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Experimental simulation of creep fatigue damage in the PFBR control plug mock-up

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ABSTRACT: Towards validating the life prediction calculations of control plug, the most critical high temperature component in the Prototype Fast Breeder Reactor (PFBR), thermal shocks and in turn creep-fatigue damages are simulated on the control plug mockups. This paper deals with the basis of simulations and preliminary test results obtained so far.

1. INTRODUCTION

Fast Breeder Reactor (FBR) structures operating at high temperatures are subjected to severe thermal shocks and inturn high creep fatigue damage. These components are designed in accordance with rules of design code RCC-MR (1993). In some cases they call for detailed inelastic analysis towards reducing undue conservatism in the elastic analysis route of the design code. One such critical component in an FBR is control plug (CP). Since the CP is positioned just above the core (Fig 1) it is subjected to all thermal transients of the reactor core. Structurally, the CP is made up of thin cylindrical shells (outer shell and inner shell), horizontal plates (core cover plate, stay plates and thermal baffles) along with associated plate shell junctions (Fig 2). The primary stresses are mainly due to self weight which are negligible. Under normal operating conditions, the CP is more or less under isothermal condition at reactor outlet temperature (about 820 K) and the steady state thermal stresses are negligible. The main loading to this component is due to transient following a reactor scram during which the reactor outlet temperature reduces from 820 K to 675 K in 20 s (typical values). Under such a thermal shock, the different parts of CP are cooled with different rate depending upon the position and associated thermal inertia, resulting in high temperature gradients (Fig 3). These gradients, in turn cause high thermal stresses particularly in the upper plate shell junction which is the most critical location in the CP.

Detailed elastic, inelastic and viscoplastic analysis of the CP is dealt in ref[1]. The CP decides the operating temperature of the entire plant [2]. It satisfies the creep fatigue damage limit of design code RCC-MR (1993) [3] for temperatures upto 775 K only, if the elastic route of the code is followed. However the inelastic analysis with 'Chaboche viscoplastic model' has indicated that it is possible to meet the above code rules for temperature above 825 K. It is worth mentioning that the creep-fatigue damage is brought down by decreasing the thermal shock on the CP by following sympathetic safety action (pump flow coast down to 20 % following reactor scram). With this, the CP meets the creep-fatigue damage criteria of RCC-MR (1993) through elastic route itself. The elastic and viscoplastic analysis are carried out using an in-house finite element computer code called ' CONE'. Towards validating the results, an experimental program has been undertaken in collaboration with Indian Institute of Technology, Madras.

As regards to literature on this subject, theoretical and experimental studies on a typical CP mockup are reported in ref[4] which deals with the life prediction of relatively a smaller shell structure of 8 mm thick and 160 mm outer diameter, connected to 10 mm thick support plate at middle elevation. In this case sodium is used as coolant. Similar studies are also reported by D. Marsh et al. [5&6] in which a problem of fatigue crack growth in an axisymmetric component (similar to the CP mockup) subjected to severe thermal cycling in the absence of mechanical loads is investigated. In this study, a 50 mm thick circular plate is welded at the centre of cylindrical shell of 152 mm inner diameter and 7 mm wall thickness. The structure is subjected to cold shock of 200 K with a shock rate of 10 K/s. The aim of the study is to compare the theoretical predictions of crack initiation and crack growth rates with the experimental data. In this study water was used to produce cold shock. In both the cases dealt above, the size of the geometry was relatively small. But in the study reported in the present paper, the size of the geometry is relatively large (about 240 mm outer diameter and 20 mm wall thickness). Air is used as the coolant. Eventhough the sodium is an ideal coolant, considering cost, safety (sodium fire in case of leak), operational and maintenance difficulties, air is used. Both crack initiation and propagation with and without welds at the junctions are planned to be investigated.

The present paper deals with principles involved in thermal as well as mechanical simulations, detailed experimental programme, experimental procedure and preliminary results obtained so far.

2. THERMOMECHANICAL BEHAVIOUR OF PFBR CONTROL PLUG

The PFBR-CP is in isothermal condition during normal operation and the stresses due to mechanical loads (pressure and self weight) are negligible. However, during a reactor scram, the temperatures of inner surface of the outer shell and upper stay plate fall rapidly. This introduces a maximum through wall temperature gradient of about 90 K and mean temperature difference of 100 K between outer shell and stay plate. These two temperature gradients induce high thermal stresses at the plate shell junction which normally exceed the material yield stresses. It is worth mentioning that, in the early part of the transient there are additional stresses due to thermal shock effects which are not important, because thermal shock stresses and discontinuity stresses do not occur simultaneously and further the thermal shock stress is very small when compared to discontinuity stresses.

The discontinuity stresses which are induced during the thermal transient decide the life of the component. Since the discontinuity stresses significantly exceed the material yield stress at the operating temperature, there exists residual stresses, locked up at the end of the transient. These stresses sustain during shutdown till the start of subsequent normal operation. The lockedup stresses fall due to creep relaxation during the hold period upto the next reactor scram. However, the relaxed stress values are raised back to more or less to the starting value, repeatedly after each scram. This is mainly due to the cyclic hardening characteristic of SS 316 LN. Thus it can be said that the there exists constant stresses at the critical locations during the entire normal operating period eventhougth, the control plug is at the isothermal condition.

These stresses are responsible for the possible creep damage accumulated during the hold period associated with normal operations. The accuracy of life prediction of control plug depends upon the accuracy with which the lockedup stresses are predicted. Hence the accurate prediction of the lockedup stresses is very important step in the analysis. This calls for use of a realistic constitutive model. However, there may be uncertainties in the life prediction due to possible scattering on the creep rupture data of the material.

3. SIMULATION

As stated in the proceeding section, thermal skin stresses which occur immediately following the thermal shock do not affect the lockedup stresses and in turn the creep-fatigue damage, hence emphasis is given to the simulation of discontinuity stresses which are important in the present context. The discontinuity stresses which have two components, viz. through wall temperature gradient and the mean temperature difference, must be simulated correctly in the experimental mockup. Since SS 316LN, the material of the mockup is same as that of the prototype, Youngs modulus (E), coefficient of thermal expansion (α) and Poisson's ratio (ν) are same. Studies have indicated that the discontinuity thermal stresses are not strong functions of radius and thickness of the shell, provided the central plate is having matching rigidity with outer shell. Hence the final parameter which affects the stresses is axial and through wall temperature gradients. It is worth noting that these gradients are in turn functions of applied fluid temperature and heat transfer coefficient on the associated wall surfaces.

3.1 *Simulation of heat transfer coefficient on the inner surface*

For the prototype control plug, the heat transfer coefficient value (h_{pi}) on the inner wall surface is in the order 2000-2500 W/m^2-K and the temperature drops from 820 K (T_o) to about 670 K(T_c) in 20 s following a reactor scram. Hence the heat flux on the inner surface is $h_{pi.}(T_o - T_c)$ which should be simulated. Based on judgement on the time frame to complete the tests (within 3 months per test), the isothermal temperature of the mockups is decided as 1003 K. Thermal shock is given by sending air at room temperature, that is at 303 K. Hence heat transfer co-efficient to be simulated on the inner surface of the mockup is $(h_{mi}) = h_{i.}(T_o - T_c) / (1003\text{-}303)$. This means that the heat transfer coefficient value required to be simulated on the inner surface of the mockup lies in the range of 430-530 W/m^2-K. To simulate the heat transfer of this magnitude with air, the air flow required, if it is sent through the entire inner volume, would be prohibitively high. In order to reduce the air flow requirement, air is sent through an annular space surrounding the inner surface as indicated in Fig. 4. The concept of injecting air through narrow space surrounding the metal wall of sodium valve in order to have enhanced heat transfer with less air flow has already been applied by Cho et. al [7], for the thermal shock qualification test on the sodium valves.

The heat transfer coefficient for air is the function of Nusselt Number (N_u) which inturn is a function of Reynolds Number (R_e) and Prandtl Number (P_r). The expressions are as follows:

For inner surface of the shell:

$$Nu = 0.023 x (Re)^{0.8} x (Pr)^{0.333}$$

For surface of the central plate [8]:

$$Nu = 0.332 \times (Re)^{0.5} \times (Pr)^{0.333}$$

From Nu, h is calculated as

$$h = Nu \times k_{air} / \text{characteristic dimension}$$

An optimum value of 5 mm is selected for the annular gap in the inner shell side and to have the matching heat transfer co-efficient on the surfaces of the central plate, the air gap is reduced to 4 mm. Accordingly, the air flow required is in the order of 0.25 Kg/s for the upper portion for obtaining the required heat transfer coefficients. Since geometry is symmetrical, the total flow requirement is about 0.5 Kg/s.

3.2 Simulation of heat transfer characteristic on the outer shell surface

For the prototype, the heat transfer coefficient on the outer shell surface (h_{po}) is 300 W/m^2-K and surrounding temperature remains more or less unchanged during the transient. This condition is simulated by placing a coaxial annular copper tube with sufficient thermal inertia and controlled gap from the outer cylindrical surface so that the combined conduction, convection and radiation effects will simulate the outer surface thermal boundary condition (Fig 4).

3.3 Choice of furnace and inlet air temperatures

As mentioned in the introduction, it is required to impose periodically through wall temperature gradient of 90 K and mean temperature difference of 100 K between shell and plate. For achieving this, air at room temperature (~303 K) is sent through the annular space of the mockup which is kept at about 1000 K inside the furnace. The furnace temperature remains unchanged under this condition.

3.4 Simulation of creep fatigue damage

Once the same temperature gradients are imposed on the mock up as the case of prototype, the stress and strain values are simulated correctly. Under these conditions the crack initiation is expected to occur well beyond 30 y if the mockup is kept at 820 K as in the reactor conditions. Hence the creep-fatigue has to be accelerated. The only way to accelerate the creep fatigue damage accumulation is by maintaining higher temperature during the hold period than in the actual condition. Theoretical thermomechanical analysis with Chaboche viscoplastic model and subsequent creep-fatigue estimation using RCC-MR procedure (excluding the in-built safety factors in the code) indicate that about 80 cycles each with a hold period of 24 h are required to cause crack initiation at 1000 K. Thereby, it is possible to complete tests on one mockup test within 3 months, including the study of creep crack growth.

4. EXPERIMENTAL STUDIES

Validation of the prediction of lockedup stresses by CONE code which uses a sophisticated Chaboche viscoplastic model and life prediction as per the current RCC-MR procedure is the prime motive of the experimental programme on control plug mock ups, which consist of an outer cylinder and central plate with appropriate stress concentration (Fig 4). On the mockups the following aspects are simulated. The mock up is kept under high temperature (about 950 K) in the furnace. On these mockups, it is planned to perform the following experiments:

- Imposing the required temperature gradients on the mockup by periodically sending high velocity air at room temperature (to simulate the effects of reactor scram).

- Measurement of lockedup stress values at the critical locations after application of the pre-determined thermal shocks with associated hold period (to validate the theoretical prediction of stress and strain values by in-house program 'CONE'). The stress measurements are made after cooling the mockup to room temperature.

- Detection of the crack initiation by Liquid Penetrant Inspection (LPI) by periodical interruptions to validate the life prediction of mockup (appearance of any visible cracks) in compliance with the design code RCC-MR.

- Measurement of crack propagation periodically and establish the crack growth behaviour (after crack initiation). The results are needed to comment on the accuracy of the RCC-MR Appendix 16 procedure of assessment of defects at high temperature.

- To study the effects of weld at the stress concentration zone. These results will be used for assessing the accuracy of the weld design procedure recommended in the RCC-MR code.

It is expected that the above results will form an important part of validation programme in the life assessment of FBR structures in general and control plug in particular.

4.1 Experimental facility

Basically the experimental facility requires a furnace which can be maintained at about 1000 K continuously for 3 months per test, a system to supply air at the rate of 0.5 Kg/s for maximum duration of about 50 s per transient (maximum of 80-100 transients may be required). The air supply system consists of a tank with sufficient capacity and pipe lines with associated isolation and pressure relief valves. In order to admit the air at required velocity at the annular space, pressure in the tank is maintained at about 0.15 MPa (g) and an orifice plate is located in the pipe line coming from the tank. A photograph of the whole experimental test facility is shown in Fig.5.

4.2 *Operating procedure*

Initially a mockup with the required number of thermocouples embedded in it (this mockup is called 'thermocouple mockup'), is kept in the furnace and temperature of 900 K is maintained for 3-4 h to achieve an isothermal condition. Lower temperature is selected to avoid any crack initiation on the thermocouple mockup. Then air at a pressure of 0.15 MPa and room temperature from the tank is admitted into the annular space of the mock up by opening on-off valves in a proper sequence. Noting the thermocouple readings, the duration of air flow is adjusted to the desired temperature profile. After the required profile is established, repeatability is also checked by restarting the experiment. Tests are repeated after removing and again reloading exactly in a similar way that is done for the actual control plug mockup. These trial tests help to ensure that loading and unloading do not produce any mismatch so as to alter the annular gap of the mock up. Finally the actual control plug mock up is located in the furnace and experiments are continued. No thermocouples are placed on the actual mockup to avoid any geometrical discontinuity which might otherwise, accelerate the crack initiation. However, the overall flow is measured in the actual tests during each thermal shock to ensure the repeatability. After a definite number of thermal shocks (65 shocks), The mockup was taken out after cooling the furnace to room temperature for the liquid penetrant inspection (LPI). If no visible cracks are noted, the mockup is placed in position, furnace is heated and tests are continued. Procedure is repeated for LPI after 10 more shocks. The frequency of inspection is increased for the subsequent tests till the visible cracks are noticed at the critical locations.

There are 4 critical locations, 2 at the outer surfaces near the junction symmetrically placed with reference to the central line of the horizontal plate and 2 more at the top and bottom fillet locations. Attempts are also being made for the estimation of time at which crack initiation occurs and measurement of crack propagation without disturbing the experimental setup.

5. PRELIMINARY RESULTS OBTAINED SO FAR

Temperature measurements have been made on the thermocouple mockup and adequacy of temperature profiles obtained have been ensured. The results are also compared with the theoretical predictions and comparison is satisfactory (Fig 6). The lockedup stresses are measured by hole drilling method after imposing 65 thermal shocks on the actual mockup. Fig.7 shows the arrangement for measuring the residual stress by hole drilling method. The residual stress values measured (maximum principle value is 166 MPa) are also compared with the valued predicted (183 MPa) by CONE code. After imposing 78 shocks at 1003 K, no crack initiation is noticed. This is because of possible scattering on the rupture data. Hence experiment is being continued. Very high oxidation has also been noted on the copper cylinder surrounding the mockup. It is planned to replace it with stainless steel cylinder. In order to see its effects on the simulation, theoretical analysis is in progress.

6. CONCLUSION

A detailed experimental programme to validate the life prediction analysis results for the control plug of PFBR has been described. The experiment is carriedout on the mockups madeup of same material. So far tests have been conducted and the simulation of temperature distributions during a cold thermal shock is verified. The lockedup stresses on the actual mockup after imposing about 65 thermal shocks have also been verified based on the residual stress measurement by hole drilling method. However, the theoretical prediction of crack initiation based on the RCC-MR procedure (without including factors of safety on creep and fatigue damage values) indicates that cracks would be noted after 78 thermal shocks each with hold period of 24 h, no visible crack is observed. This is found to be due to the large scattering on the creep ruture property of SS 316 LN at high temperature. Hence tests are continued. Further results will be presented in the conference.

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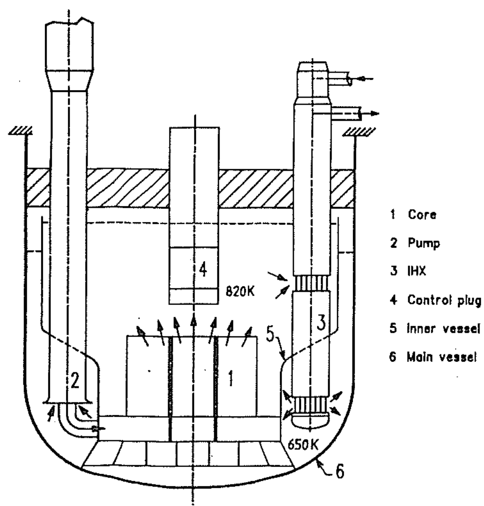

Fig.1 Position of CP above core

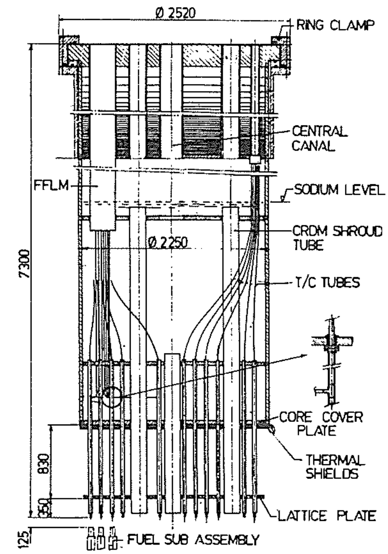

Fig.2 Details of Control Plug

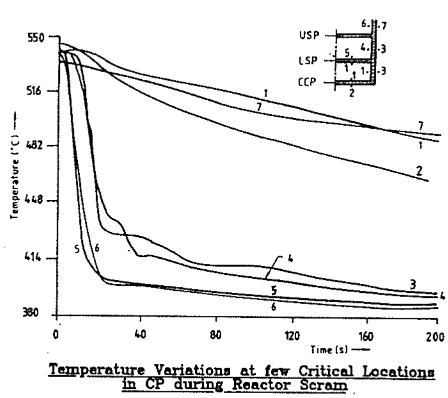

Fig. 3 Temperature gradients in different parts of CP

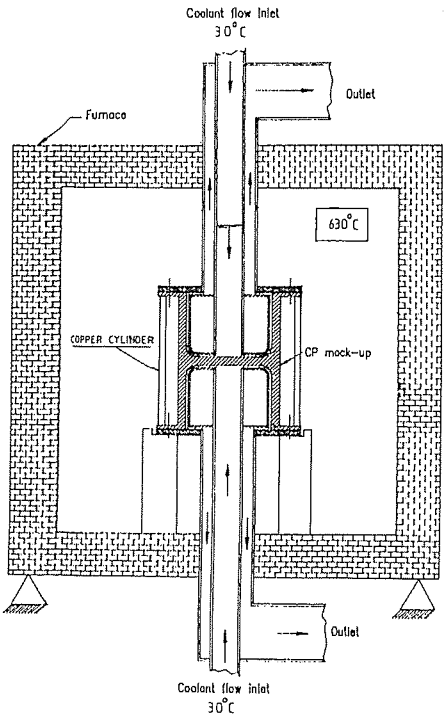

Fig.4 Control plug mock-up test setup

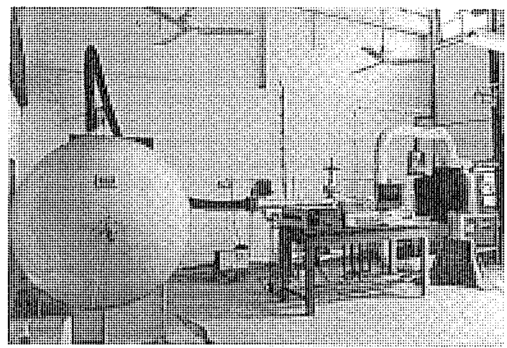

Fig.5 Photograph of complete setup

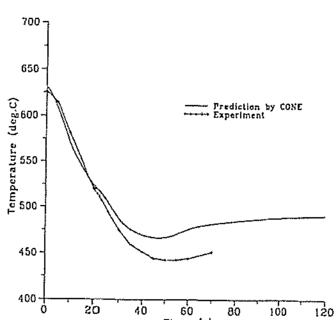

Fig.6 Comparison of experimental results & theoretical predictions

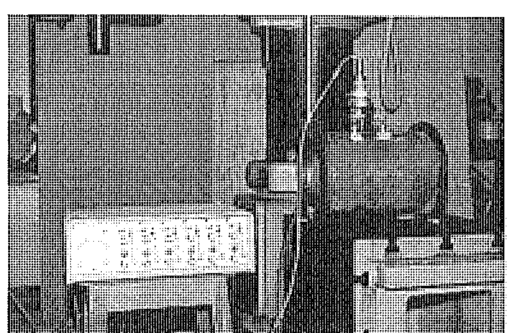

Fig. 7 Residual stress measurement setup