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Modelling of Azimuthal Effects Arising from Interaction Between Clad Deformation and Heat Transfer Under LB-LOCA Conditions

H. Laval, F. Casadei, P.M. Jones

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Abstract

The study of clad ballooning and the subchannel blockage arising from it is an important part of LWR safety research. A large amount of experimental data has been obtained over the years which has shown the importance of thermohydraulic effects on the clad ballooning process. Thus the distribution of clad strain, both azimuthally and axially within a fuel bundle are critically dependent on the detailed temperature distribution. Azimuthal clad temperature variations arise because of variations around the rod of pellet-clad gap, neutron flux, coolant temperature and surface heat transfer. They determine the pattern of straining but are also strongly influenced by it.

A simple 3-d computer model RODSWELL is being developed specifically to investigate the interactions between deformation and heat transfer. It is being used to identify the accident conditions potentially capable of producing significant subchannel blockage and to quantify the various parameters needed in the design of meaningful simulation experiments.

1. Introduction and background

The study of the "ballooning" deformation of the Zircaloy cladding of LWR fuel rods under potential loss-of-coolant (LOCA) accident conditions has for many years occupied a major role in reactor safety research studies. The concern has been that coherent ballooning of a significant number of neighbouring rods might lead to blockage of the coolant channels preventing termination of the accident by emergency coolant injection.

In a typical PWR design, coherently ballooning rods would touch at about 30% strain and could, in principle, completely block the subchannels at about 70% strain.

A vast amount of experimental data has been generated to assess the seriousness of the problem in respect to the strain capability of the cladding, the conditions giving coherency of ballooning, the effect of mechanical restraint between contacting rods and the coolability of deformed rod clusters. The main test parameters studied have been the clad temperature, the heating rate, the applied stress and the gaseous environment. Many types of tests have been performed, from single sections of cladding heated directly by Joule heating up to bundles of 8 x 8 rods using internal heaters. In reactor, tests with single rods and bundles have also been carried out. The results obtained have covered a wide range and at times considerable controversy has raged as to their relevance to "real" accident conditions.

Mann et al. [1] have recently reviewed the experimental data and the state of understanding of the physical phenomena involved. It is now clear that α-phase Zircaloy in steam and under uniform heating conditions, such as those which are achieved by direct clad heating, has a capacity for high strain. Also, because of the better cooling of the more highly strained regions of the cladding a mechanism for stabilising the process exists, giving axially extended deformation - the so-called "Hindle strain cooling effect". However, under the more realistic rod heating afforded by internal heaters the same strain cooling gives rise to azimuthal temperature differences. These are amplified by asymmetric shortening of the clad due to the creep anisotropy of alpha-phase Zircaloy giving rise to the "Erbacher hot side straight effect" which markedly reduces the effective failure strain. Fig. 1 shows experimental data [2,3,4], illustrating this effect. Burman et al. [5] have, among others, suggested that the azimuthal gradients observed can be related directly to the heat flux across the fuel-pellet gap. Wiehr et al. [6,7] have also demonstrated the importance of coolant thermohydraulics on the axial and azimuthal temperature variations in ballooning rods in simulated large-break (LB) LOCA experiments. Mann et al. [1] point out that, although no realistic experiment has produced deformations which would inhibit emergency cooling in a real accident, such experiments have not yet covered the entire envelope of conditions which might obtain following a LOCA.

The purpose of the current study is to assess in detail the interactions between deformation and heat transfer with a view to identifying the accident conditions most likely to produce significant coolant channel blockages in both large-and small-break LOCA scenarios. A quantitative definition of the experimental parameters necessary for meaningful experiments will then be made. This paper describes the computer model RODSWELL which is being developed specifically for this purpose and presents some of its first applications.

2. Model description

The RODSWELL code has been developed for the thermomechanical analysis of a single fuel rod under hypothetical accident conditions. The code calculates the variation in space and time of all significant fuel rod variables, including fuel, gap and cladding temperature, fuel and cladding deformation, cladding oxidation and rod internal pressure. The model is designed for azimuthal temperature gradients arising from pellet eccentricity, flux tilt, arbitrary distribution of heat sources in the fuel and the cladding and azimuthal variation of coolant conditions.

The accurate prediction of fuel rod behaviour during a transient also requires access to accurate material properties over a broad range of temperatures. To meet this requirement, a simplified version of the MATPRO package [8] has been introduced in RODSWELL. The fuel material is solid UO_2, the gas gap is He and the cladding material is Zircaloy.

The code combines a transient 2-dimensional finite element heat conduction code [9] and a 1-dimensional mechanical model for the cladding deformation. The fuel rod is divided into a number of axial sections and a detailed thermomechanical analysis is performed within each section in radial and azimuthal directions.

2.1 Thermal model

The thermal model provides a finite element solution of the transient heat conduction equation in radial and azimuthal directions in the fuel, the gas gap and the cladding. The axial conduction is neglected. The spatial discretization is based on a mesh of 3-node triangular finite elements (Fig. 2.a) with a linear local approximation for the temperature field. The position of the mesh nodes is considered as time-dependent and results from the mechanical analysis. The time discretization is performed by using an implicit finite difference method. This requires, at each time step, the resolution of a linear system which is achieved by the Choleski method. On the

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The radiative heat transfer in the gap between the fuel and the cladding is approximated using the radiative heat flux between two concentric cylinders, where, at each azimuthal position, the radii are the current local radii obtained from the mechanical part. The gap heat transfer due to thermal conduction takes into account the temperature jump distance. An equivalent gap conductivity is then defined as the sum of the radiative contribution and the conductive one.

The material properties required in the thermal model such as the thermal conductivity, density, specific heat capacity and emissivity, are highly dependent on the temperature. Each finite element has one assigned material (fuel, gas gap or cladding). The material properties are assumed to be uniform over each element and are calculated at each time step using the mean temperature of the element.

The heat generated in the fuel is normally known from the reactor physics analysis and given as an input data. Axial and azimuthal variations of the fuel power, together with local power peaks due to flux tilt can be treated easily. The heat generated in the cladding by external steam oxidation (when present) is calculated by using oxidation data from the mechanical model. Since, in many experimental tests, heating of the cladding is achieved electrically, either directly or by using an internal heater in place of the fuel, options have been introduced in the code for simulating these conditions. Thus, the temperature at a given point in the cladding can be forced to follow a given time history by controlling the electrical power either in the cladding or in the internal heater.

The coolant temperature, pressure and heat transfer coefficient determining the boundary conditions necessary for the calculation of the rod thermal behaviour are at present read in input as functions of time and axial position. Azimuthal variations of the coolant temperature and heat transfer coefficient can be included also.

The conditions of the fuel rod at the beginning of the transient are generated by a steady-state calculation starting from the cold conditions, i.e. the conditions of the fuel rod at ambient temperature.

2.2 Mechanical model

The mechanical model for the cladding consists of a pure membrane large deformation model based on the assumption that the centreline of the cladding cross-section remains circular in each axial section during the deformation. The cladding cross-section is divided into a suitable number of azimuthal segments, where stresses and strains are evaluated using the cladding mean radius, the local thickness and an average local temperature delivered by the thermal model.

The total strain increment in the cladding is calculated at each step as the sum of the thermal, elastic and creep contributions. For the creep analysis, the CANSWEL [10] model is used. This model includes single-phase creep (primary and secondary contributions) for the α- or β-phases of the Zircaloy, creep in the mixed phase ($\alpha + \beta$) temperature region, phase change dynamics and the effects of oxidation on the mechanical response. Time integration for the creep analysis is performed by a fourth-order Runge-Kutta procedure.

A parabolic law is used to calculate the growth of the oxide- and of the oxygen-stabilized α-layer due to steam oxidation at the outer surface of the rod. The presence of the oxide layer reduces the stress acting on the substrate metal, but only until a given strain (2%) is reached in the oxide. At this strain level, the oxide is assumed to crack and it no longer contributes to the mechanical resistance.

Recently an alternative model for the mechanical behaviour of the oxide layer has been implemented in RODSWELL as an option: it is due to Sagat et al. [11] and it describes the progressive cracking of the oxide layer and the growth of the cracks in an empirical way.

Although RODSWELL has been primarily designed for single rod behaviour analysis, an option has been introduced to describe the mechanical interaction between the rod being analysed and the surrounding ones. The mechanical restraint model is derived from that of Jones and Haste [12] and assumes that the strain of the neighbour rods is a given fraction of that of the central rod. Another basic assumption is that the point of first contact between two rods remains stationary during the interaction. The feedback action from the thermohydraulics due to channel blockage during mechanical interaction between rods is not taken into account in the present version of the model.

The fuel deformation is described by a simple model considering only the radial displacements due to thermal expansion. These are used in the thermal model to compute the pellet-clad gap conductance. A positive gap is always assumed to exist and therefore no consideration for possible clad-pellet mechanical interactions has been made in the present model.

In addition to the asymmetries which can be input due to flux tilting and external cooling, the calculation can be started with an eccentric pellet. To describe the behaviour of the cladding during deformation, three basic options can be chosen. Firstly, the left midpoint of the cladding can be fixed to simulate the "hot side straight" effect. Alternatively the cladding axis can be fixed to maintain a certain pellet offset throughout the calculation. Finally, the centre of gravity of the cladding cross-section can be kept fixed to enable demonstration of the strain cooling effect. The centre of the fuel cross-section is also always kept fixed and is assumed as the origin of the coordinates.

A final source of azimuthal asymmetry which can be input is the initial wall thickness of the cladding which is allowed to vary cosinusoidally around the circumference. This simulates the non-uniformity arising from the clad machining and guarantees a realistic non-uniform strain distribution even when all other boundary conditions are nominally symmetric.

The internal pressure of the rod is calculated according to the perfect gas law, by assuming that the plenum has a constant volume and that the gas contained in it has the temperature of the coolant at the upper axial section. However, the actual volume of the fuel-cladding gap and the temperature of the gas contained in it are calculated by the code.

For the time integration, automatic time-step selection criteria have been implemented: a macro time-step for the thermal analysis is first defined, so as to limit the temperature change per step to a prescribed amount. Then, a micro time-step is computed for the mechanical analysis, so as to ensure that the total strain increment per sub-step be limited to a prescribed value.

As a failure criterion, a limit of 300% local engineering hoop strain at any azimuthal clad segment is used at the moment. This value was chosen because it predicts mean failure strains in reasonable agreement with an analytical integration [13], with experimental data [2,3,4] and with a KfK model [3] (see Fig. 1). However, the value of 300% is still under consideration. Fig. 2.b illustrates the deformed mesh at failure for a typical eccentric pellet calculation.

The RODSWELL code has been coupled to the interactive plot-system TPLOT [14] for the production of the time histories of the most relevant quantities such as temperatures, strains, etc. Plottings of the initial and deformed meshes, of the temperature distribution and of the azimuthal variation of strain and temperature in the cladding at each axial section may be performed as well.

3. Code applications

3.1 Steady state temperature asymmetries

As a first application simple thermal calculations were made of the magnitude of the steady-state azimuthal temperature differences which result from various sources of non-uniformity assuming thermohydraulic conditions within the range of those expected in a LB LOCA. Thus bounding values of heat transfer coefficient of 50 and 500 W/m^2 K were taken together with a nominal coolant temperature of 573K and the resulting azimuthal temperature differences were calculated for ± 5% cross-pin variations in fuel power density, coolant temperature and heat transfer coefficient. Nominal clad dimensions (9.5 mm o/d, 0.57 mm wall) and UO_2 pellet diameter (8.37 mm) were taken as representative of "fresh fuel" and clad and pellet were assumed to be concentric. For comparison, the effect of pellet eccentricity was calculated both for the above geometry and for a simulated "pre-irradiated rod" defined as having zero clad-pellet gap at full power operating conditions. The motivation for this latter comparison was to check whether the use of fresh fuel rods in experiments can be expected to give results prototypical of real reactor fuel.

The results of this analysis are given in Table I, where the various sources of asymmetry are seen to yield similar values of temperature difference, pellet eccentricity being the major effect. Irrespective of the source, the heat transfer coefficient assumed is seen to be very important in determining the magnitude of the resultant temperature non-uniformity.

To assess the maximum cross-pin temperature differences which might be expected during ballooning, steady-state calculations were also done for eccentric pellets in clad geometries corresponding to various ballooning strains. These are illustrated in Fig. 3 where again a marked effect of heat transfer coefficient can be seen. It is noted that these maximum temperature asymmetries, if existing during deformation, would preclude a high failure strain (see Fig. 1).

3.2 Transient deformation effects

Having established the level of temperature differences which might be present at the onset of ballooning, it remains to find the effect of transient deformation itself. Starting from the eccentric pellet cases for fresh and pre-irradiated fuel, idealized ballooning conditions were simulated. Thus the heat transfer, coolant temperature and rod power were maintained constant and the clad deformation model switched on. A nominal clad temperature of 1073K was chosen to ensure alpha-phase properties. Full pellet eccentricity was assumed to simulate the hot-side-straight effect and a range of rod filling pressures simulating start and end of life of a PWR rod was used to give different timescales to the deformation process. A further value of coolant temperature was included as was a third geometric state - a uniform pellet-clad gap of minimum size to simulate a uniformly crept-down cladding - "collapsed clad" to act as a control with a minimum starting temperature non-uniformity.

Typical results of these calculations are illustrated in Figs. 4 - 6. These show respectively: the time histories of the fuel and clad temperatures, demonstrating the strain cooling effect; the azimuthal temperature differences arising from the increasing pellet eccentricity and finally the clad strain developing asymmetrically.

Table II gives as results the time to fail, the initial and final values of the azimuthal temperature differences and the resulting mean hoop strain at failure. The interesting observations to make here are:

a) the very marked effect of increasing heat transfer coefficient in generating large temperature gradients and low failure strains;
b) a significant effect of failure time. Thus with high rod pressure there is insufficient time to develop high gradients before failure, especially with a low heat transfer coefficient;
c) a considerable reduction in gradients with a higher coolant temperature suggesting it is the surface heat flux rather than just the heat transfer coefficient which is important;
d) no correlation between the initial and final gradients showing that it is the eccentricity which develops during the deformation which dominates;
e) a good correspondence between the failure strain predictions and the observed experimental relationship (Fig.1).

To clarify the above observations a further series of runs have been made. Here the rod internal pressures were maintained constant at values calculated to give failure times of 1, 10 and 100 seconds and the peak clad temperature was also held constant by adjusting the power. Fresh fuel geometry was assumed in all cases. The results are shown in Fig. 7 where the maximum azimuthal gradients are plotted as a function of the nominal surface heat flux for the initial steady state and for the various failure times. It can be seen that the nominal surface heat flux is a reasonable parameter to take for predicting the azimuthal gradients in both steady state and transient conditions for these nominally constant temperature situations. The deviations between the curves for different coolant temperatures can be attributed to the changing flux due to the resulting temperature changes; however they are not large. In situations giving continuously increasing clad temperatures, the heat flux in the gap will have an additional contribution because of the thermal inertia of clad and the resulting temperature gradients can be expected to be even higher than those calculated here.

3.3 Implications for ballooning-blockage studies

As seen earlier balloon strains at failure of the order of 60 - 70% are required in many rods to give significant subchannel blockages. The hot-side straight model used in these calculations is expected to produce the maximum temperature non-uniformities and hence the minimum failure strains. Thus, if the conditions giving minimum strains of about 70% can be predicted, the potential problem area can be identified. From Fig. 1, 70% strain can only be achieved with azimuthal temperature gradients less than about 20K. For ballooning times of 10 - 100 seconds, Fig. 7 shows that the nominal surface heat flux must be less than about $5 \times 10^3 - 1 \times 10^4 W/m^2$ if the gradients are not to exceed this value under nominal constant temperature conditions. These are very low values, corresponding to fuel powers of the order of 0.5 - 1% of operating levels and are only achieved by decay heat under small-break LOCA conditions. In a large-break LOCA where the decay heat is of the order of 5%, heat fluxes as low as required could only be approached under adiabatic heat-up conditions when approximately 80% of the available heat will be used in raising the UO_2 temperature. This conclusion is born out by the REBEKA test results [6] where large strains were only found during adiabatic heat-up.

It will be remembered that a second necessary condition for significant channel blockage is coherency of ballooning between neighbouring rods. The conditions favouring this are thought to require high heat transfer and thus are likely to conflict with those giving high strain. This aspect of the problem will be the basis of a future RODSWELL analysis.

4. Conclusions

The simple 3-d computer model RODSWELL, being developed to study in detail the interaction between clad deformation and heat transfer, predicts failure strains in good agreement with experimental observation.

It also confirms the current state of understanding of the deformation problem in demonstrating the importance of heat flux in determining azimuthal temperature non-uniformities and failure strains.

After further development and validation, it is expected to be capable of being used as a tool to identify any reactor accident conditions which may lead to significant coolant channel blockages.

Preliminary indications are that such conditions are unlikely to be achieved in a LB LOCA but may exist in the wider range of possibilities afforded by small-break LOCA accidents.

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TABLE I : Steady-state ΔT resulting from azimuthal variations in power density, coolant temperature, heat transfer coefficient and pellet-clad gap (nominal T_{clad} = 1073 K).

Heat transfer coefficient (W/m² K)	Power density (W/m³)	Coolant temperature (K)	Pellet eccentricity*	Steady-state ΔT clad (K)
50	$Q_0 \pm 5\%$	573	0	1.2
50	Q_0	573 ± 5%	0	2.4
50 ± 5%	Q_0	573	0	2.1
50	Q_0	573	F	6.0
50	Q_0	573	P	2.3
500	$Q_0 \pm 5\%$	573	0	8.9
500	Q_0	573 ± 5%	0	17.9
500 ± 5%	Q_0	573	0	14.7
500	Q_0	573	F	36.0
500	Q_0	573	P	16.0

* F : fully eccentric pellet with "fresh fuel" geometry
P : fully eccentric pellet with "pre-irradiated rod" geometry

TABLE II- RODSWELL calculations of ballooning for various starting gaps (T_{clad} = 1073 K).

Coolant temperature (K)	Heat transfer coefficient (W/m² K)	Rod filling pressure (MPa)	Clad status*	ΔT clad at the steady state (K)	ΔT clad at failure (K)	Mean engineering hoop strain at failure (%)	Time to failure (s)
573	50	5	F	6.1	14	65	1.1
			P	2.4	16	70	1.5
			C	0.1	25	67	2.4
		2.5	F	5.7	58	39	56
			P	2.2	59	41	84
			C	0.1	60	41	161
	500	5	F	37	150	23	3.0
			P	17	169	23	6.8
			C	0.5	169	23	9.8
		2.5	F	36	178	21	46
			P	15	178	22	62
			C	0.5	180	23	70
773	50	5	F	3.7	6.0	90	0.7
			P	1.5	5.9	100	0.9
			C	0.03	11	101	1.7
		2.5	F	3.6	39	51	30
			P	1.3	39	51	38
			C	0.04	40	51	71

* F : fresh fuel
P : pre-irradiated rod
C : collapsed clad

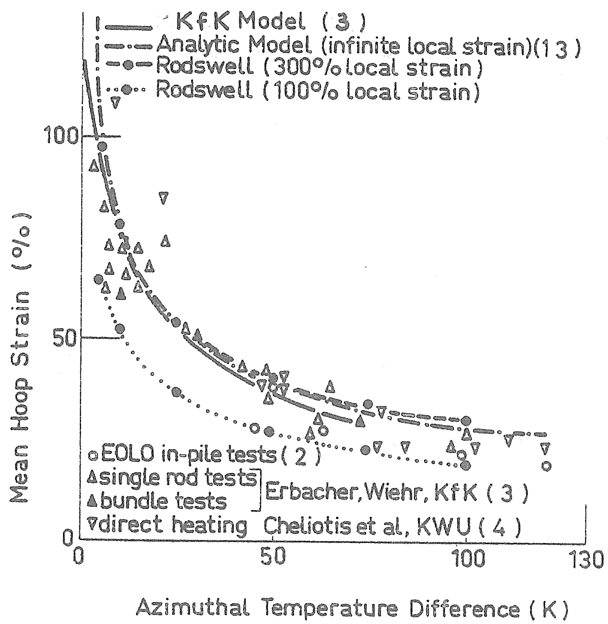

Fig. 1 Influence of azimuthal temperature gradient on burst strain (experimental data and model comparison)

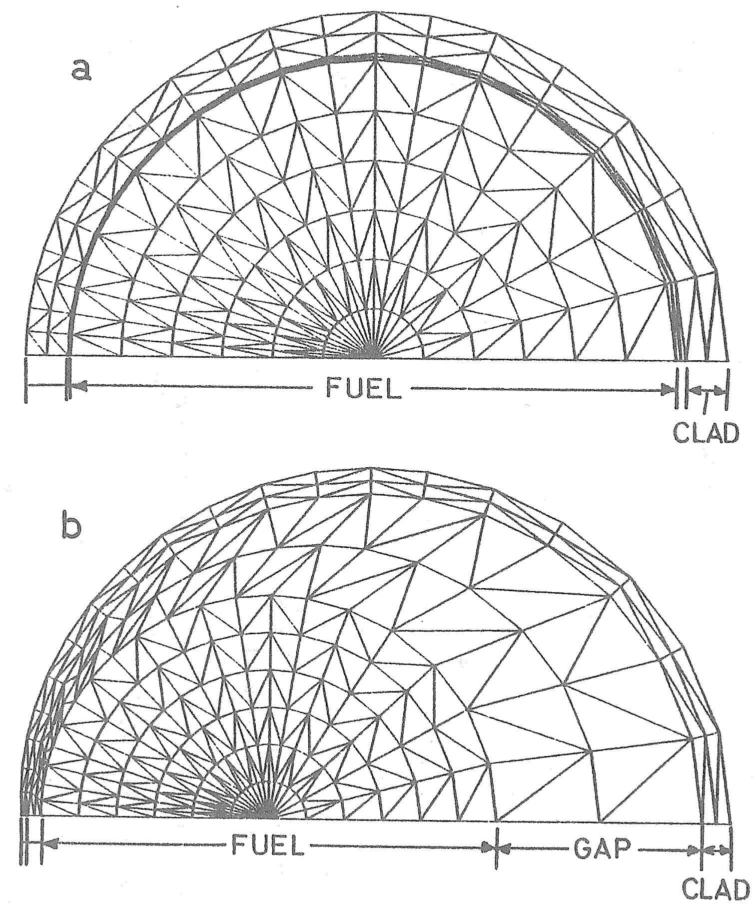

Fig.2.a Finite element mesh as used for the thermal analysis (typical starting configuration for an eccentric pellet calculation)

Fig.2.b Deformed finite element mesh at clad failure

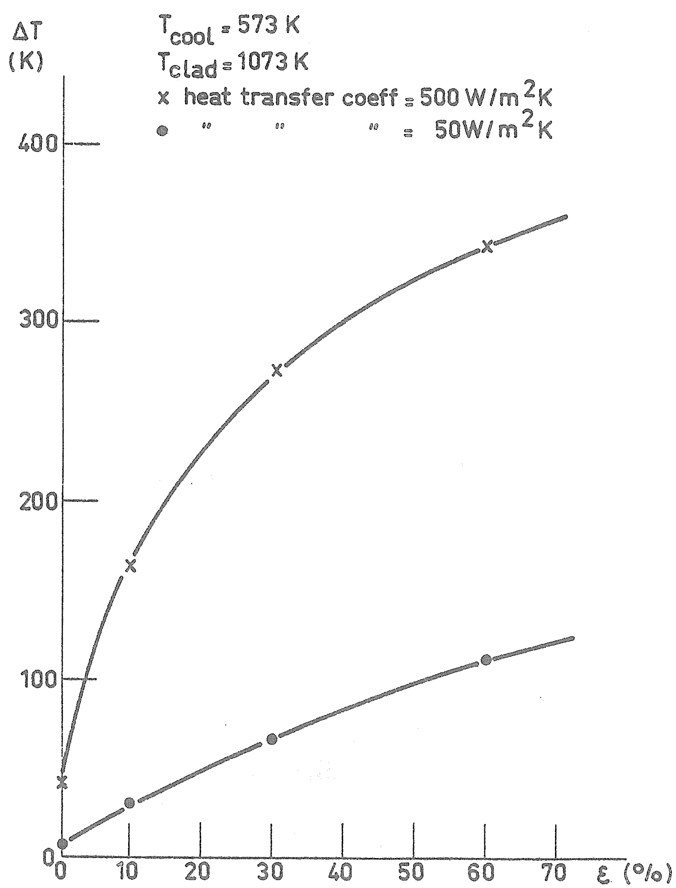

Fig.3 Steady-state azimuthal ΔT for an eccentric pellet as a function of clad strain

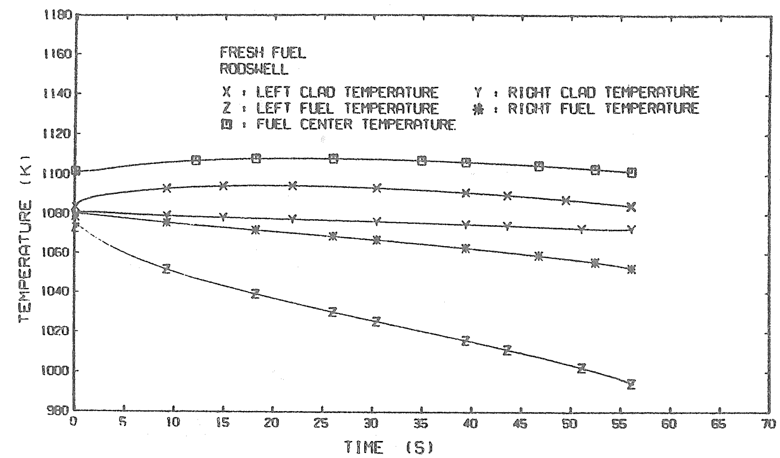

Fig.4 Time history of relevant fuel and cladding temperatures during ballooning (eccentric pellet, constant power case)

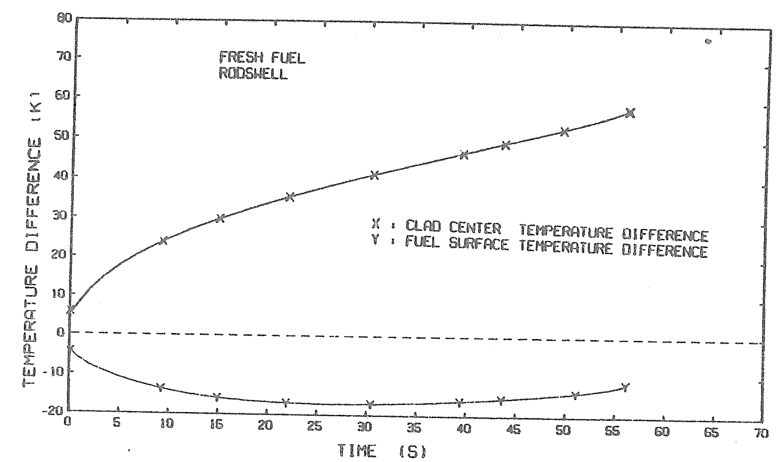

Fig.5 Time history of fuel and cladding azimuthal temperature gradients

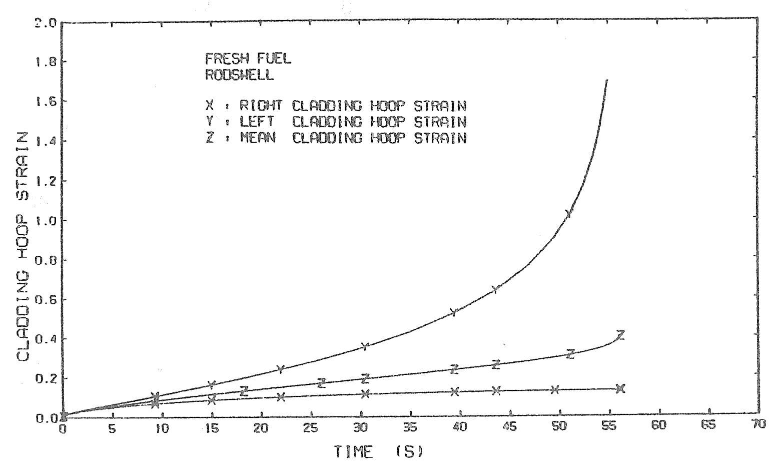

Fig.6 Time history of maximum, minimum and mean clad hoop strain

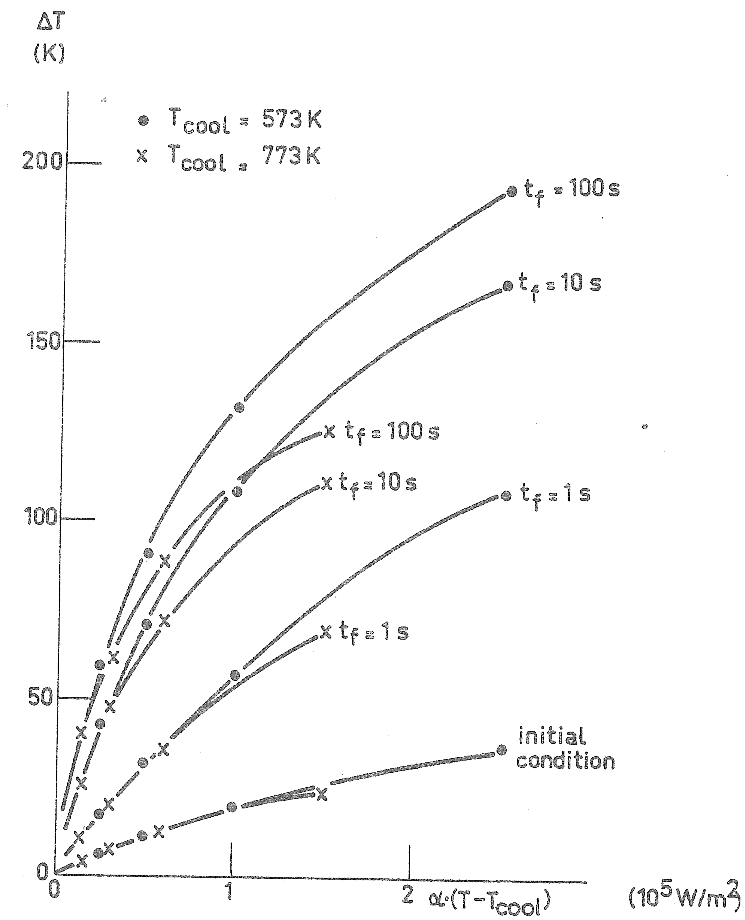

Fig.7 Azimuthal ΔT due to pellet eccentricity as a function of nominal surface heat flux for various failure times

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