Assessing the factors affecting the water chemistry parameters in the auxiliary water system of a nuclear power plant

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Abstract

Cooling towers are used as a final heat sink which cools the reactor auxiliary systems and transfers the heat energy to the atmosphere. The reliability endowed upon the cooling tower operation in a nuclear power plant is considerably high when compared to other power plants since the proper functioning of auxiliary systems is crucial for the decay heat removal from the core. Hence, appropriate chemistry control is mandatory in the operation of cooling towers for corrosion control, scale prevention, and control of biological growth. The operating data and water chemistry parameters like conductivity, turbidity, free residual chlorine, pH, cycles of concentration, chlorides, hardness, and alkalinity are analyzed for a typical nuclear power plant. The effect of the individual water quality parameter is correlated by the Pearson matrix to find its influence on the system water chemistry parameter. It is observed that the build-up of chloride ions in the cooling water is the major contributing factor for the cooling tower feed and bleed operations. The aspect of reducing the feed and bleed operation is analyzed, and suitable modifications are suggested to reduce water consumption.

Keyword Cooling tower · Blowdown · Water chemistry · Cooling water · Corrosion control · Water reduction

Abbreviations

CT	Cooling tower
TDS	Total dissolved solids
EC	Electrical conductivity
COC	Cycle of concentration
FRC	Free residual chlorine
M-alk	Methyl orange alkalinity
P-alk	Phenolphthalein alkalinity
LSI	Langelier saturation index
RSI	Ryznar stability index
Turb.	Turbidity
TH	Total hardness
CH	Calcium hardness
MH	Magnesium hardness

1 Introduction

A typical nuclear power plant encompasses reactor core, reactor containment system, safety-related primary and secondary heat transport systems, conventional and steam-water systems, electrical and instrumentation systems, fuel handling, and radioactive waste management systems. Most of the components and instruments deployed in the above systems require cooling water systems for regular operation. Failure of cooling water system is critical and hence, is provided with Class: III power supply sourced from diesel generators to increase the availability of safety-related nuclear systems during normal and accident conditions [1]. Auxiliary cooling water systems are required for heat removal from safety-related components like compressors, safety-related unit coolers, nitrogen

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systems which are essential for nuclear heat removal and reactor operations. The heat loads from cooling water are ultimately released to the atmosphere through cooling towers. The reliability of the system is the probability that it will meet the minimum performance requirement when called upon. The reliability of the cooling water system with respect to the chemistry aspect deals with the probabilities of not encountering the chemistry-related failures in the system so that it delivers its intended function. Failure mechanisms are symptoms of underlying influence factors like process conditions (water chemistry, temperature, pressure, flow), operational, and organizational factors. Reliability growth is increased by modifying these influence factors [2, 3]. Based on the operating experience of the nuclear power plant, the failure rate of the cooling tower to open is 28.4 per million hours which is a demand related failure condition unable to operate the necessary component to accomplish the intended function [4]. So it is imperative that maintaining the healthiness of cooling water systems is highly required for the safe operation of reactor systems whose unavailability will require the reactor to be shut down immediately. Apart from severe system failure, undesirable chemistry violations are immediately visible in operational parameters like temperature, pressure drops, efficiency, and system output. To avoid the catastrophic failure of the cooling water system, strict chemistry control, monitoring, and assessment of the systems should be regularly performed and logged as part of the preventive maintenance.

By practicing stringent guidelines with proper monitoring and assessment of water quality parameters, it is possible to increase the reliability of critical equipment and prevent the outages of power plants [5]. Proper chemical conditioning is a viable option to prevent and control the undesired phenomena in the water and steam cycle. The measurement and observation of slight variations in pH give the trend of chemistry-related damages [6, 7]. To effectively control the scaling and corrosion products, the system should be sampled and analyzed for assessing the concentrations of control parameters at regular time intervals. The critical metrics for monitoring the physical properties of the system are by studying the system conditions like operating pressure, temperature, flow rate, and that for monitoring the chemical properties is by estimating the control parameters like pH, conductivity, etc. [8–12]. The material degradation of carbon steel is mainly due to corrosion, wear, and cracking due to cyclic stresses or high mechanical loads. The major contributor is the aqueous corrosion of carbon steels in the form of general, crevice, pitting, galvanic, and deposit corrosion. The main factors involved in material degradation are the material constituents, water quality, and system operating conditions [13]. The operating state of the system, like

temperature, pressure, and the flow rate, has influenced the system chemistry and material degradation property. For example, the rise in temperature increases the amount of carbonate scale. Turbulence in the system also promotes scale formation [13–15]. The reliability of the chemistry control is highly improved after establishing immediate control over the source water chemistry analysis [16]. Most of the research has been extensively carried out in the field of corrosion, scaling, deposition rates, and its associated phenomena. Through a detailed literature review, it is understood that many articles were available in the steam and water cycles of power plant. The research work and water conservation studies for auxiliary water systems is not undertaken.

The gap between the water resources and the demand is steadily increasing due to the rapid industrialization and urbanization [17]. At this moment, it is highly imperative to study the aspect of water conservation with strict chemistry control being adhered simultaneously. The modification enforced on the cooling cycles, retrofitting the cooling method, proposing diligent operation and maintenance (O&M) strategies, technology changes, process control and management strategies reduces the water consumption [18–21]. Preceding and foregoing research focus mainly on the improvement of feed pre-treatment, CT blowdown water reuse or alternative make-up water [22–24]. Assessing the variations in the source water quality is important for any power plant to optimise their cost. This assessment helps to identify the countermeasures to avoid water chemistry problems [25].

The optimization of CT operation with the use of membrane capacitive deionized water reduces water consumption and cost [26]. But, the research work related to minimization of feed and bleed operation concerning the operating and environmental condition is very few. The daily make-up water is added into the system daily, which is calculated as a function of evaporation, blowdown, and drift loss. This make-up water addition can further be reduced by understanding the system behavior and its chemistry requirements. This will minimize plant water consumption. This paper studies the effect of make-up water quality on the system water chemistry and determines the limiting parameter using response surface methodology. Further trend analysis of the system water chemistry was carried to determine the influence of each constituent on the system bleed operation. The main objective is to monitor and analyze the chemistry parameters and their significance in water consumption.

This work is carried out in the following fashion—Collection and analysis of make-up and system water samples, preparation of a correlation matrix between the make-up & the system water, determining the control parameters, methods of chemistry controls established in the system,

credible results, and benefits envisaged after incorporating the chemistry control measures in the system.

2 Materials and methods

2.1 Description of the study area

A typical section of the Raw Water Cooling system with unit coolers is taken for this study. It is a closed-loop cooling water system whose main objective is to remove the reject heat into the atmosphere through evaporative cooling. Due to the raw water loss (drift losses, evaporation losses, and blowdown losses), the freshwater is fed into the system through make-up lines. The cooling water circuit analyzed here contains a Counter Flow Induced Draft Cooling Tower with four cells, two numbers of unit coolers, Chemical dosing system, and raw water pumps. The scheme of the cooling water circuit is presented in Fig. 1.

The raw water requirements for the cooling water circuit is around 2160 m³/hr for various plant operations. The capacity of the cooling tower is 540 m³/hr per cell. The

prevailing atmospheric environmental conditions of the proposed area are given below:

Maximum dry bulb temperature: 43 degree Celsius.

Minimum dry bulb temperature: 25 degree Celsius.

Design Wet bulb temperature: 28 degree Celsius.

The design data of the cooling tower is given below:

Maximum drift loss: 0.01% of total CT water.

Design hot water inlet temperature: 39 degree Celsius.

Design cold water outlet temperature: 32 degree Celsius.

2.2 Design provisions for proper chemical control in cooling water system

1. An on-line self-cleaning filter designed for 10% of the total cooling water flow rate is provided in the CT basin to clean the suspended solids up to 50 microns.
2. The cooling water system is designed for a cycle of concentration of about 3.0 since the increased level of dissolved salts will promote scale forming property

Legend:

1. Sodium Hypochlorite Dosing Pumps	2. Raw Water Makeup	3. Cooling Tower
4. Hot Raw water line from Cooler	5. Bleed line	6. Cold Raw Water from CT
7. Raw Water Pumps	8. Raw Water Pump Header line	9. Hot Raw Water to CT
10. Hot Service Water to Unit Cooler	11. Unit Cooler	12. Cold Service Water from Unit cooler
13. Sodium hypochlorite storage tank		

Fig. 1 Cooling water systems for auxiliary systems of nuclear power plant

of the ions. To avoid scaling, system water should be treated with scale preventing chemicals together with regular desludging (Table 1). Usually, draining of one cell of CT basin is undertaken for desludging activities based on the requirements.

3 Experimental procedure

The water samples were collected from Cooling Tower Basin in standard 500 ml Jar using proper sampling procedures. The water quality parameters like pH, Electrical Conductivity, Turbidity, Free Residual Chlorine, cycles of concentration measured with chloride as the base parameter

Table 1 Control parameters for cooling water system

Description of parameters	Range
Cycle of concentration	COC < 3;
Turbidity	< 2 NTU
Residual chlorine	0.25 to 1 ppm

is assessed. All volumetric determination is done as per the standard method for the examination of water and wastewater [27]. The sampling parameters and monitoring the frequency of the system water are provided in Table 2.

4 Results and discussion

4.1 Analysis of make-up water quality parameters on the system

The make-up water quality parameter and system water quality observed for three months are analyzed using *t*-test for a range of values lying in the 95% confidence interval (Table 3). pH, Electrical conductivity, chloride content does not show temporal variation when compared to other parameters like turbidity, hardness, and alkalinity. The variation observed for the individual system water quality parameters is less when compared to that of make-up water quality since only a fraction of system water is being replaced by the make-up water. Hence the

Table 2 Sampling frequency and its significance on the system performance [13]

Parameter	Sampling frequency	Purpose	Effect on the system
Process parameter			
Temperature	Daily	To quantify the system performance	Indicates the efficiency of the heat exchanger. Identifies the possibilities of cooling failures
Pressure	Daily	Evaluates the structural integrity	Indicates the scaling, choking across the heat exchanger
Flow rate	Daily	Indicates the system physical operating condition	Ensures proper water circulation and water availability for design heat removal
Water chemistry parameter			
pH	Daily	Indicates the acidic or alkaline state of the system	Corrosion is a function of pH
Electrical conductivity (EC)	Daily	A measure of dissolved ionic species in water	Metal corrosion and Salt deposition on the heat exchanger tubes;
Turbidity	Daily	To measure the presence of insoluble particulates in the system	Interferes with equipment operation, choking of the equipment
Alkalinity	Weekly	Represents the ability to neutralize an acid. Quantifies free hydroxyl, carbonate and bicarbonate ions	React with a hardness to form scale
Total hardness	Weekly	Presence of calcium and magnesium ions	Scaling and salt deposition
Sodium as CaCO ₃	Weekly	Evaluates the build-up of sodium ions	Salt deposition on the system;
Silica	Weekly	Ensures proper water chemistry	Silica causes scaling and fouling problems
Iron	Weekly	Quantifies the corrosion products in the system	Indicates the presence of material degradation
Chloride	Daily	Ensures proper water chemistry	Most aggressive agent in corrosion
Cycles of concentration (COC)	Daily	Cycles indicate the level of critical water quality parameter w.r.t to make-up water	An important parameter to determine the feed rate and cost
Free residual chlorine (FRC)	Daily	Measures the water potential to promote bio growth	Heat exchanger performance deteriorates; microbial accelerated corrosion occurs

Table 3 Reported range of values in make-up and system water quality parameters

Water quality parameter	Make-up water				System water			
	95% Confidence interval				95% Confidence interval			
	Lower	Upper	Mean	S.D	Lower	Upper	Mean	S.D
pH	6.90	7.40	7.14	0.40	8.23	8.34	8.29	0.09
EC ($\mu\text{S}/\text{cm}$)	796	879	837	65	2489	3191	2840	552
Turbidity, NTU	1.60	4.90	3.25	2.60	1.23	2.77	2.00	1.20
M-alk, ppm	22	45	33	18	95	145	120	39
CH, ppm	14.90	39.80	27.30	19.58	54.23	68.27	61.25	11.05
MH, ppm	10.40	21.40	15.90	8.62	25.94	49.89	37.92	18.85
Na, ppm	129.90	227.60	178.80	76.80	425.86	880.31	653.08	357.62
Silica, ppm	1.80	2.80	2.30	0.79	7.63	11.20	9.42	2.80
Iron, ppb	54.40	143.1	98.75	69.80	53.36	125.31	89.30	56.62
Chloride, ppm	271	337	304	51	807	1171	989	286

Fig. 2 Effect of make-up pH on system pH and system LSI

time-based variation is prominent in make-up water rather than system water.

4.2 Make-up pH, alkalinity, conductivity

The make-up water pH was found to be in the range of 6.4 to 7.8. The system pH does not show significant variation to this operating range (Fig. 2). The effect of make-up water pH on system M-alkalinity (Methyl Orange alkalinity) and P-alkalinity (Phenolphthalein alkalinity) was seen when the pH is above 7. A slight increase in the OH^- ions were seen in the system when pH is above 7. At pH above 7, the M-alkalinity is found to increase by an amount equal to P-alkalinity. This states that there is an increase in OH^- ions as make-up water pH goes beyond 7. The

Fig. 3 Effect of make-up pH on system alkalinity

carbonate and bicarbonate ions do not increase when compared to the hydroxyl ions (Fig. 3).

The make-up conductivity tested were found to be in the range of 700–1000 $\mu\text{S}/\text{cm}$. Figure 4 states that a definite relation cannot be arrived between the EC and system sodium & chloride levels due to clustering values. A correlation value of Makeup EC and System Sodium & chloride levels from Table 4 is also not significant. It was deduced that the system limits could not be maintained if the make-up conductivity goes above 950 $\mu\text{S}/\text{cm}$ (Fig. 4). Other system parameters were not altered much. From the make-up water analysis, it can be stated that the make-up electrical conductivity does not exceed the critical values with 95% confidence (Table 3).

The make-up water M-alkalinity and P-alkalinity was not influencing the system water chemistry parameters as their levels are very less in the source water itself. Similarly,

Fig. 4 Effect of make-up conductivity on system sodium and chloride ions

there is no prominent influence of make-up water calcium and magnesium hardness in the system.

4.3 Make-up RSI, LSI

The make-up RSI was found to be in the range of 9 to 13.1. It was found that the alkaline environment is prevalent in the system due to the addition of sodium hypochlorite as a biocide. There is a strong dominance of the formation of sodium hydroxide in the system, which reduces the RSI in the system. It is understood that the system RSI of 8 and below is seen to be neutral, and no unruly results were seen in the system (Fig. 5).

The make-up LSI was seen to be in the range of 0.8 to 3.35. As make-up LSI was increased, there is a directional tendency of the system to go from corrosive to scaling conditions. The system LSI did not go beyond +0.5 and −0.5 during this test period. Even though the make-up RSI and LSI values were high, the system RSI and LSI levels were found to be within limits.

4.4 Correlation between system water and make-up water quality

The Pearson's correlation coefficient determines the degree of a linear relationship between any two variables on a scale of −1 (perfect inverse relation) through 0 (no relation) to +1 (perfect sympathetic relation) [28]. The Pearson correlation matrix (Table 4) is utilized to study the effect of individual make-up water parameters on the system water chemistry condition. The water quality parameters whose correlation value has a significance level of 0.01 is discussed in the subsequent lines.

It was observed that make-up pH is influencing the formation of system chloride ions, system electrical conductivity linearly [29]. A negative correlation exists between the make-up water Ryznar Stability Index (RSI) and electrical conductivity. The system chloride and sodium concentration are influenced by the make-up sodium and chloride content. The make-up iron content establishes a negative relation with system RSI, LSI. The turbidity of the water is not governed by the make-up pH or conductivity. Turbidity levels increase due to the presence of suspended solids, organic matter, or any other inorganic substances. System Operation data is studied to analyze the levels of turbidity. It was found that lower levels of biocide and improper flushing of the system lines increase the turbidity. To maintain the turbidity levels, it is necessary to maintain the free residual chlorine levels within 0.25 to 1 ppm. The other make-up water parameters like P-alkalinity, Magnesium Hardness, silica content does not affect the system water quality parameter to a significant level since their concentration is minimal in make-up water. There is no prominent influence of make-up water electrical conductivity on the system individual water quality parameter. From this correlation, we can state that make-up water qualities like sodium, chloride, RSI, LSI has a noticeable influence on the system. The above study indicates that the critical parameter to be observed is chloride and sodium concentration. In most of the systems, hardness, silica, and conductivity play a significant role. This study highlights the importance of studying, analyzing, and decision making in individual systems rather than applying existing guidelines.

4.5 Optimization of critical parameters:

Response surface methodology is utilized in a wide spectrum of research activities to design and optimize the experimental runs [30–33]. This method is adopted to determine the critical values of make-up chloride and sodium content to prevent chemistry violations in the system. These critical parameters are optimized using design expert for the reported range of values obtained for the make-up water using central composite design [34–37]. The limiting values identified for the above make-up water to maintain amicable system water chemistry condition is given as follows:

Makeup chloride content: 295 mg/l as CaCO_3 .
 Make-up sodium content: 116 mg/l as CaCO_3 .
 System chloride content: 850 mg/l.
 System sodium content: 500 mg/l.

Figures 6 and 7 shows the response surface graphs for sodium and chloride levels in the system. The interrelation between the make-up sodium and system sodium

Table 4 Pearson correlation matrix for make-up and system water quality parameters

Variable	Mark-up water parameter													
	pH	EC	Turb.	TDS	M-alk	TH	CH	MH	Na	Si	Iron	Cl	LSI	RSI
Mark-up water parameter	pH	1.00												
	EC	0.17	1.00											
	Turb.	0.61	0.00	1.00										
	TDS	0.17	1.00	0.00	1.00									
	M-alk	0.49	-0.10	0.77	-0.10	1.00								
	TH	0.73	-0.14	0.67	-0.14	0.73	1.00							
	CH	0.71	-0.20	0.74	-0.20	0.78	0.97	1.00						
	MH	0.58	0.04	0.32	0.03	0.43	0.82	0.65	1.00					
	Na	0.66	0.21	-0.06	0.20	-0.21	0.31	0.24	0.40	1.00				
	Si	-0.34	-0.29	-0.11	-0.29	0.04	-0.06	0.01	-0.21	-0.50	1.00			
	Iron	0.64	0.14	0.77	0.14	0.84	0.82	0.81	0.62	0.08	-0.04	1.00		
	Cl	0.62	0.10	-0.06	0.10	-0.01	0.39	0.26	0.60	0.78	-0.50	0.24	1.00	
	LSI	-0.88	0.01	-0.75	0.01	-0.80	-0.94	-0.93	-0.72	-0.35	0.16	-0.86	-0.45	1.00
	RSI	-0.80	0.06	-0.76	0.06	-0.85	-0.95	-0.95	-0.73	-0.24	0.10	-0.89	-0.38	0.99
System water parameter	pH	0.66	0.42	0.39	0.42	0.47	0.67	0.60	0.64	0.57	-0.42	0.65	0.56	1.00
	EC	0.80	0.30	0.61	0.30	0.69	0.71	0.65	0.67	0.38	-0.43	0.75	0.41	-0.81
	Turb.	0.17	-0.46	-0.40	-0.46	-0.32	0.13	0.07	0.23	0.44	0.03	-0.34	0.44	-0.01
	TDS	0.80	0.30	0.61	0.30	0.69	0.71	0.65	0.67	0.38	-0.43	0.75	0.41	-0.81
	P-alk	0.65	0.55	0.39	0.55	0.43	0.67	0.56	0.75	0.47	-0.28	0.71	0.58	0.66
	M-alk	0.46	0.40	0.27	0.41	0.58	0.46	0.43	0.43	0.23	-0.22	0.72	0.32	-0.57
	TH	0.43	-0.17	0.43	-0.17	0.43	0.62	0.56	0.60	0.16	-0.09	0.63	0.20	-0.61
	CH	0.51	0.05	0.36	0.05	0.41	0.64	0.56	0.65	0.31	-0.17	0.63	0.35	-0.64
	MH	0.36	-0.28	0.44	-0.28	0.41	0.56	0.52	0.53	0.06	-0.04	0.58	0.10	-0.56
	Na	0.71	0.39	0.10	0.38	-0.02	0.51	0.42	0.58	0.88	-0.33	0.39	0.78	-0.44
	Si	0.37	0.31	0.18	0.30	0.14	0.33	0.30	0.31	0.22	0.37	0.56	0.27	-0.35
	Iron	0.14	0.06	-0.20	0.06	0.24	0.13	0.04	0.30	0.07	-0.19	0.15	0.59	-0.22
	Cl	0.84	0.18	0.31	0.18	0.31	0.71	0.62	0.73	0.82	-0.43	0.57	0.73	-0.68
	LSI	-0.63	-0.33	-0.40	-0.34	-0.62	-0.69	-0.64	-0.65	-0.40	0.30	-0.81	-0.47	0.75
	RSI	-0.60	-0.30	-0.38	-0.30	-0.62	-0.67	-0.61	-0.62	-0.35	0.26	-0.80	-0.42	0.73

Table 4 (continued)

Variable	System water parameter												
	pH	EC	Turb.	TDS	P-alk	M-alk	TH	CH	MH	Na	Si	Iron	RSI
Mark-up water parameter													
pH	1.00												
EC	0.71	1.00											
Turb.	-0.17	-0.15	1.00										
TDS	0.71	1.00	-0.15	1.00									
P-alk	0.91	0.68	-0.16	0.68	1.00								
M-alk	0.66	0.75	-0.32	0.75	0.63	1.00							
TH	0.18	0.60	0.04	0.60	0.26	0.49	1.00						
CH	0.37	0.69	-0.01	0.68	0.43	0.62	0.93	1.00					
MH	0.06	0.51	0.06	0.51	0.13	0.38	0.98	0.82	1.00				
Na	0.72	0.47	0.28	0.47	0.75	0.43	0.27	0.45	0.15	1.00			
Si	0.27	0.21	-0.11	0.21	0.51	0.44	0.39	0.44	0.33	0.57	1.00		
Iron	0.32	0.18	0.15	0.18	0.37	0.34	-0.19	-0.05	-0.26	0.15	0.02	1.00	
Cl	0.78	0.78	0.23	0.78	0.71	0.62	0.56	0.68	0.46	0.85	0.37	0.13	1.00
LSI	-0.80	-0.85	0.20	-0.85	-0.77	-0.94	-0.60	-0.75	-0.47	-0.61	-0.46	-0.29	1.00
RSI	-0.72	-0.83	0.20	-0.83	-0.70	-0.95	-0.67	0.80	-0.54	-0.55	-0.47	-0.26	0.99
													1.00

Influence of make-up water parameters on system water parameters with a significance level of 0.01 is bold

Fig. 5 Effect of make-up pH on make-up LSI, RSI and system LSI, RSI

Fig. 6 Response surface graphs for system chloride

is predominant. Make-up sodium does not have a significant change in the system chloride. The same trend is observed in the system chloride levels. The residuals are regularly distributed along the straight line for both the response variable. Only a little deviation is reported in Figs. 8 and 9. Therefore, the model could be used for dependent variable prediction. The analysis of variance is presented in Tables 5 and 6, which evaluates the significance of the model. R^2 value of the regression model for both the parameters is close to 1, which indicates that there is a small difference between the predicted and measured value. The p -value is less than 0.0001 for system sodium and 0.0002 for system chloride levels. It is understood that the system is having a good fit.

Fig. 7 Response surface graphs for system sodium

Fig. 8 Normal probability plot of the residuals for system sodium

To summarise the work, the relation between the make-up water and system water chemistry is analyzed and assessed. It is found that the make-up water parameter chloride and sodium have got a definite positive relation with system sodium and chloride content. The methods to optimize the water chemistry limits and in turn, save water were studied, and the following is recommended from the study.

- Limit the make-up water sodium and chloride levels to 110 and 290 mg/l.

Fig. 9 Normal probability plot of the residuals for system chloride

Case 1: Make-up water sodium and chloride levels more than the limiting parameter for a maximum of 5 days.

Generally, the Nuclear power plant employs a separate Demineralized Plant to produce demineralized water (DM water) for its steam-water system. The option of mixing the make-up water with demineralized water for a maximum of five days is seen a viable option if the limiting criteria is not met in any of the days. The DM plant for a nuclear power plant is designed with 100% redundancy. Hence it will cater to the make-up water requirement at site. The production cost of DM water is justifiable only when it is used for a maximum of five days. The detailed aspect of

mixing DM water and make-up water is yet another area of research.

Case 2: Make-up water sodium and chloride levels more than the limiting parameter continuously for six days or more in a week.

With 95% confidence, it is seen that make-up water chemistry levels do not violate continuously for more than five days. If any of the reported violations repeatedly occur for more than five days, it is recommended to design, install an appropriate raw water treatment system.

With the above limiting values on sodium and chloride, it is possible to reduce blowdowns by 1 number per 25 days. The requirements of code to limit chloride are 250 ppm [38]. However, in the absence of a good source, it is permitted to use till 1000 ppm. The levels of sodium and chloride in make-up water can be checked every day. If higher levels of make-up sodium and chloride are seen in any of the day, system process parameters are studied to forego the usage of make-up water for that particular day. The decision to abstain or limit the feed operation can be established with the above sodium and chloride levels. This aspect of developing and assessing a warning system based on the risk associated with the seasonal and temporal deterioration of raw water quality can be undertaken by probability estimation methods [39–41]. Further water reduction aspects were studied by investigating the system water chemistry parameters and bleed operation.

4.6 Analysis of the system water chemistry conditions

Typical Weekly review of the system sample was undertaken to study the effect of Electrical Conductivity, Chloride ions, and TDS on Cycles of Concentration (Table 7). It was seen that Chlorides were found to increase the cycles of concentration on the majority.

Table 5 ANOVA table for the parameter system chloride

Source	Df	Sum of squares	Mean square	F value	p-value Prob > F	
Model-system chloride	9.458E+005	5	1.892E+005	28.78	0.0002	Significant
A-makeup chloride	7.110E+005	1	7.110E+005	108.19	< 0.0001	
B-makeup sodium	301.87	1	301.87	0.046	0.8364	
AB	756.25	1	756.25	0.12	0.7444	
A ²	2.209E+005	1	2.209E+005	33.62	0.0007	
B ²	2587.88	1	2587.88	0.39	0.5502	
Residual	46,002.55	7	6571.79			Not significant
Lack of fit	21,465.75	3	7155.25	1.17	0.4262	
Pure error	24,536.80	4	6134.20			

$R^2 = 0.95$; $R^2_{adj} = 0.92$; CV (%) = 8.09

Equation : System Cl. = $904.2 + 298.12 * A + 6.14 * B + 13.75 * AB + 178.21 * A^2 - 19.29 * B^2$

Table 6 ANOVA table for the parameter system sodium

Source	Sum of squares	df	Mean square	F Value	p-value	Prob > F
Model-system sodium	8.488E+005	5	1.698E+005	117.20	< 0.0001	Significant
A-makeup chloride	374.16	1	374.16	0.26	0.6269	
B-makeup sodium	6.771E+005	1	6.771E+005	467.45	< 0.0001	
AB	324.00	1	324.00	0.22	0.6506	
A ²	7912.18	1	7912.18	5.46	0.0521	
B ²	1.698E+005	1	1.698E+005	117.22	< 0.0001	
Residual	10,139.26	7	1448.47			
Lack of fit	7846.46	3	2615.49	4.56	0.0883	Not significant
Pure error	2292.80	4	573.20			

$R^2 = 0.99$; $R^2_{adj} = 0.98$; CV (%) = 4.96

Equation : System Na. = $884.2 + 6.84 * A + 290.92 * B + 9 * AB + 33.73 * A^2 - 156.23 * B^2$

Table 7 Weekly variation of cycles of concentration with different parameters

Week	COC based on conductivity	COC based on TDS	COC based on chloride
Week 1	3.0	3.0	3.3
Week 2	2.9	2.9	3.1
Week 3	3.0	3.0	3.2
Week 4	2.7	2.7	3.1
Week 5	2.6	2.6	3.0
Week 6	3.0	3.0	3.0
Week 7	2.9	2.9	3.1
Week 8	3.5	3.5	3
Week 9	2.9	2.9	3.2
Week 10	3.1	3.1	3

Fig. 10 Reportable deviation of water chemistry parameters

The main contributing factor to blowdown is Cycles of concentration due to chloride concentration. Other parameters were found to be in the range most of the time. Of the total samples tested for cycles, nearly 40% of the samples were slightly above the normal range (Fig. 10). COC was found to be within limits after adhering to the make-up water quality limiting criteria and adopting strict chemical conditioning.

One hour of system bleed requires nearly 50 m³ of water. The total blowdown water for the period was 8815 m³. With proper Chemistry conditioning, unnecessary blowdowns of 500 m³ water due to turbidity level violation and 360 m³ water due to limiting criteria could have been avoided (Fig. 11). Hence, nearly 10% of the water has been saved by practicing limiting criteria, proper monitoring, and chemistry conditioning in the plant. The overall study indicated that with appropriate chemical conditioning and minimal blowdowns, it is possible to maintain system healthiness and also save water.

Fig. 11 Water Savings with precise Chemistry Control

5 Conclusion

The following are the conclusions arrived from this work.

- The determining factor for the cooling water system bleed operation is found to be the cycles of concentration with chloride content.
- A definite correlation exists between the make-up water qualities like pH, sodium, chloride on the system water quality parameters- EC, chloride, and sodium ions.
- By limiting the critical values of make-up sodium to 116 mg/l (CaCO_3) and chloride to 295 mg/l (CaCO_3) along with strict chemistry conditioning, it is possible to save nearly 10% of the water.

From this study, It can be stated that proper monitoring and chemical conditioning helps to conserve not only water but also the operation & maintenance cost of the system equipment. The cost of repairing the leakages, leak ingress of radioactive water due to poor chemistry control in the nuclear power plant is considered severe. Hence, the chemistry-related damages and failures were given due importance to prevent outages in the field of research. The above limiting criteria provide some insight into preventing chemistry-related failures. The studies on the aspect of simulating and testing the specific industrial condition rather than common industrial conditions need attention. This study can further be extended to field-specific optimization of free residual chlorine levels for controlling turbidity levels in the system.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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