations with equal frequency. The frequency distributions of the results as rod internal pressure and cladding strain which are generated by the Monte Carlo calculation are evaluated and compared with the design criteria. Up to now, this methodology has been applied to licensing calculations for PWRs and BWRs, UO_2 and MOX fuel, in 3 countries. Especially for the insertion of MOX fuel resulting in power histories with relatively high linear heat generation rates at higher burnup, the statistical methodology is an appropriate approach to demonstrate the compliance of licensing requirements.

1. INTRODUCTION

The insertion of MOX fuel assemblies in LWRs can be guided by different aims, e.g. maximum reduction of Pu stockpile, maximum operational flexibility, no modification of the existing fuel management strategy, no safety penalties and if possible, no economic penalties, c.f. [1] to [4]. In any case it is important for design and licensing purposes to describe the expected behavior of the MOX fuel rods as precisely as possible based on appropriate methods and codes.

It was found that design analyses with statistical methods, using the fuel rod code CARO, fulfill the requirements on accuracy and reliability not only for UO_2 fuel, but also for MOX fuel, especially for modern core designs with higher enrichments and more demanding fuel rod power histories.

In the following, the features of the fuel rod code CAR0 with respect to MOX fuel will be described and an overview of the statistical methodology, its application to MOX fuel rods and the current status of its introduction into licensing will be given.

2. MOX FUEL CHARACTERISTICS AND THEIR MODELLING WITH CAR0

The insertion of MOX fuel assemblies in a reactor core normally takes place after insertion of already licensed UO_2 fuel assemblies.

To perform design calculations, all aspects of MOX fuel which could lead to a different behavior, have to be considered: material properties, neutronic de-sign characteristics, and irradiation behavior. The following points have to be addressed:

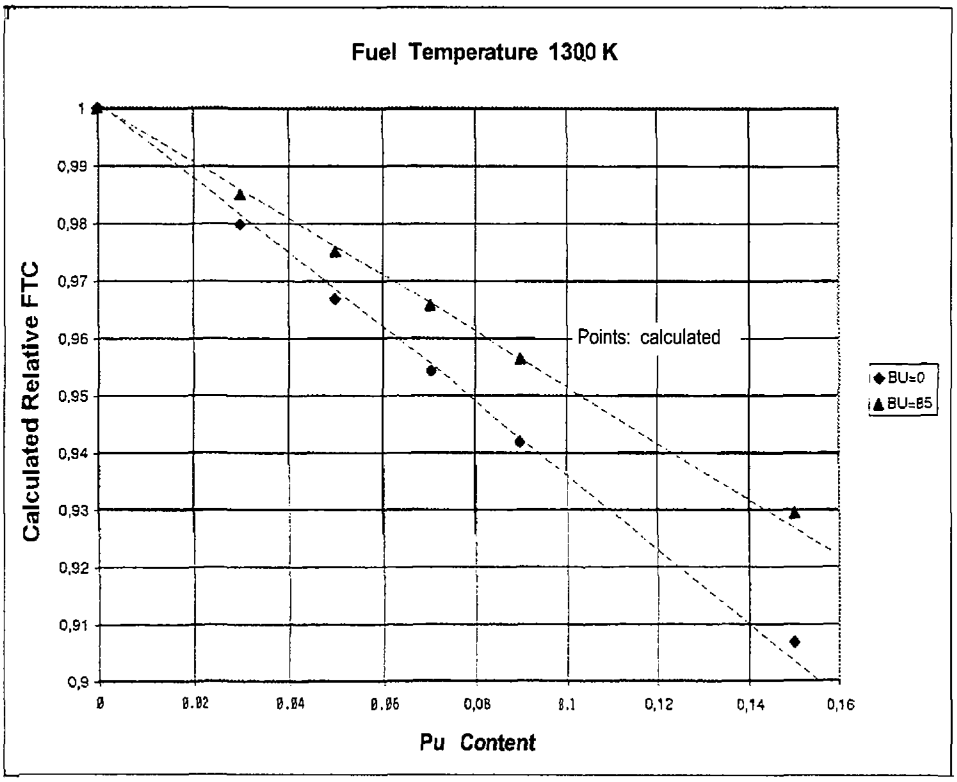

FIG. 1: Relative fuel thermal conductivity reduction versus Pu content

a) material properties of MOX fuel
  - melting point as a function of burnup
  - fuel thermal heat conductivity as a function of burnup
  - grain size, porosity distribution
  - thermal elongation

b) neutronic design characteristics
  - radial power density distribution in the pellet
  - power histories
  - neutron flux

c) irradiation behavior
  - fission gas release, ratio of Xe to Kr
  - densification / swelling of the fuel
  - He release

Examples of the modeling of these effects in the fuel rod code CAR0 are given in the following Figures. Figure 1 shows the reduction of the fuel thermal conductivity versus the Pu content. The reduction decreases with burnup due to the saturation of the influence of the defect concentration on the fuel thermal conductivity. In Figure 2, the radial power density distribution of MOX fuel compared to UO_2 fuel is given for a burnup of 0, 30, and 70 MWd/kgM. These two examples show minor differences between UO_2 and MOX fuel, but the next feature has significant influence: the evolution of linear heat generation rate with time. Figure 3 indicates two power histories of equal burnup, one for UO_2 fuel and one for MOX fuel, with the typically slower decrease of reactivity for MOX fuel. This, in turn, leads to a relatively higher fission gas release of MOX fuel rods. It can be asked if this typical difference in power histories explains the observed higher fission gas release of MOX fuel.

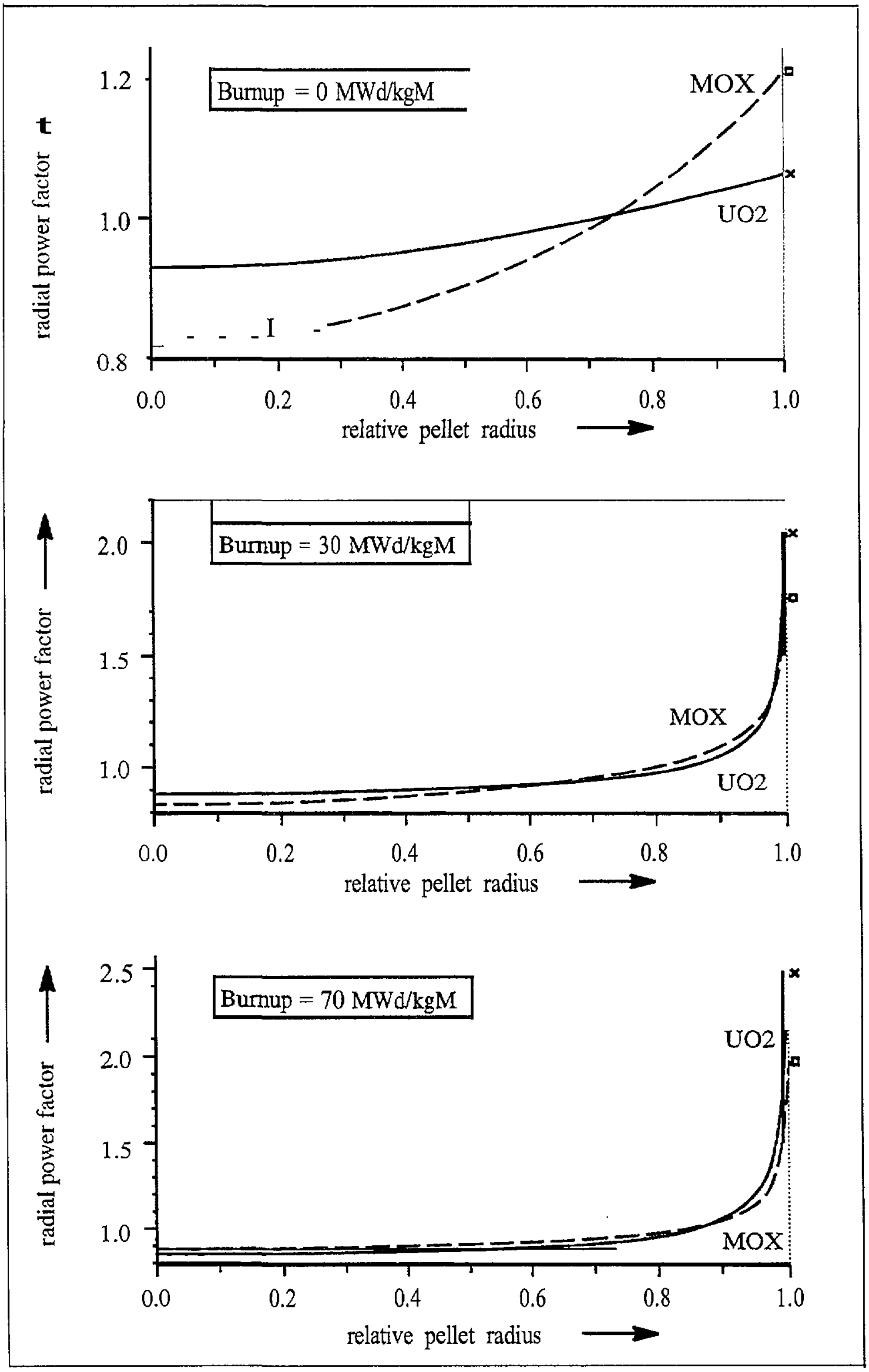

FIG. 2: Radial power density distribution for different burnups

For CARO this question can be answered as follows: Taking into account the above mentioned MOX features explicitly via modeling of the separate effects or implicitly via validation by a broad data base of measured values, see Table 1, it is demonstrated by Figure 4, that there is no systematic deviation between calculated and measured fission gas release values for UO_2 and MOX fuel, using the same set of modeling parameters. This is also confirmed by [5], [6], [7].

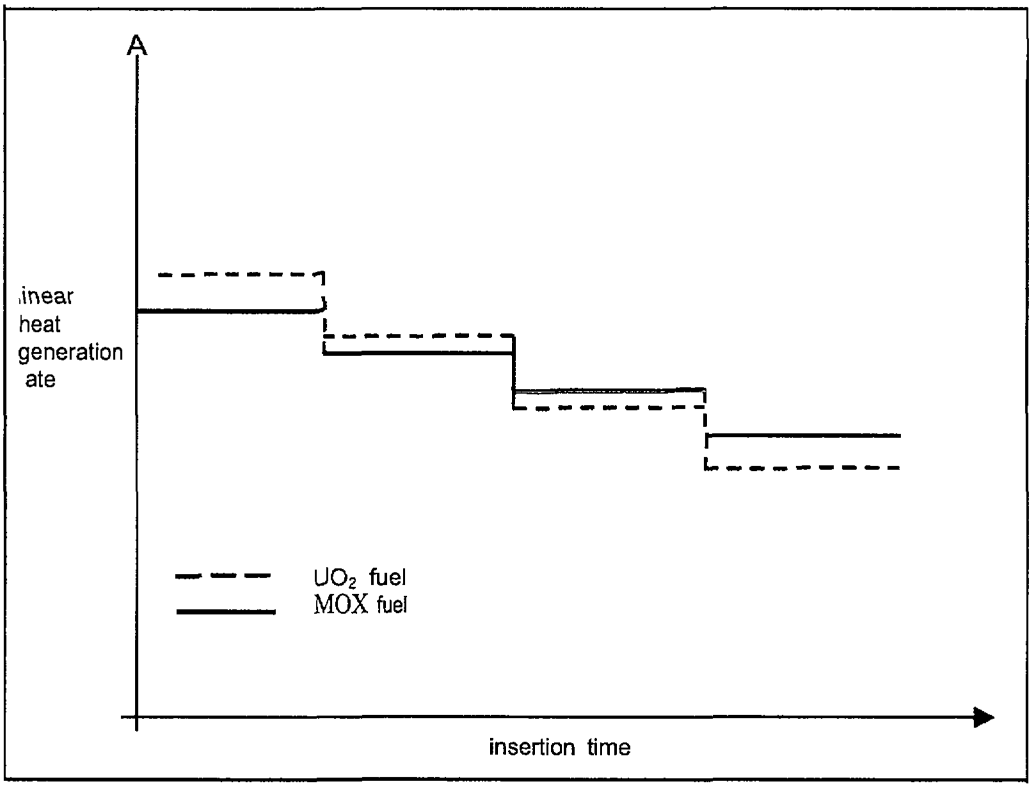

FIG. 3: *Typical power histories for* UO_2 and *MOX fuel* with *equal* burnup

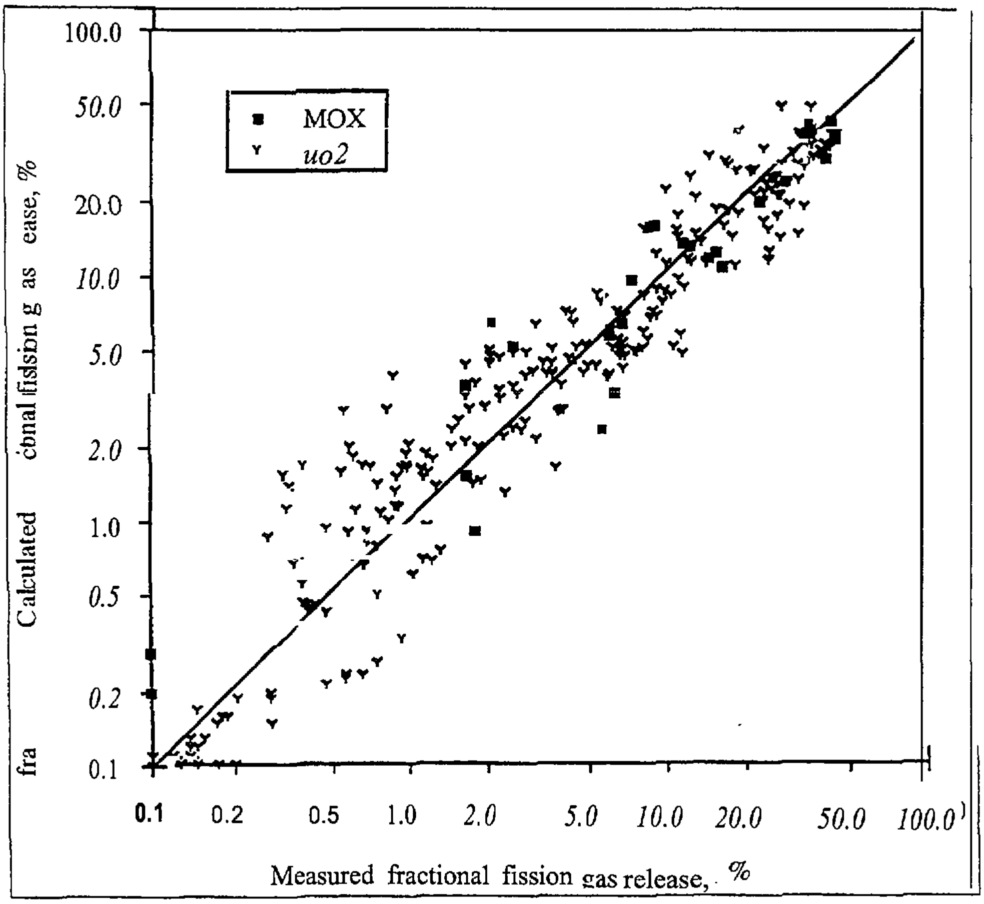

FIG. 4: Validation of the fission gas release model for PWR fuel rods: Comparison measured/with CARO calculated values

TABLE 1. VALIDATION DATA BASE FOR CARO: FISSION GAS **RELEASE VALUES** FOR **PWR** FUEL

	1990	1996	1999
Number of fuel rods	114	267	316
Maximum fuel rod burnup [MWd/kg]	53.5	77.8	90
Number of fuel rods with burnup > 60 MWd/kg		4	19
Number of fuel rods with MOX fuel	**13**	**28**	**40**

3. STATISTICAL METHODS

Statistical methods in fuel rod design have received more and more attention during the last years. This is demonstrated not only by some recent publications on this subject, c.f. [8] to [13], but also by the fact that the American National Standard for Light Water Reactors, Fuel Assembly Mechanical Design and Evaluation [14], quotes explicitly the option to use "probability analyses in which the variances of independent parameters are statistically combined".

Of course there are different ways to use statistical methods in fuel rod design, as described e. g. in [9] or [11]. One method is presented in short in the following. It has been applied to fuel rod licensing for several projects, both PWR and BWR, UO_2 and MOX fuel.

3.1 Description of the method

The scheme of the statistical method is shown in Figure 5 (a description in more detail is given in [15]): Monte Carlo calculations are performed using the fuel rod code CARO. For each run with CARO, the set of input data is modified: parameters describing the design of the fuel rod (geometrical data, density etc.) and modeling parameters are randomly selected according to their individual distributions. Power histories are varied systematically in a way that each power history of the relevant core management calculation is represented in the Monte Carlo calculations with equal frequency. (The complete set of all occurring power histories is provided by nuclear core design via interface data file, which is automatically transformed into an input data file for the fuel rod code.)

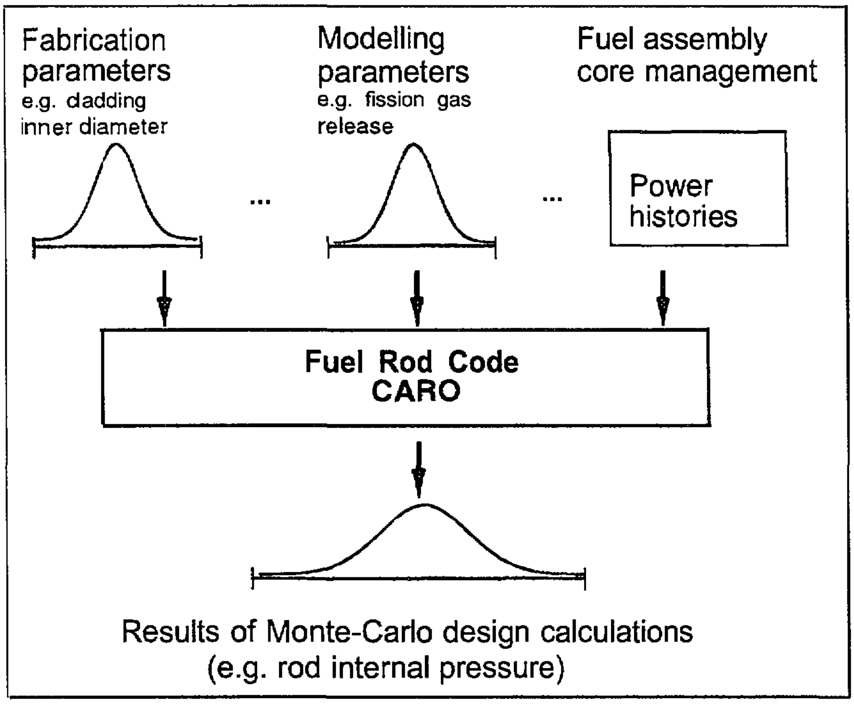

FIG. 5: Scheme of statistical fuel rod design

The frequency distributions of the results as rod internal prasure and equivalent cladding strain which are generated by the Monte Carlo calculations are evaluated and compared with the design criteria.

By this methodology, two aspects of fuel rod design are getting higher importance than within the frame of conservative deterministic methods: the distributions of fabrication parameters and the consideration of power histories.

3.2 Treatment of fabrication parameters

For conservative deterministic design calculations, only the tolerance limits of fabrication parameters are important. For statistical design calculations, certain assumptions on the distribution of the most important fabrication parameters are necessary.

It was shown by exhaustive statistical analyses of quality control data, e. g. of pellet diameter and cladding inner diameter [16], that the following assumption is justified: all distributions of fabrication parameters are represented by a Gaussian distribution, cut off at 3 σ, where the ± 3 o-limits coincide with the two tolerance limits.

3.3 Treatment of power histories

As statistical calculations are based on a set of real given power histories from a certain core management calculation, it has to be checked if the design analyses are valid for following cycles, too.

Additionally, variations of the set of power histories from cycle to cycle should be covered and margins for core management purposes should be available. Therefore, the Monte Carlo calculations are performed with modified power histories: The original fuel rod power factors of each cycle, resulting from core management calculations, are multiplied by chance and independent of each other with a constant factor. This factor has a Gaussian distribution around 1 with a scattering of 2 σ (the distribution is cut off at 2 σ).

By this method the batch averaged burnup stays about constant. The maximum fuel rod burnup increases slightly because some power histories which have already a relatively high burnup are multiplied by chance by factors greater than 1 in the average. The power jumps between two cycles, important for fission gas release, are partly increased also.

An example for a typical 1300 MW PWR is given in Figure 6: In this case, the fuel rod powers are multiplied by a value of + 20 %. This means that the factors are in the interval [0.8, 1.21. For each burnup interval (steps of 0.1 MWd/kg(U)) the maximum fuel rod averaged power (including the described statistical variation) of each fuel assembly is plotted against fuel rod burnup, together with an upper envelope. With this set of power histories, the design analysis is performed and the design criteria have to be fulfilled.

In the same Figure, a dashed curve is integrated which is the upper envelope of the maximum powers <u>without</u> statistical variation. The gap between the two curves provides the desired margins..

4. APPLICATION OF THE STATISTICAL METHODOLOGY TO MOX FUEL RODS

As discussed in Chapter 2, higher fission gas release can be expected for MOX fuel rods compared to UO_2 fuel rods, if burnup and fuel management strategy are the same. Especially in case of a fuel rod design analysis for high burnup in connection with highly demanding power histories, a realistic assessment of the expected behavior of the fuel rods is important. This realistic assessment can be assured by using the statistical design methodology, based on a fuel rod code which is validated against a broad database of experience feedback up to high On the basis of a realistically calculated distribution of the expected maximum rod internal pressure values the decision on the feasibility of a fuel reload scheme is much better justified than on deterministic worst results with unknown margins, not taking into account the expected frequency of the occurrence of such results.

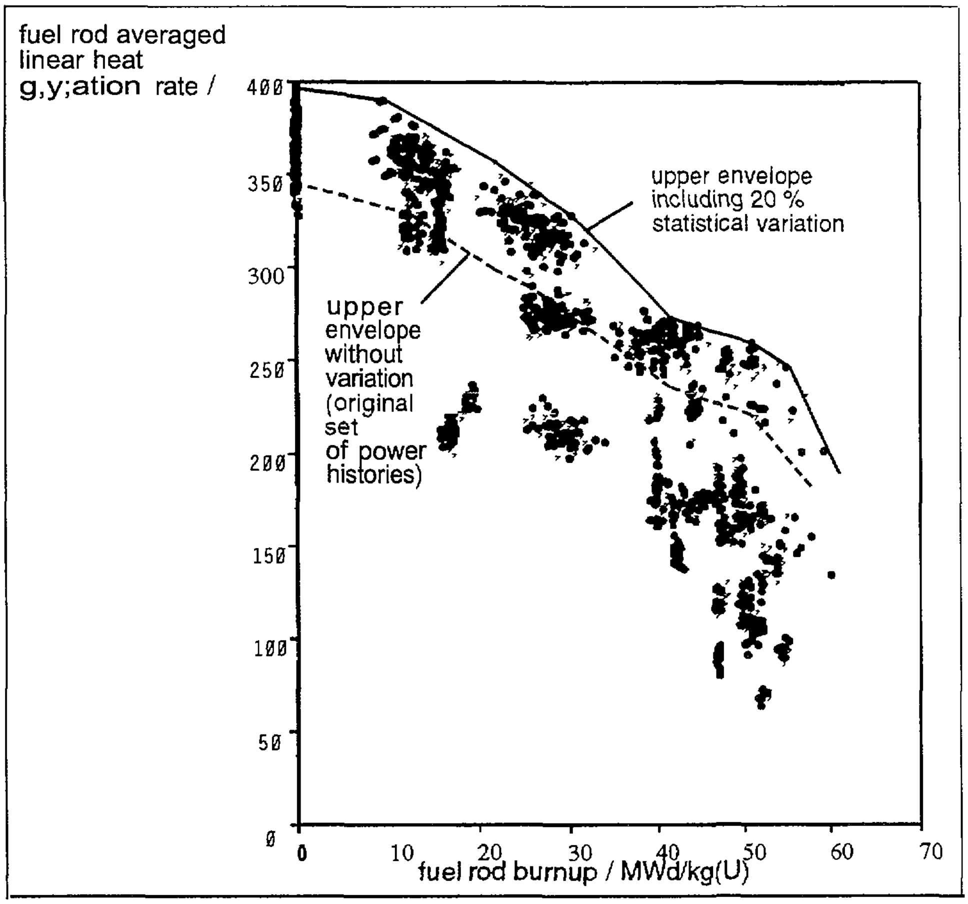

FIG. 6: Comparison of maximum averaged fuel rod linear heat generation rate with and without statistical variation

In Figure 7, two examples of maximum fuel rod internal pressure distributions are shown for two different plants A/B, containing fuel rods with/without lower plenum. The corresponding burnup distributions, depending on the individual optimized reload strategy for each plant, include values up to 69 resp. 67 MWd/kg(M).

From the results of the Monte Carlo calculations (several thousand runs with CAR0 in each case) it can be derived, that the internal pressure of a certain limited number of rods exceeds the coolant pressure with a certain probability, but the small number of extreme values of the distribution do not violate the design criteria.

5. STATUS OF INTRODUCTION INTO LICENSING

The confirmation of the statistical methodology as an appropriate tool for design analysis was given by the fact, that this methodology has been accepted by our customers, see e.g. [3], and successfully applied for licensing. The Swiss Federal Nuclear Safety Inspectorate (HSK) published its positive assessment of our methodology in [17].

Up to now licensing analyses with statistical methods have been performed for 10 different plants in 3 countries, for PWR and BWR, and for UO_2 and MOX fuel rods. Another analysis, using statistical methods, the calculation of core damage extent during a hypothetical loss of coolant accident, is currently being licensed.

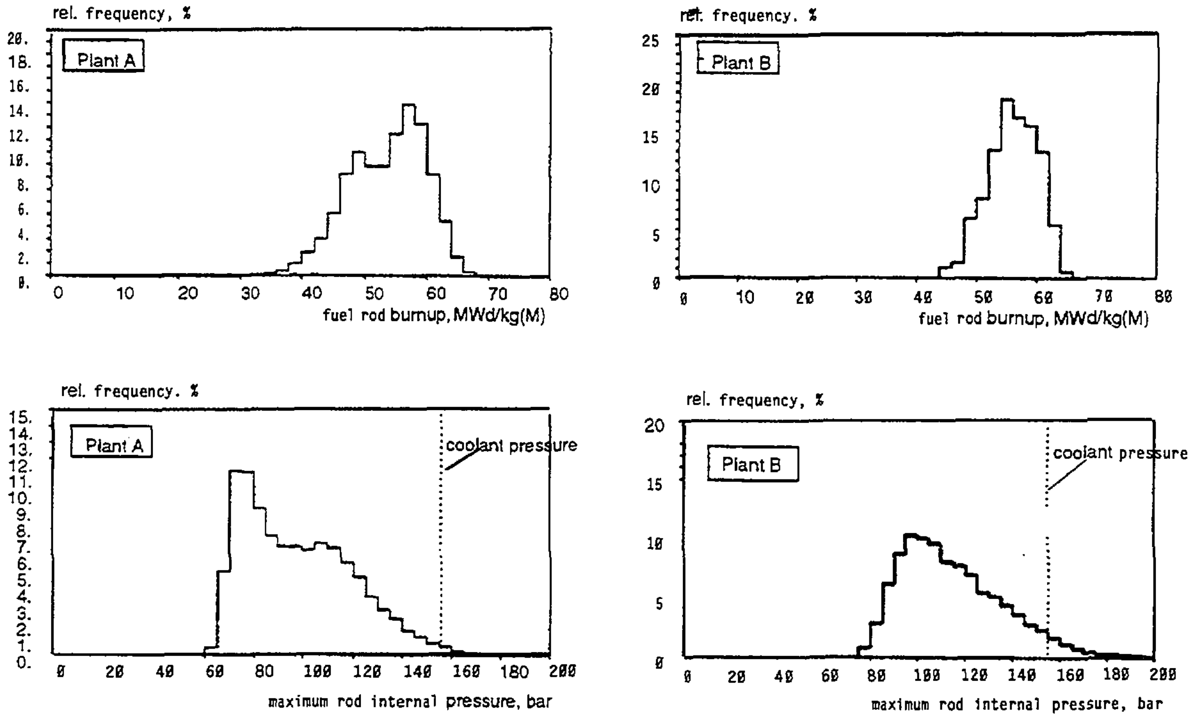

FIG. 7: Frequency distributions of fuel rod burnup and maximum rod internal pressure for MOX fuel rods in two plants

The introduction of the new methodology revealed interesting discussions with customers and licensing authorities which led to improvements and further development of the statistical methods.

6. SUMMARY AND OUTLOOK

The advantages of the fuel rod design using statistical methods in connection with a modern fuel rod code (burnup dependent fuel thermal conductivity, mechanistic fission gas release model and validation against a data base up to high burnups) have been largely discussed in [15].

The improvements of fuel rod design consist of:

- consistent treatment of code uncertainties and distributions of fabrication parameters
- possible sensitivity assessment of fabrication parameter effects and power history influences
- realistic assessment of margins, especially for higher burnups and more demanding core management strategies, e.g. for MOX fuel
- possible on-line fuel rod design with core management calculations
- possible extension to class-2 and core damage extent analysis
- possible consistent extension to dry storage design analyses

The statistical design methodology is a powerful tool to realistically assess the behavior of the fuel rods in a reactor core. It has the capability of characterizing the degree of conservatism through the statistical evaluation of numbers of fuel rods coming close to a design limit or by making statements about the statistical certainty for the actual occurrence of extreme cases. Since fuel insertion conditions are becoming more and more demanding as well as knowledge about performance affecting mechanisms and experience data bases has been increasing, the classical deterministic method should be replaced by a statistical one which provides more, especially more differentiated information about fuel rod behavior.

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