INVESTIGATION OF THE EFFECTS OF FOULING AND PITTING CORROSION ON THE EFFICIENCY OF PLATE HEAT EXCHANGERS

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Abstract

In power plants, heat exchangers remove heat from a hot fluid to a cooler fluid. Due to their outstanding heat transfer capabilities and corrosion resistance, plate heat exchangers (PHE) manufactured of 316L stainless steel is frequently employed. Fouling and pitting corrosion, on the other hand, can seriously harm PHEs, resulting in lower heat transfer effectiveness, shortened lifespans, and even catastrophic failure. This research investigates how well PHEs (Plate Heat Exchangers) can be preserved from fouling and pitting corrosion, with the Olorunsogo power station as a case study. The research involves analyzing PHE plates using Metallography protocols ASTM E-407-9 standards, Chemical analysis of raw water, reverses osmosis water, CT (Cooling Tower) feed, and CT bleed water, and Cleaning and Maintenance for mitigation of fouling and pitting corrosion. The analysis of CT water indicated that the chloride levels in the CT feed (142 ppm) and bleed water (709 ppm) were elevated beyond the limits specified by the gas turbine manufacturers. The high levels of total dissolved solids (TDS) in the raw (2020 ppm) and CT bleed water (3060 ppm), combined with a more notable corrosion potential of the plate sample (47.62 mV) compared to CT feed water (71.43 mV), led to severe fouling and pitting corrosion in the plates and CT piping network. After cleaning and maintenance, the calculated COP of 2.256 confirms that the PHEs are functioning effectively.

Key Words - COP, Chemical Analysis, Fouling, PHE, Pitting corrosion, Metallography protocols

1. Introduction

Plate heat exchangers (PHE) are frequently used in the thermal generating and utilization industries. Plate heat exchangers are classed by [1] based on their design, transfer processes, amount of surface compactness, flow arrangements, number of passes, phase of the process fluids, and heat transfer process. [2], [3] conducted extensive research to improve performance. More than 90% of industrial heat exchangers have fouling issues, despite research on the prevention of pitting and crevice corrosion [4], [5]. The amount of heat that can be transmitted across the heat exchanger surface is seriously affected by the level of fouling.

According to [6], fouling formation also decreases the cross-sectional area of the tubes or flow channels and raises the fluid's resistance as it passes over the surface. In ASTM G46 [7], the effects of pitting corrosion on several metals and alloys, including steel, iron, and aluminium, are described. The impact of fouling on heat transfer over the heat exchanger surface is significant.

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An excellent heat exchanger design is critical to the safety and efficient operation of power generation equipment. To improve the effectiveness of PHEs, it is essential to conduct research that precisely outlines the investigative techniques for identifying fouling and pitting corrosion. As a result, a maintenance schedule for preventative maintenance must be created [8].

The primary objectives of this research are to explore and recommend solutions for the widespread fouling and pitting corrosion that reduce PHE performance and provide maintenance guidance to protect heat exchangers in power plants from these issues. The Olorunsogo generating power plant in Ogun State will be a particular focus of the study as it assesses PHE performance in detecting and avoiding fouling and pitting corrosion. Therefore, it is essential to develop systematic control measures to forestall these problems during operations.

1.1 **Empirical reviews**

Plate heat exchangers, also known as plate-and-frame heat exchangers, are frequently used in power plants, central cooling systems, the chemical sector, and dairy and food processing facilities. [9] assert that their materials' exceptional heat transfer capabilities enable a highly compact design and simple disassembly for cleaning, maintenance, or altering the heat transfer area by adding or deleting plates. Channels are created when the plate pack is crushed and mounted on a frame. These channels are sealed with the surrounding gasket on each plate. The opposite-flowing motion of the hot and cold fluids causes heat transfer across adjacent channels.

According to [10],[11] PHE plates are made from different materials, including 316L stainless steel (SS), which offers exceptional cooling water corrosion resistance. However, a plate heat exchanger's overall corrosion stability is determined by the properties of typical cooling water, including the concentration of chloride ions, temperature, pH, conductivity, hardness, and alkalinity. Internal leakage has recently posed a danger to the effectiveness and safety of some PHEs utilized in China's heating power plants. Studies by [12-15] suggest that local plate corrosion, including local cracking and perforation, may be more responsible for internal PHE leakage than previously thought.

Many heat exchanger types convey 90% of the thermal energy used in energy production and management. Heat exchangers are common industrial equipment used in industries, including power plants, and the chemical, petroleum, food, aerospace, and nuclear sectors. [16], asserts that the shell-tube heat exchanger is most frequently employed. [17], provides illustrations of the typical heat exchangers used as condensers and evaporators in air conditioners, refrigerators, oil coolers, and car radiators. Concentric tube (or pipe) heat exchangers contain ducts for the entrance and departure of the two fluids, and one pipe is put inside the other. They are arranged either in counterflow or parallel flow, where the heated fluid travels through the annular space between the outer and inner tubes in the same direction as the cold fluid in the inner tube is filled with air (in which the two fluids flow in parallel but opposite directions [18]. They produce a thermal driving force by parallel-circulating fluid streams at varying temperatures.

This results in forced convection, which transfers heat from or to the product at relatively low flow rates and high temperatures or pressures. [19] Model a concentric tube heat exchanger device to teach students about heat exchangers that use the counter-flow direction to raise the temperature of the cold fluid and lower the hot fluid temperature. The system has two pipes, an electric motor, thermocouples, and valves. [20] Developed a model to conduct a numerical analysis to analyze the pressure drop and heat transfer coefficient in an unbaffled shell-and-tube heat exchanger. The heat exchanger's shell, which had a 108 mm diameter and a 5.85 m length, had 19 tubes. The flow and temperature fields inside the shell and tubes were clarified using computational fluid dynamics.

[21], presented research on the multi-objective optimization of the heat transfer area and pumping power of a shell-and-tube heat exchanger to provide designers with different Pareto-optimal solutions that capture the trade-off between the two objectives of optimizing heat exchanger performance. The conclusion was made after nine different parameters were considered, including the tube layout pattern, the number of tube passes, the baffle spacing and cut, the tube-to-baffle and shell-to-baffle diametrical clearances, the tube length, the tube outer diameter, the tube wall thickness.

A quick and exclusive non-dominated sorting genetic algorithm from the MATLAB multi-objective genetic algorithm module was utilized for the optimization. Two case studies from the open literature were used in the research [22] to confirm the improvements in design that the method produces. The results of the case studies demonstrate better values of the two objective functions were obtained than those obtained using the existing approaches such as Pareto-optimal solutions that show costs for optimal design were also found to be lower for both case studies than those described in the literature [23].

[24] Analyzed heat exchanger configurations using TEMA standards, considering initial and operational costs. Results showed a new design technique significantly lowers overall cost compared to original designs, conventional genetic algorithm designs, and previous approaches. The study used a genetic algorithm to minimize the objective function of the new design.

[25] Carried out research on shell and tube exchanger design optimization using teaching learning-based optimization (TLBO) algorithms to minimize annual costs. Two case studies were used to demonstrate the effectiveness of the recommended approach. Results showed that increasing the number of tubes reduced side flow velocity and heat transfer coefficient. Reducing shell diameter reduced capital investment, increased flow velocity, and enhanced heat transfer coefficient.

Around 0.25 percent of the GDP of industrialized nations is estimated to be needed to mitigate fouling heat exchangers [26], [27]. More than 90% of industrial heat exchangers have fouling issues. The environmental impact of heat transfer fouling has also been influenced by the disposal of cleaning agents [28] Therefore, it's crucial to identify the contributing component to fouling and create new tools or techniques to reduce it throughout the processing of maize.

2. Methods and Experimental Design (ASTM G46-49)

The four experimental design processes that make up the approach used in this study are as follows:

a. Macroscopic morphology analysis of failed heat exchanger plates;
b. Chemical analysis of raw water, reverse osmosis (R/O) water, CT feed, and CT bleed water;
c. Heat exchangers Cleaning and Maintenance for mitigation of fouling and pitting corrosion; and
d. Evaluation of (COP) Coefficient of Performance of PHEs.

2.1 Macroscopic Morphology Analysis

These procedures were carried out to determine the microstructure of metallic materials for the analysis of their properties and processing history [28]. The samples were extracted from the undamaged and corroded areas for a microstructural examination.

The specimens were cold-mounted to the ground according to ASTM E-407-9 Metallography protocols. Afterwards, they were polished and subjected to electrolytic etching using 10% oxalic acid, which complies with ASTM E-407-9 standards. The ASTM E-407 standard practice provides instructions for several metallographic sample preparation procedures, including cutting, mounting, grinding, polishing, and electrolytic etching of metallic materials.

The metallic materials were prepared for electrolytic etching, and the specimen's surface was cleaned of any grease, dirt, or oxide films [29]. The specimen was connected as the anode, and a platinum cathode was connected to a low-voltage direct current (DC) power supply. Thereafter, the specimen was immersed in a 10% oxalic acid electrolyte solution, which is suitable for most metallic materials. A current density of 0.2 to 2.0 A/cm2 was applied to the surface area of the specimen for a duration of 5 to 60 seconds. The specimen was then thoroughly rinsed with distilled water and dried with hot air. Finally, the specimen was observed under a microscope, with the etched structure revealed by the electrolytic attack presented in Figure 1.

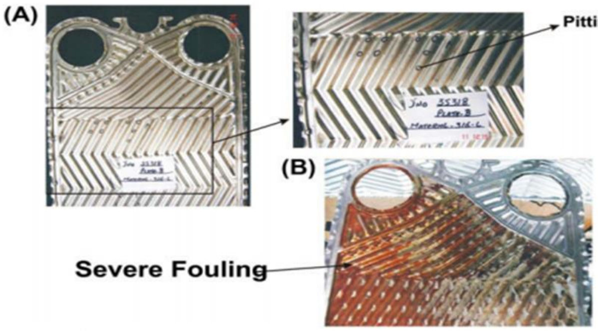

Figure 1. Failed plates (A) severely pitted plate (B) fouling at the plate.

2.2 Chemical analysis of raw water, reverse osmosis (R/O) water, Cooling Tower (CT) feed and CT bleed water

A standard chemical analysis [30] entails adding sulfuric acid in a concentration of 10-15 and at a dose of (kg/CT/24 h to the CT water to prevent excessive scaling, corrosion, and algae formation. The Boven et al, 2007 method was used. Sulfuric acid (H_2SO_4) was utilized to regulate the pH of the cooling tower water (CT water). The dose levels indicated by the Local Supplier "A" (LS-A) for operating parameters and water quality will then be adjusted as shown in Table 1. According to the operating procedure documents, the CT water was required to have a low concentration of chlorides, hypo-chlorides, and dissolved solids, specifically ranging between 0.0 - 0.001 ppm.

Table 1. Cooling tower (CT) water additions.

Additives	Quantity
A.C 220	0.450 kg/CT/24 h
A.C 204	0.200 kg/CT/24 h
A.C 460	2.0 kg/CT/168 h
Sodium hypo-chlorite	0.5 kg/CT/48 h
Sulfuric acid	10–15 kg/24 h

After 2000 hours of operation of the power engines, scheduled maintenance was carried out, and severe pitting and fouling were discovered in the open-circuit system towards the CT water side, as shown in Figure 1. In addition, the pipeline of the CT system showed severe pitting and blistering. However, no pitting or sludge deposition was observed on the closed-circuit side. Metallurgical and electrochemical analyses were conducted on the perforated plates that were damaged due to pitting corrosion. The composition of raw, R/O, CT feed and bleed water was carefully monitored, and the chloride levels in these water samples were measured in the laboratory using the data in Table 2.

Table 2. LS-B Cooling Tower (CT) specifications

CT parameters	**Values**
System volume	5 m^3
Recirculation rate	120 m^3/h
Temperature drop	6 ^{0}C
Water quality	Reverse osmosis (R/O)
Evaporation	0.457 to 0.015 m^3/h
Bleed off	0.015 m^3/h
Bleed off	0.472 m^3/h

2.3 Heat exchangers cleaning and maintenance for mitigation of fouling and pitting corrosion

Proper cleaning and maintenance are crucial for ensuring the efficient operation of heat exchangers [31]. Regular maintenance not only helps keep the heat exchanger functioning well, but also improves its overall performance, reduces the need for emergency repairs, and facilitates easy opening and closing. Although there is a cost associated with cleaning heat exchangers, it is significantly less than the cost of production loss resulting from an unscheduled shutdown of the system.

2.3.1 Cleaning Procedures

It is important to keep the plates free of fouling, which can lower heat transfer efficiency and result in erroneous temperatures, in order to guarantee a heat exchanger works effectively. The surfaces that transfer heat must be kept clean to ensure effective performance. Cleaning agents compatible with the composition of the gasket and plate metal are used to remove silicates, calcium sulfate, or carbonate from the plate surfaces to clean up incrustation or scaling. By using the proper cleaning techniques, sediments that can also build up on heat transfer surfaces—such as metal oxides, silt, alumina, and diatomic organisms—were eliminated. Adopting the right cleaning techniques helps to get rid of bacteria, nematodes, and protozoa that can cause biological fouling.

Plate heat exchangers are cleaned without disassembly. Cleaning-in-Place (CIP) equipment is used. CIP involves a combination of time, temperature, and concentration to provide both chemical and mechanical cleaning to the heat exchanger. The process typically involves cleaning lime deposits, passivating surfaces to reduce susceptibility to corrosion, and neutralizing cleaning chemicals before draining. In CIP, chemical cleaning involves four steps: an alkaline clean to remove organic buildup, rinsing with a high-flow water flusher to remove loose debris and remaining residue from the alkaline step, acid cleaning to dissolve and soften fouling materials more deeply, and a final rinse. Personal protective equipment (PPE) such as safety boots, safety gloves, and eye protection are used in all cleaning processes to prevent injury.

Regular maintenance is necessary to keep the heat exchanger in good condition. This includes cleaning the plates and replacing gaskets as needed to prevent leaks. The maintenance also involves pressure testing, specifically a hydrostatic leakage test, to ensure that the heat exchanger is properly sealed internally and externally. The test is conducted one media side at a time while the other side is open to ambient pressure. The heat exchanger was closed after maintenance to ensure the dimensions of the plate pack complied with the manufacturer's specified tolerance for optimal functioning. Over-tightening can cause plate damage, while under-tightening can result in plate leakage. The four bolts, numbered 1 to 4, were tightened evenly until the correct dimension is reached. To lubricate the threads of the tightening bolts, EP Gleitmo 800 grease or an equivalent was used, and the suspension wheels on the pressure plate and the connection plates were greased.

2.4 Evaluation of Plate heat exchanger Coefficient of Performance (COP)

Thermodynamically,

$$COP = \frac{Q_H}{W_{net,in}} \qquad (1)$$

where, Q_h is the heat supplied to the hot reservoir and $W_{net,in}$ is the work input, and Q_c is the heat supplied to the cold reservoir.

$$\therefore \quad COP = \frac{Q_c}{|Q_h - Q_c|} \qquad (2)$$

Heat Rejected by Hot fluid,

$$Q_h = \acute{m}_c . C_{ph} \; (t_{hot,in} - t_{hot,out}) \qquad (3)$$

Heat Absorbed Cold fluid,

$$Q_c = \acute{m}_c . C_{pc} \; (t_{cold,out} - t_{cold,in}) \qquad (4)$$

Where C_{ph} and C_{pc} are the respective specific heats of hot and cold fluids,

Hot fluid, $Q_h = \frac{1\times10^3\times1.8723\times(107.62-61.01)}{3600} = 24.24$

as C_p steam =1.8723 kJ/kgK

Cold Fluid, $Q_c = \frac{1\times10^3\times4.187\times(47.88-33.31)}{3600} = 16.92kW$

as C_p water = 4.187 kJ/kgK

Applying equation (2), $COP = \frac{Q_c}{|Q_h - Q_c|}$

$$\text{COP} = \frac{16.92}{24.24-16.92} = 2.256$$

3. Results and Discussion

3.1 Results

The investigation into PHEs collected on a daily basis from 2017 to 2021 and provided yearly average figures for nine combined cycle gas turbine units. The data collected comprised operational factors, cooling water quality, control chemicals, and temperature and pressure readings for the plate heat exchanger. The results of the investigation are presented in Tables 3, which were utilized to calculate the overall mean values to determine the coefficient of performance (COP) of plate heat exchangers.

Table 3. Annual Mean Values of Plate Heat Exchanger Units Properties

Yearly Average of Units	Steam Water Properties			Cooling Water Properties		
	$P_{V,in}$ $[MPa]$	$t_{V,in}$ [°C]	$t_{c,out}$ [°C]	$P_{w,in}$ $[MPa]$	$t_{w,in}$ [°C]	$t_{w,out}$ [°C]
1	0.53	100.0	57.1	0.43	31.7	48.0
2	0.54	102.3	58.4	0.44	32.5	47.6
3	0.55	103.8	63.2	0.40	33.7	48.8
4	0.54	104.1	64.3	0.39	33.7	48.9
5	0.57	105.6	57.1	0.41	32.3	48.3
6	0.58	112.2	60.1	0.39	32.9	47.7
7	0.61	115.4	59.4	0.38	33.1	47.2
8	0.56	116.7	60.4	0.42	34.3	46.1
9	0.51	108.5	69.1	0.46	35.6	48.3

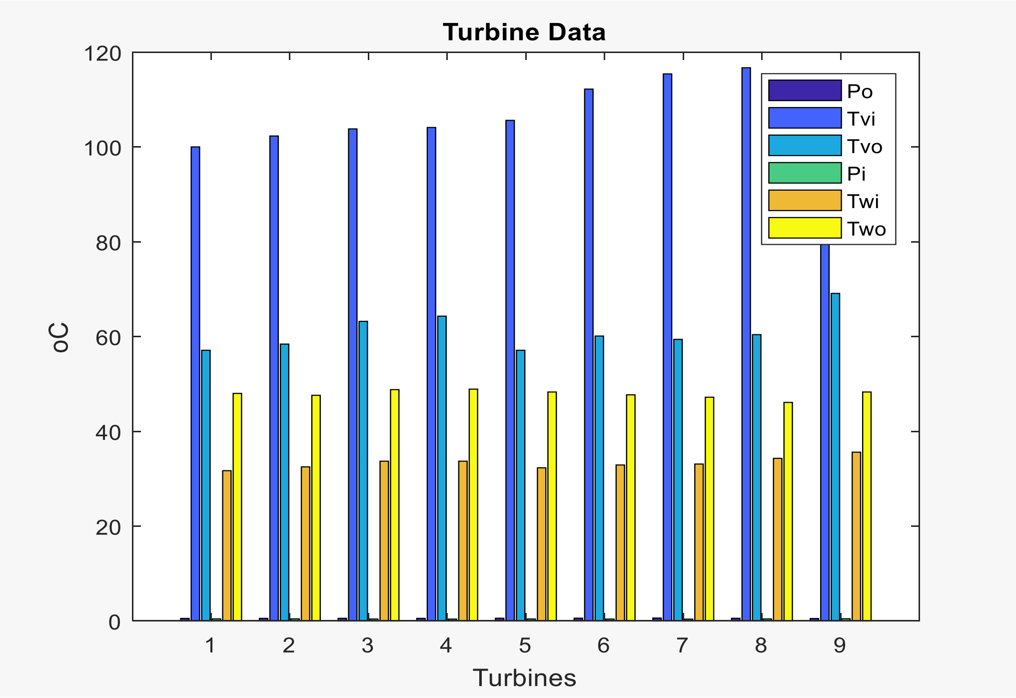

Figure 2. Turbine Data of Inlet and Outlet Temperatures and Pressures

Table 4. Chemical analysis of raw, reverse osmosis (R/O), CT feed and CT bleed water

Parameters	**Raw water**	**R/O water**	**CT feed water**	**CT bleed water**
pH	7.40	6.23	6.97	7.05
TDS (ppm)	2020	54.9	503	3060
Ca hardness (ppm)	105.7	3.48	29.05	168.5
Mg hardness (ppm)	62.94	0.61	9.11	80.91
Total hardness (ppm)	522.5	11.0	110.0	753.5
Chloride (ppm)	496.0	14.2	142.0	709.0
Ferrous (ppm)	0.60	0.365	0.04	0.248
Lead	Traces	Traces	Traces	Traces

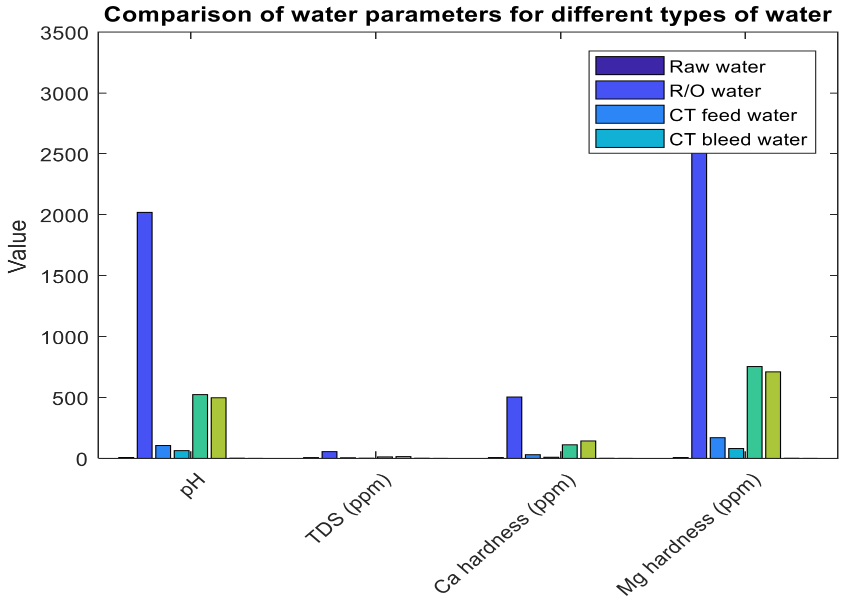

Figure 3. Comparison of Chemical analysis parameters for different type of water.

3.2 Discussion

Plate heat exchangers formed part of a power generation system, and failed due to pitting and perforation. The heat exchanger was designed to transfer heat from the close-circuit jacket and primary cooling system auxiliary water by cooling it with open-circuit cooling tower (CT) water (secondary cooling system) to decrease the temperature by 20°C. In the open-circuit side of the CT system, almost 32 plates were perforated by the secondary cooling water. In the jacket water side of the heat exchanger, the plates were arranged in pairs, with one pair dedicated to jacket water and the other pair to CT water, resulting in 24 plates being tightened in a bundle. The internal lube oil and cylinder head jackets of the power engine were cooled by the auxiliary water and jacket water heat exchanger in a closed circuit, respectively.

Figure 3 shows the analysis of CT (Cooling Tower) water, which indicated that the chloride levels in both the CT feed (142 ppm) and bleed water (709 ppm) were elevated beyond the limits advised by power engine suppliers and manufacturers. The high levels of total dissolved solids (TDS) in the raw (2020 ppm) and CT bleed water (3060 ppm), combined with a more notable corrosion potential of the plate sample (47.62 mV) compared to CT feed water (71.43 mV), led to severe fouling and pitting corrosion in the plates and CT piping network.

In addition, the plate sample had higher resistance to pitting in CT feed water (769.82 mV) compared to bleed water (414.56 mV) due to the higher concentration of chloride in the latter. The stainless steel samples in auxiliary and jacket water displayed negative hysteresis during cyclic polarization, indicating greater resistance to pitting. The electrochemical scratch test confirmed the lower passivation potential in bleed water, as the passivation current density in CT feed and bleed water was 3.13 $\mu A/\ cm^2$ and 0.28 mA/cm^2, respectively.

The COP (Coefficient of Performance) is a metric used to evaluate the energy ratio or thermal efficiency of PHEs, and it also indicates the operating conditions of the system. After cleaning and maintenance, the calculated COP of 2.256 confirms that the PHEs are functioning effectively.

4. Conclusion

The internal leakage of 316L plates in a plate heat exchanger working in a cogeneration power plant was the focus of thorough failure investigations. The internal leakage was caused by perforations in zigzag peak connections in the low-temperature hot water side of the plates, which was established based on test results. When perforations form, fretting, crevice corrosion, and pitting all work in concert. Additionally, plate heat exchanger design flaws play a significant role in the favourable position of perforations, and the high Cl content in low-temperature hot water is the principal cause of such severe perforations in ASS 316L plates. This research effort concludes by outlining crucial procedures for diagnosing the causes and effects of fouling and pitting corrosion, as well as for preventing and protecting plate heat exchangers damaged by fouling and pitting corrosion for improved performance.

Acknowledgment

We sincerely appreciate the Olorunsogo Power Station Sagamu, Ogun State, Nigeria authorities for their technical assistance.

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