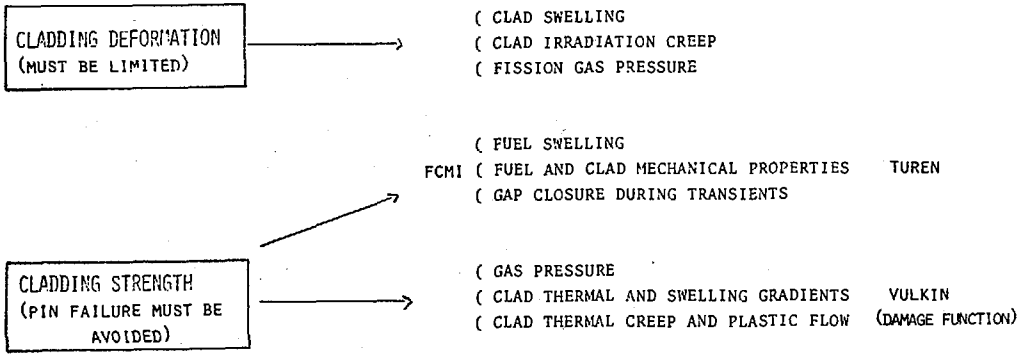
II - CLADDING MECHANICAL BEHAVIOUR






# EXPERIMENTAL AND THEORETICAL REQUIREMENTS FOR FUEL MODELLING

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From a scientific point of view it may be considered that any event in the life of a fuel pin under irradiation should be perfectly well understood and foreseen ; from that deterministic point of view, the whole behaviour of the pin may be analysed and dismantled with a specific function for every component part and each component part related to one basic phenomenon which can be independently studied on pure physical grounds. When extracted fron the code structure the subroutine is studied for itself by specialists who try to keep as close as possible to the physics involved in the phenomenon ; that often leads to an impressive luxury in details and a subsequent need for many unavailable intput data.

It might seem more secure to follow that approach since it tries to be firmly based on theoretical grounds. We should think so if the phenomenological situation in the pin were less complex than it is. Just as for Hi-fi the value of a code is that of it's less valuable key-component ; so, whatever the scientific concern in developing highly sophisticated physical models, and as long as some of the pieces will be missing in the puzzle, we consider of no help the incorporation into the general codes of models whose level of elaboration and precision is well above the overall uncertainty ; we rather think that such models may induce an over-estimation of the whole code capability even when they do not conceal behind fittable parameters their own inaptitude to cope with the complexity of the described phenomena.

That clear-cut assessment was necessary to define the more technological and seemingly rather rough approach we adopt with regard to fuel modelling : our codes are not designed for an ambitious and, in our opinion, out-of-scope exact reproduction of the detailed features happening during an irradiation. They are designed to help as a tool in a fuel design procedure which is mainly based on experimental testing. We should not be too confident in the absolute values pedicted by the codes, but we actually take care of the relative trends

they indicate and that is what we need to make sure that our technological purposes are fulfilled.

We are indeed aware that such codes would not be adequate for off-normal operating conditions since for the accidental transient conditions the key-phenomena would not be the same as for steady-state or slow transient conditions.

The orientation given to fuel modelling is based on our two main technological constraints which are :

- no fuel melting
- no cladding failure.
- no excessive cladding deformation

In this context, the only relevant models are those which have a significant influence on the maximum temperatures in the fuel or on the cladding damage ; hence the selection between key-models and unrelevant models which will next be done.

Before that, we have yet to define the operating limits of the codes. The fuel pin undergoes many changes during the irradiation, and the problems encountered at beginning of life are not the same after some burn up. Cladding and fuel are clearly well better defined at beginning of life with no fission products ; when the amount of fission products grows larger, we may get some reaction with the cladding which besides is modified by irradiation damage ; a more or less thick layer grows between cladding an fuel made out from a mixture of cladding, fuel and fission products compounds with rather ill-defined thermal and mechanical properties ; the fuel is perturbed too, with plutonium and fission products segregations, gas bubles, modified oxygen content, modified thermal properties.

Code designers are confronted to a very complex situation which has nothing to do with the relative simplicity of beginning of life and it appears a hopeless trial to look for a purely physical thermal and mechanical description of the pin at this stage. We think that codification must then use rather crude methods such as virtual mean properties and empirical laws just to keep close to the experimentaly determined behaviour.



The operating conditions we intend to follow with the fuel modelling concerned in this meeting are those which are normal for reactor operation, that is steady state and cycling (so, there is no need for code extrapolation in a field where no or few experimental tests have been performed). Subsequently, empirical laws for the elementary models are quite adapted to our needs.

For the fuel design purposes, not fully physically based models are still sufficient as far as the parametric studies concern geometrical and fuel composition variations rather than operating conditions. If these are concerned too, a recalibration of the codes by experimental testing must be provided.

We shall now make a review of the models which are implied in codification of fuel behaviour first at beginning of life and then at steady-state. The models will be introduced in relation to our two purposes : thermal behaviour and mechanical behaviour.

## I - Beginning of life

By beginning of life we mean the first stages of the irradiation of a fresh pin including rising of the power and fuel rearrangement within the pin. Depending on the irradiation conditions these stages may take a few hours, a few days or a few weeks. The end of this period is reached when the gap between fuel and cladding is closed and the eventual central hole is formed.

The codes used to describe the beginning of life are for the thermal behaviour and for the mechanical behaviour.

We shall distinguish two stages during beginning of life. The first one is the first rise to power during which the fuel and the cladding do not come to contact with standard pin design ; there is therefore no problem of mechanical interaction between fuel and cladding and the problems are merely thermal. During this stage we might get some restructuration, fuel relocation and expansion through retained gases. These phenomena lead to a decrease in fuel maximum temperature and it is precisely why we ignore them during this first stage to get an upper limit of what would be the maximum temperature if the reactor were rised to power very fastly : in order to get

Some margin in the power to melt investigation we prefere not to rest upon the help afforded by such time consuming mechanisms.

An other phenomenon goes the other way and might give a temperature increase, it is the release of initially retained gases; we take it into account, including a certain amount of pollution in the gas plenum.
In the second stage of the beginning of life are included all the phenomena leading to the further steady-state stage : pore migration, plutonium and uranium migration, fuel relocation, fuel swelling, fission gas release.
The only migration phenomenon we include in the first stage is oxygen migration since it has been shown experimentally to be instantaneous

A) - First rise to maximum power

Since we are only concerned with variations in reactor operating conditions which are slow when compared to thermal inertia in the pin, the Sodium-cladding-fuel system is always calculated in stationary state. The temperature chart is obtained by a simple iterative calculation involving local conductance and heat generation with no direct incidence of time.

For fast breeder reactors we have no neutron absorption in the fuel and the heat generation is the direct picture of the fissile atoms distribution which is initially homogeneous.

The heat removal from the pin by the sodium flow will not be developed here since it would lead us outside of the pin ; the thermal-hydraulics of the subassembly are derived with special codes ; for our needs, a simple equivalent-channel model with a balance between heat flux through the cladding and heat flow through the axial odium flow is sufficient to give us the mean temperatures in the sodium along the pin. Then the outer cladding temperature is calculated with a classical heat transfer model by coolant flow. The inner cladding temperature is, in turn, obtained with a law for thermal conductivity of the cladding. Up to now we have not encountered any major uncertainty source for temperature evaluation and the inner cladding temperature will be known with less



than 10 degrees C of uncertainty. The first difficulty is reached with the gap between cladding and fuel ; here the heat conductance may be low enough so that the temperature drop between fuel and cladding is to vary of several hundreds of degrees C. In this respect, the model for heat transfer through the fuel-cladding gap must be retained as a most relevant one.

Related to that problem is the size of the gap which is determined by the differential thermal expansion between cladding and fuel. The thermal expansion of cladding and fuel is produced under thermal gradients, so that thermal stresses are induced in the cladding and in the fuel. We first meet here the problem of coupling between thermal and mechanical behaviour.

It appears that in that case, there is no need for an exact mechanical treatment :

- The cladding undergoes pure elastic strains and further irradiation creep under the thermal stresses does not result in a cladding expansion different from that calculated assuming a thermal expansion with the mean temperature.
- At powers as low as 100 W/cm the hoop thermal stresses go above the yield stress of the fuel and radial cracking occurs with essentially no plastic flow.

When exact mechanical calculations are compared to simple ones performed with a mean thermal expansion for the cladding and a o-stress yielding for the fuel no significant difference can be found.
So we think that coupling of our mechanical and thermal codes is not necessary as long as there is no mechanical interaction between fuel and cladding, that is before the end of beginning of life.

An other problem related to the gap heat transfer is the eccentricity of the fuel in the pin. Calculations performed with a bi-dimensionnal code show that although, the effect on fuel surface temperature may be not negligible, it has only second order effect on fuel maximum temperature ; we therefore do not need a bi-dimensionnal code.

After the determination of the outer temperature of the fuel we have to calculate the fuel temperatures taking into account the fissile atoms distribution (which is perturbed by restructuration and void and plutonium migration).

Heat transfer through the fuel depends on the local thermal conductivity which is known to depend highly on the four following parameters :

- temperature
- oxygen content
- Plutonium content
- porosity

the first two being of special weight.

We furthermore know from out of pile measurements that thermal conductivity is largely scattered even for a same fabrication. It is clear that since the major temperature drop occurs within the fuel, the effective thermal conductivity is the most meaningful data to be introduced into the codes. We say "effective" as it is not clear whether the out of pile data may be used in pile with no care of restructuration effects (especially at high temperature) and irradiation effects (especially at low temperature).

Thermal conductivity is known to depend on oxygen content. This effect has been proved to still exist in pile and, although it is quite smaller than out of pile, it remains in the range of some hundred degrees C which is enough to be taken into account in fuel modelling. We therefore had to calibrate our thermal conductivity in function of stoichiometry on in pile experimental measurements (which include oxygen migration). We can list down what are the requirements for modelling of the first rise to power stage :

- a heat transfer model between fuel and cladding
- an experimental determination of in pile thermal conductivity for the fuel
- an experimental determination of the in pile effect of oxygen content on fuel thermal conductivity;

B) Transition stage to steady-state

As we shall see, there is no new mechanical problem during this sta during this stage and the fuel temperatures can only decrease.



However, the thermal state of the fuel after full restructuration is of major concern when one think of taking advantage of a pre-irradiation stage at intermediate power level in order to reach afterwards a higher nominal power level thanks to the thermal improvment afforded by restructuration.

To describe this stage we shall neither need a true coupling between our thermal and mechanical codes since there is not yet mechanical interaction between fuel and cladding.

On the cladding side , the mechanical calculation of the thermal stresses relaxation by irradiation creep does not lead to a variation in cladding geometry : the effect of thermal creep remains very small ; so for the pressure of the standard gas plenum ; irradiation swelling does not yet appear.

On the fuel side many things occur :

1 - As we previously noted, but we must describe the pore migration towards the hot center line of the fuel.

For that we have developed a semi-physical model which does not describe the formation of lenticular pores but which allows a true calculation of the flux of the vapor fuel species. The partial pressures of these species are calculated taking into account the local oxygen partial pressure. This rather sophisticated model allows a parametric study based on stoichiometry but is not really indispensable and might be replaced by empirical laws governing matter transport. It has yet the advantage of calculating by the way the plutonuim and uranium migration associated to pore migration which otherwise should be empirically determined. Any way, we must keep in mind that from a thermal point of view, the PU/(U+Pu)variations are of second order before central hole formation and that we cannot avoid some empirism in the description of that late phenomenon since a fine description of pore formation, interlinkage and retention would be too heavy.

2 - Even a rather crude model will so give the mean radial matter transport through the fuel and hence the evolution of porosity and cracking volume in function of time. In this manner we obtain

crack healing in the hot part of the fuel. With crack healing we recover the mechanical integrity of the fuel and the possibility of developing new stresses associated to thermal or volume changes. This will particularly hold for power cycling : due to the irreversibility introduced by fuel restructuration, hoop and radial stresses will be generated in the hot part of the fuel when power is lowered; if the fuel is hot enough, it will come out some plastic flow or creep before cracking. This will in turn induce irreversibility when coming back to full power. Here we find something leading to fuel relocation.

3 - The fission gas generation fills up the fuel with gas bubles ; although they are not alone responsible for fuel swelling, they may contribute, especially at beginning of life, to fuel expansion. More ready are the gases issued from the volatile elements which are present initially in the fuel as impurities ; they also may contribute to a fast fuel expansion.
Because of early gas release, there might be a substantial pollution and heat transfer degradation in the gap before gap closure.

4 - The rate of gap closure remains one of the most important unknown for beginning of life modelling Due to the low thermal conductance in the gap, it's closure affords the main temperature variation (several hundreds degrees C.). The kinetics are still unknown because experiments are rather rare and mechanisms too numerous and complex ; for example the cycling mechanism described higher in § 2 is certainly not alone since gap closure has been found to occur even without cycling.

If we try to extract the most relevant models that are required for this stage we find :

- a model describing gap closure as a whole
- a model for central hole formation.



## II - Steady - State

### A) - Thermal behaviour

As we already pointed out, we enter then a phase of the irradiation where we are to find many unknowns. Actually we know that, at least for a long time, there will not be major thermal problems with the fuel : the decrease in fuel temperature obtained through restructuration and fuel relocation is high enough to allow a long respite time before thermal conductance and conductivity degradation could lead to find again the initial maximum temperature. That time is experimentally evaluated basing on the evolution with burn up of fission gases retention and micro-structure of the fuel.

Yet, the steady-state fuel maximum temperatures might be required for fuel design taking into account that they are more representative than the transient ones at beginning of life as regards the permanent margin between nominal power and power to melt.

For this purpose we have once more to deal with thermal conductance between fuel and cladding and through the fuel.

For the second point, it has been experimentally shown that the thermal conductivity of fuel simulating various burn up is only slightly decreased by fission products (less than a few per cent below 10 at % burn up). The effect of oxygen content of the mixed oxide should be stronger and a model (or a law) is needed for the mean oxygen content variation with burn up. Furthermore, for power to melt the decrease in melting temperature of the irradiated fuel must be taken into account.

For the first point we are bound to get a coupling between our mechanical and thermal codes. We know that the thermal conductance will strongly depend on the quality of the contact between fuel and cladding There indeed exist a few models to treat the thermal conductance between two solids in contact taking into account the contact pressure, the roughness of the surfaces, the gas environment etc... The problem

is in fact to properly determine the contact pressure which depends on fuel swelling rate, cladding deformation rate, fuel and cladding creep properties ; so for the roughness which is far from being known due to cladding-fission products and fuel chemical interaction. Furthermore, early enough, a layer begins to build between original cladding and fuel and the conductance problem in the gap turns to become a heat transfer problem through a multi-conponent medium, one component of which is thermally undefined.

From the complexity of the situation we infer that an enpirical experimental law is needed rather than a lot of short-coming models. Moreover since were are dealing with melting problems, the experimental conductance law should be based on power to melt measurements as a function of burn up.

It is then quite clear that such a conductance law will not be a universal law but will have to be recalibrated for every type of design. For this reason we think that the end of life over-heating of the fuel turns rather to fall out of the codification scope.

B) - Mechanical behaviour

The main problems for fuel pin modelling during steady state are clearly the problems of fuel containment (fuel pin integrity) and pin deformation (in relation to channel reduction, pin to pin interaction, bundle to subassembly interaction).

These two problems are treated by two different types of codes.

a) - Pin damage

For this problem, it is well known that the evolution of the mechanical properties of the steels under irradiation are of primary importance and that they are badly handled. There is a lot of scatter in the ductility, yield strength, thermal and irradation creep measurements with often a disconcerting dependancy on the ingot origin.



Even if these properties were well defined it would not be practicable to deal with local weakening of the cladding induced by corrosion.

We therefore do not try to use too deterministic damage functions and only trust on conservative laws.

We use strain criteria including plastic flow and thermal creep under the pressure in the gas plenum of the pin and internal stresses in the cladding. The calculation is of safety type and is performed by the VULKIN code.

No account is taken of the stresses that may originate from mechanical interaction between fuel and cladding since, as far as we know, they are not high enough to induce any damage in the cladding apart from specific cases which are treated separately.

b) - Pin deformation and fuel-cladding mechanical interaction

Here is the main action field of our code which is particularly concerned with the many stresses that are applied on the cladding from the inside of the pin.

There remains still a large amount of the pin deformation that comes from external interactions (especially with the wire) but they are out of the scope of fuel modelling

For a proper analysis of the cladding deformation we need fundamental properties of the steel under irradiation such as :

- swelling rate as a function of temperature, time and dose
- irradiation creep as a function of temperature
- coupling between swelling and creep
- thermal creep of the steel.

We then need information on fuel behaviour :

- fission gas release
- fuel swelling rate
- fuel-cladding gap closure rate when gap is re-opened
- irradiation creep of the fuel
- plastic properties of swollen and fission products doped fuel.

Here the use of the code has proved to be efficient as it has allowed to disqualify the mechanical interaction between fuel and cladding(under constant-power operation and as long as there remain cracks or central hole)as a relevant competitor for cladding deformation.

There remain some operating conditions under which strong mechanical interaction between fuel and cladding might occur and we actually need a code to evaluate the consequences of cycling under many operating conditions.

The most relevant models necessary to analyse thoroughly the situation are :

- gas retention at low power and release during transients
- swelling behaviour of the fuel during transients
- gap closure rate at intermediate power.

CONCLUSIONS

As may be seen we try to keep a rather pragmatic view on codification with a special focus on a few determinant aspects of fuel behaviour and no attention to models which are nothing but decorative. Fuel modeling is merely considered as a link between our experimental pieces of knowledge ; it serves as a guide for further improvments in fuel design and as so happens to be quite useful.



On this basis we have described what are the main lacks in our understanding of fuel behaviour. They are mainly concerning :

- thermal transfer through the fuel and through the gap
- fuel relocation at beginning of life and during the steps at intermediate power during cycling
- evolution of cladding mechanical strength under irradiation.

We intend to focus our attention on these critical points within the frame of our experimental program with realistic in pile testing.