XA0056248

ASSESSMENT OF CLAD INTEGRITY OF PHWR FUEL PIN FOLLOWING A POSTULATED SEVERE ACCIDENT

B.K. DUTTA, H.S. KUSHWAHA, V. VENKAT RAJ
Reactor Design and Development Group,
Bhabha Atomic Research Centre,
Mumbai, India

Abstract

A mechanistic fuel performance analysis code FAIR has been developed. The code can analyse fuel pins with free standing as well as collapsible clad under normal, off-normal and accident conditions of reactors. The code FAIR is capable of analysing the effects of high burnup on fuel behaviour. The code incorporates finite element based thermo-mechanical module for computing transient temperature distribution and thermal-elastic-plastic stresses in the fuel pin. A number of high temperature thermo-physical and thermo-mechanical models also have been incorporated for analysing fuel pins subjected to severe accident scenario. The present paper describes salient features of code FAIR and assessment of clad integrity of PHWR fuel pins with different initial burnup subjected to severe accident scenario.

1. INTRODUCTION

The integrity of fuel rods under normal, off-normal and accident conditions is an important consideration during fuel design of an advanced nuclear reactor. The fuel matrix and the sheath form the primary barriers in preventing the release of radioactive materials into the primary coolant. An understanding of the fuel and clad behaviour under different reactor conditions, particularly the severe accident conditions, is always desirable for the safe operation of nuclear reactors and mitigation of the consequences of accidents, if any. The severe accident conditions are typically characterized by the energy deposition rates far exceeding the heat removal capability of the reactor coolant system. This may lead to clad failure due to large scale pellet-clad interaction or even clad melting. The fuel rod performance is affected by many interdependent complex phenomena involving extremely complex material behaviour. The versatile experimental data base available has led to the development of powerful analytical models to characterize fuel under extreme scenarios. A number of fuel performance analysis codes have been developed in different parts of the world based on such analytical models. In BARC, the code 'FAIR' has been developed over the last seven years [1]. This code is based on the application of the finite element method for thermo-mechanical modelling and mechanistic modelling of various phenomena affecting the fuel behaviour. The code is capable of analysing the effects of high burnup on fuel behaviour. The code has been validated against a set of data from operating fuel pins subjected to normal and off-normal conditions at high burnup, as a part of the IAEA-Coordinated Research Project (CRP) on FUMEX (FUel Modelling at EXtended burnup). The code 'FAIR' has been subsequently modified to handle fuel pins subjected to extreme accidental scenarios.

During severe accident conditions, the mode of failure of clad is essentially due to clad ballooning. This occurs due to a combination of rod internal pressure and clad temperature. The combination of internal pressure and clad temperature leads to large scale thermal creep in the clad material. The magnitudes of pressure and clad temperature primarily depend upon two input parameters. These are, the amount of energy deposited in the fuel pellet and the coolant heat transfer coefficient. As a part of the present analytical study, a severe accident scenario involving LOCA with the coincidental failure of ECCS has been considered. This is one of the dual failure accidents considered for PHWRs. For such a scenario, the fuel pin failure is characterized by the large scale clad ballooning with the progress of accident time. Based on the data available in published literature, the analytical criterion selected for clad failure is the accumulation of a predefined local creep strain.

The creep strain rates calculated as a function of rod pressure and clad temperature for each time step are integrated with respect to time to obtain the cumulative creep strain. A parametric study has been performed to assess the clad failure time with the burnup of the fuel pin during the course of the accident.

The following sections deal with the description of the code 'FAIR', the accident analysis procedure, the results of the parametric study and the conclusions drawn through the present study.

2. DESCRIPTION OF CODE 'FAIR'

The code 'FAIR' models various physical, chemical and mechanical phenomena occurring in a nuclear fuel during its residence period in a reactor using mechanistic principles. This code is capable of analysing the complex material behavior of fuel pins and the interactive nature of various phenomena affecting the fuel pin behavior. The code is equipped with high burnup modelling capabilities, such as pellet thermal conductivity degradation with burnup, redistribution of radial flux at high burnups, enhanced fission gas release at high burnups. The organisation of this code follows the proven principles of fuel rod modelling, such as, coupling between thermal, mechanical and fission gas release modules, concurrent analysis of different axial sections of fuel rods to consider fission gas mixing. In addition to this, local analysis such as clad ridging can also be performed. The modular nature of the code offers flexibility in incorporating modifications to model fuels of different materials and reactors. A separate module has been incorporated in the code FAIR for performing statistical analysis of fuel pins. Besides the sequential version of the code FAIR, a parallel version is also developed and implemented on a parallel processing system [2]. This parallel version facilitates high speed computation by performing simultaneous analysis of different axial sections of fuel pins for considering axial fission gas mixing.

2.1. Thermo mechanical module of FAIR

The thermo mechanical module of the code FAIR is based on 2-D axisymmetric Finite Element Method [3]. The thermal analysis module can analyse both steady state and transient situations. Both Dirichlette and Neumann boundary conditions can be analysed. The nonlinearities associated with temperature dependent material properties are solved using iterative techniques considering each step as a quasi static state. The convergence of solution is checked by specifying a convergence criterion for the norm of temperatures. Direct integration method (Crank-Nicholson scheme) is employed for analysing transient cases. The mechanical analysis module can analyse thermal visco-plastic loading conditions, which can take care of material nonlinearity of pellet and sheath due to thermal, pressure and creep loadings. The generation of nonlinear characteristic equations is done by Modified Newton-Raphson method. Additional strains on the pellet due to thermal and irradiation induced densification and swelling and strains due to pellet cracking and relocation are treated as initial strains as per standard Finite Element procedure.

The code incorporates three different high temperature creep models for use in severe accident analysis. These models are due to Holt (NIRVANA) [4], Donaldson [5] and Shewelt [6]. These models represent creep rate in an Arhenius type relation as a function of clad temperature and stress.

2.2. Salient fuel models in FAIR

For modelling fission gas release, Standard ANS 5.4 model [7], empirical model based on Halden data [8] and microstructure dependent fission gas release models [9–12] are implemented in the code FAIR. The pellet densification and swelling, grain growth, thermal and mechanical material properties are implemented based on MATPRO [13]. The thermal conductivity degradation of pellet with burnup is modelled using the data available in open literature [14,15]. The variation of flux profile across pellet radius and the change in this profile with burnup are modelled using RADAR model [16]. The code consists of a separate module for modelling the pellet-clad-interaction (PCI) induced fuel failure [17], which models crack initiation and propagation in clad as a function of the sheath strains and the amount of free Iodine available on the inner sheath surface.

2.3. Statistical analysis module of FAIR

The code FAIR incorporates Probabilistic methods of analysis based on Monte-Carlo technique. The probabilistic methods supplement the mechanistic modelling of fuel behaviour. The effect of variation in the geometry of the fuel due to manufacturing defects, in particular the gap between the pellet and the sheath, the errors in power measurement, the uncertainties in the material properties are studied by varying these parameters in a random fashion. The variations are considered to be following a Gaussian distribution. A number of repetitive analyses are performed considering these variations and the variation of output parameters such as fuel temperatures, fission gas release and fission gas pressure are indicative of the uncertainties involved in the modelling.

3. VALIDATION OF CODE FAIR

The individual models of the code FAIR have been tested and validated against the standard bench mark cases published in the literature. The performance evaluation of FAIR as an integral fuel analysis code has been done against a number of studies. One of the studies was based on an earlier project on fuel rod modelling code evaluation by Electric Power Research Institute [18]. Another study was carried out for simulating analytically the threshold power ramp criteria (P_c, ΔP_c curves) for a Pressurised Heavy Water Reactor (PHWR) fuel rod and comparing the same with the experimental database [19]. The main validation of code FAIR for high burnup fuel pins was carried out during the blind code comparison exercise of IAEA CRP on *FU*el *M*odelling at *EX*tended burnups, FUMEX [20]. The details of these validation studies can be found in References [21–23].

4. SEVERE ACCIDENT ANALYSIS OF PHWR FUEL PINS

During severe accident conditions, the rate of energy deposition exceeds the heat removal capacity of the reactor heat removal system. The likely mode of failure under such conditions is the clad ballooning. This occurs due to a combination of rod internal pressure and clad temperature. The combination of internal pressure and clad temperature leads to a large scale thermal creep of the clad. The variation of pressure and clad temperature with the time of accident basically depend upon three parameters. These are the amount of stored heat energy in the pin at the time of initiation of accident, the amount of heat energy deposited during the accident and the heat transfer conditions at the clad surface. The effect of these parameters on a 220 MW(e) Indian pressurised heavy water reactor (PHWR) fuel pin clad has been studied using the code FAIR.

The accident scenario pertains to the failure of a fuel pin, which is subjected to a power profile and heat transfer conditions similar to those obtained for a LOCA coincident with loss of ECCS. Such an accident is one of the dual failure accidents considered for PHWRs. The thermal hydraulic conditions for such scenario has been obtained using the relevant thermal-hydraulic analysis codes [24]. The analysis has been done to determine the time of clad ballooning after the accident for fuel pins having different burnups at the time of initiation of the accident. Based on the published literature, the analytical criterion selected for clad failure is the accumulation of 75% local creep strain. The calculated creep strain rates as a function of rod pressure and clad temperature for each time step are integrated with time to obtain the cumulative creep strain.

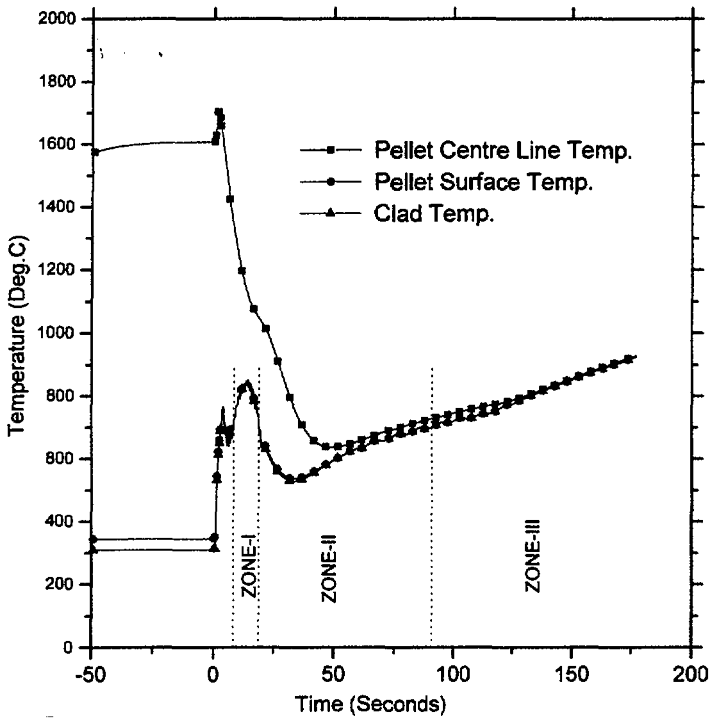

FIG. 1. A typical temperature transient in a PHWR fuel pin subjected to LOCA with ECCS failure.

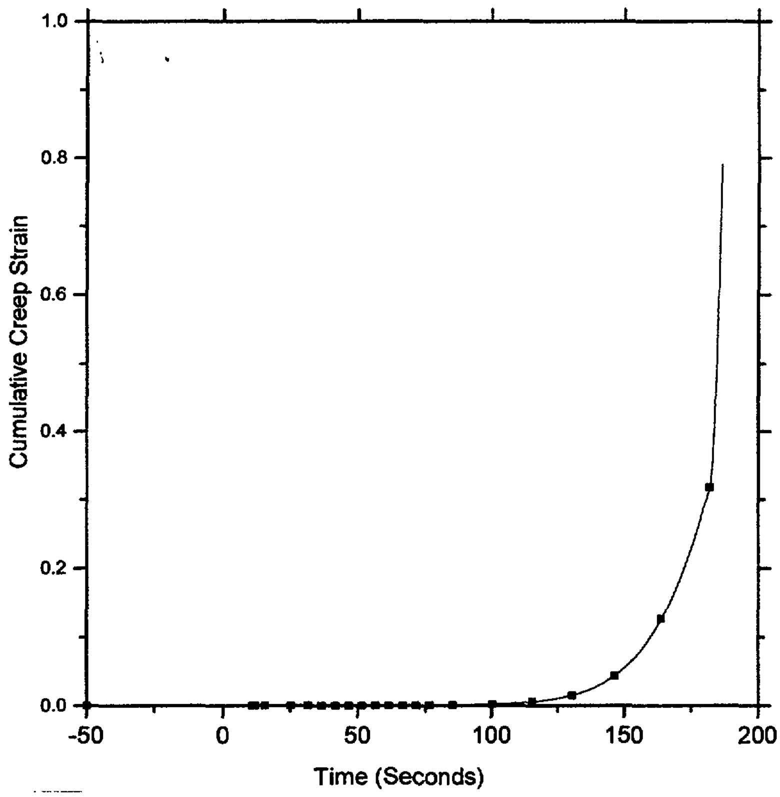

FIG. 2. A typical variation of accumulated local creep strain in a PHWR fuel pin sheath under LOCA with ECCS failure.

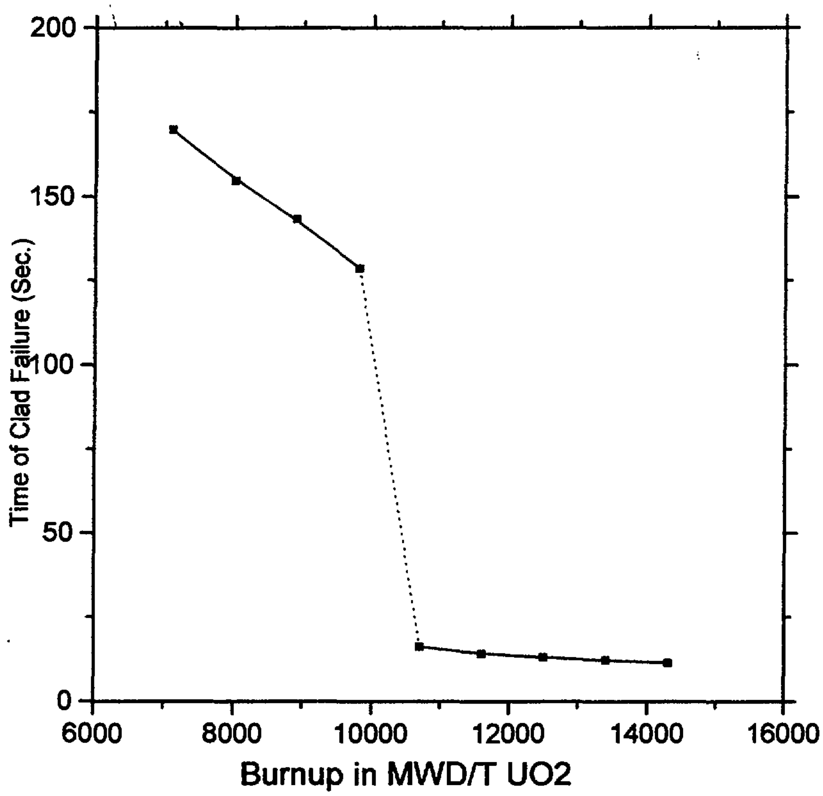

FIG. 3. Assessment of time of clad failure for a furl pin subjected to LOCA with ECCS failure.

5. RESULTS AND DISCUSSIONS

The typical variations of the fuel centre line temperature, the pellet surface temperature and the clad temperature during such an accident for a fuel pin having a burnup of 7000 MWD/T UO_2 are shown in Fig. 1. The transient clad temperature profile in this figure can be divided into three zones along the time scale. These are, the rapid increase in clad temperature just after the initiation of the accident (zone-I), followed by the time interval of moderate clad temperature (zone-II) and finally the slow mode of heating of clad to a high temperature (zone-III). A typical variation of cumulative creep strain with the time of transient is shown in Fig. 2. It may be noted here that the cumulative creep strain increases rapidly once the clad temperature-stress combination crosses a threshold value. The time of clad failure for fuel pins having different initial burnup is shown in Fig. 3. It may be noted here that the failed pins may be put in two distinct groups depending upon the time of clad failure. For the fuel pins having burnup less than 10 000 MWD/T UO_2, the time to failure is large and these lie in zone-III of Fig.1. On the other hand, the time to failure of fuel pins with burnup more than 10 000 MWD/T UO_2 is much less and these lie in zone-I.

This is essentially because the fission gas pressure available for clad ballooning increases with the burnup. For high burnup fuel pins, the gas pressure may be enough to cause clad ballooning during the initial rapid heating phase of the clad (zone-I) itself. However, clad ballooning may require more time and temperature for the lower burnup fuel pins having less fission gas pressure. For these fuel pins the time of clad ballooning lies in zone-III.

REFERENCES

[1] SWAMI PRASAD, P., DUTTA, B.K., KUSHWAHA. H.S., KAKODKAR, A., Fuel performance analysis code 'FAIR', BARC report no:BARC/1994/E/013, (1994).

[2] SWAMI PRASAD, P., DUTTA, B.K., KUSHWAHA, H.S., MAHAJAN, S.C., KAKODKAR, A., Role of BARC parallel processing system in structural analysis of nuclear components, Structural Mechanics in Reactor Technology (SMiRT-13), Paper No: F11/3, (1995b).

[3] COOK, R.D., MALKUS, D.S., PLESHA, M.E., Concepts and applications of Finite Element Analysis, 3rd ed., John Wiley and sons, (1989).

[4] SILLS, H.E., HOLT, R.A., Predicting high temperature transient deformation from microstructural models, 4th ASTM Conf. on Zirconium in nuclear industry.

[5] DONALDSON, A.T., HORWOOD, R.A., HEALY, T., Biaxial creep deformation of Zircaloy-4 in the High Alpha phase temperature range, Water reactor fuel element performance computer modelling, 1983.

[6] SCHEWELT, et al., A high temperature creep model for Zr-2.5 wt % Nb pressure tubes, Jl. of Nuclear Materials, 125, 218-235 (1984).

[7] NUREG/CR-2507, Background and derivation of ANS 5.4 standard fission gas release model, (1982).

[8] VITANZA, C., et al., Fission gas release from In-pile Pressure Measurements, Presented at Enlarged HPG meeting on water reactor fuel performance and application of process computer in reactor operation, Loen, Norway (1978).

[9] HARGREAVES, R., COLLINS, D.A., A Quantitative Model for Fission Gas Release and Swelling in Irradiated Uranium Dioxide, J. Br. Nucl. Energy Soc., 15 (1977), 311-316.

[10] NOTLEY, M.J.F., HASTINGS, I.J., A Microstructure Dependant Model for Fission Product Gas Release and Swelling in UO2 Fuel, Nucl. Engg. Design, 56 (1980), 163-175.

[11] WHITE, R.J., TUCKER, M.O., A New Fission Gas Release Model, J. Nucl. Mater., 118 (1983) , 1-38.

[12] NAKAJIMA, T., SAITO, D.H., A Comparison between Fission Gas Release Data and FEMAXI-IV Code Calculations, Nucl. Engg. Design, 101 (1987), 267-279.

[13] HAGRMAN, D.L., REYMANN, G.A., MASON, R.E., MATPRO-Version 11 (Rev.2) - A handbook of material properties for use in the analysis of light water reactor fuel rod behaviour, NUREG/CR-0497, TREE-1280 Rev.2, (1981).

[14] OTT, C., Testing of the Integral Fuel Behaviour Code TRANSURANUS using Halden Test Fuel Data, Presented at the Halden Extended Programme Group Meeting in Storefjell (N), (1993).

[15] LUCATA, P.G. et al, IAEA-TECDOC-697, 165-171, (1993).

[16] PALMER, I.D., HESKETH, K.W., JACKSON, P.A., A model for predicting the radial power profile in a fuel pin, Light Water Reactor Fuel rod Computer Modelling, (Gittus, J.H. Ed.), (1985), 321-335.

[17] JAMES YU-CHEN YAUNG, A model of pellet cladding interaction to simulate operational ramp failure of water reactor fuel, Ph. D Thesis, University of California, Los Angeles, (1983).

[18] EPRI-NP-369, EPRI report on Light water reactor fuel rod modelling code evaluation (1977).

[19] PENN, W.J., LO, R.K., WOOD, J.C., Candu fuel - power ramp performance criteria, Nuclear Technology, 34 (1977), 249-268.

[20] IAEA/IND/7348, Participation Agreement between IAEA and BARC (India) on Coordinated Research Project FUMEX (1993).

[21] SWAMI PRASAD, P., DUTTA, B.K., KUSHWAHA, H.S., KAKODKAR, A., A Development of computer code for PHWR fuel element analysis, Structural Mechanics in Reactor Technology (SMiRT-12), Paper No:C03/4, (1993).

[22] SWAMI PRASAD, P., DUTTA, B.K., KUSHWAHA, H.S., MAHAJAN, S.C., KAKODKAR, A., Fuel Analysis code FAIR and its high burnup modelling capabilities (Invited Paper), Structural Mechanics in Reactor Technology (SMiRT-13), Paper No: C04/1 (1995).

[23] SWAMI PRASAD, P., DUTTA, B.K. , KUSHWAHA, H.S., KAKODKAR, A., Performance of code FAIR in IAEA CRP on FUMEX. BARC report - BARC/1996/E/022, (1996).

[24] GUPTA, S.K. et al., Personal Communication of Thermal Hydraulic data (1998).