The Application of Simulation and Diagnostic Systems to Water Treatment in Power Plants and Industrial Steam Cycles

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ABSTRACT: The use of computers to aid in data collection and troubleshooting in power plants and other industrial processes has been practiced for many years. More recently, the use of sophisticated simulation tools and expert systems have been developed and applied successfully to aid in the optimization of water chemistry programs and overall plant operation. In this paper, the use of these tools to provide real-time decision support, provide early warning of abnormal conditions, and to improve overall plant communications and awareness is described.

INTRODUCTION

Water chemistry strongly influences corrosion and other materials degradation mechanisms in steam power plants. Chemistry-related problems can cause component failures, decrease energy conversion efficiency, and are a leading cause of unplanned outages in steam plants. Understanding and managing water chemistry are thus critical to maximizing the availability, profitability, and safe operation of steam plants. For aging units, proper water chemistry control may represent the key to continued economic operation. In recent years, advanced simulation tools and diagnostic systems have been used to improve chemistry control in power plants and industrial steam boilers. This paper reviews the underlying technology in use and presents several case studies where this technology has been used for early detection of problems, interpretation of chemistry data, and optimization and control of chemical treatment.

THEORY

The fundamental basis for any simulation or diagnostic technology is a detailed model that describes the chemical behavior of additives and impurities throughout the steam cycle. Ideally, the model will be based on relevant thermodynamic and transport processes in the steam cycle. A thermodynamic model must consider dissociation, vapor/liquid and liquid/solid equilibrium in a multi-component aqueous solution. The thermodynamic model must then be coupled with appropriate heat and material balances to describe both the local chemistry and cycle transport of impurities and additives. This goal is difficult to achieve because a wide range of environmental conditions exist in a typical power plant or industrial boiler steam cycle. The conditions can range from near ambient temperature and less than atmospheric pressure in the condenser to temperatures and pressures in excess of 300^{o}C and 70 bars in other parts of the plant. Liquid, saturated (0-100 percent quality), superheated and supercritical steam can exist in different locations in the steam cycle. The composition of the liquid phase is of most concern relative to corrosion. The concentration of additives or impurities in the liquid phase can range from part per trillion (ppt) to the wt % level.

One of the most detailed thermodynamic models that can be used for steam plant chemistry analysis is EPRI's MULTEQ code (1). Although originally developed for nuclear plants, the database and applicability of the code has been expanded to most additives and impurities found in all types of conventional power plants and industrial steam cycles. The MULTEQ database currently contains 230 species, including 70 solid phases and new species can be easily added. The database also contains several redox couples important to corrosion of steam cycle materials.

STEAM CYCLE SIMULATION

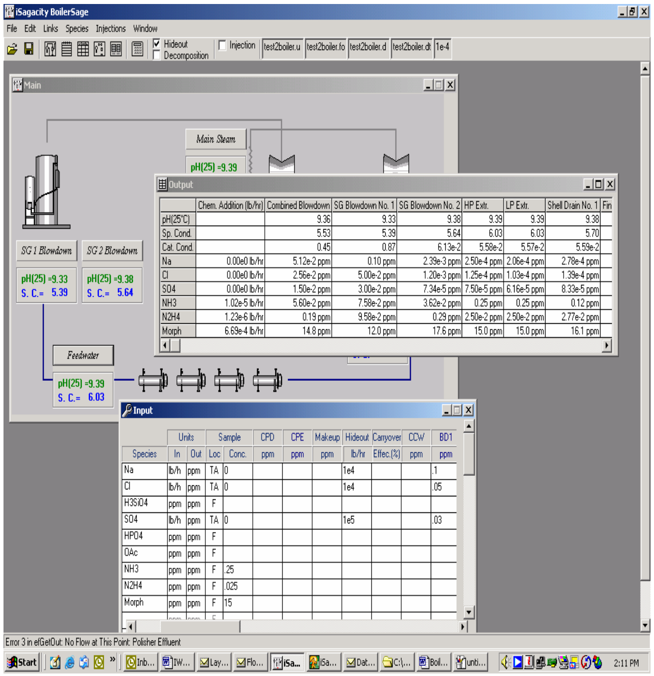
Thermodynamic models by themselves are helpful, but they can be made much more useful to the plant chemist if they are integrated with a complete steam cycle simulation. iSagacity and EPRI have developed several steam cycle simulation tools that can be used for fossil, nuclear or other conventional boiler steam plants. iSagacity's BoilerSage (2) is an interactive Windows ® program designed to provide in-depth modeling capabilities for steam cycles with conventional recirculating and once-through boilers and for combined cycle plants with heat recovery steam generators. BoilerSage allows the user to model transport of chemical species, boiler hideout, decomposition, condensate polisher/demineralizer impurity removal, as well as the ability to have attemperation lines and injections into the flow stream.

Tools like BoilerSage combine a thermodynamic engine (in this case MULTEQ) with a detailed heat and material balance for the steam cycle. The distribution of additives and contaminants in the steam cycle is calculated in terms of solute flows in the steam/water system. A typical steam cycle may include a steam loop that passes from the final feedwater, split to multiple boilers, combined steam transport to a high-pressure turbine, intermediate-pressure turbine, moisture separator and low-pressure turbine to the condenser, and returned to the boilers via the feed train. The steam cycle may also include multiple extraction lines, vents and drains as well as condensate demineralizers, blowdown flash tanks and makeup systems. The heat and material balances must consider the amount of flow and connectivity of all steam and liquid crossflows, vent and drain paths, etc. to properly simulate the transport of additives and impurities. The thermodynamic properties of all components in the system must also be known at each mixing and separation point. A typical run for an industrial boiler using BoilerSage is shown in Figure 1. The calculations not only gives the concentration of species throughout the steam cycle (some are shown in Figure 1), but also other properties such as the room temperature and at temperature pH and the conductivity of the solution. This information can be used to optimize pH control in the steam plant as described in one of the case studies at the end of this paper. The measured conductivity and pH can also be compared to the predicted values to cross check the sensors.

ADVANCED CHEMISTRY DIAGNOSTICS

Diagnostic tools can take many forms. It is common practice for steam plant operators to directly diagnose chemistry problems from one or more measurements that are made in the system. Interpretation of some chemistry data can be quite straightforward and advanced tools are not needed. For example, a direct measurement can be made of the oxygen scavenger to determine if the addition rate needs to be changed. For more complex problems that require interpretation of several different measurements and consideration of other plant conditions, diagnostic tools can be helpful to both the trained plant chemist and to operators with only minimal chemistry training.

Simulation tools like BoilerSage can be used off-line to perform what-if analyses and to help interpret plant chemistry. As previously discussed, calculated values of measurements can be compared to grab sample and or in-line instruments as a cross check and to determine when recalibration of instruments is needed. Simulation tools can also be used to help diagnose operational problems such as condenser leaks, loss of chemical treatment, demineralizer leakage, etc.



Output

	Chem. Addition (lb/hr)	Combined Blowdown	SG Blowdown No. 1	SG Blowdown No. 2	HP Extr.	LP Extr.	Shell Drain No. 1	Fin
pH(25°C)		9.36	9.33	9.38	9.39	9.39	9.38	
Sp. Cond.		5.53	5.39	5.64	6.03	6.03	5.70	
Cat. Cond.		0.45	0.87	6.13e-2	5.58e-2	5.57e-2	5.59e-2	
Na	0.00e0 lb/hr	5.12e-2 ppm	0.10 ppm	2.39e-3 ppm	2.50e-4 ppm	2.06e-4 ppm	2.78e-4 ppm	
Cl	0.00e0 lb/hr	2.56e-2 ppm	5.00e-2 ppm	1.20e-3 ppm	1.25e-4 ppm	1.03e-4 ppm	1.39e-4 ppm	
SO4	0.00e0 lb/hr	1.50e-2 ppm	3.00e-2 ppm	7.34e-5 ppm	7.50e-5 ppm	6.16e-5 ppm	8.33e-5 ppm	
NH3	1.02e-5 lb/hr	5.60e-2 ppm	7.58e-2 ppm	3.62e-2 ppm	0.25 ppm	0.25 ppm	0.12 ppm	
N2H4	1.23e-6 lb/hr	0.19 ppm	9.58e-2 ppm	0.29 ppm	2.50e-2 ppm	2.50e-2 ppm	2.77e-2 ppm	
Morph	6.69e-4 lb/hr	14.8 ppm	12.0 ppm	17.6 ppm	15.0 ppm	15.0 ppm	16.1 ppm	

Input

	Units		Sample		CPD	CPE	Makeup	Hideout	Carryover	CCW	BD1
Species	In	Out	Loc	Conc.	ppm	ppm	ppm	lb/hr	Effec.(%)	ppm	ppm
Na	lb/h	ppm	TA	0				1e4			.1
Cl	lb/h	ppm	TA	0				1e4			.05
H3SiO4	ppm	ppm	F								
SO4	lb/h	ppm	TA	0				1e5			.03
HPO4	ppm	ppm	F								
OAc	ppm	ppm	F								
NH3	ppm	ppm	F	.25							
N2H4	ppm	ppm	F	.025							
Morph	ppm	ppm	F	15							

Error 3 in efGetOut: No Flow at This Point: Polisher Effluent

Figure 1: Typical Input Chemistry and Simulation Results

Tools are now available to perform the diagnosis on-line in real time without the need for an operator to interpret the output. Several vendors have developed systems that provide this functionality. Our experience with application of systems of this type includes EPRI's SMART chemWorks and iSagacity's Remote Manager product. SMART chemWorks has been installed and is used as a real time monitoring system in over 33% of the US nuclear plants. Remote Manager is now being applied to both fossil power stations and industrial steam cycles. The biggest benefit of on-line diagnostic system compared to an off-line analysis is the ability to detect the problem early and correct it before damage is done to the plant.

Both SMART chemWorks and Remote Manager use steam cycle chemistry models as the intelligence engine that drives their diagnostic capabilities. All of the benefits of off-line simulation described above can be leveraged to greater benefit when performed on-line. One very powerful use of the model is to generate "fingerprints" of system behavior under faulted or abnormal conditions. The fingerprint or scenarios for a plant are created by simulating a faulted condition and tracking how each of the measurements throughout the plant should change when the scenario occurs. Using pattern recognition algorithms, real time data from the plant can be continuously compared to a library of scenarios to determine which fingerprint best matches the current condition. This technique rapidly diagnoses plant conditions and does not require the implementation of a complex set of rules.

The remainder of this paper describes a few case studies of how simulation and diagnostic tools have been applied in operating plants for both optimization of water chemistry control and for early detection of operating problems. Simulation tools can and have also been used directly to aid in training operators in the detection of water chemistry problems.

CASE STUDIES

Our experience has shown that the types of on-line diagnostic systems described above can be used quite successfully to detect and diagnose chemistry upset conditions.

Case Study A: Detection of a Condenser Leak

One of the scenarios frequently detected is condenser in leakage. The following example is from the use of SMART chemWorks at a nuclear station. At approximately 15:00 on May 3, 2000 a small condenser leak began to increase during power operation. Figure 2 shows the sodium concentration in the steam generator blowdown (ppb).

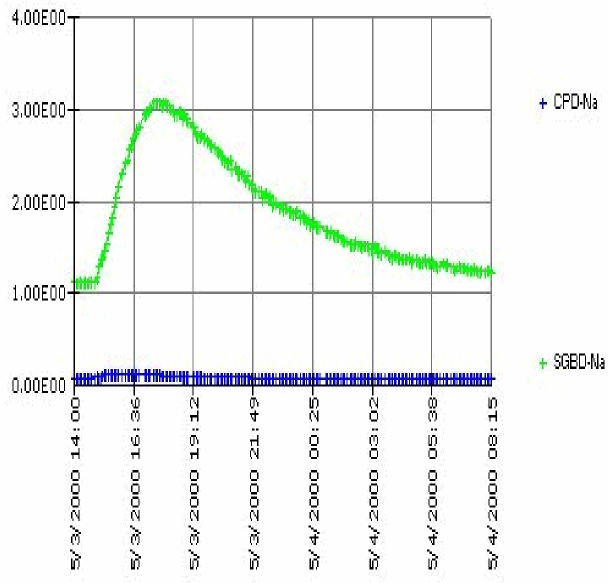


Figure 2: Condensate (CPD) and Steam Generator (SGBD) Sodium Levels

The response from the system is shown in Figure 3. The system outputs the diagnosis in terms of a confidence level ranging from 0 to 100%. The Figure shows that as the condenser leak began, the diagnosis went from predicting normal chemistry with a high confidence, to predicting a small condenser leak with a high confidence. An alert was sent by pager to the plant at 15:58 and as corrective actions were taken, the system returned to diagnosing Normal Chemistry. At this plant, chronic low levels of leakage exist, and the sensitivity has been adjusted to account for this baseline leakage.

Case Study B: Chemical Addition

An example of a chemical addition problem noted at a Boiling Water Reactor is shown in Figure 4. Figure 4 shows an increase in reactor water conductivity that began around 11:30. The conductivity monitor reached its maximum of 0.5 µmhos/cm and was above that level for several hours. At 12:30, the system diagnosed a Loss of Hydrogen feed with high confidence, as shown in Figure 5.

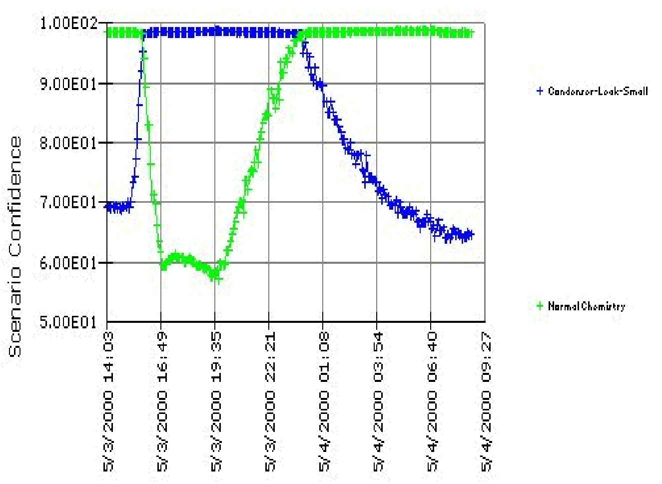


Figure 3: Scenario Diagnosis – Small Condenser Leak

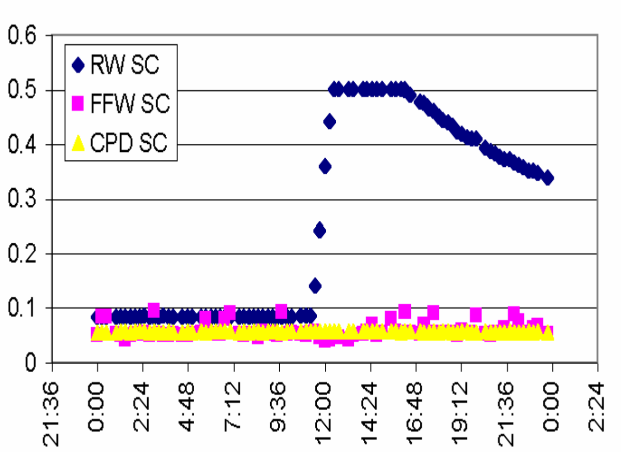


Figure 4: Specific Conductivity (RW-Reactor Water, FFW-Final Feedwater, CPD-Condensate Pump Discharge)

At this point in time, the feedwater hydrogen measurement was still showing in its normal range. There was some question if the system was being correctly diagnosed since the hydrogen reading was still showing the expected value. At about 15:45, the hydrogen level began to drop as shown in Figure 6. It is believed that sample line delays resulted in the feedwater hydrogen monitor not detecting the loss of hydrogen at the same time as the increase in specific conductivity was detected. In the future, this plant can rely on the system diagnosis for this scenario rather than waiting for confirmation from the lagging monitor.

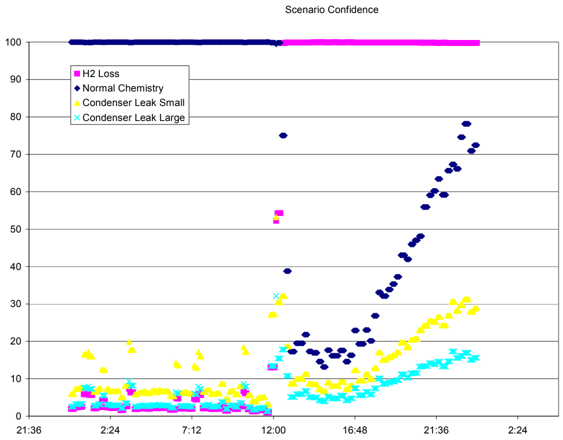


Figure 5: Hydrogen Loss Scenario Diagnosis

Similar benefit is obtained when this system detects a loss of chemical addition for a species that is added continuously, but monitored infrequently. Such is the case with amine pH control in conventional boilers and steam cycles. This technique is very good at detecting changes in amine concentration based on the changes in conductivities and pH values around the plant, thus the plant can be monitored continuously for an underfeed or overfeed of chemicals even though measurements for those constituents may be taken only once a week.

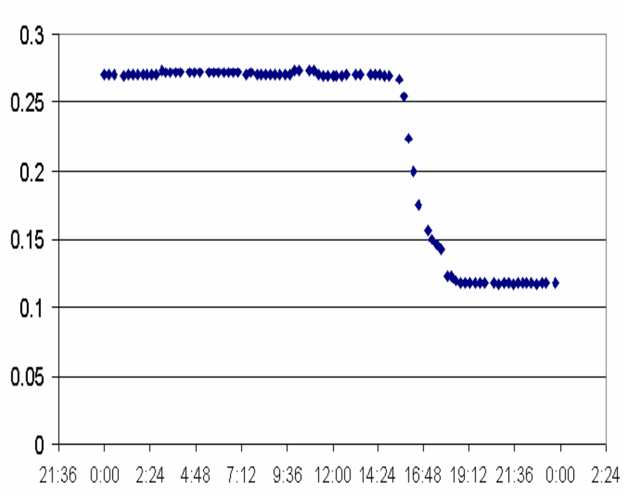


Figure 6: Feedwater Hydrogen (ppm)

Case Study C: Control of pH in an Industrial Boiler

The control of corrosion product transport, particularly from the two phase portion of the steam cycle, into industrial boilers has a direct impact on operating costs through increases in chemical cleaning frequencies, boiler under deposit corrosion, or loss of boiler efficiency. The use of volatile amines can measurably increase the pH in the steam cycle and reduce iron corrosion rates. However, the breakdown of the amines into small chained organic acids can reverse the pH effect and increase iron oxide transport.

The BoilerSage simulation tool was used to calculate the pH effects of a common amine (morpholine) and its potential breakdown effects in a commercial industrial boiler system. The results of these calculations are shown in Table 1 and Figure 7. The industrial boiler system that was modeled contains a bank of 8 high pressure boilers (600 psig) and six low pressure boilers (150 psig). The high pressure boilers operate currently on phosphate treatment with carbohydrazide in the feedwater, which produces about 1 ppm of feedwater ammonia. The addition of 15 ppm morpholine was being evaluated in the plant to address the elevated iron corrosion rates. However, there exists a small amounts of copper deposited in the boilers. Copper is known to catalyze the thermal breakdown of morpholine, primarily into acetic acid. The effect of the morpholine along with the production of acetate was evaluated in the simulator.

The simulation first addressed the current system using carbohydrazide in the feedwater, which produced 1 ppm of ammonia in the feedwater, and phosphate treatment in the high pressure boiler. The second simulation overlaid 15 ppm of morpholine in the feedwater. The third simulation decomposed 1% of the morpholine in both boiler banks to and produced acetate as the breakdown product. The forth simulation increased the breakdown to 5%, and the fifth simulation increased the breakdown to 10%. To effectively evaluate the pH control program, the pH(t) and the neutral pH(t), designated as pH(n), were evaluated at various temperatures in the two phase regions of the steam cycle. The term Delta pH refers to the difference between the pH(t) and pH(n) and gives a relative amount of pH protection at each temperature that was evaluated; the greater the Delta pH, the better the pH protection. As a rule of thumb, a Delta pH of 1 or greater is optimal for minimizing iron corrosion transport.

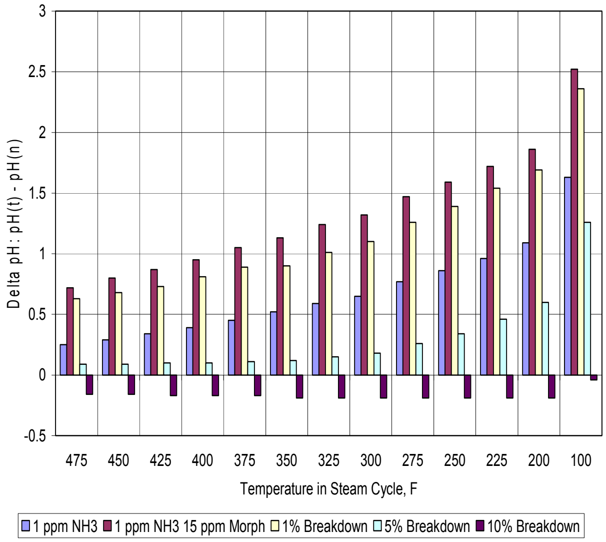


Figure 7: Simulated pH Protection with Various Breakdown Amounts of Morpholine

A measurable improvement is made in the steam cycle pH with the addition of morpholine. However, at temperatures greater than 375 F, a delta pH of 1 is not attained even without any breakdown of the morpholine. With about 1% or less breakdown of morpholine, processes in the steam cycle that operate at >325 F are not adequately protected. At the 5% to 10% breakdown, the addition of morpholine is worse than the original ammonia program. The plant personnel have since considered amines of higher base strength and better thermal stability such as mono ethanolamine (MEA) and methoxypropylamine (MOPA).

SUMMARY

Advanced chemistry simulation and diagnostic tools are no longer just a concept. They have been deployed successfully in a number of plants including nuclear, fossil and industrial steam cycles. Originally these tools were used in corporate offices to analyze what happened in the plant after the fact. Today, the analysis is automated and is performed in real-time with the results broadcast to plant operators and managers via the web and through e-mail alerts. As a result, these tools can be used to provide real-time decision support, provide early warning of abnormal conditions, and improve overall plant communications and awareness. As the cost of wireless sensors continue to go down and networked hand-held PDA's become more prevalent, this will allow communication with even the most remote parts of the plant.

The cost benefit of implementation of these systems is significant. The avoidance of one unplanned outage, the improved thermal performance that can be achieved by improved chemistry control justifies the use of these tools. Additionally these tools make the existing chemistry staff or those responsible for chemistry much more effective at their job. This can translate into direct cost savings.

ACKNOWLEDGEMENTS

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2. BoilerSage: Steam Cycle Chemistry Simulation Tool, iSagacity, 2003.

Table 1: Case Study of pH control in an Industrial Steam Cycle

Ammonia and Morpholine

	475 F	450 F	425 F	400 F	375 F	350 F	325 F	300 F	275 F	250 F	225 F	200 F	100 F
pH(t)	6.31	6.39	6.48	6.58	6.71	6.84	7	7.12	7.36	7.57	7.79	8.04	9.32
pH(n)	5.59	5.59	5.61	5.63	5.66	5.71	5.76	5.8	5.89	5.98	6.07	6.18	6.8
pH(25°C)	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53	9.53
Cond.	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74	8.74
NH3	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Morph	15	15	15	15	15	14.9	14.9	14.9	14.9	14.9	14.9	14.9	14.9

Ammonia and Morpholine with 1% Morpholine Breakdown to Acetate

	475 F	450 F	425 F	400 F	375 F	350 F	325 F	300 F	275 F	250 F	225 F	200 F	100 F
pH(t)	6.29	6.37	6.45	6.55	6.68	6.79	6.95	7.08	7.32	7.53	7.75	8.01	9.29
pH(n)	5.59	5.59	5.61	5.63	5.66	5.71	5.76	5.80	5.89	5.98	6.07	6.18	6.80
pH(25°C)	9.53	9.53	9.53	9.53	9.53	9.52	9.52	9.52	9.52	9.52	9.52	9.52	9.52
Cond.	8.72	8.72	8.72	8.72	8.72	8.70	8.70	8.70	8.70	8.70	8.70	8.70	8.70
Acetate	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
NH3	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Morph	14.98	14.98	14.98	14.98	14.98	14.88	14.88	14.88	14.88	14.88	14.88	14.88	14.88

Ammonia and Morpholine with 5% Morpholine Breakdown to Acetate

	475 F	450 F	425 F	400 F	375 F	350 F	325 F	300 F	275 F	250 F	225 F	200 F	100 F
pH(t)	6.22	6.27	6.34	6.44	6.55	6.61	6.77	6.9	7.15	7.37	7.61	7.87	9.16
pH(n)	5.59	5.59	5.61	5.63	5.66	5.71	5.76	5.8	5.89	5.98	6.07	6.18	6.8
pH(25°C)	9.51	9.51	9.51	9.51	9.51	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
Cond.	8.63	8.63	8.63	8.63	8.63	8.56	8.56	8.56	8.56	8.56	8.56	8.56	8.56
Acetate	0.14	0.14	0.14	0.14	0.14	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
NH3	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Morph	14.9	14.9	14.9	14.9	14.9	14.8	14.8	14.8	14.8	14.8	14.8	14.8	14.8

Ammonia and Morpholine with 10% Morpholine Breakdown to Acetate

	475 F	450 F	425 F	400 F	375 F	350 F	325 F	300 F	275 F	250 F	225 F	200 F	100 F
pH(t)	5.68	5.68	5.7	5.73	5.77	5.82	5.9	5.97	6.14	6.31	6.52	6.77	8.05
pH(n)	5.59	5.59	5.6	5.63	5.66	5.7	5.75	5.79	5.88	5.97	6.06	6.17	6.79
pH(25°C)	9.07	9.07	9.07	9.07	9.07	9.04	9.04	9.04	9.04	9.04	9.04	9.04	9.04
Cond.	8.36	8.36	8.36	8.36	8.36	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44
Acetate	3.4	3.4	3.4	3.4	3.4	3.58	3.58	3.58	3.58	3.58	3.58	3.58	3.58
NH3	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Morph	14.3	14.3	14.3	14.3	14.3	14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1