HIGH TEMPERATURE DESIGN OF CLASS-1 PIPING SYSTEMS IN SODIUM COOLED FAST BREEDER REACTOR

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ABSTRACT

Piping systems in Sodium cooled Fast Breeder Reactors (SFRs) are designed to operate at high temperature (820 K), and cyclic thermal loads for longer period [3]. These features introduce creep-fatigue damage under complicated cyclic thermo-plastic deformations for SFRs piping systems. Safety Graded Decay Heat Removal (SGDHR) is one of the class-1 piping system [2] available in 500 MWe Prototype Fast Breeder Reactor (PFBR). Proper design code rules were not available for the design of high temperature class-1 piping systems for the SFRs. RCCMR RB 3600 - 2007 version [3] come out with matured design rules of high temperature class-1 piping rules. Accordingly, the design of SGDHR piping system has been carried out with detailed numerical analysis. The major failure modes considered for the design of high temperature sodium cooled class-1 piping system are time dependent excessive deformations, time dependent plastic instability, creep rupture, creep damage, creep progressive deformations and creep-fatigue damage and its interaction.

Based on these conditions, piping supports have been selected and optimized its location and type to achieve uniform load distribution and there by the minimum stresses at critical locations. Creep-fatigue damage assessment was the governing failure mode towards finalising the design of SGDHR main & fast dump piping circuit. Tee locations for branching the fast dump piping circuit from the main piping system was the most critical location from the creep-fatigue damage consideration. Extra loops have been introduced to get sufficient flexibility to absorb downward anchor movement of Air Heat exchanger (AHX) to reduce the stresses at the connected Tee and bend locations. Additional restraints also introduced in the main lines, close to the fast dump line branch connection, to reduce in-plane bending moment acting at the Tee junction due to the thermal expansion of the main line. Further details about the high temperature design of class-1 piping system in sodium cooled fast breeder reactor are given in this paper.

INTRODUCTION

Many accidents are reported in the past due to the failure of the piping systems. Hence proper design of the high temperature class-1 piping systems is necessary for the smooth operation of Fast Breeder Reactors (FBRs). The maximum operating conditions coolant temperature in case of 500 MWe Prototype Fast Breeder Reactors (PFBR) is 820 K. Hence the class-1 piping systems in PFBR are designed to operate at high temperature of 820 K. Safety Graded Decay Heat Removal (SGDHR) piping system is one of the class-1 piping system available in PFBR. It is a safety graded passive direct reactor cooling system. It consists of four independent loops each having mainly two hot lines (from DHX outlet to expansion tank inlet and expansion tank outlet to AHX inlet) and one cold line (from AHX outlet to DHX inlet). SGDHR main line sodium is planned to be dumped into SGDHR storage tank by opening the valves in the fast dump piping circuit. Fast dump pipe lines have been taken as branch connections from the bottom most portions of the hot and cold lines of the SGDHR main circuit. The general assembly layout of the SGDHR main and dump lines in SGB-1 with the associated components and vessels are shown in Fig.1. The SGDHR piping system runs on both reactor containment building (RCB) and steam generator building (SGB). Two loops of SGDHR main piping system are in RCB-SGB1 and other two loops are in RCB-SGB2. Penetrations are provided on the RCB-SGB common wall and appropriate bellows are provided to prevent any leakage from RCB to SGB.

To avoid sodium fire inside RCB, due to any sodium leak, guard pipes are provided around the sodium piping with inert gas in the annular space. The space between the main pipe and guard pipe is compartmentalised by welding main pipe and guard pipe together along the pipe length at fixed intervals. During normal operating condition, the main pipe and guard pipe temperature will be different, hence bellows are provided in each compartment to absorb the differential thermal expansion between the main pipe and the guard pipe. The size of the bellows are selected such that, the effect of differential thermal expansion is not adding any thermal duty to the main pipe. The inter space between the main and guard pipe is filled with nitrogen. This compartmentalisation not only helps to reduce the bellow duty for the guard pipe but also helps to locate the sodium leak from the main pipe.

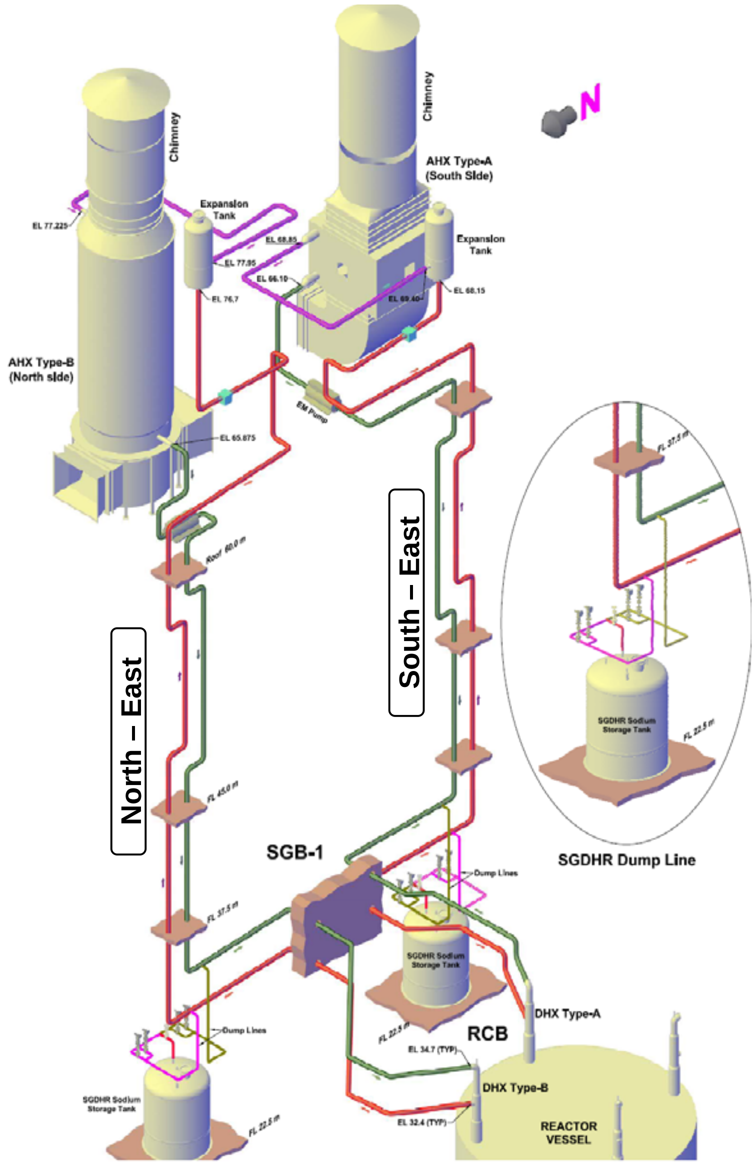

Fig.1: General assembly layout of the typical class-1 piping system in PFBR

This paper describes about high temperature design philosophy carried out for SGDHR main and fast dump piping system. Design safety category of SGDHR main piping system belongs to class-1 piping system and these piping systems are operated in elevated temperature regime. High temperature (820 K) and cyclic thermal loads for longer period introduce creep-fatigue damage under complicated cyclic thermo-plastic deformations for SFRs piping systems. Hence the design of class-1 piping systems in SFRs has been performed based on the advanced numerical analysis. Details of such analysis are presented in this paper.

DESIGN LOADS

SGDHR piping system is designed to operate in creep regime. Hence SS 316 LN is selected as the structural material for these piping systems. Normal operating temperature for the SGDHR piping system is 823 K. Under normal operating condition, the pressure and weight are the mechanical loads acting in the piping system. Design pressure for the SGDHR main and the fast dump lines is 0.7 MPa and the weight of the major piping components considered for the analysis.

Under normal operating condition, SGDHR main lines from DHX outlet to AHX inlet are at 823 K and the lines from AHX outlet to DHX inlet are at 793 K. SGDHR fast dump line also remains at the same temperature of the main line up to the pneumatically operated valve (VPOna) and temperature of the remaining portions (up to SGDHR storage tank) is at the same temperature (573 K) of the SGDHR storage tank.

Towards checking the ratcheting failure mode, the range of thermal cycle has been considered between the temperatures of normal operating conditions (as mentioned in the above paragraph) to the ambient condition (308 K). As per RCCMR, if the occurrence of any cyclic loading is small (say less than 20 cycle), then fatigue damage is negligible. Thus towards checking the fatigue damage, the range of thermal cycle has been considered between normal operating conditions with the reactor shutdown condition (473 K). The anticipated total number of occurrences for this thermal load cycles for SGDHR piping system is 861. Apart from the above mentioned temperatures, the thermal expansions of the associated vessels and equipments will act on the pipelines as an imposed displacement loading. These kinds of displacement loadings imposed by the vessels and equipments in to the piping systems are known as thermal anchor movements. The calculated thermal anchor movements for the SGDHR main and fast dump line.

DESIGN CRITERIA

The design criteria have been chosen as per the elevated temperature class-1 piping procedures of RCC-MR, RB 3600 [3]. Maximum operating temperature of SGDHR piping system is 823 K and it lies in the creep regime. Thus creep effect has been considered for the analysis of SGDHR piping system. The various failure modes, which would affect the piping, are explained below:

Rules for Preventing 'P' - type Damage

'P' type damages are those types of damages, which can result from the application of steadily and regularly increasing loading. The main characteristic of this type of loading is that it can cause failure in single application itself. It is mainly controlled by the primary stress intensity. The different types of failure modes, which come under 'P' type damage, are explained below:

Immediate Excessive Deformation, Plastic Instability & Fracture: In case of higher values of loading, irreversible plastic deformation may occur. Once yielding begins, further plastic deformation takes place very easily. Then the overall permanent deformation begins to increase rapidly (excessive deformation.). When the loading continues to increase beyond elastic zone, it weakens the piping and the yield strength will increase due to strain hardening. Whenever weakening of the structure dominates the increase of yield strength due to the change of shape, the deformation becomes unstable. It is known as plastic instability.

Immediate excessive deformation, plastic instability and fracture can be prevented by controlling the primary membrane (P_m) & membrane plus bending (P_m+P_b) stress intensities well below the allowable limit. The allowable stress intensity (S_m) depends up on the σ_y and UTS. S_m value is given in RCCMR appendix A3 [4]. Under level - A loading conditions, P_m should be $\leq S_m$ and $P_m + P_b \leq 1.3\ S_m$.

Time dependent Excessive Deformation & Plastic Instability: When piping is subjected to loadings for a long time at high temperature, deformations evolves with time and can consequently produce excessive deformation and plastic instability due to creep. Time dependent excessive deformation and plastic instability can be prevented by controlling the accumulated strains and rupture stress at the end of design life at the operating temperature. It can be achieved by limiting creep usage fraction (U) below the allowable limit. The creep usage fraction is the ratio of maximum operating period (t) to the maximum allowable time (T). The maximum allowable time (T) is determined on the basis of the time dependent allowable stress intensity (S_t), which is given in RCCMR appendix A3 [4].

Rules for Preventing 'S'- type damages

The 'S' type damages are those, which can result only from the repeated application of loadings. Limiting primary plus secondary and peak stress intensities controls mostly 'S' -type damages. The different types of failure modes covered by criteria of S type damages in RCC-MR are

Progressive deformation (Ratcheting): When the piping is subjected to cyclic loading, the overall plastic deformation continues to increase as every loading cycle induces additional deformation and the structure gradually changes shape from its original. This behavior is called progressive deformation (Ratcheting). It depends upon maximum primary stress intensity (P_m+P_b) and the maximum range of secondary stress intensity (ΔQ_{ij}). The increase in deformation due to cyclic load effect can happen in the absence as well as in the presence of creep. In the presence of creep, the ratchetting is known as load affected deformation growth. Otherwise the deformation by creep is predominantly caused when the cyclic deformations are in the form of thermal deformations.

To prevent ratchetting, the maximum primary plus secondary stress intensity range [Max.(P_m + P_b) + Max.(ΔQij)] have to meet the shake down criteria ($\leq$ 3.0 S_m). If the shake down criteria has not met, then by controlling the limit on effective primary stress intensities (P_1 , P_2 & P_3). P_1 depends up on Max (ΔQ_{ij}) / Max P_m, P_2 depends up on Max (ΔQ_{ij}) / Max (P_m+ P_b) and P_2 depends up on Max (ΔQ_{ij}) / Max (P_m+ ϕP_b) and the respective allowable limits are given below:

Allowable limit of P_1	<	1.3 Sm
Allowable limit of P_2	<	1.69Sm
Plastic strain + associated creep strain at 1.25 times P_1	<	1%
Plastic strain + associated creep strain at 1.25 times P_3	<	2%

Creep-Fatigue Damage: When the piping is subjected to cyclic loading, it may undergo changes in shape (deformation) with respect to time. If these variations are many in number and of large amplitude, then it can cause cracking. In comparison with other type of damages these macroscopic cracks may not cause much reduction in strength of the piping. But in case of high temperature piping, creep deformations during each cycle will accelerate the appearance of crack. Structural integrity against creep-fatigue damage can be ensured only if the allowable number of cycles at each point of the piping system is more than the actual operating number of cycles. Per cycle fatigue damage per cycle (V_{pc}) and creep damage per cycle (W_{pc}) has to be computed separately to compute the allowable number of cycles based on creep-fatigue interaction. V_{pc} = 1/N depends up on the $\Delta\varepsilon_{total}$ = $\Delta\varepsilon_{el+pl}$ + $\Delta\varepsilon_{fl}$. 'N' can be obtained from the design fatigue curve available in RCCMR appendix A3 [4] for a given temperature and $\Delta\varepsilon_{total}$. W_{pc} can be obtained by taking the ratio of the total hold time per cycle to the maximum allowable time in hours obtained from the minimum rupture curve available in RCCMR appendix A3 [4].

Creep-fatigue interaction diagram of SS 316 LN is given in Fig.2. From this figure, the point "P" represents creep and fatigue damage ('W_{pc}' and 'V_{pc}') per cycle. Thus by measuring the remaining life (PQ or P'Q' depending up on the value of 'V_{pc}' and 'W_{pc}') the allowable number of cycle can be obtained from Fig.2.

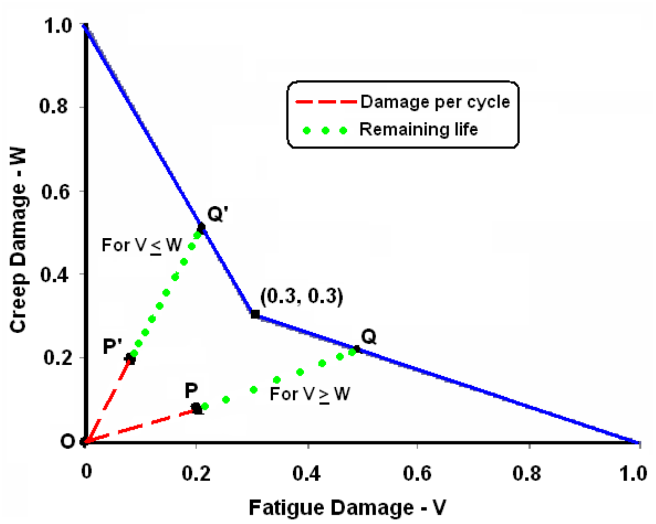

Fig.2: Creep-Fatigue interaction diagram for SS 316 LN as per RCCMR A3 [4]

ANALYSIS

Finite element (FE) analysis have been carried out for the SGDHR main and fast dump lines. Pipe element has been used for the FE analysis. Guard pipes are provided for the SGDHR main lines within RCB. Bellows have been selected such that the guard pipe stiffness is not going to influence the main pipe stiffness. Hence these guard pipes are not modelled for the finite element analysis. Total mass of the guard pipe insulations have been accounted for the analysis. The valves, flow meters are modeled as equivalent rigid elements. Fast dump lines are taken as a branch connection from the main lines (from the DHX outlet to expansion tank inlet line and from the AHX outlet to DHX inlet line); hence these lines are also modelled together with the SGDHR main lines for the high temeprature analysis. The associated vessels and equipments are not modeled in the analysis, and its effect is simulated by applying the thermal anchor movements at respective nozzle locations.

Pipe Supports Selection

Based on the static analysis, pipe supports have been selected for the SGDHR main and fast dump piping system. The selected static supports can be broadly categorised into two category weight supports and thermal restraints.

Weight Supports: Supports responsible to take care of the total weight of the SGDHR main and fast dump piping system belongs to this category. Selected supports contain rigid rods (SRT), variable spring hangers (SSV) and constant effort spring hangers (SSC). SRT selected at those locations where the vertical displacement is negligible under normal operating conditions otherwise spring supports (SSV & SSC) have been selected. Size and the type of these supports have been decided based on the various operating conditions. Among these supports SRT is the cheapest and SSC is the costlier support. Even though at some critical locations SSC has been selected instead of SSV to have uniform load distribution and there by minimum stresses of the SGDHR piping system.

Thermal Restraints: Thermal restraints (SRG) have been used at the appropriate locations to control overall thermal deformations of the SGDHR main and fast dump lines. These thermal restraints also provide additional rigidity to the piping system and it is more beneficial in case of seismic loading conditions.

Results & Discussion

Bending and torsional moments obtained from the finite element (FE) analysis are combined as per RCCMR RB [3] procedures to get the respective stress intensities. Appropriate stress intensification factors are multiplied along with those stress intensities to account for the geometrical effect of piping products (Tees & bends). The summary of these results are presented below:

'P'- type Damage: Maximum value of the P_m has been found at the bend locations of the SGDHR main piping system. The D/t ratio of the main pipe is more than that of the fast dump line. The maximum value of P_m for the SGDHR piping system is 23.0 MPa and it is very much smaller than that of the allowable stress intensity limit of 96 MPa. Maximum value of the $P_m + P_b$ for all the 4 loops of the SGDHR piping system is 73.5 MPa, which is lower than the allowable stress intensity limit of 124.8 MPa.

The creep usage fraction, U(Pm) is negligible. Maximum value of the $U(P_m + \phi P_b)$ for all the 4 loops of the SGDHR main & fast dump piping system 0.0512, which is lower than the allowable limit of 1.0.

Thus all the points of the SGDHR main and fast dump piping system have been protected against the 'P'- type damage.

Progressive deformation (Ratcheting): The maximum primary plus secondary stress intensity range [$\text{Max.}(P_m + P_b) + \text{Max.}(\Delta Qij)$] for all the 4 loops of the SGDHR main & fast dump piping system is 338.1 MPa which is lower than the allowable stress intensity limit of 364.5 MPa. Thus all the points of the SGDHR main and fast dump piping system have been protected against the Ratcheting criteria.

To account for the effect of creep on ratcheting, the accumulated permanent strain (due to plasticity and creep) has to be ensured well below the allowable limit. Accordingly, accumulated permanent membrane strain (ε_m) and membrane plus bending strain (ε_{mpb}) have been computed at all the points of the of the SGDHR main and fast dump piping system. The Maximum values for all the 4 loops of the SGDHR piping system are lower than the maximum allowable strain of 1% & 2% respectively.

Creep-Fatigue Damage: Maximum allowable number of cycle has been computed for all points on the SGDHR main and fast dump piping system for a period covering all the events of loading conditions based on the above mentioned creep-fatigue damage rule. The minimum value allowable number of cycle obtained for this system, from the RCC MR A3 [4] design fatigue curve, is 870 and it is higher than the actual number of cycle of 861. Thus all the points of the SGDHR main and fast dump piping system have been protected against the creep-fatigue damage.

CONCLUSION

High temperature design of all the 4 loops of SGDHR main and fast dump piping system have been carried out as per the elevated temperature class-1 piping design philosophy described in RCC-MR RB 3600. Pipe supports have been selected based on the high temperature piping design procedure. Comet pipe supports have been selected, the size and type of supports has been selected based on the normal operating conditions of SGDHR piping system. Towards finalizing the layout and the location of the supports, detailed finite element analysis has been carried out. The torsional and bending moments obtained from finite element analysis of all the 4 loops of SGDHR main and fast dump piping have been appropriately combined towards qualifying various piping failure modes like excessive deformations, plastic instability, creep damage, progressive deformations and creep-fatigue damage.

Thermal deformations of the SGDHR main line is transferred to the fast dump line, thus sufficient flexibility has been provided for the fast dump line to absorb these deformations apart from its own thermal load. A few of the piping supports have been changed from SSV to SSC to achieve uniform load distribution and there by the stresses at critical locations of the SGDHR piping system has been minimised. Creep-fatigue damage assessment was the governing failure mode towards finalising the SGDHR main & fast dump piping layout.

Additional restraints are included in the main lines, close to the fast dump line branch connection, to reduce in-plane bending moment acting at the Tee junction due to the thermal expansion of the main line. X & Y directional restraints at the RCB-SGB common wall location helps to reduce the lateral duty requirement for the SGDHR RCB-SGB penetration bellows. Some of the bend radius for the main lines has been changed from 304.8 mm to 410 mm to meet the creep-fatigue damage criteria. Long running high temperature vertical lines are present in the SGDHR main piping system. Large magnitudes of the out-of-plane bending moment caused by the vertical expansion of these lines are responsible for higher stresses at the above bend locations. The failure due to creep-fatigue was observed more in case of the SGDHR type-B bends in comparison to SGDHR type-A bends. It is mainly due to the large thermal anchor movement (42.4 mm) imposed by the AHX-B into the main lines apart from its own thermal expansion. The design checks have been performed for the SGDHR main and fast dump piping system to qualify against major piping failure modes. The results indicated that all the points of the SGDHR main and fast dump piping system met all the high temperature class-1 piping design code requirements to prevent excessive deformations, plastic instability, progressive deformations and fatigue with creep effect for a period covering all the events of level-A loading conditions. Accordingly all the 4 loop of SGDHR main and fast dump piping layouts, number, type and support locations have been finalized.

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