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Assessment of Water Chemistry in the Hybrid Cooling System of a Thermal Power Plant Using ICP-MS Analysis and Comparison with EPRI Guidelines

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ABSTRACT

Cooling systems in thermal power plants play a decisive role in maintaining steam cycle efficiency, enhancing equipment reliability, and reducing maintenance costs. The chemical quality of water in these systems is one of the most critical factors affecting corrosion rates, scale formation, and heat transfer degradation. In the present study, the water chemistry and corrosion behaviour in the hybrid (dry-wet) cooling system of a sample thermal power plant were investigated. This plant, with a nominal capacity of 1000 MW, supplies the bulk of its water demand from treated municipal wastewater and employs a combination of dry and wet cooling towers to reduce water consumption. Sampling was conducted on demineralised water, recirculating water of the dry tower, inlet water to heat exchangers, wet tower water, and makeup water. General parameters including pH, electrical conductivity, TDS, temperature, and salinity were measured. Additionally, the concentrations of metallic elements were determined using ICP-MS. The results indicated that the demineralised water exhibits exceptionally high purity and is virtually devoid of metal ions, whereas in the dry cycle, a significant increase in aluminium concentration up to approximately 260 ppb was observed, indicative of active corrosion in the aluminium radiators of the dry tower. In contrast, in the wet tower, the concentrations of calcium, sodium, potassium, silica, copper, and zinc increased markedly, attributable to evaporation, concentration of dissolved solids, and the use of wastewater as make-up water. Comparison of the results with EPRI guidelines revealed that although iron and copper levels fall within acceptable ranges, the elevated aluminium concentration may be regarded as the primary indicator of heat transfer equipment degradation. Accordingly, the revision of the water chemistry control programme, continuous monitoring of dissolved aluminium, and reassessment of the dry tower operating conditions are proposed as the most critical management strategies. The findings of this research can serve as a basis for the development of intelligent corrosion monitoring programmes in power plants equipped with hybrid cooling systems.

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Introduction

Thermal power plants, as the primary suppliers of electrical energy in many countries worldwide, depend on cooling systems with stable performance to maintain steam cycle efficiency. The proper functioning of condensers and cooling towers not only enhances plant efficiency but also plays a significant role in reducing fuel consumption, lowering pollutant emissions, and extending equipment service life. On the other hand, the global water crisis and limited access to fresh water have driven many power plants towards dry cooling, hybrid systems, and the reuse of municipal and industrial wastewaters. Although the use of dry cooling towers significantly reduces water withdrawal, the differing heat transfer conditions, equipment materials, and circulating water quality can give rise to novel corrosion patterns. In such systems, aluminum radiators and tubes are typically exposed to varying temperatures, dissolved oxygen, and thermal stresses; inadequate water chemistry control may lead to increased aluminum dissolution and reduced heat transfer efficiency. Conversely, in wet towers, evaporation concentrates dissolved ions, promotes mineral scaling, and exacerbates localized corrosion.

In recent years, guidelines published by the Electric Power Research Institute (EPRI) have emphasized the importance of continuous water quality monitoring, corrosion product control, and measurement of dissolved metallic elements as a cornerstone of power plant operational management. Among analytical techniques, inductively coupled plasma mass spectrometry (ICP-MS), owing to its high sensitivity and capability for simultaneous multi-element determination at ppb levels, has become a standard tool for corrosion monitoring in the power generation industry [1]. Despite the increasing deployment of hybrid cooling systems, field studies based on actual operational data particularly in power plants equipped with Heller-type dry towers remain limited. Much of the existing research has focused on simulation or laboratory investigations, providing scant information on the real-world behavior of systems under industrial operating conditions. Accordingly, the analysis of operational data from power plants can play a pivotal role in the development of preventive maintenance strategies and the improvement of water chemistry control programmes. The present study aims to assess the water chemistry behavior in the hybrid cooling system of a sample thermal power plant. Water samples were collected from various sections of the cooling cycle and examined using chemical tests and ICP-MS analysis. The results were then compared with the requirements and recommended limits set forth in EPRI guidelines to identify the most significant corrosion indicators and operational risks. It is anticipated that the findings of this research will contribute to the development of condition monitoring programmes, reduction of equipment corrosion rates, and enhancement of the reliability of power plants equipped with dry and hybrid cooling systems [2].

Literature Review

Importance of Water Chemistry in Thermal Power Plant Cooling Systems:

Water chemistry is one of the most critical factors affecting the performance, reliability, and service life of power plant equipment. In thermal power plants, water not only functions as the heat transfer fluid but also comes into direct contact with numerous metallic surfaces, including condensers, heat exchangers, cooling towers, and transmission lines. Any alteration in the chemical composition of water can give rise to phenomena such as corrosion, scaling, biofouling, and reduced heat transfer efficiency. EPRI studies have shown that more than 30% of unscheduled outages of heat transfer equipment in power plants are directly or indirectly associated with inadequate water chemistry control [2].

In cooling systems, water quality not only influences equipment corrosion but also affects condenser thermal performance. According to reports in the literature, an increase in deposit thickness of merely 0.5 mm on heat transfer surfaces can reduce thermal efficiency by up to 8%. Furthermore, corrosion products arising from metal dissolution may accumulate in other sections of the circuit, leading to secondary fouling. Over the past decade, owing to the global water crisis and increasing environmental constraints, numerous power plants have shifted towards the use of municipal wastewater, brackish waters, and dry or hybrid cooling systems. While these changes have reduced freshwater consumption, they have significantly increased the complexity of water chemistry control [3].

Cooling Technologies in Thermal Power Plants

Power plant cooling systems are generally classified into three main categories:

- ✓ Wet cooling towers.
- ✓ Dry cooling towers.
- ✓ Hybrid systems.

In wet towers, the heat transfer process occurs primarily through water evaporation. This method offers high thermal efficiency but entails considerable water consumption. According to the International Energy Agency (IEA, 2022), a substantial portion of global industrial water withdrawal is attributable to thermal power plants. In contrast, dry cooling systems, which operate mainly on sensible heat transfer, reduce water consumption by more than 90%.

However, their performance is heavily influenced by ambient temperature; studies have shown that under high-temperature conditions, dry tower efficiency can be up to 15% lower than that of wet towers [4]. To overcome the limitations of both systems, hybrid technologies have been developed. In such systems, a portion of the thermal load is dissipated by the dry tower and the remainder by the wet tower. Studies conducted by Yousefpour et al. (2025) have demonstrated that hybrid systems are capable of reducing water consumption by approximately 70% while simultaneously mitigating the efficiency losses caused by ambient temperature [5]. The sample power plant in this study employs the same approach, operating dry and wet towers in combination within the circuit, thereby providing a valuable case for the study of corrosion behaviour in such systems.

Corrosion in Power Plant Cooling Systems:
Corrosion represents one of the most significant operational challenges in cooling systems. As defined by NACE International, corrosion is the progressive degradation of materials through chemical or electrochemical reactions with their surrounding environment. In power plant cooling systems, various forms of corrosion are observed:

- ✓ Uniform corrosion.
- ✓ Pitting corrosion.
- ✓ Crevice corrosion.
- ✓ Galvanic corrosion.
- ✓ Under-deposit corrosion.
- ✓ Flow-accelerated corrosion.

Studies by Ghahreman Afshar et al. (2023) indicate that the greatest economic losses in cooling towers arise from localized and under-deposit corrosion, as these types typically progress without discernible early warning signs. In cooling circuits, parameters such as pH, electrical conductivity, dissolved oxygen, chloride, sulphate, silica, and temperature constitute the most critical factors governing corrosion rates [6].

Aluminum Corrosion in Dry Cooling Towers
With the increasing deployment of Heller-type dry cooling systems, the use of aluminum in radiator construction and heat transfer surfaces has grown. This is attributable to aluminum's high thermal conductivity, low weight, and adequate oxidation resistance. Despite these advantages, numerous studies have demonstrated that aluminum can undergo severe corrosion under specific conditions. Davis (2018) reported that the most influential factors affecting aluminum corrosion include [3]:

- ✓ pH below 5 or above 9
- ✓ Presence of chloride ions
- ✓ High dissolved oxygen levels
- ✓ Elevated temperatures
- ✓ Turbulent flow conditions

Research has shown that in closed cooling systems, an increase in dissolved aluminum concentration in water serves as a direct indicator of corrosion of aluminum surfaces. In power plants equipped with dry towers, progressive aluminum dissolution can reduce tube wall thickness, impair heat transfer efficiency, increase leakage probability, and transport corrosion products to other sections of the cycle. Accordingly, numerous industrial guidelines, including those of EPRI, identify dissolved aluminum monitoring as a key health indicator for equipment [2].

The Role of Dissolved Metallic Elements as Corrosion Indicators:
One of the most important condition-monitoring methods in power plants involves measuring the concentration of dissolved metals in water. According to the EPRI (2021) guideline, the following elements are recognized as key corrosion indicators [1]:

Element	Probable Source
Fe	Carbon steel
Cu	Copper alloys
Al	Aluminum surfaces
Zn	Galvanized coatings
Ni	Stainless steels
Cr	Alloy steels

An increase in the concentration of any of these elements typically signals the activation of a corrosion mechanism in some part of the system. Turner et al. (2019) demonstrated that online monitoring of dissolved metals can predict the onset of corrosion several months prior to the observation of leakage or equipment failure.

Application of ICP-MS in Power Plant Corrosion Monitoring:
Inductively coupled plasma mass spectrometry (ICP-MS) is one of the most accurate techniques for elemental analysis at very low concentrations. The method offers the following advantages:

- ✓ Detection limits in the ppt to ppb range.
- ✓ Simultaneous multi-element measurement.
- ✓ High accuracy and reproducibility.
- ✓ Capability for corrosion product monitoring.

Recent studies have shown that ICP-MS exhibits substantially higher sensitivity than traditional methods such as atomic absorption spectroscopy (AAS) in detecting early stages of corrosion. In the power generation industry, this technique is widely employed for steam cycle monitoring, demineralized water quality assessment, treatment system performance control, and equipment corrosion surveillance [7].

EPRI Guidelines in Water Chemistry Management:

The Electric Power Research Institute (EPRI) is one of the most authoritative bodies for establishing water chemistry standards in power plants. Its Cycle Chemistry Programme provides a set of permissible limits and control indicators for various equipment. According to these guidelines:

- ✓ Dissolved iron should be maintained below 2 to 10 ppb.
- ✓ Dissolved copper should be below 10 ppb.
- ✓ Cation conductivity should be kept at the minimum practicable level.
- ✓ Corrosion product transport to the steam cycle should be controlled.

Studies by Turner (2019) have shown that power plants that fully comply with EPRI guidelines experience up to a 35% reduction in corrosion-related maintenance costs [8].

Use of Wastewater in Power Plants and Associated Corrosion Challenges:

In recent years, the use of municipal wastewater as a power plant water source has grown significantly. Studies by Panagopoulos (2023) indicate that wastewater reuse can reduce freshwater withdrawal by more than 80%. However, such water sources typically contain chlorides, sulphates, organic matter, silica, and heavy metals, which can elevate the risks of corrosion and scaling. Research conducted at power plants in China, India, and South Africa has demonstrated that the use of wastewater without an appropriate water chemistry control programme is a primary factor in increased corrosion rates in cooling towers [9].

Existing Knowledge Gap and Novelty of the Present Study:

A review of previous studies reveals that the majority of published research has focused on wet cooling towers or laboratory-scale investigations. Furthermore, most studies have addressed only a single metal or a single section of the cooling circuit. In contrast, field studies based on actual operational data from power plants equipped with dry-wet hybrid systems particularly those featuring Heller-type dry towers remain extremely limited. In addition, little information is available concerning aluminum corrosion behavior under real operating conditions in Middle Eastern thermal power plants [10].

The principal novelty of the present study is summarized in the following aspects:

- ✓ Utilization of actual operational data from a sample power plant.
- ✓ Simultaneous investigation of demineralized water, the dry cycle, and the wet tower.
- ✓ Application of ICP-MS for the identification of corrosion indicators at ppb levels.
- ✓ Direct assessment of aluminum equipment corrosion in the dry tower.
- ✓ Comparison of results with EPRI requirements and recommended limits.
- ✓ Provision of a framework for the development of condition monitoring and predictive maintenance systems in power plants equipped with hybrid cooling systems.

This research gap underscores the importance of the present study and can serve as a basis for formulating novel corrosion control strategies in thermal power plants with minimal water consumption.

Materials and Methods

Introduction to the Power Plant and the Studied System:

This research was conducted at a sample thermal power plant. The plant is a steam power facility comprising four generation units, each with a nominal capacity of 250 MW, yielding a total installed capacity of 1,000 MW. The primary fuel is natural gas, with heavy fuel oil (mazut) utilized under emergency conditions. The generated electricity is transmitted to the national grid via 230 kV and 400 kV transmission networks. The bulk of the plant's water demand approximately 89% is supplied from treated municipal and industrial wastewater. To minimize groundwater extraction, a hybrid cooling system incorporating both dry and wet cooling towers has been implemented. During the cold seasons, the dry tower is operated almost exclusively, whereas in the warmer months, the system operates in hybrid mode, employing both dry and wet towers simultaneously to maintain cooling water temperature within the desired range. This configuration facilitates water consumption reduction while preserving thermal reliability.

Specifications of the Cooling System:

The cooling system of Unit No. 1, selected as the subject of this study, comprises the following components:

- ✓ Condenser with approximately 14,000 copper tubes of one-inch nominal diameter.
- ✓ Dry cooling tower equipped with aluminum tubes and fins.

- ✓ Shell-and-tube heat exchangers.
- ✓ Carbon steel transmission pipelines.
- ✓ Two main circulating water pumps.

Each pump is capable of delivering a flow rate of approximately 17,500 m³/h, and when operating simultaneously, the total circulating water capacity reaches about 30,000 m³/h. The operating pressure of the circuit is reported to range between 2.5 and 3 bar. Cooling water enters the condenser at approximately 30°C and, after absorbing the latent heat of the exhaust steam from the turbine, exits at around 40°C.

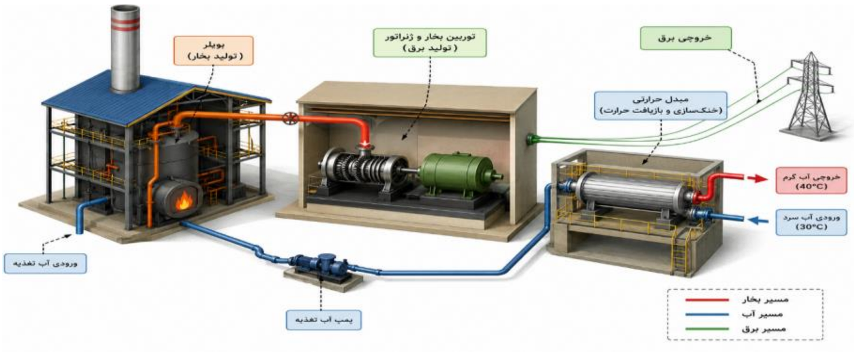

Figure 1. Schematic layout of the heat exchanger, boiler, and turbine in relation to one another

The dry tower is of the Heller type, equipped with tube-fin radiators. The pressure within the dry tower tubes ranges between 3 and 5 bar. The fins are manufactured from aluminum alloy Al 99.5H, and the tubes are constructed from pure aluminum Al 99.5. The dry tower comprises six sectors, each sector containing nine delta units.

Figure 2. View of a delta unit and the arrangement of tubes in the dry tower

This tower comprises six sectors, with a total of 28,800 tubes having an internal diameter of 21.18 mm. The water exiting the condenser, after passing through the main headers, is distributed through these tubes and dissipates its heat to the ambient air via sensible heat transfer. During the hot seasons, to augment the heat rejection capacity, shell-and-tube heat exchangers are introduced into the circuit between the dry tower and the wet tower, thereby reducing the water temperature by approximately 5°C prior to re-entering the condenser. The design specifications of these exchangers include eight twin exchangers, a tube length of 9 metres, and a steel shell. Depending on the ambient temperature conditions, the number of exchangers in operation can be adjusted. For instance, in winter, when the ambient temperature falls below 20°C, the exchangers are not required. However, in summer, when air temperatures exceed 35°C and the temperature differential with the incoming water at 40°C proves insufficient, the entire thermal load is transferred to the wet tower; in practice, the dry tower then serves merely to convey the water flow, with negligible heat transfer taking place. The design specifications of the exchangers are presented below:

- ✓ **Material:** Admiralty
- ✓ **Fluid quantity:** 7,777.7696 kg/s
- ✓ **Temperature:** 44.1 - 36.67 °C
- ✓ **Pressure:** 4.3 bar

- ✓ **Length:** 9,000 mm
- ✓ **Pitch:** 29 mm
- ✓ **Number of passes:** 1
- ✓ **Tube number:** 3,000
- ✓ **Shell outer diameter:** 1,828 mm
- ✓ **Shell side free area:** 7.462 m²

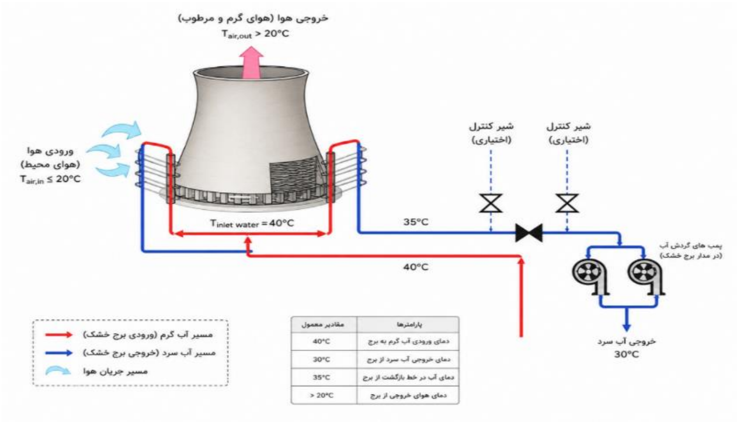

Figure 3. Schematic of the dry tower and its inlet and outlet connections

During the hot seasons, when the temperature differential between the return water from the condenser and the ambient air temperature at the plant site is approximately $20^{\circ C}$ or less (e.g., water at $40^{\circ C}$ and ambient air at $30^{\circ C}$), the wet tower is also brought into service within the main system. Under these conditions, the temperature gradient between the water entering the tower and the ambient air is less than $20^{\circ C}$, and upon contact between the water and air, the water temperature drops to approximately $35^{\circ C}$. To achieve further cooling down to $30^{\circ C}$, a shell-and-tube heat exchanger is installed between the dry and wet cooling towers, which reduces the water temperature by about $5^{\circ C}$. During the winter season, this exchanger is bypassed and removed from the circuit.

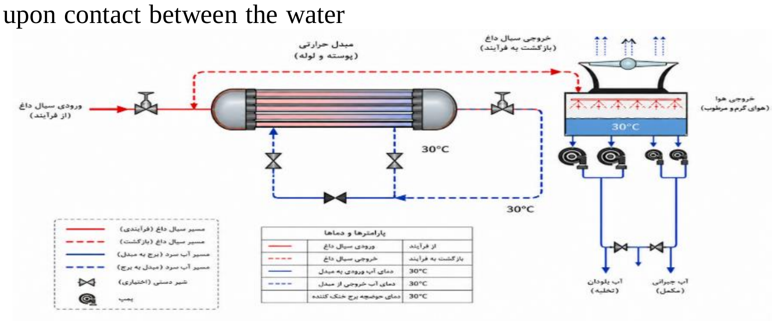

Figure 4. Schematic of the heat exchanger with the wet cooling tower

Sampling Programme:
Sampling was conducted under normal operating conditions of the power plant. To obtain a comprehensive picture of water quality variations across the cooling circuit, samples were collected from five principal points:

- ✓ Demineralized water.
- ✓ Dry tower recirculating water.
- ✓ Shell-and-tube heat exchanger inlet water.
- ✓ Wet cooling tower water.
- ✓ Wet tower make-up water.

All samples were collected in clean polyethylene containers and transported to the laboratory for chemical testing and elemental analysis in accordance with the plant's standard laboratory procedures.

Measurement of General Water Quality Parameters:
At the plant's chemistry laboratory, the following general water quality parameters were measured:

- ✓ Temperature.
- ✓ pH.
- ✓ Electrical conductivity.
- ✓ Total dissolved solids (TDS).
- ✓ Salinity.

These indicators served as the primary criteria for assessing water chemistry status and for comparing conditions across different sections of the cooling circuit. The measured values for the various samples formed the basis for analyzing changes arising from water contact with metallic equipment and from concentration processes in the wet tower.

Measurement of Metallic Elements Using ICP-MS:

To evaluate equipment corrosion behavior, the concentrations of dissolved metallic elements were determined using inductively coupled plasma mass spectrometry (ICP-MS). Owing to its high sensitivity in the ppb range, this method enables the detection of trace amounts of elements originating from corrosion products. In this study, the concentrations of aluminum (Al), iron (Fe), copper (Cu), zinc (Zn), sodium (Na), potassium (K), calcium (Ca), and silica (Si) were measured. The primary analytical focus was placed on Al, Fe, and Cu, as these elements respectively represent corrosion of the aluminum, steel, and copper components of the system. Results are reported as mass concentrations in ppb or ppm and were used for comparison with EPRI-recommended limits.

Data Analysis Method:

The obtained data were analyzed at two levels:

- ✓ **Descriptive analysis:** Comparison of water quality parameters and elemental concentrations at different points in the circuit to identify trends and determine sections susceptible to corrosion or scaling.
- ✓ **Comparative analysis:** Comparison of results with EPRI-recommended limits to assess equipment corrosion status and the degree of compliance of operating conditions with water chemistry requirements.

Given that the study aimed at a field analysis of a power plant under real operating conditions, emphasis was placed on the engineering interpretation of results and the identification of potential sources of corrosion products.

Corrosion Assessment Framework:

For the interpretation of results, the following indicators were considered:

- ✓ Increased dissolved aluminum concentration as an indicator of corrosion of dry tower aluminum equipment.
- ✓ Increased dissolved iron as an indicator of steel equipment corrosion.
- ✓ Increased dissolved copper as an indicator of corrosion of the condenser and exchangers containing copper alloys.
- ✓ Increased calcium, silica, and electrical conductivity as indicators of scaling propensity.
- ✓ Increased zinc as an indicator of degradation of galvanized coatings or zinc-containing alloys.

Finally, by integrating information from chemical tests, ICP-MS analysis, and system operating conditions, the corrosion and scaling status of each section of the cooling circuit was assessed, and the results were compared with EPRI guidelines.

Results and Discussion

Analysis of General Water Quality Parameters

General water quality parameters were measured at five points in the cooling circuit: demineralized water, the dry cycle, heat exchanger inlet water, the wet tower, and wet tower make-up water. The results indicate that variations in water quality across different sections of the circuit are a direct function of operating conditions, equipment type, and water supply source. The measured data including pH, electrical conductivity, TDS, temperature, and salinity are presented in the following table.

Table 1. General analysis of water samples from different sections of the power plant

Sample Point	Cond. (µS/cm)	TDS (ppm)	% NaCl	Temp (°C)	pH
Demin	1.15	0.57	0.00	22.60	8.74
Dry Tower (Dry cycle)	6.06	3.04	0.00	31.00	7.61
Make-up – Wet Tower (Wastewater)	1600.00	800.00	3.10	24.00	7.80
Wet Tower (Cooling water)	8400.00	4210.00	16.50	29.00	7.57
Shell & Tubes (Entry Heat Exchanger)	6.24	3.12	0.00	36.00	–

The demineralized water exhibits very low electrical conductivity and TDS, indicative of the proper performance of the demineralization unit and the effective removal of dissolved ions. Upon entry into the dry cycle, a moderate increase in conductivity and TDS is observed, which may arise from water contact with metallic surfaces, initial dissolution of corrosion products, and minor ion ingress from equipment. In contrast, the wet tower water shows a substantial increase in conductivity and TDS, consistent with the concentration effect due to evaporation and the use of wastewater as make-up water. This trend is in agreement with studies by Panagopoulos et al. (2023) concerning wastewater reuse systems in power plants. From an engineering perspective, the marked difference between the water quality of the dry cycle and that of the wet tower indicates that the degradation mechanisms affecting equipment in these two sections are not identical. In the dry cycle, metal corrosion predominates, whereas in the wet tower, scaling and fouling play a determining role alongside corrosion.

Analysis of Dissolved Metallic Elements Using ICP-MS:

The ICP-MS results reveal that the concentrations of metallic elements differ considerably across the various circuits. The most significant finding is the increase in aluminum concentration in the dry cycle to approximately 260 ppb, while iron and copper concentrations in the same section remained very low.

Table 2. Detailed ICP-MS results for demineralized water and dry cooling tower recirculating water

	Fe (ppb)	Al (ppb)	Cu (ppb)	Zn (ppb)	Ca (ppm)	Na (ppm)	K (ppm)	Si (ppm)	Sn (ppb)
Demin	< 10	< 10	< 1	< 1	< 0.01	< 0.01	< 0.01	< 0.01	< 1
Dry Cycle	< 10	260.00	4.30	14.18	0.45	< 0.01	< 0.01	0.16	< 1
	Ag (ppb)	As (ppb)	Ba (ppb)	Be (ppb)	Bi (ppb)	Cd (ppb)	Ce (ppb)	Co (ppb)	Sr (ppb)
Demin	< 1	< 1	3.21	< 0.2	< 1	< 1	< 1	< 1	8.49
Dry Cycle	< 1	< 1	15.75	< 0.2	< 1	< 1	< 1	< 1	18.94
	Cr (ppb)	Cs (ppb)	Dy (ppb)	Eu (ppb)	Gd (ppb)	In (ppb)	La (ppb)	Li (ppb)	Ta (ppb)
Demin	< 1	< 1	0.16	< 0.1	< 0.5	< 0.5	< 1	< 1	< 1
Dry Cycle	< 1	< 1	< 0.1	< 0.1	< 0.5	< 0.5	< 1	< 1	< 1
	Lu (ppb)	Mg (ppm)	Mn (ppm)	Mo (ppb)	Nb (ppb)	Nd (ppb)	Ni (ppb)	P (ppm)	-
Demin	< 0.1	< 0.01	< 0.01	< 1	< 0.1	< 0.5	< 1	0.01	-
Dry Cycle	< 0.1	0.19	0.02	< 1	< 0.1	< 0.5	< 1	0.01	-
	Pb (ppb)	Pr (ppb)	Rb (ppb)	S (ppm)	Sb (ppb)	Sc (ppb)	Se (ppb)	Sm (ppb)	-
Demin	0.01	< 1	< 1	< 0.01	< 1	< 1	< 1	< 0.1	-
Dry Cycle	0.01	< 1	< 1	< 0.01	< 1	< 1	< 1	< 0.1	-

This pattern indicates that, under the operating conditions studied, the primary source of corrosion products is the aluminum equipment of the dry tower, while the steel and copper equipment exhibited acceptable performance. In contrast, the wet tower water displayed higher concentrations of calcium, sodium, potassium, silica, copper, and zinc, reflecting the combined effects of solute concentration, evaporation, and gradual dissolution of certain alloys. This finding is consistent with the studies of Turner et al. (2019), which demonstrated that increases in dissolved elements can serve as a predictive indicator for assessing equipment corrosion status prior to the occurrence of mechanical failures.

Examination of the water chemistry results across the three conditions demineralized water, the dry cycle, and the wet tower indicates that water quality and dissolved element concentrations are strongly influenced by operational conditions and contact with metallic equipment. The demineralized water, which enters the system as the primary feed, exhibits exceptionally high purity, with all heavy metals and major ions either below detection limits or reported at negligible levels. Such a composition is entirely consistent with expectations for deionized water and, by itself, provides neither a basis for corrosion nor any scaling potential. Thus, upon entry into the circuit, the demineralized water constitutes a neutral and ideal baseline.

Analysis of Aluminum Corrosion Behavior in the Dry Tower:

The increase in dissolved aluminum concentration in the dry cycle represents the most significant finding of this study. According to the system data, the heat transfer surfaces of the dry tower are constructed from high-purity aluminum, and the circulating water comes into direct contact with these surfaces. The aluminum concentration of approximately 260 ppb, accompanied by very low levels of iron and copper, indicates that degradation has been largely confined to the aluminum equipment. This behavior may arise from a combination of the following factors:

- ✓ Temperature variations and thermal stresses during the operating cycle.
- ✓ Presence of dissolved oxygen in the closed loop.
- ✓ Water chemistry conditions and localized pH fluctuations.
- ✓ Flow velocity within the aluminum tubes and damage to the protective oxide layer.

Studies by Davis (2018) and Song & Atrens (2020) have likewise demonstrated that the stability of the natural aluminum oxide layer diminishes under such conditions, allowing gradual metal dissolution to commence.

Based on the data obtained in this study, the following mechanism is proposed for aluminum corrosion in the dry tower:

Stage 1: Entry of low-conductivity demineralized water into the circuit.

Stage 2: Contact of water with aluminum surfaces and formation of a thin protective oxide layer.

Stage 3: Development of thermal stresses, temperature fluctuations, and alterations in chemical conditions.

Stage 4: Localized breakdown of the oxide layer and onset of aluminum dissolution.

Stage 5: Increase in dissolved aluminum concentration in the circulating water.

Stage 6: Transport of corrosion products to other sections of the circuit and potential formation of aluminum-based deposits on heat transfer surfaces.

This model, grounded in the field data of the present study and the relevant scientific literature, may be validated in future research through electrochemical testing and surface examination.

Comparison with EPRI Guidelines and International Studies:

Based on the data obtained, the concentrations of iron and copper fall within the acceptable ranges prescribed by EPRI guidelines, whereas the elevated dissolved aluminum level warrants particular attention.

Since EPRI does not provide a fixed numerical limit for aluminum, assessment is conducted on the basis of trend monitoring. Accordingly, a sustained increase in aluminum concentration should be regarded as an operational alert, necessitating corrective actions such as revision of the water chemistry control programmed, continuous aluminum monitoring, and inspection of heat transfer surfaces.

Study	Key Finding	Comparison with the Present Study
Davis (2018)	Aluminum sensitivity to water chemistry conditions	Consistent; dissolved aluminum increase was observed.
Song & Atrens (2020)	Role of oxide layer degradation in corrosion initiation	Consistent with the mechanism proposed in this study.
Turner et al. (2019)	Dissolved metals as corrosion monitoring indicators	The ICP-MS results of this study confirm this approach.
Panagopoulos (2023)	Increased ionic load in wastewater-based systems	Consistent with the behavior observed in the wet tower.
EPRI (2021)	Need for corrosion product monitoring in power plant cycles	The findings of this study affirm the applicability of these guidelines.

Continued Analysis of the Wet Tower:

In the wet tower, the chemical profile of the water undergoes a fundamental transformation. The concentrations of copper (135.9 ppb) and particularly zinc (454.2 ppb) are several times higher than in the dry cycle. At the same time, the aluminum concentration (30 ppb) is considerably lower than in the dry tower, indicating that aluminum corrosion is reduced under these conditions and is of lesser significance compared with the dry circuit. The key feature of the wet tower is the presence of very high concentrations of major ions, including calcium (355.8 ppm), sodium (1,230 ppm), potassium (117.2 ppm), and silica (29.66 ppm). These elevated values are indicative of evaporation and concentration effects, as well as the ingress of dissolved solids from auxiliary water sources into the tower. Such a composition, in addition to exacerbating corrosivity, can lead to extensive scaling of calcium carbonate, silicates, and complex salts, which in turn promotes localized under-deposit corrosion. Overall, the results demonstrate that in the dry cycle, the predominant phenomenon is aluminum corrosion, with dissolved Al concentration serving as the primary chemical indicator. In contrast, the wet tower presents a high-ionic-strength environment with significant corrosion potential for copper and zinc alloys, coupled with a high propensity for scaling and under-deposit corrosion. Demineralized water at the point of entry exhibits no inherent corrosive potential; however, upon entering the circuit and being subjected to operational conditions, it gradually transforms into an aggressive environment for various alloys. This progression clearly illustrates that the differing operating conditions (dry versus wet) and their resultant chemical compositions determine the type and severity of corrosion in each section of the cooling tower system.

Proposed Framework for Condition Monitoring:

Based on the findings of this study, a four-stage framework for corrosion management in power plants equipped with dry towers is proposed:

- ✓ **Continuous water quality monitoring:** Daily measurement of pH, conductivity, TDS, temperature, and dissolved oxygen.
- ✓ **Periodic monitoring of dissolved metals:** Conducting ICP-MS analysis on a monthly basis or in accordance with operational conditions.
- ✓ **Trend analysis:** Focusing on the trend of aluminum concentration changes rather than relying on a single absolute value.
- ✓ **Corrective actions:** In the event of an increasing trend, reviewing water chemistry, inspecting aluminum surfaces, evaluating equipment performance, and adjusting operating conditions.

This framework can serve as a basis for the development of predictive maintenance systems in power plants equipped with hybrid cooling systems.

Uncertainty Analysis:

Although the measurement of metallic elements in this study was performed using ICP-MS, as with any analytical method, the results are subject to various sources of uncertainty. The most significant sources include:

- ✓ Variations in sampling conditions.
- ✓ Potential contamination of sampling containers.
- ✓ Calibration errors of the ICP-MS instrument.
- ✓ Measurement repeatability errors.
- ✓ Temporal changes in water quality between sampling and analysis.

To minimise these errors, the following measures are recommended for future studies:

- ✓ Perform at least three independent replicates for each sample.
- ✓ Employ certified reference materials for quality control.
- ✓ Report the limit of detection (LOD) and limit of quantification (LOQ) for each element.
- ✓ Provide the relative standard deviation (RSD) for each measurement.

Reporting these indicators in accordance with ISO/IEC 17025 and ASTM guidelines will enhance the reliability and traceability of the results.

Corrosion Risk Assessment Matrix:

Based on the results of this study, the equipment status can be assessed semi-quantitatively in terms of corrosion risk.

System Section	Primary Indicator	Risk Level	Recommended Action
Demineralized water	Very low conductivity	Very low	Continue current programmed
Copper condenser	Low Cu	Low	Periodic monitoring
Steel pipelines	Low Fe	Low	Annual inspection
Aluminum dry tower	High Al	High	Monthly ICP-MS monitoring and surface inspection
Wet tower	High Ca, Si, Zn	High	Concentration cycle and scaling control

This information indicates that the aluminum dry tower constitutes the most critical point in the system and should be prioritized in maintenance programmers. The results of this study demonstrate that periodic monitoring of metallic elements can provide a sound basis for the transition from reactive maintenance to predictive maintenance. With at least one year of monitoring data, the development of an intelligent corrosion prediction system becomes feasible. Such a system could employ algorithms such as Random Forest, XGBoost, or LSTM to predict aluminum concentration or the likelihood of corrosion occurrence. In this case, input variables would include pH, conductivity, TDS, temperature, flow rate, dissolved oxygen, and metal concentrations, while the model output could be the probability of exceeding an alert threshold or the predicted value of dissolved aluminum.

Conclusion

In this study, the water chemistry and corrosion behavior of the hybrid cooling system of a sample thermal power plant were evaluated using general water quality parameter measurements and ICP-MS analysis. The results demonstrated that water quality in different sections of the circuit is strongly influenced by the type of cooling system, equipment materials, and operating conditions. Demineralized water enters the circuit with very low electrical conductivity and dissolved ion concentrations; however, after circulation through various sections, significant changes in its chemical composition occur, originating from contact with metallic equipment and operational processes. These findings are consistent with data reported in the literature. One of the most significant outcomes of this study was the observation of elevated dissolved aluminum concentration in the dry cycle, while iron and copper levels remained low. This pattern indicates that, under the operating conditions examined, corrosion occurred primarily in the aluminum equipment of the dry tower, whereas steel and copper components exhibited more favorable conditions. In contrast, the increased concentrations of major ions and certain metals in the wet tower are consistent with evaporation and solute concentration, elevating the potential for scaling and under-deposit corrosion. Comparison with EPRI guidelines revealed that although iron and copper indicators fall within acceptable limits, the rising trend in dissolved aluminum may serve as an early warning indicator for the progressive degradation of aluminum heat transfer surfaces. Accordingly, continuous monitoring of dissolved aluminum should be incorporated as a core component of water chemistry control programmes in power plants equipped with dry towers. From a practical standpoint, this study demonstrates that the combination of periodic general water quality monitoring with ICP-MS analysis constitutes an effective tool for the early detection of corrosion products and the support of predictive maintenance programmers. The principal contributions of this research are as follows:

- ✓ Provision of a field study based on real operational data from a steam power plant equipped with a hybrid cooling system;
- ✓ Identification of dissolved aluminum as the most significant corrosion indicator in the dry circuit;
- ✓ Comparative analysis of the chemical behavior of the dry circuit and the wet tower;
- ✓ Proposal of a conceptual framework for condition monitoring and corrosion management;
- ✓ Elucidation of the application of ICP-MS as a preventive monitoring tool in thermal power plants.

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Authors' Contributions

All authors contributed to data analysis, drafting, and revising of the paper and agreed to be responsible for all the aspects of this work.

References

[1] EPRI. Cycle Chemistry Guidelines for Fossil Plants, 2021.
[2] EPRI. Condenser and Feedwater System Integrity Guidelines, 2015.
[3] Davis J.R. Corrosion of Aluminum and Aluminum Alloys. ASM International, 2018.
[4] Song G., Atrens A. Corrosion Mechanisms of Aluminum Alloys. Progress in Materials Science, 2020.
[5] Yousefpour A, Mehdizadeh M, Ghasemi Nejad H, Esmaeilpour M, Abdi N, Valaee M, Esmaeilzadeh M. Investigating corrosion caused by improper operation in CWT regime of a combined cycle power plant; Causes and solutions.
[6] Ghahraman Afshar M, Esmaeilpour M, Ghasemi Nejad H, Esmaeili N. Detection and Analysis of Microbial Influenced Corrosion in Cooling Tower of Shahid Mofateh Power Plant. Journal of New Materials. 2023 Jan 21;13(50):46-59.
[7] Maul Betsch J., DiFilippo M. Hybrid Cooling Technologies for Power Plants, EPRI Report.
[8] Turner D. et al. Trace Metal Monitoring in Power Plant Water Chemistry. Power Plant Chemistry, 2019.
[9] Panagopoulos A. Wastewater Reuse in Thermal Power Plants. Journal of Cleaner Production, 2023.
[10] IEA. Water and Energy Nexus Report, 2022.