Dynamic Operation of Ultrafiltration Membranes for Potable Water Production

Christopher C. Boyd and Steven J. Duranceau

In March 2010, the University of Central Florida (UCF) began a two-year ultrafiltration (UF) pilot test at the Lake Manatee Water Treatment Plant (WTP) in Manatee County. In September of that same year, a second UF pilot study commenced at the Mission San Jose WTP in Fremont, Calif. The Lake Manatee and Mission San Jose WTPs were identified as excellent pilot test locations, because the facilities treated two distinctly different surface water sources. The Lake Manatee WTP treats water from the Lake Manatee Reservoir with alum coagulation, flocculation, sedimentation, and periodic powdered activated carbon (PAC) dosing for seasonal taste and odor events. In contrast, the Mission San Jose WTP practices ferric chloride coagulation with upflow solids contact clarifiers to treat water from the Sacramento delta.

Fouling management is a critical component of UF operation for surface water treatment, and coagulation, along with other processes such as preoxidation and adsorption, are useful pretreatment options for UF membranes (Howe & Clark, 2006; Huang et al., 2009; Campinas & Rosa, 2010; Gao et al., 2011). While pretreatment improves feed water quality to UF processes, the selection of process parameters is also important for fouling management. A strong correlation exists between flux and membrane fouling (Field et al., 1995; Howell, 1995; Wu et al., 1999; Bacchin et al., 2006), and the selection of items such as the backwash frequency and duration are also significant (Kim & DiGiano, 2006; Smith et al., 2006). Regardless of the pretreatment and operating strategies, fouling inevitably develops at the membrane surface. Accordingly, it is important to identify viable cleaning chemicals and chemical maintenance protocols for the water being treated (Yuan & Zydney, 2000; Katsoufidou et al., 2008; Strugholtz et al., 2005; Zondervan & Roffel, 2007; Porcelli & Judd, 2010; Liu et al., 2006).

Surface water variability (Ouyang et al., 2006; Boyd & Duranceau, 2012) and the dynamic operation of pretreatment processes result in a continuously changing feed water quality to UF membranes. Accordingly, performance improvements may be made possible by varying UF operating protocols in response to changing inputs. This article presents the results of a study designed to assess the impact of dynamic UF process operation on membrane fouling and productivity. Tools for analyzing process data during dynamic operation are presented, along with additional recommendations for implementing dynamic operating protocols.

Description of Ultrafiltration Pilot Units

The Lake Manatee and Mission San Jose UF pilots were each equipped with a single Durasep UPF0860 (Toyobo CO. Inc) hollow-fiber UF membrane operated in an inside-out direct filtration mode. Durasep UPF0860 membrane fibers are manufactured from hydrophilic polyethersulfone (PES) blended with polyvinylpyrrolidone and provide 150,000 dalton cutoff and 430 ft^2 of surface area. The pilot units operated at a constant flux and recorded process data at regular intervals using onboard pressure sensors, feed and filtrate turbidity meters, and flow meters. Filtrate was collected in storage tanks for use during backwashes and chemically enhanced backwashes (CEBs). A programmable logic controller (PLC) was employed to automate the pilot units and two onboard chemical injection systems enabled routine CEBs.

Process Data Analysis

Process Performance Assessment

In this article, the filtration, backwash, and CEB functions of an ultrafiltration process are termed "process events." These process events are further organized into sequences and cycles, where a sequence consists of a consecutive filtration and backwash event, and a cycle contains a number of sequences culminating in a CEB. Collectively, successive sequences and cycles determine the performance of UF processes by influencing membrane fouling. UF process performance may be assessed by temperature correcting the transmembrane pressure, or TMP (U.S. Environmental Protection Agency, 2005). The temperature-corrected TMP (TCTMP) adjusts for the effects of water temperature on operating pressure. Membrane-specific temperature correction factors (TCFs) may also be used (Duranceau & Taylor, 2011).

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(Equation 1)

$$TCTMP_{20°C} = TMP_T(TCF) = TMP_T\,(\mu_{20°C} \div \mu_T)$$

Where,

- $TCTMP_{20°C}$ is the TMP temperature corrected to 20 °C
- TMP_T is the TMP recorded at temperature T
- $\mu_{20°C}$ is the absolute viscosity at 20°C
- μ_T is the absolute viscosity at temperature T

The operating TCTMP is dynamic with respect to time and influenced by both mass removal during filtration and the development of "irreversible" fouling. Here, irreversible fouling is defined as fouling that is unresolved by physical or chemical maintenance and is characterized using postbackwash and post-CEB TCTMP values. Accordingly, the post-backwash TCTMP reports the operating pressure after a backwash and incorporates membrane fouling that was not resolved by physical separation. Likewise, the post-CEB TCTMP reports the operating pressure after a CEB and incorporates chemically unresolved fouling development. Postbackwash and post-CEB TCTMP values may be used to determine items such as the frequency of maintenance events and the need for more intensive chemical clean-in-place (CIP) procedures.

Implementation of Data Analysis to Assess Performance Changes

An investigation of the impact of different pretreatment options on UF membrane fouling was conducted at the Mission San Jose WTP. Process parameters were held constant during the study to isolate the impact of pre-

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treated feed water on membrane performance, and the pretreatment performance summary is presented in Figure 1. (Note that the post-backwash TCTMP values reported in the figure represent the last backwash in each cycle). Prior to the pretreatment change, the operating, postbackwash, and post-CEB TCTMP data were in close proximity. These results indicate minimal mass loading during filtration and negligible physically and chemically unresolved fouling development. In contrast, the second pretreatment option enhanced membrane fouling. Variations in the operating TCTMP suggest increased mass loading during filtration, and the elevated post-CEB TCTMP values indicate an increased chemically unresolved fouling tendency. Accordingly, the second pretreatment option increases process operating costs and necessitates a new chemical maintenance protocol.

Process Productivity Benchmarking: Process Recovery, Process Utilization, and Filtrate Encumbrance

In direct filtration, the process recovery quantifies the volume of usable filtrate that is not consumed during maintenance events (i.e., backwashes and CEBs). Process recovery values typically range between 95 and 98 percent in drinking water applications (MWH, 2005) and may be calculated using Equation 2. While the process recovery quantifies the fraction of feed water available for downstream processes or distribution, it does not account for the lost production time associated with operating functions such as maintenance events, valve actuations, and integrity tests. A new process utilization term is presented as Equation 3 that benchmarks UF productivity in terms of the theoretic maximum filtrate volume ($V_{Fil,Max}$). Since the calculation of $V_{Fil,Max}$ assumes continuous filtrate production at a constant flux over the duration of operation, any operating function that consumes filtrate or reduces available filtration time encumbers a fraction of the $V_{Fil,Max}$ and reduces the process utilization. Thus, the process utilization represents the extent to which the UF process approaches ideal performance.

(Equation 2)
Percent Process Recovery
$= [(V_{Fil} - V_{BW} - V_{CEB}) \div V_{Feed}](100)$

(Equation 3)
Percent Process Utilization
$= [(V_{Fil} - V_{BW} - V_{CEB}) \div V_{Fil,Max}](100)$

Where,
- V_{Fil} is the volume of filtrate produced
- V_{BW} is the volume filtrate consumed during backwashes
- V_{CEB} is the volume of filtrate consumed during CEBs
- V_{Feed} is the volume of feed water
- $V_{Fil,Max}$ is the theoretical maximum filtrate production

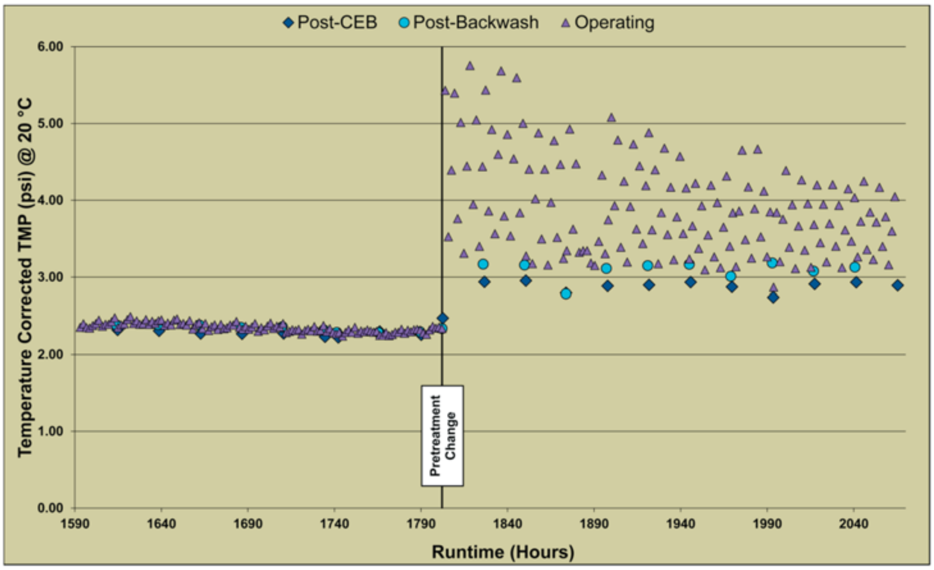

Figure 1. Mission San Jose Ultrafiltration Pilot: Process Assessment

Table 1. Test Plan

Configuration Number	1a,b	2	3	4	5	6
Filtration Duration (min)	45	45	45	**50**	**60**	**75**
Filtration Flux (L/m^2-hr)	82.9	82.9	82.9	82.9	82.9	82.9
Backwash Duration (sec)	60	**40**	40	40	40	40
# Sequences / Cycle	31	31	**62**	62	62	62
Total Filtrate (gal/wk)	13959	140588	142005	142508	143270	144036
Backwash Water (gal/wk)	9349	6262	6350	5733	4792	3851
CEB Water (gal/wk)	1858	1858	929	929	619	619
Net Filtrate (gal/wk)	12838	132468	134726	135846	137858	139566
UF Process Recovery (percent)	**92.0**	**94.2**	**94.9**	**95.3**	**96.2**	**96.9**
UF Process Utilization (percent)	**87.2**	**90.0**	**91.5**	**92.3**	**93.7**	**94.8**

Dynamic Operation

Systematic Approach to Dynamic Operation

A pilot-scale test of dynamic process operation was conducted at the Lake Manatee WTP. The primary test goal was to increase productivity while maintaining sustainable process performance. To accomplish this goal, a systematic approach was taken to incrementally increase process recovery and utilization by varying a single operating parameter at a time and monitoring performance. Table 1 presents a summary of the different operating configurations evaluated during testing, with parameters in bold indicating a change from the previous parameter value. As shown in the table, the initial operating configuration (Configuration 1) had process recovery and utilization values of 92.0 percent and 87.2 percent, respectively. Increases in the recovery and utilization were achieved by altering the backwash duration, CEB frequency, and filtration duration within the acceptable range of values recommended by the membrane manufacturer. These parameters were selected based on an evaluation of filtrate encumbrance and a desire to decrease chemical use.

Figure 2 presents the results of the initial filtrate encumbrance evaluation for the UF pilot. Routine backwash events encumbered 9.51 percent of the $V_{Fil,Max}$ (inclusive of valve actuation), whereas CEBs encumbered a total of 3.03 percent. Accordingly, it was determined that the most significant filtrate production improvements could be achieved by altering the backwash protocol (Configuration 2). A decrease in the CEB frequency in Configuration 3 yielded an additional productivity improvement while halving chemical consumption, and the final three configurations increased process recovery and utilization by incrementally extending the filtration duration from 45 to 75 min.

Assessing Performance During Dynamic Operation

Figure 3 presents the postbackwash and post-CEB TCTMP data for the six operating configurations. Configuration 1 has been subdivided into two parts to reflect differences in the CEB chemical protocols. The initial CEB protocol called for consecutive citric acid and sodium hypochlorite CEBs; however, an injection issue limited the pilot to sodium hypochlorite CEBs only. The CEB system was repaired for Configuration 1b, and sodium hydroxide was added to the sodium hypochlorite solution to elevate the pH above 10. The new CEB protocol successfully reduced the chemically unresolved fouling developed during Configuration 1a and maintained stable post-CEB TCTMP values.

Table 2 presents a summary of the average post-CEB TCTMP data for the six operating configurations. Post-CEB TCTMP values generally increased marginally with increasing process recovery and utilization. However, a two-week pilot shutdown prior to the start of Configuration 5 resulted in a slight reduction in chemically unresolved fouling relative to Configuration 4. The 75-min filtration time in Configuration 6 yielded the highest average post-CEB TCTMP, and the plot of post-CEB TCTMP versus runtime in Figure 3 indicates an upward trend in chemically unresolved fouling development.

The TMP required to maintain constant flux production influences UF process operating costs. Figure 4 provides a percentage-based distribution of the TCTMP values recorded during each configuration. The poor CEB performance of Configuration 1a is reflected in the elevated operating pressures observed at

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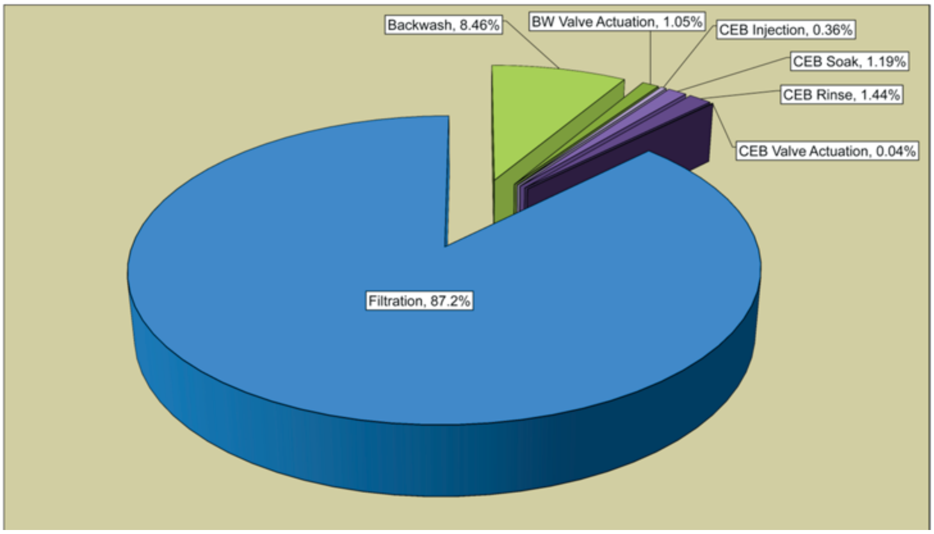

Figure 2. Filtrate Encumbrance for Configuration 1

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the start of testing. In Configuration 2, decreasing the backwash duration by 20 seconds did not significantly affect operating pressures; however, the subsequent reduction in CEB frequency (Configuration 3) resulted in a greater percentage of TCTMP values between the range of 2.17 to 2.67 pounds per sq in. (psi). Configuration 6 yielded the highest operating pressures as a result of chemically unresolved fouling development and greater mass accumulation during the extended filtration time.

Recommended Operating Configuration

The criteria for selecting an operating configuration were ranked in the following order of importance: (1) demonstration of sustainable performance, and (2) process recovery and utilization values greater than 95 percent and 92 percent, respectively. These goals were intended to allow for an acceptable level of filtrate production, while assessing the feasibility of minimizing chemical use and CIP frequency. The pilot test results show that operating Configurations 4–6 achieved the process recovery and utilization targets. However, Configuration 6 yielded the highest average post-CEB TCTMP values and operating pressures. The consecutive upward trend in post-CEB TCTMP values for Configuration 6 may also have indicated the start of a chemically unresolved fouling trend. Based on these results, Configuration 5 was identified as the most sustainable and productive option.

Figure 5 presents the filtrate encumbrance for Configuration 5. The changes to the backwash duration, CEB frequency, and filtration duration decreased the filtrate encumbrance of the backwash from 9.51 to 5.14 percent. Total CEB encumbrance also improved with a decrease from 3.3 to 1.01 percent of the $V_{Fil,Max}$. These productivity improvements are reflected in the volume of filtrate produced per UF module, as shown in Figure 6. Under operating Configuration 5, net filtrate production was increased by 9,472 gal/week to 137,858 gal/week. Operating Configuration 6 would have yielded an additional 1,707 gal/week per module relative to Configuration 5, but may also have increased CIP frequency.

Table 2. Lake Manatee Ultrafiltration Pilot
Chemically Enhanced Backwash Assessment

Configuration Number	1a	1b	2	3	4	5	6
Ave. Post-CEB TCTMP (psi)	1.90 ± 0.14	1.67 ± 0.05	1.76 ± 0.05	1.87 ± 0.03	1.86 ± 0.04	1.78 ± 0.03	1.95 ± 0.04

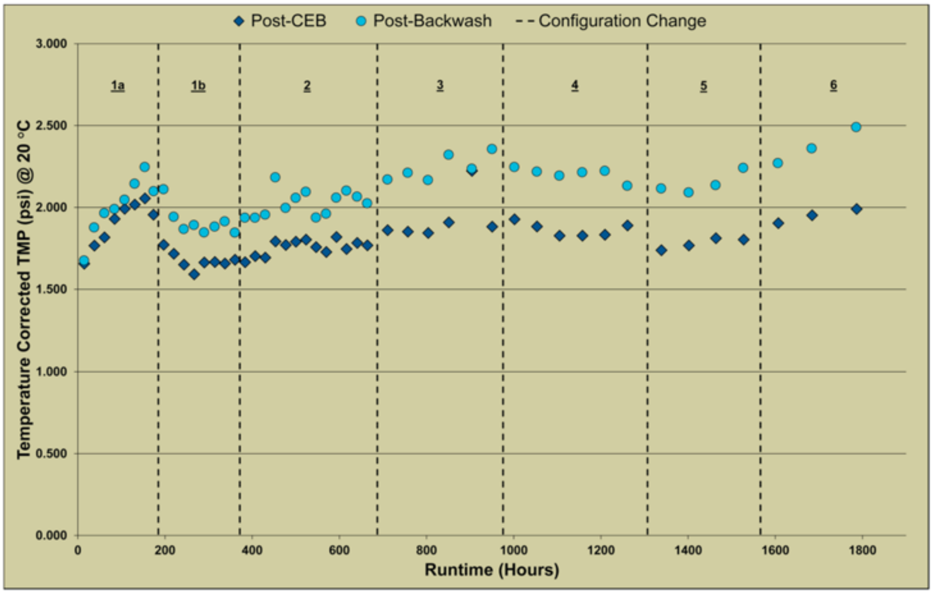

Figure 3. Lake Manatee Ultrafiltration Pilot: Process Assessment

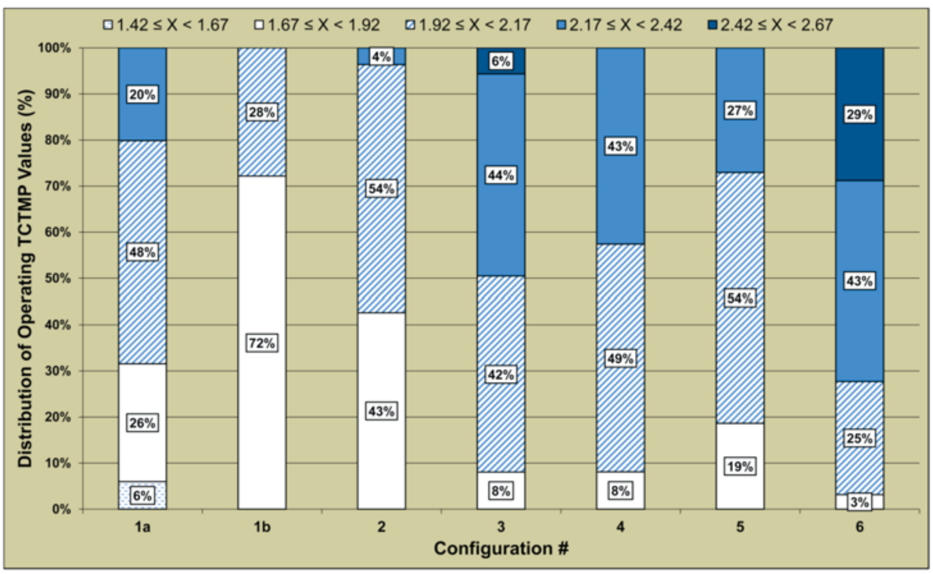

Figure 4. Lake Manatee Ultrafiltration Pilot: Operating TCTMP Distribution

Conclusions and Recommendations

The dynamic operation of a surface water UF pilot successfully increased membrane productivity, while maintaining sustainable fouling management. A systematic test plan was developed using the concept of filtrate encumbrance, and membrane performance was evaluated using operating, postbackwash, and post-CEB TCTMP values. Using these techniques, process recovery and utilization values of 96.2 percent and 93.7 percent were achieved. A site-specific cost-benefit analysis is recommended to enhance decision making relative to dynamic process operation. This economic analysis component should focus on identifying the tradeoffs between operating costs and filtrate production at increasing process utilization values.

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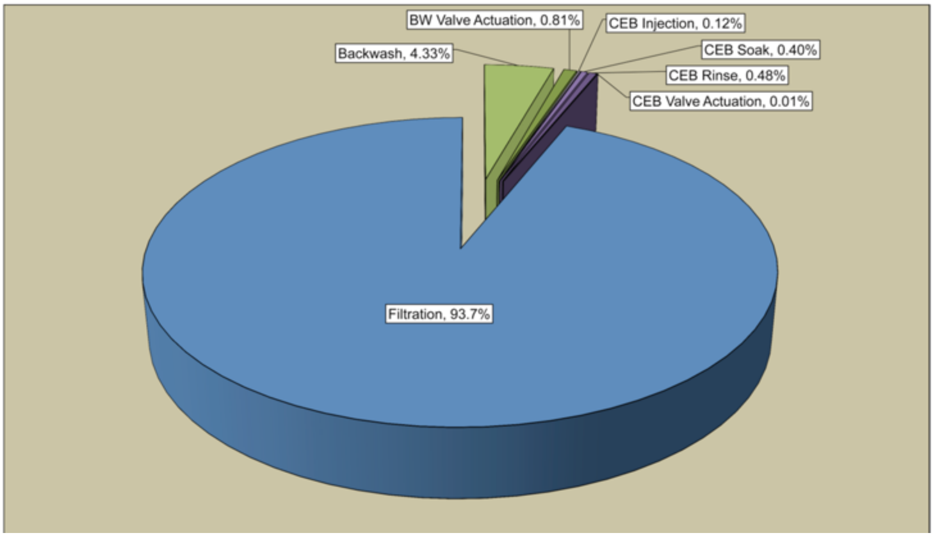

Figure 5. Filtrate Encumbrance for Configuration 5

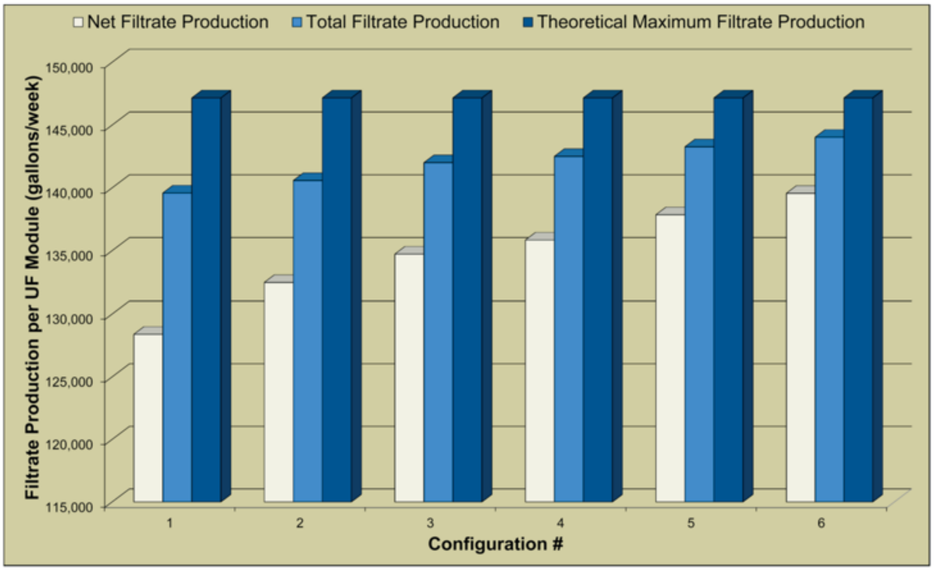

Figure 6. Comparison of Net, Total, and Maximum Filtrate Production

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