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Flow and Stress Analysis of Aged Penstock of Sundarijal Hydropower Plant (SJHPP)

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Abstract

Sundarijal Hydropower Plant (SJHPP) is the second oldest hydropower plant of Nepal, and it is being upgraded from 640kW to 970kW with the replacement of all hydro-mechanical and electromechanical parts excluding penstock after 85 years operation of the plant. The penstock is coetaneous to the plant and needs to be examined for the safe operation of the plant in the future. This paper investigates the actual condition of the existing penstock based on flow and stress analysis with an analytical approach as well as using commercial software. Furthermore, it also analyzes the critical thickness of the three analysis domain, which reflects the rupture thickness of the penstock. The velocity and pressure distribution profile using commercial software show undisturbed velocity streamlines with increased velocity from inlet to outlet throughout the analysis domain. However, in the analysis domain one, the velocity is disturbed in the branched section, and flow seems to be higher through the smaller cross-section. The head loss on all six-analysis domains is computed and stress is found to be below allowing working stress of 127.49 MPa throughout all domains. Evaluations of the critical thickness of the analysis domain of one, five, and six found that the thickness of 5.5mm, 1.3mm, and 2.4mm with the corresponding equivalent stresses 260.30 MPa, 264.69 MPa, and 271 MPa respectively is just below the yield stress of the material. The domain five with the factor of safety (FOS) 2.6793 is found to be unsafe under Indian Standard (IS) penstock design code for the regular operation of the plant.

Keywords

SJHPP, Aged Penstock, Head Loss, Equivalent Stress, Critical Thickness, Operational Safety

1. Introduction

Sundarijal Hydropower Plant (SJHPP) is under Nepal Electricity Authority (NEA), located at Sundarijal, 15 km northeast of Kathmandu with an installed capacity of 640 kW and annual design generation of 5.338 GWh. It was commissioned in 1934 AD in a grant from the British Government. Both the Pelton units, each with 320 kW, are in regular operation and can operate in full load when required. The penstock and station flows are part of the water supply system to Kathmandu Valley. The Bagmati River is the principal river. It originates on Shivapuri lekh (ridge) at an elevation of about 2,650 meters and drops to 1,340 m over a distance of about 8 km. In the upstream region near Sundarijal, two streams, the Nagmati, and the Syalmati, come to join this river.

SJHPP is the second oldest hydropower plant of Nepal, and the plant has been going for rehabilitation works, which includes replacement of all the hydro-mechanical and electromechanical equipment excluding penstock. The Rehabilitation work also upgrades the plant from 640 KW to 970 KW. The plant has come into operation from 1934 AD. After completion of the rehabilitation work, the feature of the plant will be:

Table 1: Proposed salient feature of SJHPP

Type	Run of River
Location	Sundarijal, Kathmandu
Operational Capacity	970 kW
Annual average energy	7.18 GWh
Gross total head	216.6 m
Total length of Penstock	1386 m
Diameter of Penstock	0.45 m
Headrace diameter	0.61 m
Turbine	2, Horizontal

(Source: NEA)

The hydropower-plant is in operation for almost 85 years, and it exceeds the standard operation time of 40 to 50 years. The plant is being upgraded with a higher installed capacity than the existing one. Due to the continuous operation of the penstock beyond its general life period, it is crucial to examine penstocks for the reliable operation of the plant in the future. The extensive operation of penstocks results in the reduction of its thickness. The penstock thickness proceeding to the critical thickness may lead to the rupture of the penstock. This can be a catastrophic incident to a densely populated area of Sundarijal.

A penstock is a pressure conduit that is used to convey water from the reservoir to the turbine inlet. The safe design and operation of the penstock are essential for the safe operation of the plant.

Since penstocks are always exposed to water, corrosion, and wear develop with time and lead to a decrease in the wall thickness, which may affect the structural stability of the penstock in the long-run [1]. It has been reported that the amount of annual corrosion is approximately 0.02mm/year [2].

A significant proportion of penstocks are over 40–50 years old, and historically, the majority of penstock failures have occurred in either new facilities or the ones that were over 50 years old [3].

According to IS, the stresses in the penstock of surface penstocks are subjected to circumferential and longitudinal stresses [4]. The stresses in the pipe at the mid-span and the support are characterized as:

1. At mid span:
   (a) Hoop stresses developed due to internal pressure,
   (b) Longitudinal stresses developed due to its weight and weight of water by beam action,
   (c) Longitudinal stresses developed due to sliding friction over the supports, and
2. At supports:
   (a) Circumferential stresses developed at the supports due to bending caused by internal pressure,
   (b) Longitudinal stresses developed at the support due to beam action.

The thickness of a steel penstock decreases over the years; therefore, it shall be measured as required. If the thickness of the steel penstock decreases due to corrosion and wear, and the decrement exceeds the corrosion allowance, the thickness cannot meet the designed condition, and thus the penstock will be subjected to critical conditions.

The material composition plays a vital role in mechanical strength and characterizes the penstock material.

The Residual Life Assessment (RLA) has been carried out in 2016 by NEA and reported that the mechanical strength of the materials used in penstock of SJHPP [5] is tabulated as:

Table 2: Mechanical test properties of Penstock of SJHPP

S.N.	Test Parameters	Value Observed
1.	Ultimate Tensile Strength (MPa)	382.48
2.	Yield Stress (MPa)	277.44
3.	(%) elongation	26.74
4.	Hardness in (HBW 10/3000)	107
5.	Bend Test at (2t X 180°)	Satisfactory

(Source: NEA)

The flow and stress analysis of the existing penstock has been carried out analytically and using commercial software ANSYS. The analysis domain has been selected on the basis as:

(a) Domain One: Lowest position (i.e., 216m Head) of penstock including bifurcation,

(b) Domain Two: 25m above and second bend from the lowest position of the penstock,

(c) Domain Three: 50m above from the lowest position of the penstock,

(d) Domain Four: 75m above from the lowest position of the penstock,

(e) Domain Five: 100m above the lowest position and minimum thickness point of the penstock,

(f) Domain Six: First, bend on the penstock from the lowest position of the penstock, excluding bifurcation.

The 3D model has been prepared for each analysis domain in solid works and is exported to ANSYS Fluent and STATIC STRUCTURAL for analysis and is compared with the analytical solution. Furthermore, critical thickness has been evaluated in three analysis domains (domain one, five, and six).

Assumptions:

- The material of the penstock is homogeneous.
- The flow in penstock is viscous.
- The fluid is incompressible and Newtonian.
- Reference pressure for calculation purpose: 1 atm.

2. Flow Analysis

A. Analytical Flow Calculation

The analytical flow calculation has been performed on each analysis domain, which includes the velocity, pressure, maximum surge head, Reynolds number (Re), and head loss. The maximum surge head, friction loss, bend loss, and branch loss has been calculated by using the following formula as:

$$Re = \frac{\rho v d}{\mu} \tag{1}$$

$$H_s = 2\frac{VL}{gt} \tag{2}$$

$$h_f = \frac{fLv^2}{2gD} \tag{3}$$

$$h_b = K_b\frac{v^2}{2g} \tag{4}$$

$$h_{branch} = K_p\frac{v^2}{2g} \tag{5}$$

The total pressure has been calculated by adding static pressure and surge pressure. By using equations (1) and (2), the total internal pressure, velocity, and Reynolds number (Re) of each analysis domain have been calculated, which shown in table 3.

Table 3: Flow calculation in selected segment of penstock

S.N.	Hydrostatic Head (Hh) m	Surge Head (Hs) m	Total head (H) m	Internal pressure (p), Pa (gH)
Domain 1	216.6	69.45	286.05	2806150.5
Domain 2	191.6	69.45	261.05	2560900.5
Domain 3	166.6	69.45	236.05	2315650.5
Domain 4	141.6	69.45	211.05	2070400.5
Domain 5	116.6	69.45	186.05	1825150.5
Domain 6	213.81	69.45	283.26	2778780.6

The velocity of each domain is 4.78 m/s, and the flow is turbulent in each domain with Reynolds number (Re) 2151000.

Real Time Data:

The commissioning of unit 2 has been completed currently, and one pressure meter is set in analysis domain one to measure the static pressure and total pressure during load rejection. The load rejection test carried out in a 25% increment of load up to 110% of rated capacity. The observed value of pressure is shown below in figure 1.

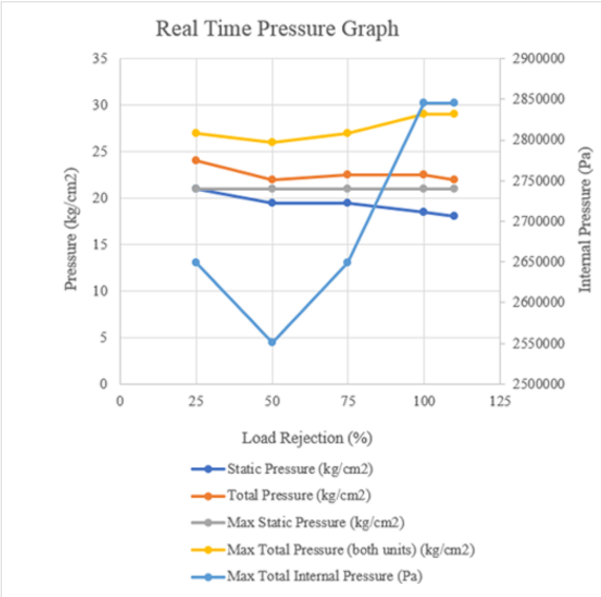

Figure 1: Load Rejection (%) Vs Pressure

The observed pressure data are for unit 2 only, and based on that, the surge pressure has been doubled for both units. By this, from figure 1, the maximum internal pressure is 2844900 Pa for domain one, which is 1.38% greater than the analytical solution.

The head loss calculation has been calculated by using equations (3) to (5) and found as in table 4.

Table 4: Head loss calculation

S.N.	Friction Loss (m)	Branch Loss (m)	Bend Loss (m)	Total Loss (m)
Domain 1	0.2463	0.5825	0.246	1.709
Domain 2	0.248	-	0.145	0.393
Domain 3	0.124	-	-	0.124
Domain 4	0.124	-	-	0.124
Domain 5	0.124	-	-	0.124
Domain 6	0.248	-	0.058	0.294

B. Flow Simulation

The 3D solid model of each analysis domain has been prepared, and Finite Volume Discretization of an unstructured tetrahedron was taken for discretization. The optimum element size has been assured by an independent mesh test and found to be 50mm. Since the flow is turbulent, y^+ value has been found to be 44.1 with corresponding wall spacing 0.23mm for reference length 0.45m.

Simulation Setup:

The setup is assigned with the following parameters:
Reference Pressure: 1 atm
Inlet: Static Pressure/ Mass flow rate
Outlet: Static Pressure/ Mass flow rate
Wall: No Slip Wall
Roughness: 4.5×10^{-5} m
Turbulence: K-ε turbulence model with TI 5%
Solution Method: P-V Coupling
Maximum No. of Iteration: 300
Solver: Second Order
Convergence Criteria: 10^{-3}

The calculation has been performed in Fluent Solver, and the results are processed in CFD Post-processing.

The head loss calculation can be evaluated by using CEL expression. The following expression has been used to evaluate head loss:

$$h=\left(\frac{p}{\rho g}+\frac{v^2}{2g}+Z\right)_{inlet}-\left(\frac{p}{\rho g}+\frac{v^2}{2g}+Z\right)_{outlet} \quad (6)$$

By using the above expression, the head loss of each analysis domain was found to be 1.472m, 0.362m, 0.132m, 0.132m, 0.132m, and 0.269m, respectively, from domain one to six.

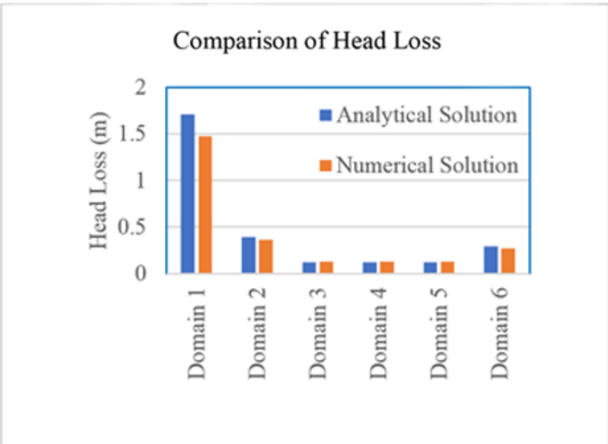

Figure 2: Analytical Vs. Numerical Solution Head loss

The maximum error in the head loss has been found in domain one due to the complexity of the geometry of bifurcation, and other analysis domains are comparable, which is shown in figure 2. The value obtained from the standard charts for friction factor, bend loss coefficient, and branch loss coefficient are also the reason for the error.

3. Stress Analysis

A. Analytical Stress Calculation

The analytical structural calculation of the selected segment includes the stresses associated with penstock due to internal pressure and surge pressure. The stresses on the penstock are circumferential (hoop stress), longitudinal stress, and other stresses associated with penstock. By calculating these stresses, the equivalent stress has to be determined and used for thickness calculation. According to IS Surface Penstock Design Code:

(i) The circumferential (hoop) stress is calculated by using formula,

$$S_y=\frac{pd}{2t} \quad (7)$$

(ii) The longitudinal stress due to beam action is calculated by using formula,

$$\sigma_1=\frac{M}{Z} \quad (8)$$

(iii) The longitudinal stress due to sliding friction is calculated by using formula,

$$\sigma_s=\frac{\Sigma Pf}{A}+\frac{a\Sigma Pf}{Z} \quad (9)$$

Where,
ΣPf = μW$\cos\beta$
A = Area of Pipe,
a = Eccentricity of frictional force relative to pipe,
μ = Friction Coefficient,
W = Total Weight of Pipe and Water, and
β = Angle with horizontal, in degree.

(iv) The circumferential bending stress is calculated by using formula,

$$\sigma_b=\frac{M}{Z},\ \ and\ \ M=CP_1r \quad (10)$$

Where,
C = Moment Coefficient,
P_1 = Total Reaction at Supports, and
r = Radius of pipe, in mm

(v) The shear stress is calculated by using formula,

$$\tau = \frac{W}{2A} \quad (11)$$

The resultant longitudinal stress has been calculated by using,

$$S_X = Max\{(|\sigma_l| + |\sigma_s|)\&(|\sigma_l| + |\sigma_b|)\} \quad (12)$$

Since the Shear Stress is negligible in comparison of Hoop Stress and Resultant Longitudinal Stress, Equivalent Stress is calculated by using Hencky Mises Theory formula, as

$$\sigma_e = \sqrt{S_x{}^2 + S_y{}^2 + S_x \times S_y} \quad (13)$$

Table 5: Equivalent Stress

S.N.	Thickness (t), m	Equivalent Stress (σ_e), MN/m^2
Domain 1	0.0072	89.188
Domain 2	0.0086	68.4
Domain 3	0.0086	61.86
Domain 4	0.0072	66.21
Domain 5	0.0040	104.66
Domain 6	0.0086	74.19

According to IS, it is recommended that under normal operating conditions, the working stresses with a factor of safety of 3 based on minimum ultimate tensile strength shall be adopted for designs. But in no case, the maximum stresses obtained by equation (12) shall exceed 1/2 of yield strength of the material[4].

From table 2, the ultimate tensile strength and yield stress of the existing penstock are 382.48 MPa and 277.44 MPa, respectively.

The maximum stress of existing penstock can be calculated as:

$$Maximum Stress = \frac{1}{2} \times Yield Strength of material \quad (14)$$

And the working stress of existing penstock can be calculated as:

$$Working Stress = \frac{Ultimate Tensile Strength of Material}{3} \quad (15)$$

By using equations (14) and (15), the maximum stress and working stress were calculated and found to be 138.72 MPa and 127.49 MPa respectively.

From table 5, the equivalent stresses on the analysis domain show that it is below the working stress and safe for the operation of the plant. However, the operational safety of the plant needs to be examined for at least 30-40 years.

B. Stress Analysis by ANSYS

The ANSYS STRUCTURAL has been applied to calculate the stress distribution in selected domains. A finite element method (FEM) discretization of an unstructured tetrahedron was taken for discretization. The optimum element size has been assured by an independent mesh test and found to be 50mm.

The solution process starts discretizing the equilibrium equations for every node, it prepares then global stiffness matrix (GSM), which is followed by calculating displacement vector, and then strain and solver equalize the given loads to equivalent von-misses stress for the domain.

The parameters selected for the numerical simulation are: Total internal pressure and supports on the pipe. Since the penstock supports are saddle and anchor blocks, it is challenging to represent the existing physical structure. Thus, some assumptions have been considered for supports, which may truly represent the physical structure.

Assumptions:

(i) Inlet end fixed and another end free for domains three, four, and five.

(ii) Inlet end fixed, outlet end free and bend section with elastic support of stiffness 8.75×10^9 N/m^3 for domain two and six.

(iii) Inlet end fixed, both outlets end free with the same elastic support for branch section for domain one.

The geometrical modeling of the analysis domain has been carried out with design software solid works 2018 and exported to ANSYS STATIC STRUCTURAL. The domains have been prepared with minimum thickness recorded during thickness measurement and assumed to represent the whole analysis domain.

Table 6: Mesh Summary

Mesh Type	Tetrahedrons
Element Size	50 mm
Relevant Center	Fine
Smoothing	High

The analysis of each domain has been performed, and the results of the analysis compared with the analytical solution are shown in the graph below.

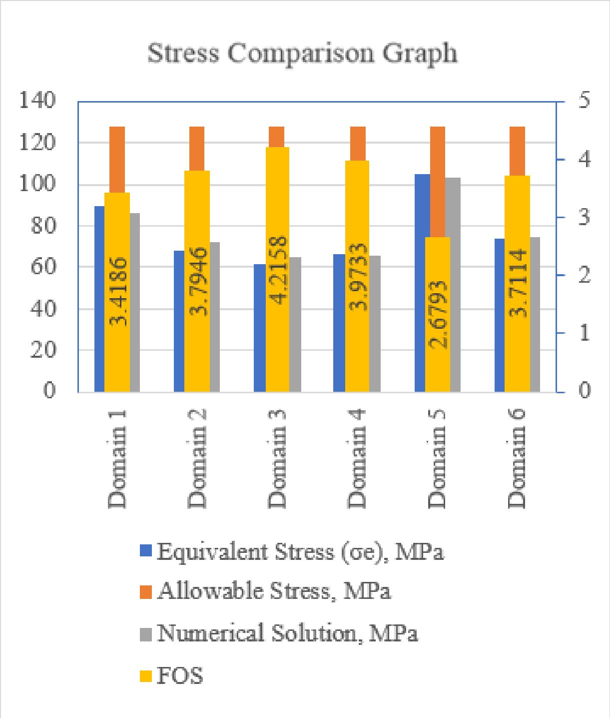

Figure 3: Stress Comparison and FOS of Analysis Domains

Both analytical and numerical solution agrees with each other where equivalent stress is below the allowable stress. However, in Domain five, the factor of safety is 2.6793, which is below the design standard value. Thus, based on the factor of safety, it can be said that the domain 5 is unsafe for the operation of the plant and requires immediate attention.

4. Critical Thickness Evaluation

The critical thickness of selected analysis domains of penstock is the thickness, which is before the rupture of the penstock has been calculated by decreasing the thickness of the domain and evaluating stress and factor of safety. For the evaluation of critical thickness, three analysis domain has been chosen for study (domain one, five, and six).

The domain one has the branch section and has no sickle plate in the branched part. As per the design standard, the branch section is designed with a sickle plate for stress distribution in the branched section. Structural analysis of this domain found that the higher stress at the intersection of the branch section. This stress is taken to evaluate the critical thickness.

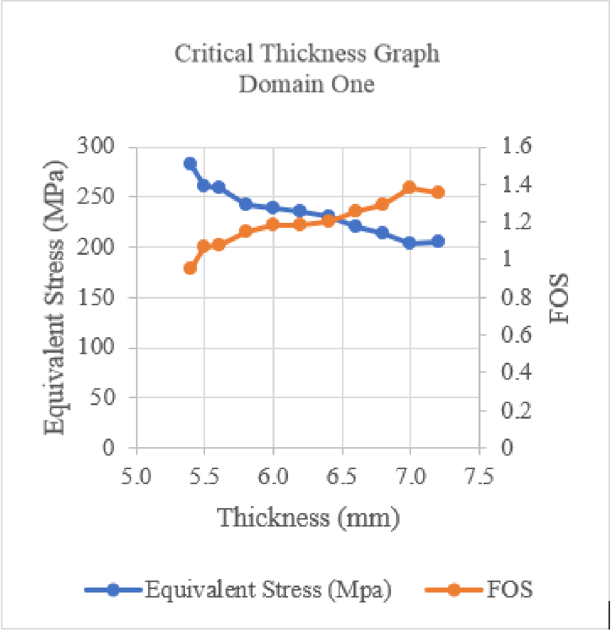

Figure 4: Evaluation of Critical Thickness of Domain one

The critical thickness of domain one is found to be 5.5 mm with equivalent stress 260.30 MPa.

The domain five is the minimum thickness domain, and stress analysis on domain five is shown in Figure 5.

The critical thickness of the domain is found to be 1.3 mm with equivalent stress 264.69 MPa. However, according to the IS penstock design code, the recommended minimum thickness shall be (D+50)/400 cm to resist the distortion during fabrication and erection. Thus, the critical thickness for this domain is 2.375mm.

The domain six includes the bend section, and stress analysis for the critical thickness of it is shown in Figure 6.

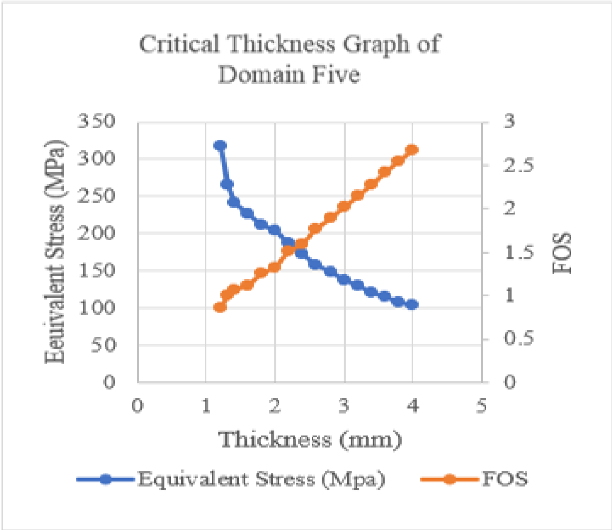

Figure 5: Evaluation of Critical Thickness of Domain five

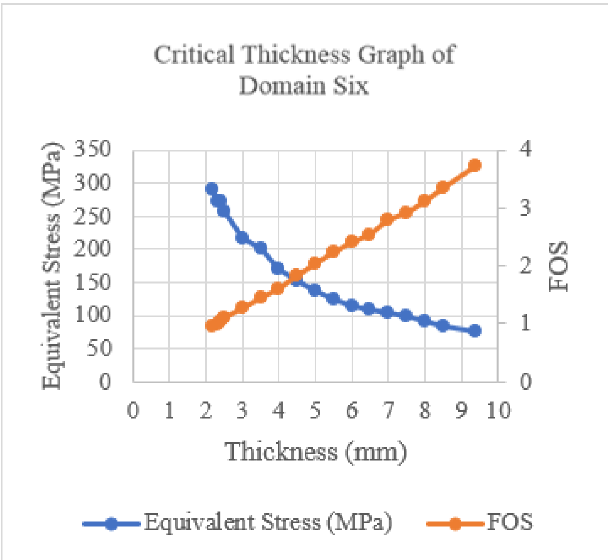

Figure 6: Evaluation of Critical Thickness of Domain six

The critical thickness of domain six is found to be 2.4 mm with equivalent stress 271 MPa.

5. Conclusion

The study envisaged the flow and structural aspects of the aged penstock of SJHPP. The following conclusions are set forth.

- The consistent agreement of velocity streamlines and pressure distribution results from flow analysis except for the branched section of domain one.
- Due to the small diameter of the penstock and high velocity of water, the head loss of the analysis domain is higher, and it can be concluded that the major loss of the penstock is high.
- The error of stress analysis of numerical solutions with respect to the analytical solution is within six percent. The analytical solution is a more conservative type. The value obtained from the standard chart and table for the analytical solution is the cause for differing the result. The assumptions considered for the numerical solution is also the reason for the error.
- The results of equivalent stress obtained from both analytical and numerical solutions in each domain are below the allowable working stress. However, the FOS of domain five is 2.6793 which is below the design standard of the penstock.
- The critical thickness of domain one is 5.5mm, domain five is 2.375mm, and domain six is 2.4mm. The difference in actual thickness and critical thickness is small in domains one, and five and these analysis domains are unsafe according to design standard. Thus some kind of protective measure shall be carried out for the safe operation of the plant.

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