# STATUS OF MODELS DESCRIBING THE MECHANICAL PERFORMANCE OF COATED PARTICLE FUELS

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## SUMMARY

If one follows the evolution of coated particle stress models one finds that progress has been limited to the following achievements:

(i) Progression from the description of single-layer shells to complex multi-layer shells and inclusion of kernel-coating interactions and the fabrication phase. [Essentially a progression towards more complicated boundary conditions.]
(ii) Increase in physical accuracy by the inclusion of irradiation-induced dimensional changes, creep (steady-state and transient) and kernel swelling in addition to elastic deformation and thermal expansion. [Essentially an extension of the constitutive equation.]
(iii) Improved mathematical methods employed for the solution of the basic differential equations, resulting in drastically reduced computation times.

The basic physical assumptions underlying all models published so far have however remained the same and are limiting their area of applicability (agreement with experimental observations) to low fast neutron dose levels and steady state irradiation conditions.

The most serious limitation is due to the assumption of mutual independence of the various physical processes which are combined in the constitutive equation. Irradiation-induced dimensional change data which have been obtained for an unrestrained specimen are assumed to apply in exactly the same way to all finite zones within a PyC coating layer, while experimentally it has been shown that zones of originally identical PyC characteristics develop different microstructures (anisotropies) according to their individually different irradiation (stress-strain) histories.

It is therefore proposed to include a feed-back loop containing a PyC model in the structure of the stress models, so that the material data for individual zones could be updated according to their irradiation histories. A considerable amount of materials data for PyC would have to be obtained in order to make such an approach quantitative, but already a very simple rheological PyC model is expected to eliminate the present restrictions and improve greatly the logical structure of the models.

Further improvement is also required with respect to the failure criteria which are employed in order to predict fracture. In addition to the commonly used "limiting hoop stress" and "limiting radial stress" failure criteria, some experimental evidence for "limiting shear stress" and "limiting creep strain" failure criteria is available.

## 1. Introduction

The safe and economic operation of an HTR (High Temperature Gas Cooled Reactor) relies on the adequate retention of fission products in the coated particle fuel. As the particle coating forms the primary fission product barrier its mechanical integrity is very important, although because of the large number of coated particles in the core of a power reactor ($\sim 10^{10}$), the consequence of an individual failure is negligible compared with failure in any other reactor system. Consequently coated particle stress models are not required to be as pessimistic or sophisticated as the fuel element models for other reactor systems.

In addition there are clear physical reasons why not only the stress model but also the engineering problem of structural design is much simpler in the case of coated particle fuel. Table I compares an HTR coated particle with an LMFBR fuel pin with respect to geometry, materials, operating conditions and induced phenomena, all of which have to be taken into account and described by the respective mathematical models.

In the basic mathematical equations describing the mechanical state of the coating or canning there is a striking similarity between the two cases, which extends even to the notation normally used and the principal material phenomena and boundary conditions. At this level the HTR coated particle stress problem appears more complicated than the LMFBR pin problem because of the anisotropy and inhomogeneity of the particle "canning". Nevertheless, because of the small physical size of the HTR coated particle the mechanical and thermal analyses are separable in practice and the operational variables temperature, dose and burn-up are independent functions of time alone and not of any spatial co-ordinates. On the otherhand for the LMFBR fuel pin the mechanical and thermal analyses are closely related through the dimensional behaviour of the fuel and canning. The dose and burn-up depend on the axial position and temperature is a dependent variable of time, dose, burn-up and the axial and radial co-ordinates.

Clearly the HTR coated particle stress problem is the simpler one. It also benefits from a faster turn-round time in irradiation testing because of the much lower fast neutron dose levels required.

The small physical size of HTR coated particles and the large number within a power reactor core is nevertheless not entirely beneficial. The small size is responsible for relatively-large unintentional variations from particle to particle within a production batch and with the large number of particles involved makes quality control and quantitative post-irradiation examination a very tedious task.

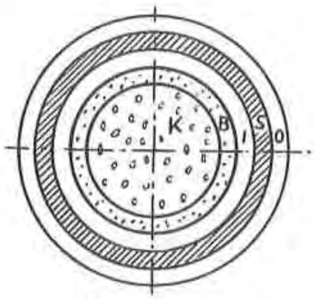
## 2. Evolution of Coated Particle Stress Models

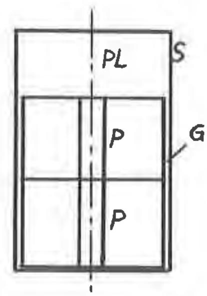
From early experimental observations of coated particle failure it became obvious that the forces resulting from the build-up of internal fission gas pressure and swelling of the kernel during irradiation could cause high stress levels within the coating layers, resulting in fracture and consequent release of fission products. It was also realised, especially in particles with a multi-layer inhomogeneous coating structure that interactions between the various materials could result in differential stresses being present at the production stage before irradiation. Consequently a mathematical model which would allow a description of the mechanical state of the various coating layers as a function of coated

## Table I

### A Comparison

| HTR COATED PARTICLE | | LMFBR FUEL PIN |
|---|---|---|
| | **GEOMETRY AND MATERIALS** | |
| ~1 mm $\phi$ | | ~5 mm $\phi$ x 2,000 mm |




| HTR COATED PARTICLE | | LMFBR FUEL PIN |
|---|---|---|
| K ... Oxide Fuel Kernel | | P ... Oxide Fuel Pellets |
| B ... Porous PyC Buffer | | G ... Gap |
| I ... Inner PyC Coating | | PL ... Plenum |
| S ... SiC Coating | | S ... SST Canning |
| O ... Outer PyC Coating | | |
| | **OPERATING CONDITIONS** | |
| 900-1250$^{o}$C | Fuel Temperature | 500-3000$^{o}$C |
| 2-5 x $10^{21}$ $cm^{-2}$ NDE | Fast Neutron Dose | 2 x $10^{23}$ $cm^{-2}$ (E >0.1 MeV) |
| 5-75% FIMA | Burn-up | 5-10% FIMA |
| 700-1,500 days | Fuel Residence Time | 200-2,000 days |
| | **PRINCIPAL MATERIAL PHENOMENA** | |
| Fission Gas Pressure | | Fission Gas Pressure |
| Fuel Swelling (and Creep) | | Fuel Swelling and Creep |
| Irradiated Induced Shrinkage (PyC) | | Irradiated Induced Swelling (SST) |
| Irradiated Induced Creep (PyC) | | Irradiated Induced Creep (SST) |
| PyC/SiC Interactions | | |
| Fission Fragment Damage (PyC) | | |
| | **SECONDARY PHENOMENA** | |
| | | Axial and Radial Variations of Temperature, Dose and Burn-up |
| | | Axial Fuel Movement |
| | | Fuel Cracking and Restructuring |
| Material Property Changes (PyC) | | Material Property Changes (SST) |
| | | Interrelated Mechanical and Thermal Behaviour |

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particle design and the operating conditions was highly desirable to give a better understanding of coated particle behaviour and performance.

In the course of particle development and irradiation testing to increasingly high dose and burn-up levels more and more experimental phenomena (as listed in Table I) were found. Table II shows the major modifications and refinements which were introduced into the coated particle stress models to keep them in step with experimental facts.

So far, all published coated particle stress models assume spherical symmetry of the coating layers. They all use:

(i) an equation of equilibrium (between the stress components)

(ii) an equation of compatibility (between elongation and displacements) and

(iii) a constitutive law (relating stress and elongation)

By elimination of variables a differential equation for stress or displacement is then derived within a continuum theory approach.

The mathematical complexity of this differential equation and of the method for its solution depend on such factors as:

(i) radial variation of material properties (inhomogeneity);

(ii) anisotropy of material properties;

(iii) the type of boundary conditions (multi-layer interactions, gas pressures); and

(iv) the physical processes which have been included in the constitutive law.

Since the state of the coated particle is described by the model in terms of stress and elongation it may be checked against known failure criteria to predict fracture.

The history of coated particle stress model development as outlined in Table II can be summed up along the following lines:

(i) Starting from the treatment of a single spherical shell the geometric and boundary conditions which could be dealt with by the models were extended to include multi-layer shell interactions and also interactions with the fuel kernel, not only during steady state irradiation conditions but also during the coating process and during post-irradiation heat treatment of the particle.

(ii) The physical accuracy of the models was maintained to higher fast neutron dose levels by extending the constitutive law to include irradiation induced effects such as dimensional change, primary and secondary creep and kernel swelling, in addition to the classical elastic and thermal deformations.

(iii) As the need to investigate the effects of systematic and random particle variations led to an extensive use of the stress models it became desirable to develop faster ccomputer codes for accurate calculation and also simple analytical formulations for quick estimates of coated particle performance. These analytical formulae, are also very useful in checking the correct operation of the large computer codes.

## 3. Present Status of Experimental Confirmation

Coated particle stress models are used in many different areas of application, such as power reactor design optimisation, power reactor safety studies, fuel production and quality control, the analysis of experiments, and experimental design in fuel development. For some of these applications one is quite satisfied if the stress model provides an efficient description and interpretation of the observed performance within the experimental range of conditions. On the other hand, safety studies and especially coated particle development demand more of the model, namely that it can be used confidently for extrapolation beyond

Table II

Outline of Stress Model Development History

| Author | Geometry and Boundary Conditions | Physical Processes | | | | Method of Solution (Name of Computer Code) | References | Comments |
|---|---|---|---|---|---|---|---|---|
| | | (Classical) | | (Irradiation Induced) | | | | |
| | | Elastic Def. | Thermal Exp. | Shrinkage | Creep | | | |
| Lame (1852) | 1 thick shell | $E, \mu$ | | | | Analytic | [1, 2] | Classical Elastic Solution |
| Prados, Scott (1964) | 1 thick shell | $E_{r/t}, \mu_{r/t}$ | $\alpha_{r/t}(r), T(r)$ | $g_{r/t}(r,\Gamma,T)$ | | Analytic | [3] | Introduction of PyC shrinkage |
| Prados, Scott (1966) | 1 thick PyC shell | $E, \mu$ | $\alpha_{r/t}, T$ | $g_{r/t}(\Gamma,T)$ | | Analytic (simpler than above) | [4] | |
| Prados, Scott (1967) | 1 thick PyC shell | $E_{r/t}, \mu_{r/t}$ | $\alpha_{r/t}(r), T(r)$ | $g_{r/t}(r,\Gamma,T)$ | $K, \nu = \frac{1}{2}$ (prim. creep possible) | Numberical iteration for compatib. and boundary cond. (STRETCH) | [5–7] | Introduction of PyC Creep |
| Kaae (1969) | 2 thick shells (SiC/PyC) | $E, \mu$ | $\alpha, T$ | SiC = $g$ = 0<br>PyC = $g_{r/t}(r,\Gamma,T)$ | SiC = $K$ = 0<br>PyC = $K, \nu = \frac{1}{2}$<br>(prim. + sec. creep) | Numerical iteration | [8] | Extension to Composite Shells |
| Kaae (1969) | 3 thick shells (PyC/SiC/PyC) | $E, \mu$ | $\alpha, T$ | SiC = $g$ = 0<br>PyC = $g_{r/t}(r,\Gamma,T)$ | SiC = $K$ = 0<br>PyC = $K, \nu = \frac{1}{2}$<br>(no prim. creep) | Numerical iteration | [9] | Treatment of Gap Formation |
| Walther (1968–1969) | Max. 6 thick shells (any PyC/SiC combination) | $E_{r/t}(\Gamma,T)$<br>$_{r/t}(\Gamma,T)$ | $\alpha_{r/t}$ | $g_{r/t}(\Gamma,T)$ | $K_{r/t}(\Gamma,T)$<br>$\nu_{r/t}(\Gamma,T)$<br>(prim. creep possible) | Improved numerical iteration | [10–15] | Inclusion of Fabrication Phase, Post-Irradiation Annealing and Individual Layer Fracture |
| Williamson, Horner (1971)<br>Mancini (1972) | Thin PyC/SiC/PyC shells only (no kernel coating interaction) | | | SiC = $\dot{g}$ = 0<br>PyC = $\dot{g}_t(\Gamma,T)$<br>$\dot{g}_r$ = 0 | SiC = $K$ = 0<br>PyC = $K, \nu$<br>(prim. creep possible)<br>$\sigma_r$ = 0 | Numerical iteration ([illegible])<br>Sequential steps (PFAIL) | [16]<br>[17] | This Shell Approximations (very simple to use with slice rule) |
| Stevens (1971) | 1 thick shell only | $E, \mu$ | | $g_{r/t}(\Gamma,T)$ | $K, \nu$<br>(no prim. creep) | Analytical solution for compatib. + numberical iteration for bound. cond. | [18] | Improved Math. Treatment of Creep |
| Shipp (1972) | PyC/SiC/PyC shells only | $E, \mu$<br>SiC = $E$ = $\infty$ | $\alpha_{r/t}$ | $g_{r/t}(\Gamma,T)$<br>SiC = $\dot{g}$ = 0 | $K(\Gamma,T)$, $\nu(\Gamma,T)$<br>(prim. creep possible)<br>SiC = $K$ = 0 | Analytic + stepwise numerical | [19] | Extension of [16–18] to 3 thick shells |
| Martin (1972) | PyC/SiC/PyC shells only (no kernel coating interaction) | $E, \mu$<br>SiC = $E$ = $\infty$ | | $g_{r/t}(\Gamma,T)$ | $K, \nu$<br>(no prim. creep)<br>SiC = $K$ = 0 | Analytic | [20] | (for desk-top calculators) |

Explanation of Symbols

$E$ ... Young's Modulus
$\mu$ ... Poisson's Ratio
$\alpha$ ... Coeff. of Thermal Expansion
$T$ ... Temperature
$r$ ... Radial Co-ordinate
$\Gamma$ ... Fast Neutron Dose

$g$ ... Irradiation Induced Dimensional Change
$\dot{g}$ ... Irradiation Induced Dimensional Change Rate
$K$ ... Irradiation Creep Constant
$\nu$ ... Poisson's Ratio in Creep
$\sigma_r$ ... Stress in Radial Direction

Consideration of Anisotropy is symbolised by indices r/t
Consideration of Radial Inhomogeneity is symbolised by (r)
Functional Dependence on Dose and/or Temperature is symbolised by ($\Gamma$,T)

present experience and that it shall give valid guidelines for further improvement of particle performance. Obviously experimental confirmation of the model within the range of available experience is a minimum requirement and is discussed in this section.

Prados and Scott [4, 5] showed that the stress in a coating is the sum of two terms. The first term due to the radial pressure exerted by the internally released fission gas and possibly also by the swelling kernel, and the second due to the irradiation and thermally induced interactions within and between the coating layers caused by their inhomogeneity and anisotropy (self stressing). The first term is roughly proportional to burn-up while the second is mainly a function of fast neutron dose. Prados and Scott therefore used a log . dose/lin. burn-up plot to show failure loci and to elucidate the behaviour of plain PyC coated particles. Since such a diagram is also useful in discussing the performance of triplex coated particles (PyC/SiC/PyC), and when experimentally confirming the stress models, it is shown in Fig. 1. It refers specifically to the Dragon Reference Particle with methane-derived PyC coatings and 1200-1250$^{o}$C irradiation temperature as discussed by Graham, Hick et al., [21, 22].

The philosophy for exploring the performance limits of coated particle fuel has been also discussed in [21, 22]. Basically one distinguishes between:

(i) Accelerated burn-up tests and model experiments,

(ii) Accelerated high dose experiments,

(iii) Accelerated particle tests to power reactor dose/burn-up targets, and

(iv) Non-accelerated demonstration experiments to power reactor target values, with realistic relative and absolute rates of dose and burn-up accumulation.

Of the two stress terms mentioned earlier one depends primarily on burn-up and the other on dose. These experiments hence allow an investigation of their separate and combined effects. In a triplex coated particle (PyC/SiC/PyC) the first term concerns mainly tangential tensile stresses in the SiC layers, while the second term describes the tangential tensile stresses in the PyC layers and compressive tangential stresses in the SiC layer.

Failure loci for various values of SiC ultimate tensile strength and a limiting hoop-stress failure criterion were calculated, using a STRESS 3 data set in which the irradiation creep constant for PyC had been adjusted to the results of the Met 4 experiment by Martin [15]. Met 4 was an experiment specifically designed to test the model for its ability to calculate correctly the effects of coated particle design. Good agreement between experiment and calculation has been achieved for several models by Martin [15], Bongartz [23] and Horner [16, 24].

In the low dose, high burn-up, region the model is also in good agreement with other accelerated burn-up tests performed by the Dragon Project. Failure is due typically to a brittle fracture of the SiC layer resulting in immediate explosive bursting of the whole particle and it occurs at about 3,000 kg/cm$^2$ SiC stress.

At high dose and low burn-up levels it was found that shelling-off of the outer PyC layer and cracking of the inner PyC layer occurred, and that this was followed later by pressure bursting of the remaining SiC layer. Although this phenomenon was expected from the related work on graphite it was not known how to describe it with the available models and in order to distinguish it from the well describable "pressure failure" mode it was instrumental difficulties, and this reflects itself in some uncertainty in the calculation of shutdown stresses.

The outstanding uncertainty concerns the irradiation induced effects in PyC. Measurements of unrestrained irradiation induced dimensional changes are experimentally difficult, and the long turn-round time, the lack of a complete PyC specification and the large variety of pyrocarbons are serious difficulties in the current phase of rapid development. One is really faced with the choice of gaining a limited knowledge of a wide range of PyC varieties or a detailed knowledge of just one type.

With these data uncertainty margins there is consequently room for individual preferences as several combinations of, for example, shrinkage data and creep constants can give similar model predictions of any single aspect. Only when many experiments are considered together and several aspects, such as particle diameter changes plus observed layer fracture, are used to compare model predictions with actual post-irradiation results one can begin to discriminate soundly between alternative data combinations.

4.2 Failure Criteria

To describe material fracture the stress models have to contain some failure criteria against which the calculated mechanical state of the particle (stress, strain) is being continuously checked. A coated particle or any one of its layers can fail in several ways and thus several failure criteria have to be applied in parallel. Ideally the correct criteria would not only yield correct failure predictions for the particle on a macroscopic scale but would also explain the observable features of fracture on a micro-structural scale and hence give correct guidelines for further improvements. In this way the experimental derivation of the relevant failure criteria should involve a micro-structural examination and identification of the type of fracture and a calculation of the value of the corresponding variable (stress, elongation) with the help of a stress model run for the individual case. If a consistent set of values is obtained for similar types of fracture, then one may have found a relevant failure criterion.

All failure mechanisms are not necessarily known at present, principally because existing stress models calculate only macroscopic stresses, while fracture is a microscopic phenomenon. Some correction for microscopic deviations from the macroscopic stress pattern is therefore required, such as provided for SiC by the Griffith theory.

Limiting Hoop Stress Criterion

This is the most common failure criterion and relates the maximum tangential stress within a layer with the ultimate tensile strength of the material (UTS). For SiC this criterion seems to work well, as SiC is a brittle material whose strength is determined by the statistical distribution of microcracks. The available Weibull theory (Weibull [25, 26], Robinson [27]), based on the Griffith formula (Cottrell [28]), provides the necessary link between macroscopic stresses and microscopic phenomena. Measurement of the SiC UTS by various methods using unirradiated and irradiated material both at room temperature and above operating temperatures, yields typical values of 200-400 $MN/m^2$ ($\sim$2,000-4,000 $kg/cm^2$) for the effective mean strength of a whole spherical shell, with a Weibull modulus of $m \approx 3.8$-5.1 (Davidge et al., [29]). As these microcracks mostly occur at the surfaces of the SiC layer, and very different values for the inner and outer surface strength have been observed, the model should really apply two separate failure criteria for the two surfaces.

In PyC layers the maximum stress usually occurs at the inner surface during the early stages of irradiation, when the PyC is densifying rapidly, while later in life the stress at the outer surface is higher than at the inner surface because of the radial PyC growth. However, these later stresses are generally much lower than the earlier ones and the usual limiting hoop stress failure criterion is therefore unable to describe the observed PyC cracking at high dose levels. Moreover, the cracks often propagate slowly and as the Weibull theory seems not to apply, the link between macroscopic stresses and microstructural phenomena is missing at the moment. This might be the reason why stress models are able to describe the behaviour of triplex coated particles (PyC/SiC/PyC) more accurately than that of plain PyC coated particles.

Limiting Radial Stress Criterion

As in the practice the radial stress is always much lower than the tangential stress, there is normally no danger of tangential fracture within a coating layer, as radial fracture would occur much earlier. On the other hand debonding between layers of different materials has been frequently observed and is therefore included in several stress models with the help of a limiting radial stress failure criterion.

Limiting Sheer Stress Criterion

For the spherical geometry of coated particles maximal sheer stress levels $\tau_{45}$ occur in all planes inclined at $45^{o}$ to the radial direction.

$$\tau_{45} = \tfrac{1}{2} (\sigma_1 - \sigma_3) \qquad (1)$$

$\sigma_{1/3}$ = normal stress in tangential/radial direction

They vanish in all planes which include the radial direction and in the tangential plane.

The frequent experimental observation of PyC cracks which propagate slowly at $45^{o}$ to the radial direction suggests a limiting shear stress failure mechanism. Moreover these cracks frequently turn into the tangential direction and resemble debonding as soon as the crack tip meets a significant radial step in PyC properties (such as are visible in the metallographic sections of unirradiated particles). This failure is probably due to a high shear stress in the tangential plane, which is otherwise shear-stress-free, caused by a local deviation from spherical symmetry around the slowly propagating crack tip. The typical conical shape observed for "spearhead" cracks in buffer layers and also Stereoscan examinations of PyC cracks as discussed by Voice [30] suggests also a possible plastic fracture mechanism under the influence of shear stresses during irradiation. No corresponding failure criterion has yet been proposed, though a limiting hoop stress failure criterion might be a working approximation.

Limiting Creep Strain Criterion

PyC cracking at high fast neutron dose levels is not predicted by the usual limiting hoop stress failure criterion, but seems well accounted for by a limiting creep strain criterion (Morgand [31]). By anology with graphite (Smith [32]) one could imagine that creep strain produces an increase of volume due to the proportional generation of micro-cracks. As soon as a certain creep strain level (a critical concentration of microcracks) had been reached, these microcracks would be able to overlap and form a macrocrack, which in the model could be described by a limiting creep strain failure criterion. Alternatively one could assume that the effective strength of PyC would decrease proportionally with an increasing concentration of microcracks, with fracture occurrina according co a limiting hoop stress failure criterion. Both alternatives are included in the available options of the later STRESS 3 versions and allow a successful description of experimental results, although at the moment lacking a detailed theoretical justification.

4.3 Mechanical Behaviour of Materials

The models generally make two basic assumptions without further discussion. They assume spherical symmetry and they assume that the various processes causing deformation are mutually independent, and can be simply added in the constitutive law and described by mechanical properties.

From experimental evidence the assumption of spherical symmetry seems well justified,* as even with a deliberate selection of badly-shaped particles no difference in performance can be detected. We do know, however, from experimental evidence that the second assumption is an approximation only valid at low and intermediate fast neutron dose levels, especially for pyrocarbon. The development of anisotropy during irradiation in the various radial zones of a PyC layer is inhomogeneous and depends on the initial anisotropy as well as on the stress-strain history of the individual layers during the irradiation. (Koizlik [33, 35], Koss [34]). Yet the models describe all radial zones by the same set of shrinkage data, irrespective of such differences, as the data has often been obtained from samples irradiated in an unrestrained condition (a very special situation). We know that fast neutron dose-induced PyC cracking depends critically on the initial anisotropy of the PyC, yet the models continue to use a data set which ignores anisotropy in the specification of the material.

Of course the present assumption does provide a working model approximation for coated particle mechanical behaviour up to intermediate fast neutron dose levels, and the collection of the necessary materials data to describe the generation and effect of anisotropy is certainly a tremendous task.

Horner [24] has pointed out another limitation of present models. They are limited essentially to steady state operating conditions because we do not know how to switch from a PyC shrinkage data set referring to a specific irradiation temperature to another data set referring to a different temperature. In practice most irradiation experiments are unavoidably performed with some temperature and power cycling and the performance results are not strictly those of steady state operation.

It should be clear that further coated particle model development relies on a better understanding of material (PyC) behaviour and, ultimately, a microstructural material (PyC) model. When such a material model is finally available one would certainly wish to integrate it into the coated particle model and consequently when developing present models a position should be reserved for future material models. The proper place would be within a feed-back loop which updates the material property data set of individual radial zones according to their individual irradiation stress-strain history. With a dummy material model and the present data set there would be no change, and later simple rheological models would extend the range of description of coated particle performance. In this way the material model hypotheses could be easily tested for their macroscopic consequences.

5. Conclusions

(i) The theoretical basis of HTR coated particle models and LMFBR fuel pin models is practically the same. The practical problem of engineering design and development is

*At least for compacted particles.

however much simpler for the HTR coated particle, mainly because of its smaller physical size.

(ii) A considerable number of coated particle stress models have evolved, not basically different in their physical assumptions but rather representing different simplifications or approximations.

(iii) Within the data uncertainties coated particle stress models are generally able to describe successfully the experimentally observed performance over a wide range of irradiation conditions and particle designs.

(iv) Further improvements are desirable in the areas of materials data, especially to provide links between the continuum theory approach of the models and the microstructural aspects of material behaviour observed in coated particle fuel research and development work.

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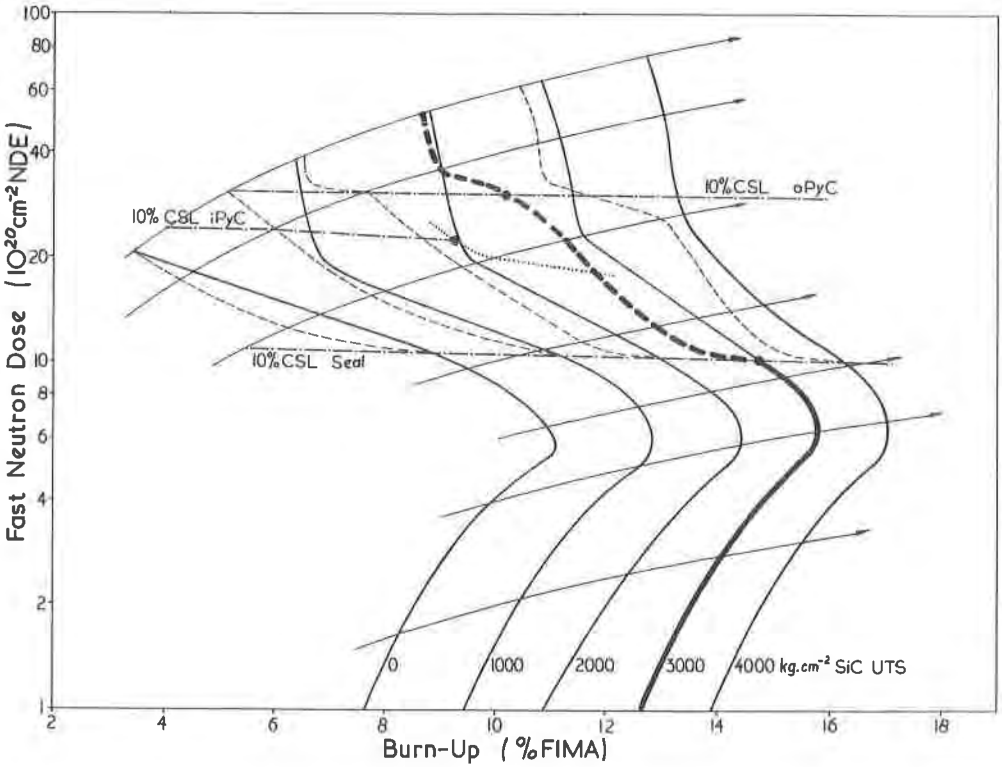


Fig. 1: Calculated Endurance Limit of Dragon Reference Particle at 1200°C (for 3000 kg/cm$^2$ SiC-UTS and 10% PyC-CSL)