

## VERIFICATION OF STRESS CALCULATIONS FOR COATED FUEL PARTICLES BY A SPECIFIC IRRADIATION EXPERIMENT

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### SUMMARY

A specific irradiation experiment has been performed to test a mathematical model for calculation of stresses in coating layers of fuel particles for a high-temperature reactor. The model was established by H. Walther, SORIN. (Lectures explaining the model and its application were given on the 1st SMiRT Conference C1/1 and C1/2.)

The stresses are induced mainly by the internal fission gas pressure and the fast dose induced dimensional changes of the coating material. High stresses can lead to breakage of the PyC- and SiC-coating layers, which results in unwanted release of fission gases.

The aim of the model is to provide evidence on the mechanical behaviour during irradiation and predict the lifetime (irradiation time until breakage) of a coated particle.

In order to get proof on the validity of the model an extensive irradiation experiment was carried out. The layout of the experiment was based upon earlier model calculations. The experiment was laid out to provide an optimum of information for investigation of the model under two different aspects: a) Does the model adequately describe all relevant mechanisms (i.e. interaction between different layers, creep, etc.)? b) Are the input material data sufficiently correct?

Since the original calculations were performed a better knowledge of material data has been obtained, therefore new stress calculations with the modified material data were performed. From these it appeared, that the actual lifetime of all particle types which were tested could be brought in a relatively good accordance with the model predictions by fitting only one material property, namely the fast dose induced creep of the PyC-coating.

It was found, that in the low dose region, where this experiment was carried out, the creep could not be regarded to be a constant, which originally was anticipated in the stress model. Instead of constant creep a transient creep must be assumed for low doses of fast neutrons. As the original model is not able to take this into account, it was simulated in the new calculations by using creep as a linear function of fast neutron dose in the input data.

Fifteen different particle types were each irradiated up to three different end-dose values. In a total of 45 combinations the agreement between calculations and actual results therefore had to be established.

With a very few exceptions a good agreement between the predictions and the results of the irradiation appeared concerning the lifetime. But there is much evidence that for the exceptions a chemical reaction (amoeba effect) took place, and this mechanism is not incorporated in the stress model. Therefore the new and significant results of the experiment were, that it is possible with adequate accuracy to predict the lifetime of coated particle fuel for high-temperature reactor use by aid of the stress model, when modified input data are used.

Verification of Stress Calculations for Coated Fuel Particles  
by a Specific Irradiation Experiment

1. Introduction

Coated particles are used as fuel in a High Temperature Reactor (HTR). Generally they consist of a spherical fuel kernel with a diameter between 200 and 800  $\mu\text{m}$  that is surrounded by different concentric coating layers either pyrocarbon (PyC) alone or a combination of pyrocarbon and siliconcarbide (SiC). The objective of the coating is to retain the fission products inside the particle until the end of irradiation. Figure 1 shows the two different types of coated particles, plain PyC coated particles (a) and a PyC coated particle with a SiC interlayer (b). In (a) the fuel kernel is surrounded by a very low density highly porous PyC layer, the so-called buffer layer. This is surrounded by a high density isotropic pyrocarbon layer (PyC-HDI). The buffer layer has to accommodate the fission recoils and the fission gases. The outer layer acts as a pressure vessel for the fission gases and a diffusion barrier for the solid fission products. This type is called the BISO-particle. (b) shows a particle that has an additional siliconcarbide layer which is inserted into the outer PyC-HDI layer. Thus the retention of solid fission products can be improved. This type is called the TRISO-particle.

2.1 Outline of the stress model

A model to predict the mechanical performance of coated particle fuel under irradiation in an HTR has been developed by Dr. Walther (SORIN). This model calculates the stresses in the coatings which are induced for instance by the fission gas pressure and the fast neutron dose induced dimensional changes of the coating materials and various other factors. This model and its application was described in detail in two lectures held at the First International Conference on Structural Mechanics in Reactor Technology, Part C, in 1971. The aim of the model is to calculate the lifetime of a coated particle which means it calculates the fast dose or burn-up or irradiation time at which the circumferential stresses in the coatings exceed their rupture stress so that the coating breaks and the fission products retained until then are released.

The purpose of the stress model is to use it for optimising the design of a coated particle such that it can withstand a desired burn-up and fast dose under certain reactor conditions such as fast flux and temperature.

There were questions open concerning the validity of the model

- a) if all mechanisms contributing to the generation of stress are taken into account adequately,
- b) if the material data used for input in the calculation are good enough.

As far as point (b) is concerned it may be remarked that the result of the calculation is influenced very much by the fast dose induced creep rate of the PyC. This quantity is difficult to measure and therefore not well defined.

## 2.2 The Coated Particle Irradiation Test

When the stress model was established in 1968 it was regarded as useful to confirm it by an irradiation test. It was desired to get evidence concerning the two points mentioned before. Therefore a coated particle irradiation test especially with regard to the stress model was planned. The contributors to this experiment were: The Dragon Project which performed the irradiation in the Dragon Reactor, KEMA, Holland, fabricated the kernels, SORIN, Italy, who made the stress calculation for the layout of the test and KFA, Jülich, who performed the stress calculation and evaluation after irradiation, the coating and the characterization of the particles and the postirradiation examination.

The specification of the particles is given in the table. The fuel composition was natural  $UO_2$  20 % and 40 % enriched  $UO_2$ . Within each enrichment 5 particle types were made partly with a plain pyrocarbon coating and with an additional SiC coating interlayer.

Each particle sort was irradiated up to three different fast dose values. These were 3.5, 7 and  $10.5 \times 10^{20}$  EDN; the nominal irradiation temperature was  $1300^\circ C$ .

By this layout of the experiment it was intended that some of the particle types should fail during the first, the second and the third irradiation cycle respectively and some should survive the whole irradiation. Thus one might expect a broad spectrum of test results to compare with the prediction of the calculation.

## 3. Calculations after irradiation, comparison with test results

The material data used in the calculation which mainly influence the results i.e. the fast dose induced dimensional changes of the PyC-HDI have been modified since the layout of the test. Therefore new stress calculations with the latest material data that were recommended by the Dragon Project were done after the irradiation was completed. A first calculation using a constant creep rate for the pyrocarbon showed that the stresses calculated for the layers of the coated particle change rapidly in the low dose range where the irradiation was performed. This can be seen from figures 2 and 3 where the tangential stresses of the significant layers of the coated particle without and with SiC interlayer are plotted versus the fast dose. There is practically no burn-up in the particular particles so the stresses are generated by the fast dose alone.

In normal stress calculations which go up to dose values of about  $40 \times 10^{20}$  EDN the creep rate is regarded as being constant as the stresses are nearly constant in the higher dose ranges which shows up in figures 2 and 3. This test was partly performed in a range where the stresses change very rapidly for plain PyC particles and do so even more for particles with SiC interlayer which is shown in figures 2 and 3. In this transient region the creep rate cannot be regarded as a constant, this fact suggests to treat the creep rate as a function of dose being high where the stresses change fast and decreasing to a constant value where the stresses become more or less constant.

Several calculations were done in order to get agreement between test and calculation results with different creep rate functions. The best agreement was achieved by fitting the creep rate in the following way:

- a) for plain PyC coated particles, with  $K_0$  being the creep constant as recommended by the Dragon Project the creep rate  $K$  was taken to be  $2 \times K_0$  at dose 0 decreasing linearly to  $K_0$  between dose 0 and  $8 \times 10^{20}$  EDN  $\text{cm}^{-2}$  and then remaining constant =  $K_0$  for higher dose values.
- b) for particles with SiC interlayer with significantly higher changes of stress the creep rate at dose 0 was taken to be  $4 K_0$  then decreasing as in case a).

In the model calculation the end of life of a particle was assumed when its calculated tangential stresses exceeded its rupture stress which was  $2000 \text{ kp/cm}^2$  for PyC. For SiC a range between 0 and  $3500 \text{ kp/cm}^2$  was assumed.

A preliminary calculation was done using a release rate of the fission gas from the kernel which had been measured for small kernels it gave a fairly good agreement with the test results. When the release rate from the kernels for all particle types of this test consisting of small and large kernels had been measured at Seibersdorf the stress calculations were repeated with these new values. The table shows the results of the visual inspection of the coated particles after irradiation and for comparison the results of the calculation with the creep rate quoted before.

The table gives the specification of each particle sort and below this the obtained dose value where a set of particles was taken out of the reactor is indicated. The circles in each irradiation cycle refer to the outcome of the visual examination of the test results: a plain circle means no breakage a circle, with a diagonal line means breakage begins and if the circle contains a cross complete fracture occurs during the cycle.

The calculation results are indicated by hatched areas. Here breakage occurs where the hatched areas begin.

No particles with natural uranium broke. Furthermore nearly all particles with  $400 \mu\text{m}$  kernels remained intact. There is only one type with a low density isotropic pyrocarbon layer plus SiC interlayer which starts to fail in agreement with the calculation result. Generally the start of failure predicted by the calculation lies between the observed start of failure and complete failure.

Keeping in mind the spread and uncertainties of the material properties arising during fabrication of the particles the agreement between test and calculation may be called satisfactory.

#### 4. Conclusions

Summarizing the outcome of this experiment, it can be said that it was possible to fit the results of the stress calculations to the test results of 15 particle types irradiated each up to 3 dose values (which means 45 cases altogether) just by fitting only one material property, the creep, which was necessary because of the low dose range where the particles were irradiated. There is much evidence that the significant mechanisms contributing to stress generation are taken into account in the model adequately, some care has to be taken that the most correct material data are used.

Acknowledgement

The above results origin from a joint experiment with participation from OECD Dragon Project (based at Winfrith, England) SORIN (Italy), KEMA (Holland) and KFA (Germany).

SORIN and KFA carried out the stress model calculations, KEMA prepared the fuel kernels of the sol-gel type, KFA performed the coating, the characterization, the pre- and post-irradiation examination of the particles and the OECD Dragon Project the irradiation of the experiment in the core of the Dragon Reactor at Winfrith.

Since the initial discussions took place in 1968 a lot of persons have contributed with excellent and valuable work for which they are acknowledged. The contributions of the following participants are particularly acknowledged; SORIN - Dr. H. Walther; KEMA - Dr. M.E.A. Hermans and Dr. J. Kani; KFA - Prof. Dr. H. Nickel, Mr. J. Baier, Dr. K. Bongartz, Dr. K. Drittler, Dr. E. Gyarmati and Mr. H. Hougaard; Dragon Project - Dr. L. W. Graham, Mr. R. Manzel and Mr. M.R. Everett.

The joint experiment has been successfully carried out and quite apart from the material advantages and wider scope possible in a collaborative exercise it has derived considerable benefit from the fund of ideas, opinions and experience which are available in multi-organizational participation.

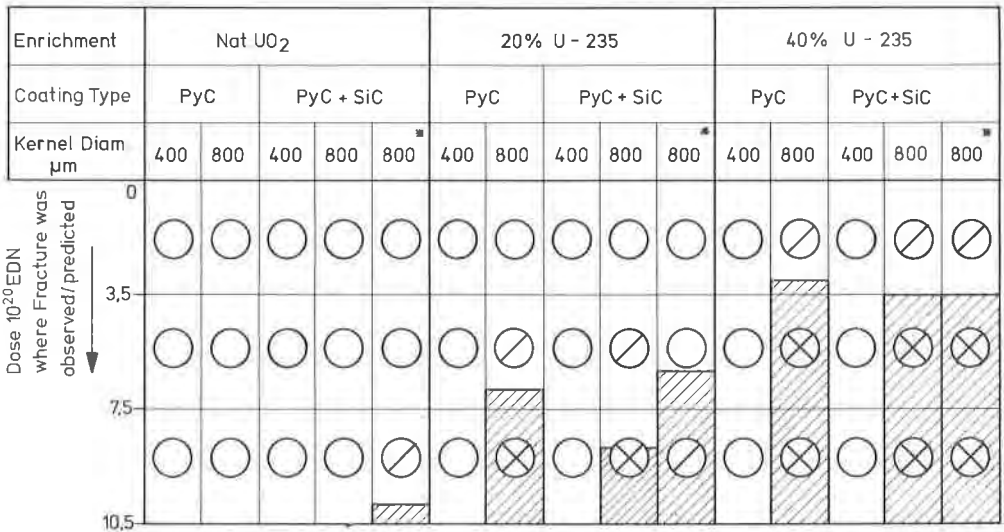


Table: Comparison between calculated and observed Lifetimes in Test DR - P4

\* This Particle had a Low Density PyC Coating.

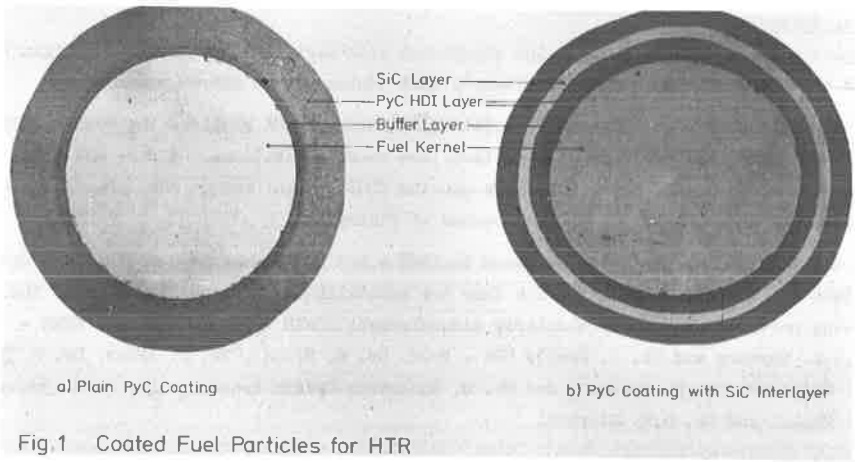


Fig.1 Coated Fuel Particles for HTR

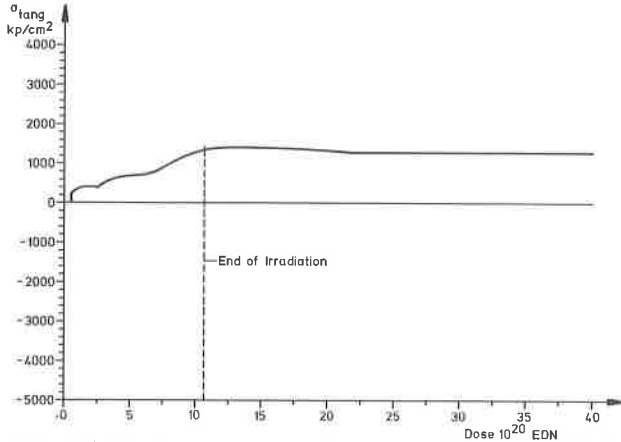


Fig.2 Fast Dose induced tangential Stresses in plain PyC Coated Particle

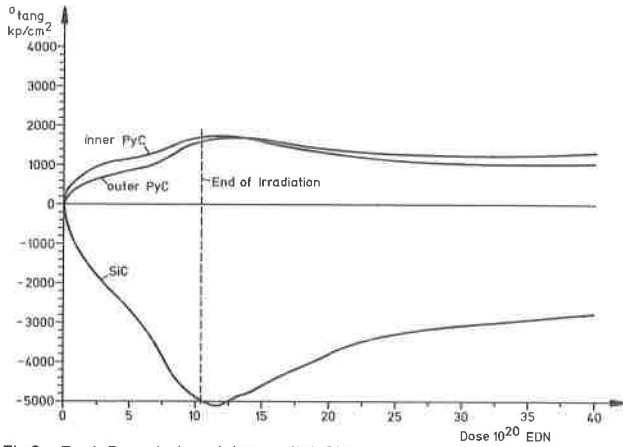


Fig.3 Fast Dose induced tangential Stresses in Coated Particle with SiC Interlayer