Evaluation of Speed Lowering of Primary Sodium Pump into Sodium Pool for 500 MWe PFBR Based on Creep Damage

P.Chellapandi*, R.Suresh Kumar#, S.Jalaldeen, P.Selvaraj, S.C.Chetal

Abstract

In 500 MWe Prototype Fast Breeder Reactor (PFBR), the Primary Sodium Pump (PSP) contained in the primary circuit circulates sodium through the core. The PSP is supported on the roof slab. The space between the roof slab and sodium free surface is filled with argon. PSP will be lowered slowly, using a flask, into the main vessel (MV) after the completion of preheating and sodium filling of the main vessel. Pump inside the flask will be at ambient condition before lowering into the sodium pool. While lowering PSP into MV sodium, one of the critical welds near the shell-flange junction at the discharge nozzle will experience thermal stress due to the hot shock offered by the sodium. The governing failure mode to ensure the structural integrity of the PSP is the creep damage developed in the weld near the junction of flange due to the discontinuity stresses that would be locked up the weld while lowering. This paper addresses the thermo-mechanical analysis carried out towards establishing the preheating temperature and speed of lowering the pump in the sodium pool. The PSP may be take in out for inspection / maintenance and lowered it back into the sodium pool around 5-10 times during the plant life. Based on this investigation, the PSP preheat temperature and lowering rate has been recommended.

Keywords: Primary sodium pump, creep, residual stress, thermo-mechanical analysis

1. Introduction

Prototype Fast Breeder Reactor (PFBR) is a 1250 MWt/500 MWe capacity, sodium cooled, pool type fast breeder reactor. The reactor consists of primary sodium circuits, which removes the nuclear heat generated in the core. Primary sodium pump (PSP) contained in the primary circuit circulates sodium through the core. PSP with other reactor internals is shown in Fig.1. PSP will be lowered slowly, using a flask, into the main vessel (MV) after the completion of preheating and sodium filling of main vessel. Pump inside the flask before lowering will be at ambient condition. During initial pump erection, the sodium temperature will be in the range of 150°C - 200°C. It is envisaged to take out the pump for inspection / maintenance and lowered again around ~5 times during the plant life [1]. For the analysis it is conservatively assumed that the pump will be corrected.
lowered into sodium at a temperature of 200°C. Maximum thermal discontinuity stress can develop at the flange-shell weld junction of the bottom discharge nozzle.

This paper investigates effect of thermal stresses induced during the lowering of PSP into sodium. Thermo-mechanical analysis carried out towards establishing the preheating temperature and speed of lowering of the pump into the sodium pool, to take the pump out for inspection / maintenance and also while lowering back is presented in this paper.

2. Primary Sodium pump (PSP)

PSP is a mechanical, centrifugal, vertical type pump with a single stage top suction impeller [1]. The principal material of construction of the pump components is SS 304 LN. PSP performs the important safety function of circulating core coolant (sodium) to remove the nuclear heat under all operating conditions. During the operation of PSP, it is partly submerged in the cold pool, which is at 397°C, partly in the argon space and partly in the RCB ambient conditions as seen in Fig.1. Schematic of PSP along with some of the important geometrical details are shown in Fig.2. The overall height of PSP is ~ 20 m and it is supported almost at the middle (roof slab) as shown in Fig.2. The top flange of the PSP supported on the roof slab is at 120°C and the pump discharge nozzle portions are at 397°C under normal operating condition.

3. Reason for Discontinuity Stresses in PSP

While lowering PSP into primary sodium, which is at a higher temperature, the pump will experience thermal stress due to the hot shock offered by the sodium. The thickness difference between the shell and flange causes discontinuity thermal stresses during lowering of the pump. The weld near to this shell-flange junction at the discharge nozzle is the critical location (location – A as shown in Fig.2) in this context. The geometry consists of a thick flange of 100 mm welded to the cylindrical shell of 40 mm thick. The magnitude of the discontinuity stress depends upon the speed at which it is lowered and the temperature difference between PSP and sodium during lowering. The primary sodium temperature during lowering is 200°C.
4. Thermo-mechanical investigation

Detailed thermo-mechanical investigation has been performed to assess the thermal stresses induced during the lowering of PSP into sodium and its effects on the component during other design basis events. Effects of sodium free level variations have been considered while performing the detailed thermo-mechanical analysis. Finite element analysis has been performed to quantify the discontinuity stresses at the critical junction while lowering into primary sodium.

4.1. Finite element investigations

Finite element investigations have been performed by CAST3M [2]. From the discontinuity thermal stresses consideration during lowering of the pump, the weld near shell-flange junction at the discharge nozzle is the critical location (location – A from Fig.2). Since the discontinuity stress due to thermal shock is local in nature, only cylindrical shell and top flange have been considered for the detailed analysis. It is modelled with 4 noded axi-symmetric solid elements (QUA4) to get the skin stress during transient loading. While lowering, the geometry will experience varying boundary condition from the heat transfer point of view. Initially the surface will be in contact with low temperature (typically say 50°C) argon, then gradually the surface will be in touch with the hot sodium. Heat transfer coefficient of argon is assumed as 5 W/m²K and that of sodium is 10000 W/m²K. Other structural material details are taken from ref [3]. Steady state isothermal analysis has been performed to confirm the correctness of the model. Pump lowering into the primary sodium is planned such that, PSP will be preheated at the argon space and then lowered into the primary sodium with a speed of 0.0017 m/s. Transient analysis has been performed for various preheating conditions of 30°C, 50°C and 100°C. Temperature distributions along with deformation of the geometry at a few critical instants for the preheating temperature of 50°C are given in Fig.3.
4.2. Results of the Transient Stress Analysis

Thermo-mechanical analysis has been performed for various preheating conditions (30°C, 50°C and 100°C) for the PSP. Variation of the von-Mises stress (nominal value) at the critical location (location- A in Fig.2) is given in Fig.4 for all the three cases. Maximum values at the critical location for each case is tabulated and given in Table-1. For evaluating the peak stress at the critical location, a Stress Concentration Factor (S.C.F) of 1.75 is obtained from ref.[4] for a fillet radius of 25 mm multiplied with the nominal stress.

| No. | Preheating temperature - oC | $\Delta\sigma_{nom}$ - MPa | $\Delta\sigma_{peak}$ - MPa | Creep damage | Effective damage |
|-----|---------------------------|--------------------------|--------------------------|--------------|-----------------|
| 1   | 30                        | 210                      | 368                      | 0.39         | 0.86            |
| 2   | 50                        | 190                      | 333                      | 0.3          | 0.77            |
| 3   | 100                       | 130                      | 228                      | 0.11         | 0.46            |
5. Damage Assessment

Because of the excellent heat transfer properties of sodium, it will transmit any changes in the coolant temperature rapidly to the structural components of the reactor. Thermal transients that are sufficiently rapid may cause local damage in the material, setting up residual stresses. These residual stresses can relax at high temperature, converting elastic strains into creep strain. The repetition of such transients can therefore result in progressive damage by both fatigue and creep mechanisms. The interaction of these damage processes might, potentially, result in more severe damage than the individual mechanisms acting in isolation. Thus creep-fatigue damage assessment has been evaluated as per design rules of RCC-MR [5] as detailed below.

5.1. Fatigue Damage

From the peak stress intensity, total elastic plus plastic peak strain ranges (Δε\textsubscript{el+pl}) for the three cases are 0.29 %, 0.26 % and 0.16 % respectively following the RCC-MR procedure. The fatigue strength reduction factor for the welds is not given for SS 304 LN in the present revision of RCC-MR. Considering a factor of 2 for welds, the number of cycles is evaluated as 600, 1000 and 5000 respectively for the three cases during raising and lowering operations. For the maximum of 5-10 operations over the entire plant life, the associated fatigue damage is negligible. However, a fatigue damage of 0.2 is possible due to thermal transients caused by normal design basis events in the cold pool components [6].

5.2. Creep Damage

Δε\textsubscript{el+pl} developed during lowering develops locked-in stress intensity at the highly stressed location which acts as an initial stress and remain during higher temperature possible during Decay Heat Removal (DHR) operations. The total duration of Safety Graded Decay Heat Removal (SGDHR) operation is divided into time temperature blocks. Using Larson Miller Parameter approach (C= 20 for stainless steel, the equivalent time at 550°C is obtained at 300 hours. The creep damage corresponding to this high temperature operation is arrived as per RCC-MR [5] procedure as highlighted below:

From the computed elasto-plastic strain range (Δε\textsubscript{el+pl}), the value of Δσ is obtained using the cyclic stress strain curve. The cyclic stress strain curve for SS316 LN is used at the same for SS 304 LN is not given in the code. All other material data such as the symmetrisation coefficient, the secondary creep strain rate and creep rupture data are taken corresponding to SS304 LN from RCC-MR. The creep reduction factor for welds is unity [7]. Using the secondary creep rate and elastic follow up factor of 3 recommended in code, the stress relaxation over the equivalent period of 300 hours is computed as a function of time.

The accumulated creep damage increases over time (Fig.5) and is obtained by adding creep damage over each small time interval. A sensitivity study is a carried out by considering time interval of 1 h or 0.1 h which did not show any appreciable change in the accumulated creep damage at the end of 40 years. The creep damages at the end of 40 years are 0.39, 0.3 and 0.11 respectively for the three cases. An effective damage is computed by accounting for the bilinear creep-fatigue damage interaction effects [3] and presented in Table-1 which indicates that the effective damages after considering the apportioned fatigue damage of 0.2 for the three cases are 0.86, 0.77 and 0.46.
6. Conclusion

The effects of thermal cycling imposed on the primary sodium pump parts during lowering into the sodium pool are quantified from structural integrity considerations. The shell flange junction at the bottom part of the pump is identified as the critical zone, which decides the preheating temperature and rate of lowering. The governing failure mode is the creep damage developed in the weld near the junction of flange due to the discontinuity stresses that would be locked up in the weld while lowering.

The cyclic temperature and thermal stresses are determined using computer code ‘CAST3M’ considering the effects of change of environment (heat transfer co-efficient and ambient temperature). With the computed stress ranges obtained by varying the controlling parameters, the creep damage accumulated during the hot transients faced by the cold pool as per RCC-MR (2002) is evaluated. Based on this investigation, it is recommended to hold the pump in cover gas space for sufficiently long time to preheat up to 50°C and then be lowered into the sodium pool at 200°C at the rate, not greater than 0.0011 m/s.

References

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