Extension of an HTR Coated Particle Failure Model to Special Applications

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Abstract

Various aspects of a model for pressure vessel failure prediction of the coated particle fuel in High Temperature Reactors (HTR) have been presented at previous SMiRT conferences. This Model has recently been extended to incorporate a new failure mechanism of the coated particles, namely silicon carbide (SiC) damage prior to irradiation.

In the older model failure of the fuel particles was assumed to occur when the fission gas pressure caused its main load bearing coating layer, i. e. a SiC shell to break. As a consequence the two adjacent pyrocarbon (PyC) shells also break. Particles may however already have a certain fraction of damaged SiC layers prior to irradiation but still intact PyC layers. These were considered as failed from the beginning of irradiation. In-pile measurement of fission gas release showed that there is a performanced benefit which steams from the gas retention of the intact PyC layers.

The new mechanism treats the PyC layers as load bearing shells in case of SiC damage prior to irradiation. Incorporation of this mechanism into the model resulted in fission gas release predictions being a factor of 10 below previous predictions. Thus the calculated releases were in fairly good agreement with the measurements.

1. Introduction

A pressure vessel failure model for HTR coated particle fuel has been development and sucsessfully applied over a period of years. It is a streamlined version of older models [1] [2] [3]. The various stages of development have been presented at previous SMiRT conferences.

The coated particle in its current design (see fig. 1) is a tiny spherical pressure vessel with an outer diameter of about 1 mm. It consists of

- a fuel kernel where fission gas and solid fission products are produced.
- a porous pyrocarbon (PyC) buffer layer which has to accommodate the fission gases in its pores.

- a combination of a SiC layer embedded in two dense PyC layers, which form the primary barrier to gaseous and metallic fission products.

The SiC layer acts as the principle load bearing shell for the fission gases and diffusion barrier for the solid fission products. The objective of the two dense PyC layers is to provide:

- a compressive stress for the SiC layer as a result of their irradiation induced shringkage
- a chemical protection for the SiC layer against solid fission products from the kernel.

This particle design is called the TRISO particle. The idea on which the pressure vessel stress model is based is as follows:

The fission gas pressure acts on the inner dense PyC layer which is elastic. The pressure is almost completely transmitted through this layer onto the rigid SiC layer, which therefore takes up the entire stress due to the gases. The resulting tangential stress in the SiC is relieved by the irradiation induced shrinkage of the two PyC layers which induce an opposite compressive component to the SiC stress. The model calculates the resulting tangential stress in the SiC. Particle failure is assumed when the calculated SiC stress exceeds its strength which is a measurable quantity [4] . The SiC layer breaks and as a consequence the two PyC layers break as well, due to the strain energy release at the onset on SiC failure.

This basic model has been continuously extended and refined. The major steps were taking into account:

- the fabrication induced statistical scatter of the particle parameters.
- the material inherent scatter of the SiC strength [5] .

This allowed the calculation of the statistical evolution of particle failure during irradiation. We will call the failure treated by the STRESS model so far "Category I failure".

Some irradiation results indicated that there exists a further failure mode which may contribute significantly to fission product release. It has not yet been treated by the model. The model proved itself flexible enough to have this failure mode incorporated as well.

2. The New Coated Particle Failure Mode to be Incorporated into the STRESS Model

The coated particles may already have defective SiC layers as a result of manufacturing abnormalities, the fundamental point of which is that the SiC has lost its load bearing capability even before irradiation. In this case the STRESS model was not applied. The prediction of the failure rate to be expected in the reactor was simply based on the assumption that the fraction of failed particles was defined by the fraction of particles with defective SiC layers. No performance benefits were claimed as result of the retention of gaseous fission products by the intact impermeable PyC layers. Measured in-pile fission gas release on such particles remained considerably below the predicted values, derived fron the fraction of defect SiC layers. This led to the conclusion that the previous assumption was too pessimistic. This had an adverse impact on plant design in that gaseous release represents a large contribution to circulating activity levels. An extension to the current pressure vessel performance model to treat partial TRISO failure (i. e. failed SiC and intact PyC layers) would remove unwarranted conservatism and lead to greater flexibility in fuel and plant designs.

Two irradiation experiments supported this point clearly. One of these experiments (HT-33 performated by ORNL and GA) included irradiation of TRISO coated fuel run to peak conditions. The post irradiation results [6] showed that while the Cs release indicated that 100 % of the SiC layers were defective, the total coating failure based on fission gas release appeared to be significantly lower. A second experiment (HT-34) was an accelerated irradiation test of TRISO particles [7] . In this test, the observed SiC failure ranged between 5 and 100 % whereas fission gas release indicated that total particle failure was up to 10 times less than the value expected from SiC failure. Pressure vessel (category I failure) calcualtions predicted zero SiC failure during irradiation. Therefore it could be concluded that in both tests the SiC must have been defective prior to irradiation. In order to achieve a more realistic prediction for TRISO particles with defective SiC layers prior to irradiation, which we call category II failure, this failure mode was incorporated into the STRESS model.

3. Outline of the New Mechanism

For a particle with a defective SiC layer prior to irradiation the following situation exists. During the first period of irradiation, the SiC layer is under compression due to the shrinkage of the two dense PyC layers. With increasing burn-up the fission gas induces a tensile stress component into the SiC such that its stress goes from compression into tension. As a defective SiC layer cannot bear any tensile stress the fission gas pressure is taken over by the two intact PyC layers as soon as the SiC stress goes through zero. At this moment there is a discontinuous increase in stress in the two PyC layers which could lead to rupture of these layers i. e. particle failure.

The model calculates category II failure using a Monte Carlo routine for the random selection of the particle parameters which are considered to be distributed according to Gauss. These are needed for the calculation of coating stresses. Another random set of rupture stresses for the SiC and the two PyC layers which are distributed according to Weibull [4] is selected as well.

Category II failure calculation is based on calculating inner pyrolytic carbon (IPyC) and outer pyrolytic carbon (OPyC) stresses at the instant the SiC stress changes from compressive to tensile (i. e. zero condition of SiC stress). The PyC stresses are then compared with their fracture strengths and particle failure occurs when both IPyC and OPyC layers have failed. If either the IPyC or OPyC layer survives for this condition, the particle is assumed to survive throughout the remainder of irradiation. The underlying assumption is that peak PyC stresses occur at this point and that irradiation induced creep relaxes stresses for higher exposures.

4. Comparison between Model Calculations and Experimental Results

4.1 Calibration of the Model Versus Experimental Results

The new failure mechanism is very sensitive to the strength distribution of the dense PyC which is used in the calculation. This is a Weibull distribution [5]

$$W(\sigma) = 1 - \exp\left[\ln 0.5 \times \left(\frac{\sigma}{\bar{\sigma}}\right)^{m}\right] \quad (1)$$

$W(\sigma)$ is the cumulative distribution for the strength. $\bar{\sigma}$ is the median strength and m the Weibull parameter which is a measure for the width of the distribution. m and $\bar{\sigma}$ were determined by an empirical normalization procedure that involved the following steps:

- selection of a representative TRISO fuel batch (HT-33 fuel with 100 % SiC failure determined from metallic release [6]);
- performing an iterative series of calculations using different $\bar{\sigma}$ and m values with the new routine;
- selecting $\bar{\sigma}$ and m values that were consistent with observed PyC failure.

This procedure resulted in a self consistent set of parameters ($\bar{\sigma}$ = 160 MPa and m = 4). Furthermore these values are consistent with failure strength distribution measurements performed on PyC rings [5] .

4.2 Calculation of PyC Failure Rates with the New Model for a Special Irradiation Experiment

Capsule HT-34 was an accelerated irradiation test [7] with 8 different batches of coated particles in a burn-up range between 6 and 12.7 % fima. From the Cs release, the SiC failure fraction was determined to be between 5.3 and 100 %. Category I failure calculations indicated that SiC failure to be expected during irradiation was very low. On the other hand fission gas release indicated that the fraction of totally failed particles was significantly below the SiC failure. Therefore SiC failure was attributed to defective SiC prior to irradiation. The expected PyC failure of fuel with defective SiC layers was then determined by category II failure calculations. Figure 2 is a plot of the predicted versus the observed total failure probabilities (derived from Kr-85 release) for HT-34 data. The open circles mark the predition based on the fraction of defective SiC prior to irradiation, the solid circles the prediction based on category II pressure failure calculations. The numbers above the circles singnify the particle batch and its irradiation conditions. The solid line defines ideal agreement between prediction and observation. The plot shows that failure rate predictions based on defective SiC lie a factor of 10 above this line. The category II calculations shift the predictions near to this line. The higher than predicted total failure of batch number 7 was rationalized on the basis of an adverse combination of large particle diameter and high irradiation temperature; these effects may be acting synergistically to initiate chemical reactions and increase stresses which are not directly attributable to pressure vessel failure. With this exception all category II results are in reasonable agreement with the observed results.

5. Conclusions

Pressure vessel failure calculations have been used for the prediction of coated particle fuel failure under irradiation. They account for two failure modes:

- Category I failure, which is termed classical pressure vessel failure and is characterized by a load bearing SiC layer. Failure occurs when the SiC stress exceeds its strength;
- Category II failure which is termed defective SiC pressure vessel failure. The defective SiC layer is incapable of bearing a tensile stress and the PyC layers are the structural support containing the fission gas pressure. Failure occurs when the PyC coatings break.

Category II type failure was incorporated into the model. It predicts 2.6×10^{-3} failure for fuel containing 2.6×10^{-2} defective SiC layers prior to irradiation. It implies that the PyC layers can retain short lived gaseous isotopes in the event of SiC failure caused by a defective coating or chemical degradation of the SiC in the early stages of irradiation.

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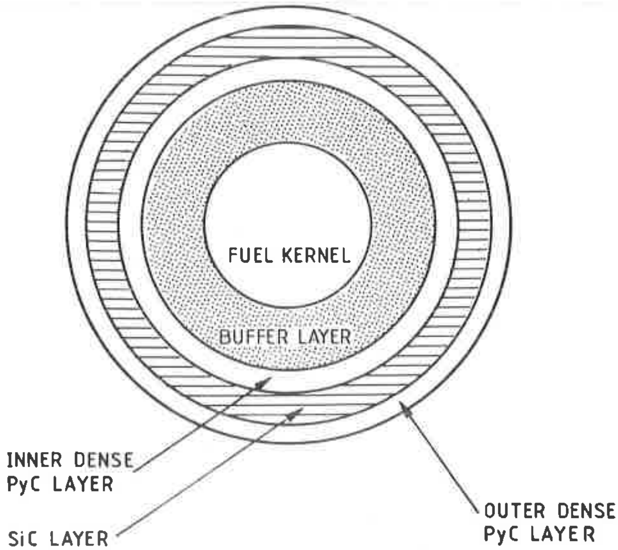

fig. 1 TRISO-coated particle geometry used in pressure vessel performance model.

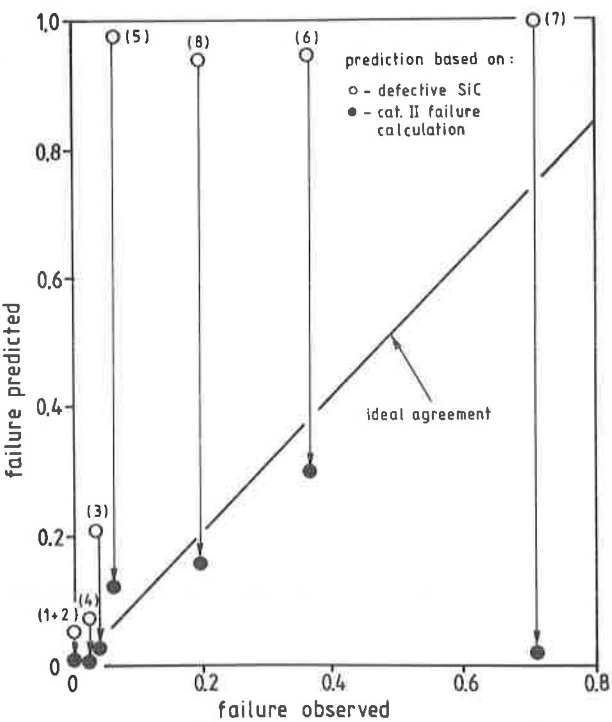

fig. 2 Comparative evaluation of predicted versus observed total failure probability on TRISO-coated fuel with defective SiC layers prior to irradiation.