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A FUEL PERFORMANCE CODE TRUST V1C AND ITS VALIDATION

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Abstract

This paper describes a fuel performance code TRUST Vlc developed to analyse thermal and mechanical behavior of LWR fuel rod. Submodels in the code include FP gas models depicting gaseous swelling, gas release from pellet and axial gas mixing. The code has FEM-based structure to handle interaction between thermal and mechanical submodels brought by the gas models. The code is validated against irradiation data of fuel centerline temperature, FGR, pellet porosity and cladding deformation.

1. INTRODUCTION

TRUST is a computer code to analyse thermal and mechanical LWR fuel rod behavior throughout its life. The code has been developed to simulate high burnup fuel behavior, especially in terms of FP gas release and pellet gaseous swelling as observed in international ramp tests. Accordingly, the code has models depicting the FP gas behavior in fuel rod including axial gas mixing. As a result, the gas models greatly increase the mutual interaction between thermal and mechanical models through, for instance, the FP gas release dependency on pellet stress, thus make the calculation more difficult. To bring an accurate numerical solution efficiently to the problem, a new code structure is devised and the gas models are assembled on the structure. This paper gives an overview of the TRUST code, validation bases and some characteristic results.

2. CODE STRUCTURE

2.1 GEOMETRICAL CONFIGURATION

TRUST code has a FEM-based structure on which thermal, mechanical and gas models are assembled. Figure 1 shows how a fuel rod is depicted by finite elements in the TRUST code. Fuel rod is divided into axial zones, and each zone is divided into radial ring elements. The thermal and mechanical models commonly use the element configuration. At the pellet and cladding gap, an element is placed per axial zone to handle mechanical contact and heat conductance. To depict FP gas concentration in free volume with axial gradient, two elements are adopted per axial zone so that a connection node comes at the center of axial zones. FP gas concentration in upper plenum is expressed by one element as well as in lower plenum, if any. A spring or sleeve element, which is only mechanical, can be inserted in upper plenum.

2.2 SOLVING SCHEME

The overall flow of the TRUST code is shown in Fig.2. After accepting data for fuel specifications and irradiation history, the TRUST code repeats the finite element assembling and global equations solving procedure, and yields results step-by-step for entire irradiation history. In the single loop iterative procedure to resolve the non-linearity of the fuel rod behavior, the assembled equations are solved simultaneously, and no inconsistency is left between fuel temperature, its deformation, and FGR over next time step. The scheme has enabled the code efficiently handling submodels related to both temperature and stress, since good communication between thermal and mechanical models are ensured in the iterative procedure to resolve the demands from both models.

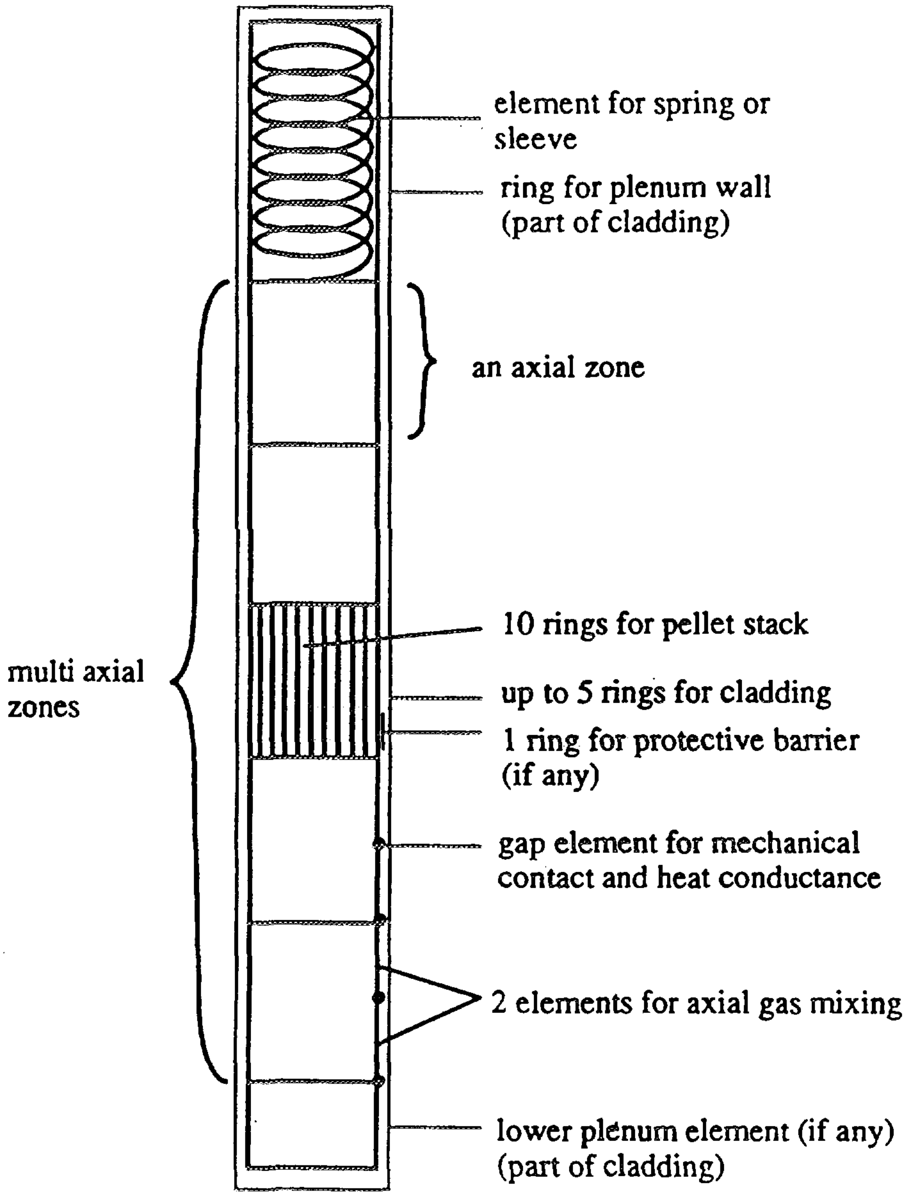


FIG. 1. Finite element configuration of the TRUST code

2.3 THERMAL MODEL

In the thermal model, a pellet thermal conductivity model depicts its reduction by accumulated soluble fission products[1], irradiation defects, and gaseous bubbles. The gap conductance is given by Ross and Stout model[2], based on the gap width, local FP gas concentration, and contact pressure implicitly written in the thermal equations. The values for them are determined in the process of solving the simultaneous equations. Radial heat generation distribution in pellet is given by a modified RADAR[3] model.

2.4 MECHANICAL MODEL

The mechanical model depicts fuel thermal expansion, creep, plasticity, pellet densification, swelling, crack, relocation, pellet-cladding contact, axial slipping, cladding irradiation growth, and resulting stress in pellet and cladding. Since most of the mechanical properties are temperature dependent, the TRUST code uses linear expansion form of inelastic strains to make direct reference to fuel temperature change, i.e.,

$$\{\varepsilon\}^{j+1} = \{\varepsilon\}^{j} + \left[\frac{\partial \varepsilon}{\partial T}\right]^{j} \delta T^{j+1} \tag{1}$$

where j is iteration number $\left[\frac{\partial \varepsilon}{\partial T}\right]^{j}$ temperature sensitivity vector and δT^{j+1} temperature increment in an iteration. The stress dependency of the strains is treated likewise.

Pellet-cladding mechanical interaction is handled as illustrated in Fig.3. Radial pellet relocation at the initial startup is simulated by translating the whole pellet rings radially. Afterwards, the pellet crack opened by the relocation is considered to be compliant and diminish its width by circumferential stress.

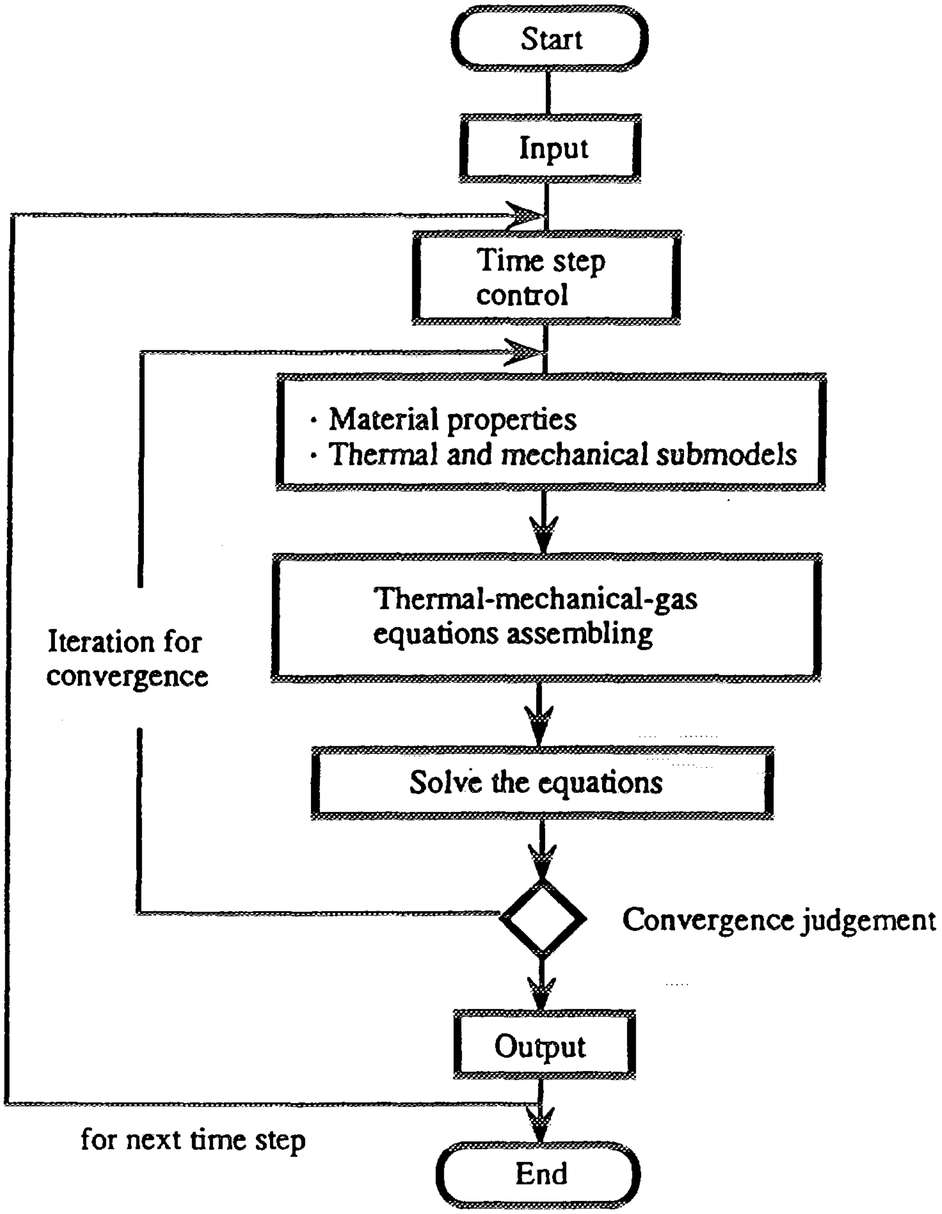


FIG. 2. Flow diagram of the TRUST code

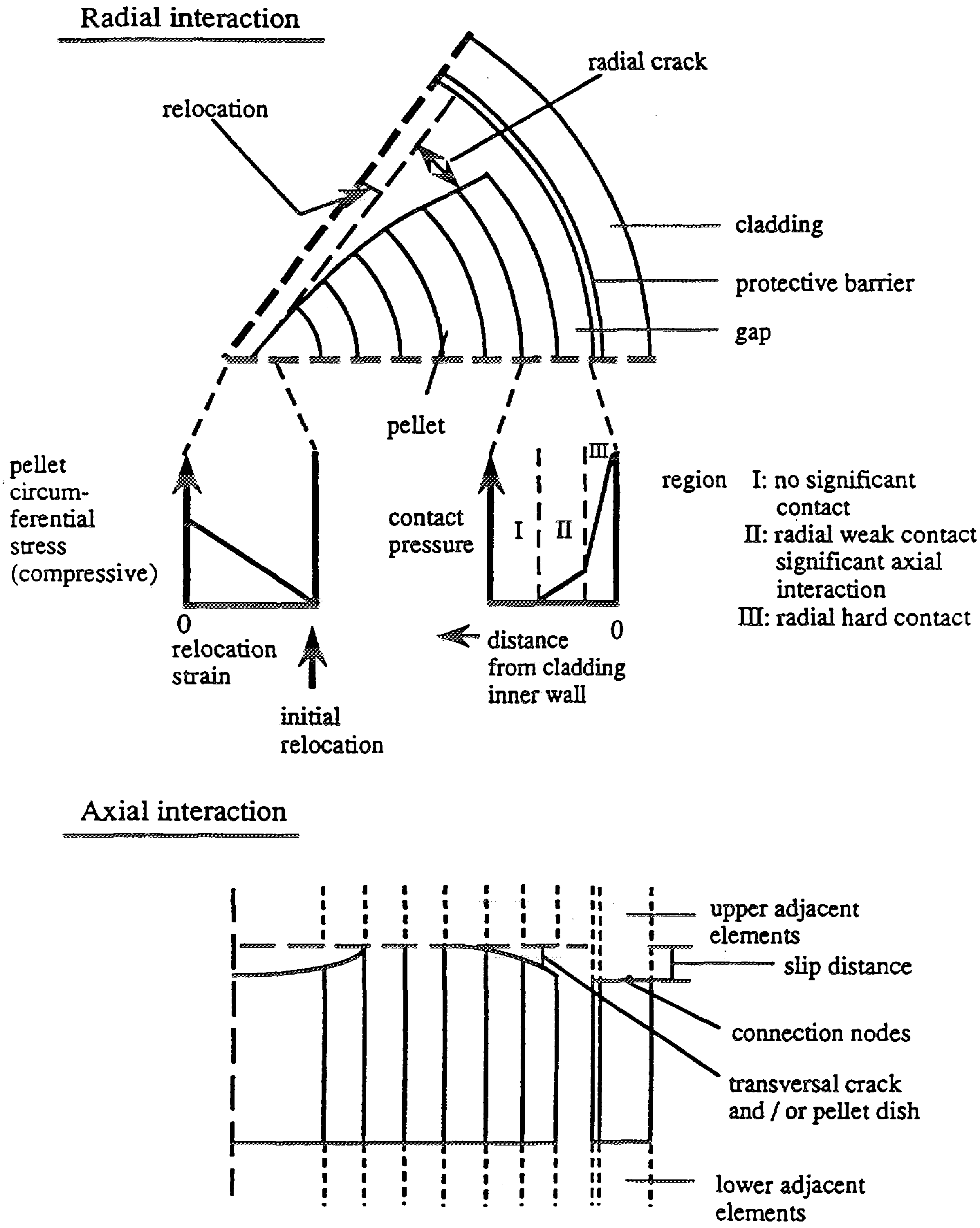


FIG. 3. Mechanical model for the TRUST code

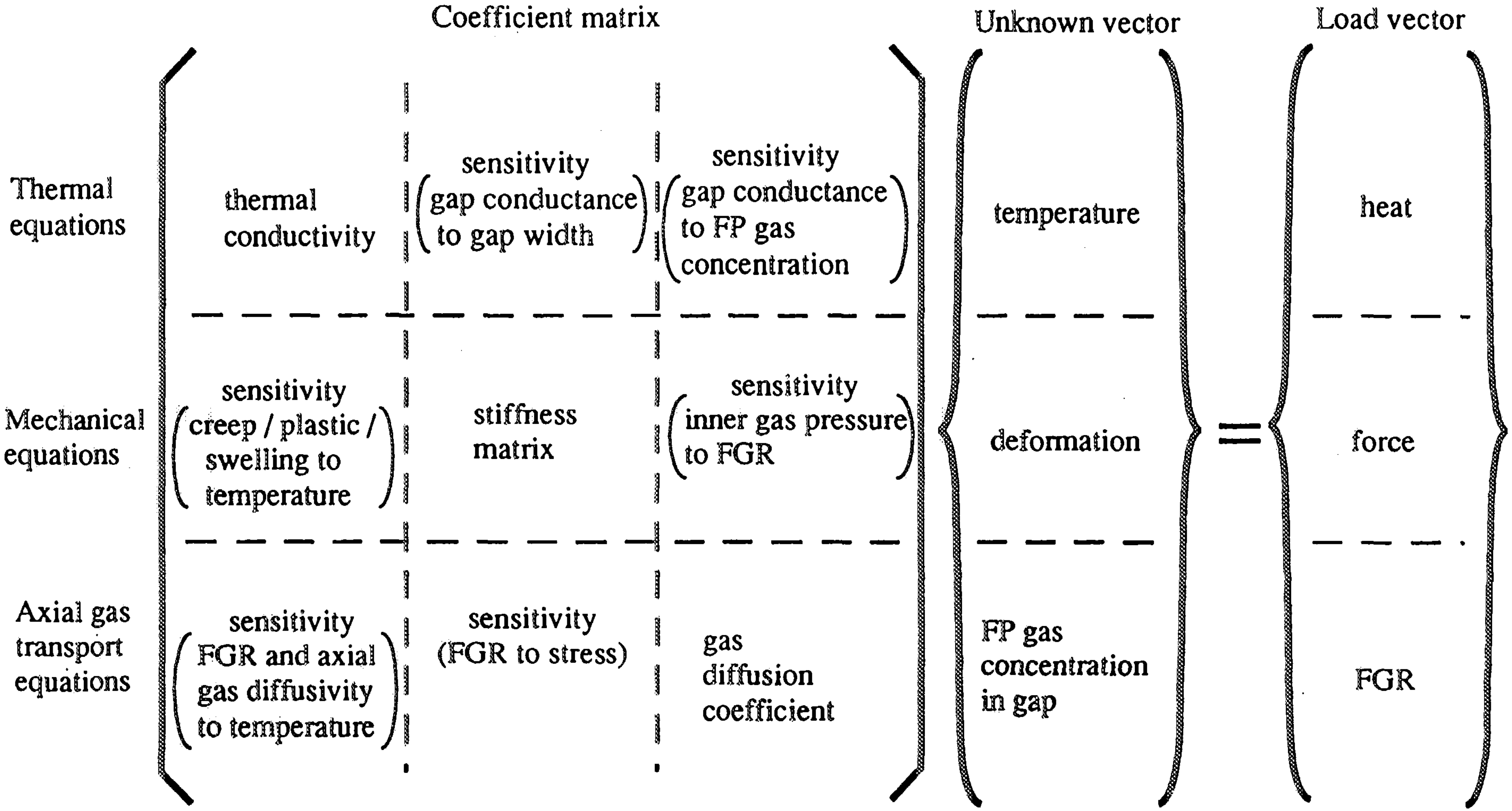


FIG. 4. Thermal/mechanical/gas equations assembling diagram

Pellet-cladding gap is modeled as though it is filled with three layers of compliant material. The innermost layer, depicted as region I in Fig.3, is made very soft to be compressive virtually without resistance. The second is made harder to elongate cladding axially under Coulomb friction. The third is for direct radial push of cladding by the pellet, having largest stiffness. The layers convey force to the cladding element as the pellet surface comes close to it, simulating the effect of the pellet fragmentation. The distance between the pellet and cladding elements is considered as the circumferentially averaged gap width in the actual fuel rod, and is used for evaluating the thermal gap conductance.

An axial force in fuel is conveyed by means of FEM connection nodes placed at the boundaries of the axial zones. To allow axial slipping between pellet and cladding, there are one connection node for cladding and the other for pellet. The pellet is stuck on the cladding if the axial force does not exceed the Coulomb friction force. While the pellet elements are made to cease conveying axial force when it transversely cracks, the cladding elements are permanently connected with adjacent ones. The model gives cladding stress as to be accumulated in the lower part of the fuel rod by the friction with pellet stack.

2.5 FP GAS MODELS

The process of FP gas diffusion in grain and on grain boundary is modelled to give FP gas release, and lenticular bubbles on grain boundary to give gaseous swelling of pellet.

Simple effective diffusion coefficient model is employed to give the FP gas transfer speed in grain radial direction. At the start of irradiation, the coefficient is set at the value measured at Harwell for UO_2 specimen[4]. The coefficient is made to be increased as the burnup proceeds in order to account for the measured FGR from irradiated rods.

The lenticular bubble is assumed to grow or shrink according to the stress field around the bubble, which is expressed in a formulation proposed by Hull and Rimmer[s]. Stress also plays a role in suppressing the FP gas transfer from the lenticular bubbles to the free volume.

Released FP gas is slowly mixed with fill gas and axially diffuses. Since pressure equilibrium throughout the rod is assumed in the gas mixing model, axial bulk gas flow occurs upon the gas release and the temperature change in free volume. The numerical instability associated with the bulk gas flow has been overcome by making the finite element boundaries movable in accordance with the bulk gas flow so that the gas does not cross the element boundary in a time step. The modified element accepts the relatively large time increment used in thermal and mechanical models, thus can be used to form a part of the simultaneous equations.

The FP gas diffusion speed in axial direction is determined by the shape of the free volume in pellet stack. Pellet central hole provides a fairly large and straight diffusion path. For the non-holed pellet stack, however, diffusion path has complicated shape due to pellet cracking. The TRUST code estimates the averaged path length and its width based on the simplified crack and gap geometry given by the mechanical model.

2.6 FINITE ELEMENT ASSEMBLING

Figure 4 is a diagram showing how the set of global equations are assembled in the TRUST code. The left hand side of the equation is the product of unknown field vector and coefficient matrix. The vector elements are chosen to be the fuel temperature and deformation as well as the FP gas concentration in gap. Thermal conductivity, fuel stiffness, and FP gas diffusion coefficient reside in the diagonal part of the coefficient matrix. In the off-diagonal part are the cross terms such as gap conductance sensitivity to gap width, and they bind the three subset of equations - thermal, mechanical and axial gas transport equations - together. The right hand side of the equations stands for the load vector consisting of fuel heat generation, external force and FGR. After assembling, the equations are handed to a solver which is designed to do the job in maximum efficiency.

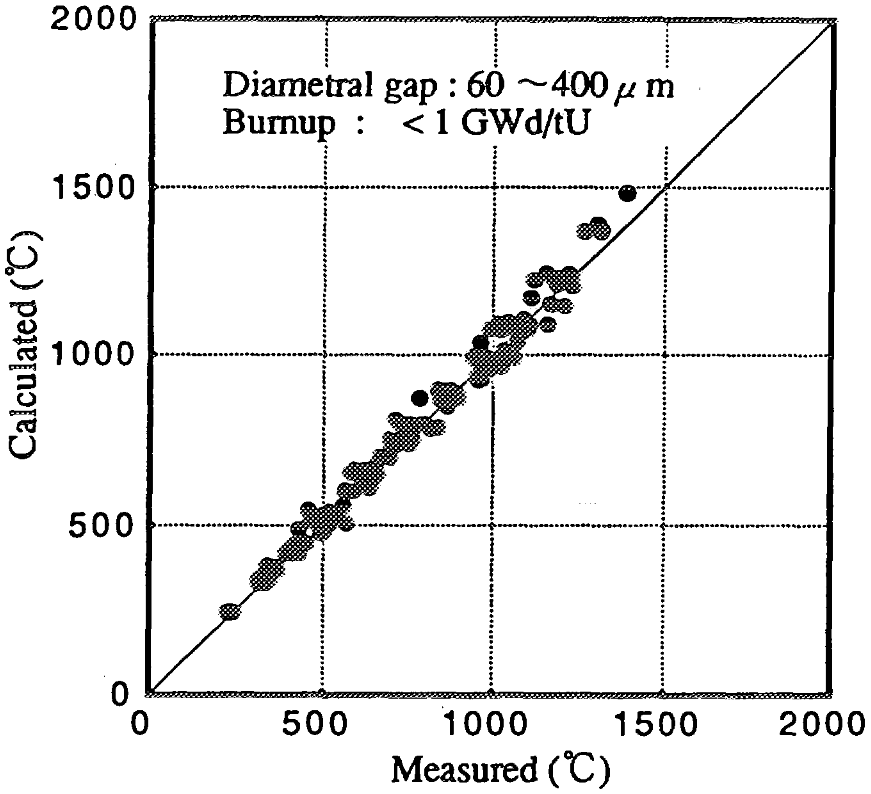


FIG. 5. Comparison of fuel centreline temperature at the beginning of irradiation

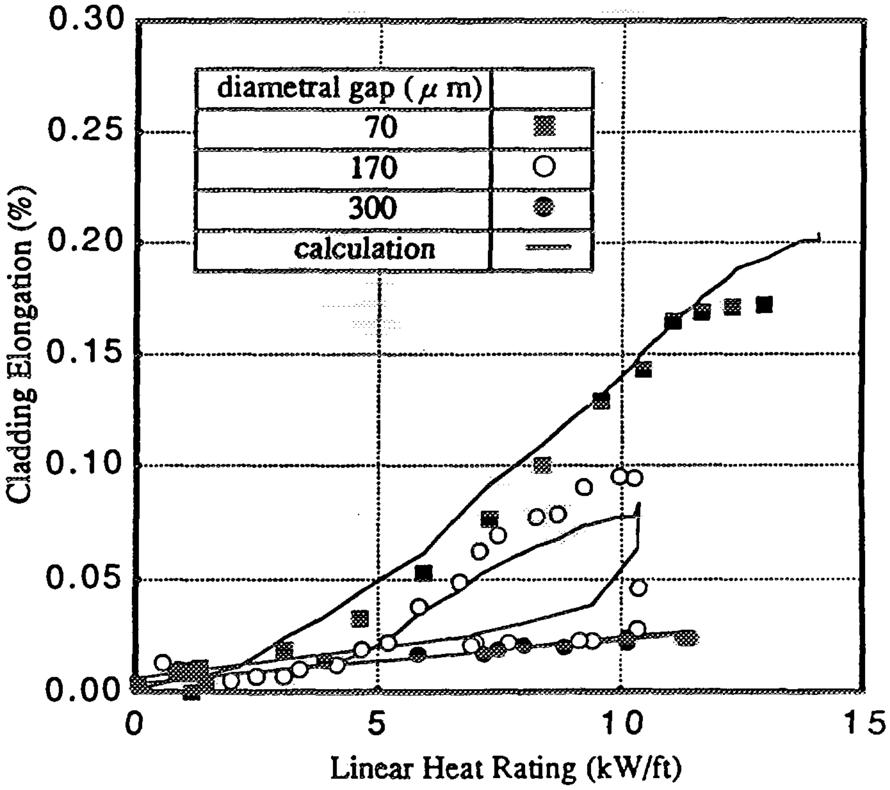
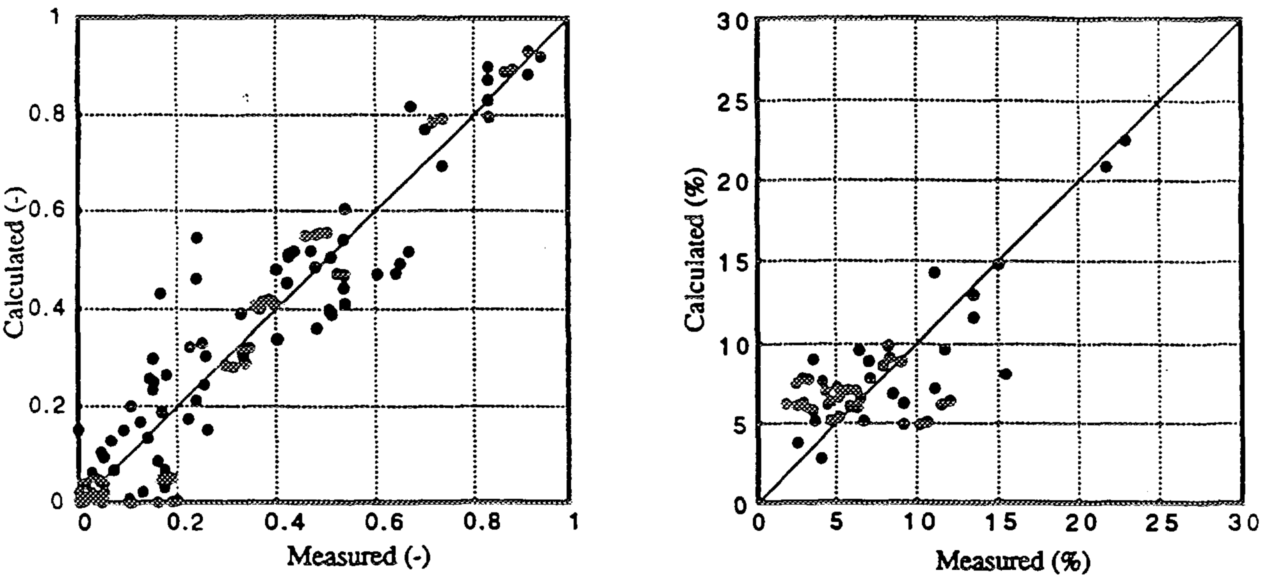


FIG. 6. Gap size dependency of cladding elongation



(a) FGR (b) Porosity

FIG. 7. Comparison of FGR and porosity (Fission Gas Release and Gaseous Swelling Model)

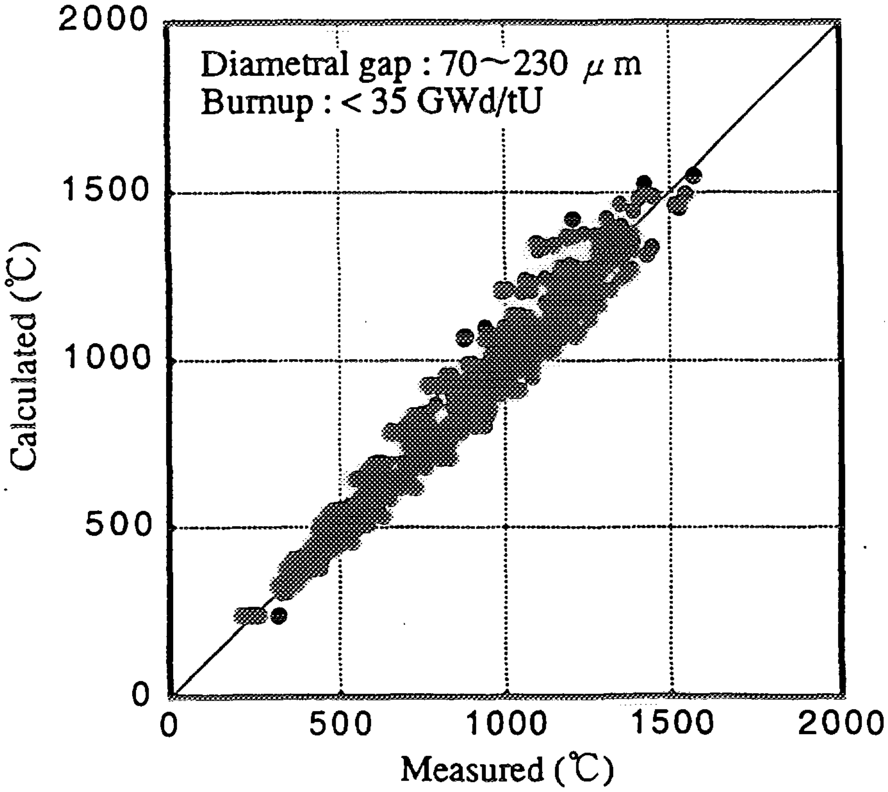


FIG. 8. Comparison of fuel centreline temperature to high burnup

3. VALIDATION DATABASE

The TRUST code has been validated through the comparison of its predictions with on-power and PIE data. The on-power data comprise fuel centerline temperature, rod internal pressure and cladding elongation. The PIE data employed are FGR, cladding permanent elongation, diameter change, pellet xenon retention, porosity and grain size. The data are from Halden irradiation test programs and other international projects, and PIEs for rods from commercial reactors carried out in NFD. Major design parameters of the fuel rods cover the manufactured diametral gap of 60 to 400μm, pellet stack length of 30 to 360cm, and initial fill gas pressure of 1 to 25atm.

4. RESULTS OF THE CODE VALIDATION

The validation of the TRUST V1c has been performed by separating the irradiation period into at the beginning of life and throughout the life, since fission gas release complicates fuel rod behavior.

The effects of initial gap size on fuel centerline temperature and cladding elongation has been firstly examined. Figure 5 compares the TRUST code predictions and the experimental data as for fuel centerline temperature at the startup, and they are in good agreement in a gap size range from 60 to 400μm. On the other hand, cladding elongation versus gap size at the startup is shown in Fig. 6. The rods with a medium and a narrow (70μm) gap size appear to become contact with cladding at 5kW/ft (160W/cm) and 3kW/ft (100W/cm), respectively, and the behavior is well simulated by the code. In addition to the effects of gap size, those of axial power profile (contact at the upper portion of a fuel rod elongates the cladding to a larger extent), pellet stack length and pellet shape on the cladding elongation has also been validated.

Prior to the code validation throughout the rod life, the fission gas release and gaseous swelling submodel has been verified independently using more than thirty cases in which sample temperature is measured. Figures 7 (a) and (b) show the comparison between calculated and measured of FGR and pellet porosity from rod ramp tests[6], UO_2 out-of-pile annealing tests[7,8], and UO_2 isothermal irradiation tests[9]. The figures show that fission gas behavior is appropriately simulated by the model.

As the most influential parameter to the fuel rod performance, validation of fuel centerline temperature has been carried out. Figure 8 compares the code predictions and measurements of fuel centerline temperature up to 35GWd/tU for the fuels with gap size of 70 to 230μm. The figure shows that the predictability of fuel temperature of the TRUST code is satisfactory.

5. CONCLUSIONS

1. A fuel performance code TRUST V1c for analyzing LWR fuel rod behavior has been successfully developed.

2. The fission gas release and gaseous swelling submodel in the TRUST code has been verified against rod on-power pressure data, UO_2 out-of-pile annealing test data and isothermal irradiation test data.

3. The code has been validated against on-power and PIE data from not only test reactors but commercial reactors. An extensive comparison of calculated fuel centerline temperature with measured has shown that the code predicts satisfactorily the fuel temperature up to high burnup.

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