Condensate Oxygen Control In A Combined Cycle System Without A Conventional Deaerator - Test Results

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ABSTRACT

An improved efficiency combined cycle power plant was provided by Bechtel for the Gilroy Energy Company. This enhancement of cycle efficiency was achieved by eliminating all feedwater heating in order to extract the maximum amount of heat from the Heat Recovery Steam Generator flue gas, resulting in a feedwater temperature of 110° F. A new approach to oxygen control was necessary because the system requires makeup water flow varying from 25 to 85% of condenser outlet flow without the use of a conventional feedwater deaerator. This project confirmed that 0_2 levels can be controlled to 0.005 cc/liter under severe makeup conditions without chemical additives or the use of a conventional deaerator.

One essential component of this unique design is the combined vacuum deaerator/condenser unit. A second major aspect of the design involves the enhanced venting system. Limited testing prior to startup and operation of the Gilroy Energy power plant indicated that oxygen in the boiler feedwater could be controlled satisfactorily with a total system approach which included both the vacuum deaerator and enhanced venting. Subsequently, further testing of a vacuum deaerator has yielded 0_2 levels at or below the design requirements of 0.005 cc/liter. Additionally, field test data of 0_2 levels from the Gilroy Energy plant are presented to verify the successful operation of the condensate oxygen control portion of this cogeneration unit.

PROBLEMS WITH DISSOLVED OXYGEN IN CONDENSERS

With the advent of two-shift and cycling operation of base load power plants, the problem of effective removal of noncondensible gases has increasingly been addressed by both condenser designers and utility end users. Power plants exporting steam for district heating (as well as cogeneration plants) are faced with stringent deaeration problems inherent in introducing large amounts of makeup water saturated with oxygen into the condenser. Any plant requiring deaeration of makeup water exceeding 3 - 5% of the total condenser flow rate (or that is required to remove oxygen from stored condensate on daily restart) must find a method of eliminating oxygen from the water other than introducing it over the condenser tubes.

Although modern steam condensers can achieve dissolved oxygen levels of 0.005 cc/liter (7 ppb) at design load and using design cooling water temperatures, this capability is seriously compromised at low loads with low cooling water temperatures. Under these conditions steam bypasses the lower section of the condenser and does not reheat the descending condensate, liquid is excessively subcooled, and dissolved oxygen levels increase. Field experience in conventional power plants has demonstrated that when operating at part load more of the power plant cycle is exposed to vacuum. This increases air leakage and also the load to the venting system, which is simultaneously losing capacity as it tries to match the lower achievable condenser vacuum. When the condenser must also cope with large flows of highly oxygenated makeup water the situation deteriorates further.

In addition to these general concerns about oxygen levels in the condensate with conventional condensers, there are problems specifically associated with cogeneration condensers. These include the high volume of makeup water, the extreme fluctuations in the makeup water flow rate, and the subsequent effects on the air removal system. The following description of a cogeneration system at Gilroy Energy can be used to highlight the demanding operating conditions placed on a condenser.

DESCRIPTION OF GILROY ENERGY SYSTEM

Gilroy Energy Company has a highly efficient combined cycle cogeneration plant provided by Bechtel which is situated next to the Gilroy Foods plant in Gilroy, California. Gilroy Energy supplies 150 psig steam to the Gilroy Foods plant for use in the production of high quality dehydrated garlic, onions, peppers and other foods. The cogeneration plant has the capability of supplying from 0 to 190,000 lbs/hr of steam for drying purposes.

Electric power produced by the cogeneration plant is sold to Pacific Gas and Electric (PG&E). The contractual agreement between Gilroy Energy and PG&E gives PG&E the option to curtail the electric output of the plant for six continuous hours each night. This option was exercised by PG&E in 1989. The requirement to completely shut down the plant every night and restart it in the morning provided a unique opportunity to test the bottoming cycle design enhancements under the most demanding conditions.

Gilroy Energy's cogeneration plant consists of a Frame 7 GE gas turbine with waste heat exhausting to a Heat Recovery Steam Generator (HRSG) which produces approximately 400,000 lbs/hr of high and low pressure steam. The AEG Kanis steam turbine has high and low pressure admissions along with controlled and uncontrolled extractions. The controlled extraction port is used to supply the steam used in the food dehydration process, while the uncontrolled extraction port supplies superheated steam which is injected into the gas turbine for emissions (NOX) control. Approximately 61,000 lbs/hr of steam used for NOX control cannot be recovered.

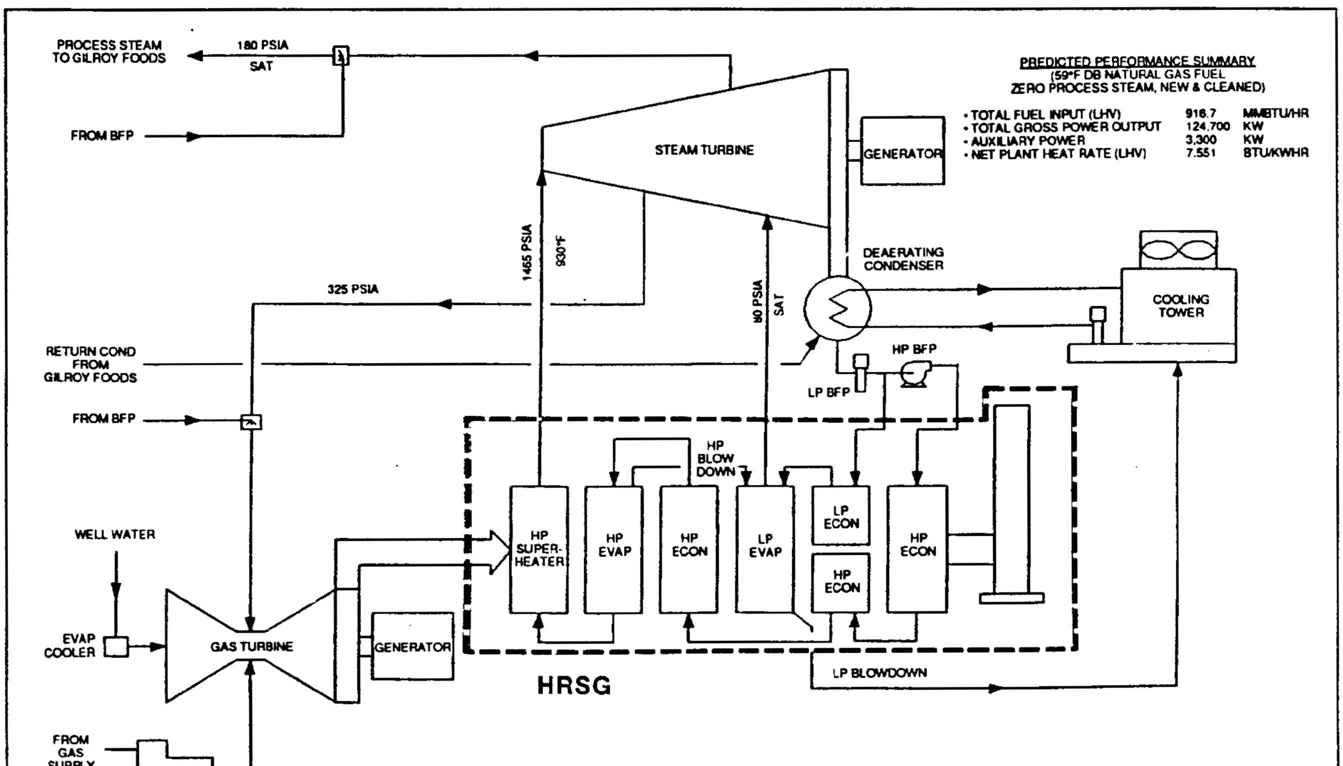
A maximum cycle efficiency is achieved by eliminating all feedwater heaters and feedwater deaerators from the steam cycle. This allows the relatively cold (110° F) feedwater entering the HRSG to extract the maximum possible energy from the HRSG exit flue gas. The exit flue gas temperature of 205 -210° F indicates that most of the latent heat associated with the condensing combustion vapors and NOX steam is indeed recovered within the bottoming cycle.

The efficiency and emissions enhancements of the cogeneration plant design can cause the makeup water requirements of the steam cycle to be 25 to 85% of the total feedwater flow. This amount of oxygen saturated makeup water, if not deaerated prior to admission to the condenser, would have created serious oxygen levels with associated corrosion problems in the condenser, feedwater piping and HRSG.

Figure 1 shows the Gilroy Energy process flow diagram. A more complete discussion of the system is presented in Reference 1.

CONDENSER DESIGN FOR IMPROVED OXYGEN CONTROL

The condenser system supplied to Gilroy Energy has been described in a previous paper (Reference 2). Figures 2 and 3 illustrate the design of the vacuum deaerator/condenser/venting system. The three main components used in removing excess oxygen from the makeup water include:



GILROY FOODS COGENERATION PLANT PROCESS FLOW DIAGRAM

Figure 1

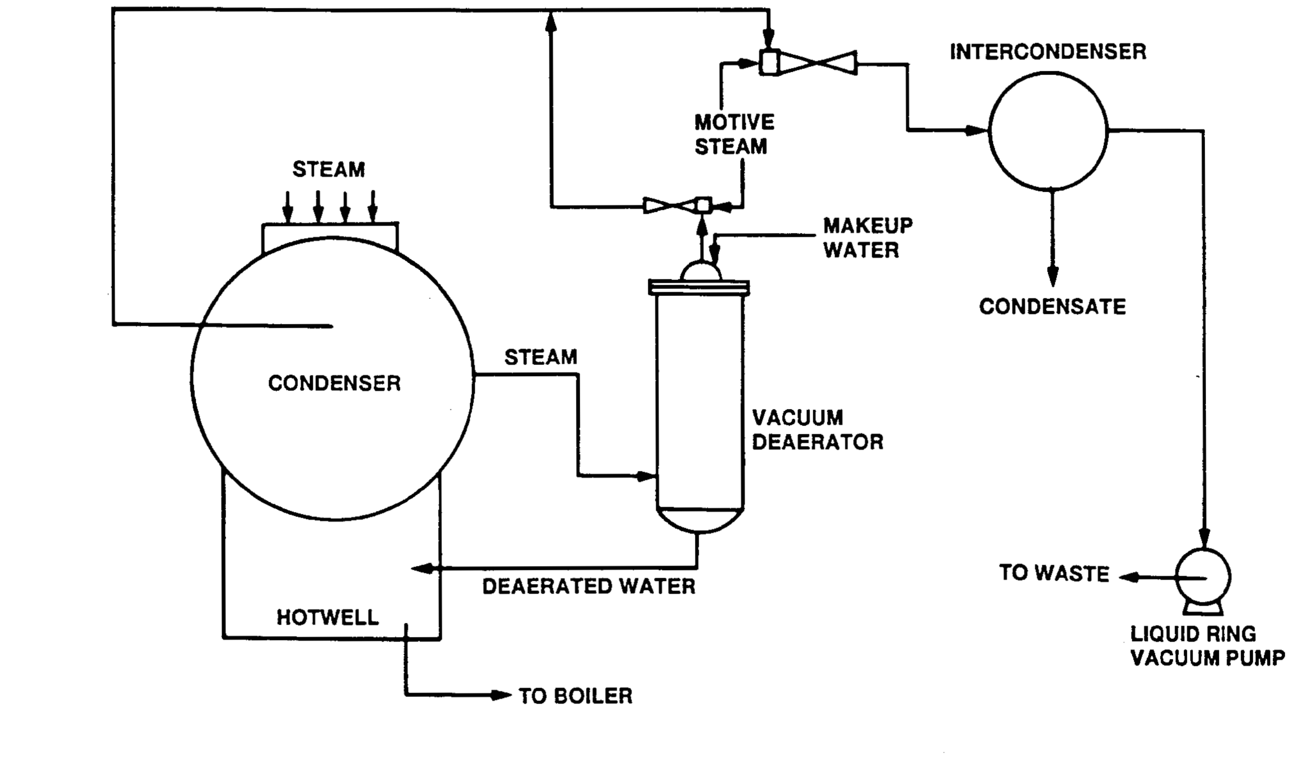


Figure 2 ENHANCED VACUUM SYSTEM

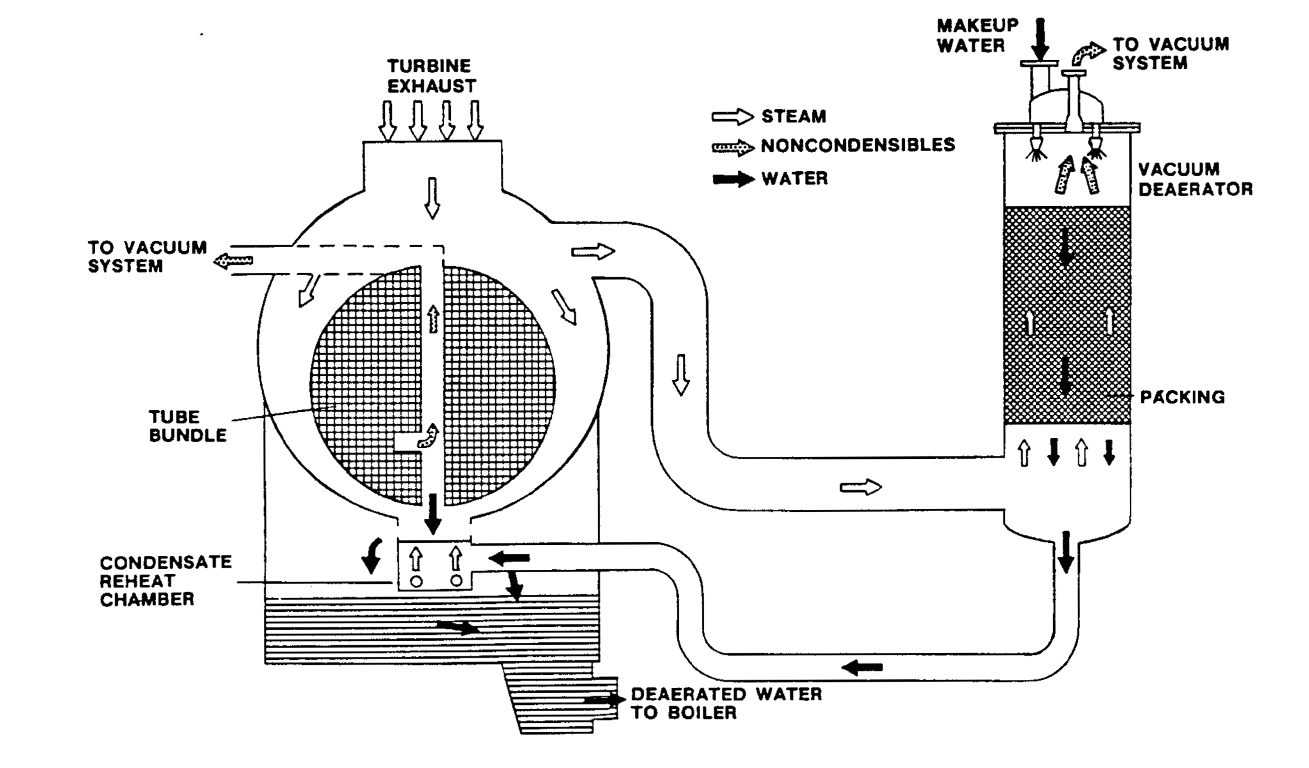
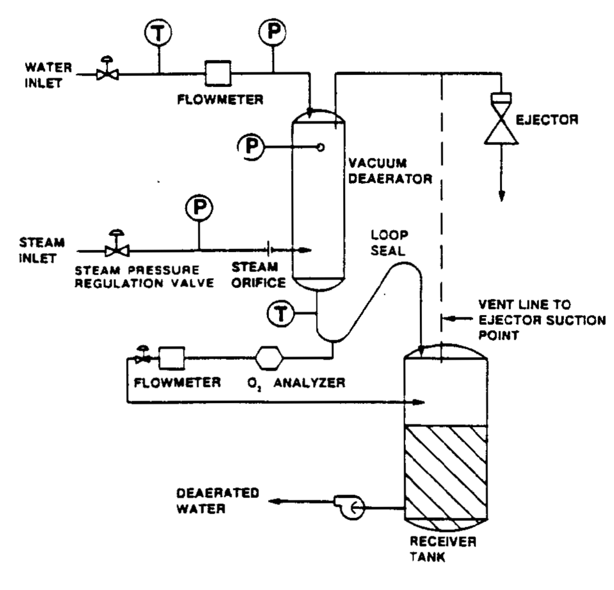


Figure 3 CONDENSER/VACUUM DEAERATOR FLOW SCHEMATIC

- A vacuum deaerator to remove noncondensible gases from the makeup water. A packed tower heated only by turbine exhaust steam at controlled flow rates was designed to remove oxygen to the desired low levels. The deaerator is connected to the condenser through steam piping and a return line to the hotwell. This arrangement allows oxygen removal from the makeup water before it reaches the condenser. Past experience and Heat Exchange Institute (HEI) limitations have indicated that when oxygenated makeup flows exceeding 3 - 5% of condenser throughput are added to the condenser, dissolved 0_2 levels will exceed 7 ppb (Bechtel/Gilroy requirements far exceed this);
- An enhanced venting system ensuring that whatever noncondensible gases are released will be removed and which maintains a low air partial pressure within the condenser. EPRI 2294 (Reference 3) suggested that condensate dissolved oxygen levels could be controlled by "overventing," i.e., maintaining a low partial pressure of air within the condenser. A venting system was provided which removes large volumes of water vapor with each pound of air in order to maintain the low air partial pressure and limit the dissolved oxygen in accordance with Henry's law. (Note: Reference 4 presents a detailed discussion of why many venting systems in existing power plants simply are inadequate for proper dissolved oxygen control, and also are unable to maintain proper vacuum at off-design conditions;)



VACUUM DEAERATOR TEST ARRANGEMENT

Figure 4

- A segregated condensate reheat hotwell to further deaerate the water from both the condenser and the vacuum deaerator. Steam injected into the hotwell reheats the condensate and acts to scrub out any reabsorbed gases. In general, deaerating hotwells have failed to operate successfully under all possible load conditions. At low loads and low cooling water temperatures, sparge steam is diverted to the excess surface area and fails to reheat the condensate. The segregated reheating hotwell provided in the Gilroy Energy condenser permitted controlled contact in a packed section located between the hotwell and the condenser tubes. No vapor bypassing is possible in this arrangement, and the packing ensures both good contact and adequate residence time between the ascending steam and the descending condensate. (Note: Reference 5 appraises USSR experiences and bubbler hotwells in general.)

The remainder of this paper will show the test data which have been taken for the vacuum deaerator (isolated), the effect of enhanced venting (isolated), and the field test data of the complete system at Gilroy Energy.

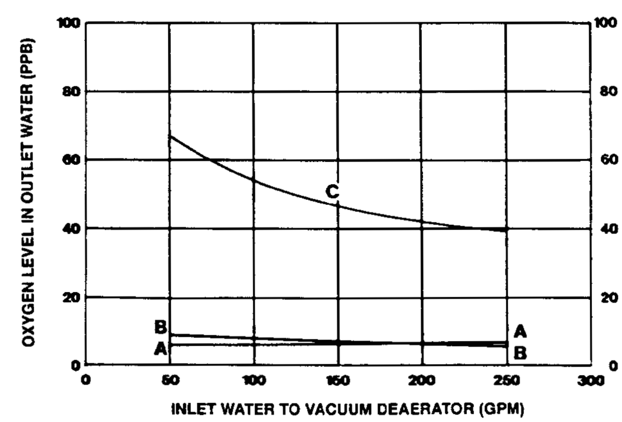


Figure 5 DEAERATION AT A SYSTEM PRESSURE OF 3.0 INCHES HG ABSOLUTE

VACUUM DEAERATOR TEST RESULTS

Because the vacuum deaerator/condenser concept is a unique application, it was necessary to test the full scale vacuum deaerator under actual operating conditions. Figure 4 shows a schematic of the test arrangement. Fresh makeup water was pumped through the flow meter to the inlet water box. Steam was introduced through an orifice which reduced the pressure to the desired design point, as well as controlled the flow. Deaerated water was accumulated in a receiving tank. Since the test system is a once-through design, the receiving tank was continuously pumped to waste. Samples for the Orbisphere Oxygen Analyzer were drawn through a loop seal to ensure continuous water flow and then discharged to the receiving tank.

The flow rate of makeup water was varied between 50 and 250 gpm, while the pressure in the vacuum deaerator ranged from 0.6 (no steam - simple vacuum degasifier) to 3.5 inches Hg absolute. In addition, several types of packing were tested in the deaerator.

The results of the vacuum deaerator testing are shown in Figures 5 - 7. Makeup water for these tests had a temperature of 60 - 65°F, with a measured oxygen content of over 8 parts per million (8000 ppb). The oxygen level in the deaerated outlet water is presented as a function of the flow rate through the vacuum deaerator and of the type of packing used. Curves "A"and"B"in

Figures 5 and 6 represent two commercially available high performance metal tower packings. Curve “C” represents an unpacked tower.

One of the most significant parameters in any deaeration process is the liquid/gas ratio. This is illustrated by comparing the results of Figures 5 and 6. When a higher pressure (3.5 inches Hg absolute) is maintained in the deaerator, the measured oxygen results are greatly improved. This is primarily due to the increased steam flow in the deaerator which enhances performance. At an

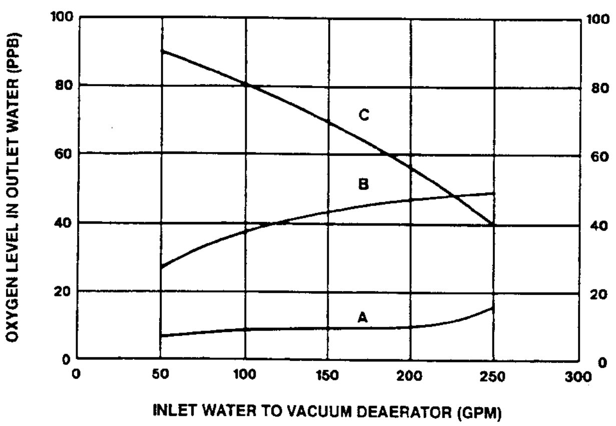


Figure 6 DEAERATION AT A SYSTEM PRESSURE OF 1.5 INCHES HG ABSOLUTE

internal pressure of 1.5 inches Hg absolute the steam flow can be insufficient to provide adequate deaeration unless the engineering design parameters are adjusted. In the case shown in Figure 6, packing “B” is obviously unacceptable, while packing “A” gives results in the 8 - 10 ppb range.

Figure 7 demonstrates the effect of this internal pressure (and corresponding liquid/gas ratio) for a single type of packing. In this specific case it is apparent that operating the deaerator at pressures of 1.5 - 3.5 inches Hg absolute gives acceptable deaeration, while operating at a pressure of 1.0 inch Hg does not because insufficient steam is available to remove the oxygen. In summation, the design of the vacuum deaerator is critical to the overall performance of the vacuum deaerator/condenser unit.

ENHANCED VENTING TEST RESULTS

In order to attain a low oxygen partial pressure inside the entire condenser under less than optimum conditions, it is necessary to use enhanced venting. The air removal system for Gilroy Energy was designed to remove many times the amount of water vapor per pound of noncondensible gas relative to a typical installation. This was done in accordance with the ratios suggested in Reference 3, and is in excess of HEI recommendations. The HEI approach utilizes the air subcooling section to reduce the load to the venting system by subcooling the noncondensible gases in order to achieve a ratio of approximately 2.2 pounds of water vapor per pound of noncondensible gas.

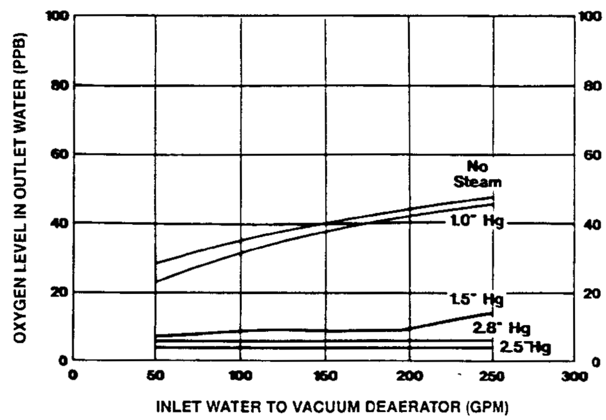


Figure 7 DEAERATION USING PACKING "A" AT DIFFERENT SYSTEM PRESSURES

The information presented in Reference 3 can be used to illustrate the effect of enhanced venting on dissolved oxygen in the condensate from the main condenser. Figure 8 is a reworking of the dissolved oxygen calculations when it is assumed that no subcooling of the noncondensible gases takes place. At a condenser pressure of 1.5 inches Hg absolute the HEI recommended air removal rate results in approximately 75 ppb of oxygen remaining in the condensate. Increasing the amount of water vapor removed to approximately 25 times the noncondensible gas rate reduces the dissolved oxygen in the condensate to the recommended value of 7 ppb. Similar results occur when the condenser is operated at a pressure of 3.5 inches Hg absolute: the HEI recommended removal of 2.2 lb. water vapor/lb. air results in more than 100

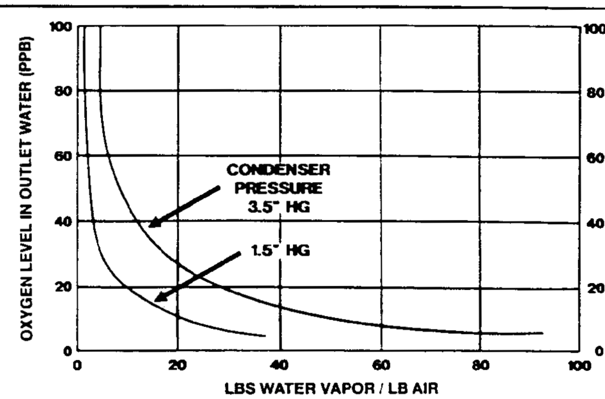


Figure 8 EFFECT OF ENHANCED VENTING ON CONDENSATE DISSOLVED OXYGEN (NO CONDENSATE SUB-COOLING) DATA FROM REFERENCE 3

ppb of dissolved oxygen; a water vapor/air ratio of approximately 65 reduces the oxygen content of the condensate to an acceptable level of 7 ppb.

The preceding discussion is intended to illustrate the basic principle which is suggested in Reference 3, i.e., reducing the partial pressure of noncondensible gases in the exhaust from the condenser will create a situation which will reduce the dissolved oxygen in the condensate. The actual removal of noncondensibles in any specific condenser is obviously dependent upon both the design of the vacuum system and the internal design of the condenser. However, it is apparent that the effect of enhanced venting is beneficial in controlling dissolved oxygen in the condensate.

GILROY ENERGY WATER CHEMISTRY PROGRAM

The Gilroy Energy Company Operations and Maintenance organization is set up to have the minimum number of highly qualified personnel operate and maintain the plant. All plant controls are as automated as possible. The chemistry control parameters are presented in Table I.

Various steam plant chemistry parameters are monitored and recorded on a continuous basis. Alarms are provided to warn the operators if parameters stray outside the normal operating limitations. In addition, appropriate parameters are tested in the chemistry laboratory using standard techniques at least once each eight hour shift to verify proper chemistry control.

The boiler feedwater oxygen level is monitored on a continuous basis using a Rexnord Dissolved Oxygen Analyzer. The output of the oxygen analyzer is transmitted to the control room for display and trend recording. Any significant change in the oxygen level is immediately indicated to the operators. If the dissolved oxygen reaches a significant level, an alarm is annunciated.

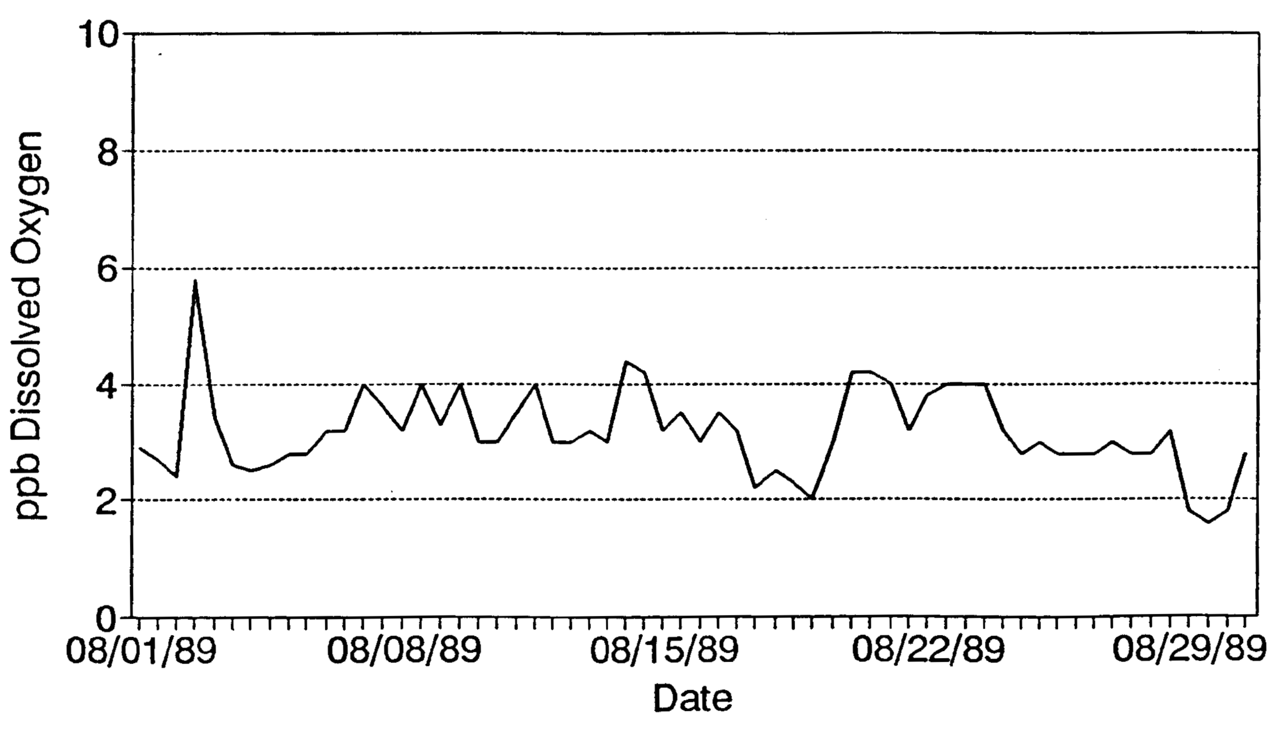
Every eight hours, an operator performs a backup oxygen analysis using a methodology developed by CHEMetrics, Inc. This analysis, which tests for dissolved oxygen in the 0 to 40 ppb range, provides the means to accurately quantify trace oxygen levels.

Table I
Gilroy Energy Water Chemistry Program

Chemistry Control Parameter	Controlling Means
High Pressure Drum pH and corrosion control	Coordinated phosphate control
Low Pressure Drum pH and corrosion control	Coordinated phosphate control
Feedwater pH control	Diethylethanolamine (DEAE)
Feedwater filtration and ion exchange	Condensate polisher (powdered mixed bed resin)
Feedwater oxygen control	Makeup vacuum deaerator, special condenser design, oxygen scavenger (sodium erthorbate)

An even more accurate trace oxygen analysis is performed monthly. This analysis is capable of quantifying dissolved oxygen to within 1 ppb in the range of 0 to 10 ppb. The results of this analysis are used to verify the accuracy of the continuous on-line dissolved oxygen analyzer.

As previously described, the primary means of oxygen control is based on the design of the condenser, makeup vacuum deaerator, and enhanced venting system. An oxygen scavenger (sodium ethorbate) is also introduced into the feedwater. The oxygen scavenger takes effect at the high temperatures encountered after the feedwater reaches the HRSG. This scavenger is not effective at the low temperature (110° F) of the feedwater at the sample point.



Gilroy Energy Condensate Dissolved Oxygen

Figure 9

For this reason, the actual dissolved oxygen levels in the economizer tubes will be even less than that indicated by the routine analyses of samples taken at the condenser hotwell.

GILROY ENERGY FIELD TEST RESULTS

More than two years of operating experience confirms that the design enhancements described in this paper perform as well as, or better than, expected. For the past two years, Gilroy Energy has operated the cogeneration plant in a wide variety of operating modes. The normal dissolved oxygen level is generally measured as less than 5 ppb. Special monthly tests show the actual steady state dissolved oxygen level to be less than 1 ppb.

A test was performed during initial plant startup to determine the dissolved oxygen content in the effluent of the makeup vacuum deaerator. A special test rig was installed which allowed the collection of a sample from the deaerator effluent which is under the influence of the condenser vacuum. At a makeup flow rate of 150 gpm of oxygen-saturated demineralized water into the deaerator, the dissolved oxygen in the effluent had been reduced to approximately 5 ppb.

Figure 9 shows the results of the boiler feedwater oxygen analyses during August, 1989. These results are typical under the following set of operating conditions:

- Plant at base load (approximately 120 Mw) for 14 hours each day;
- Condenser makeup water averaged 135 gpm (equivalent to 67,500 lbs/hr steam) while at base load;
- Process steam supplied to Gilroy Foods is 100,000 to 130,000 lbs/hr. Approximately 90% process condensate returned to the condenser;
- Plant completely off-line for six hours each day. Condenser vacuum is maintained while off-line;
- Startup each day approximately 40 minutes;
- Shutdown each day approximately 20 minutes.

The data plotted in Figure 9 is the summary of oxygen analyses recorded at 9:00 a.m. and 5:00 p.m. each day during August. It is apparent that the condensate leaving the condenser hotwell has an acceptable oxygen level of less than 5 ppb under a variety of operating conditions.

In addition to the dissolved oxygen data during the month of August, Figures 10 and 11 present the oxygen analysis for one day of operation. Figure 10 shows the dissolved oxygen content of the condensate along with the makeup water flow rate to the vacuum deaerator. Figure 11 shows the same oxygen content of the condensate along with the steam turbine load. These two figures demonstrate the ability of the vacuum deaerator/enhanced venting system to control the dissolved oxygen in the condensate to a level below 5 ppb under rapidly changing operating conditions.

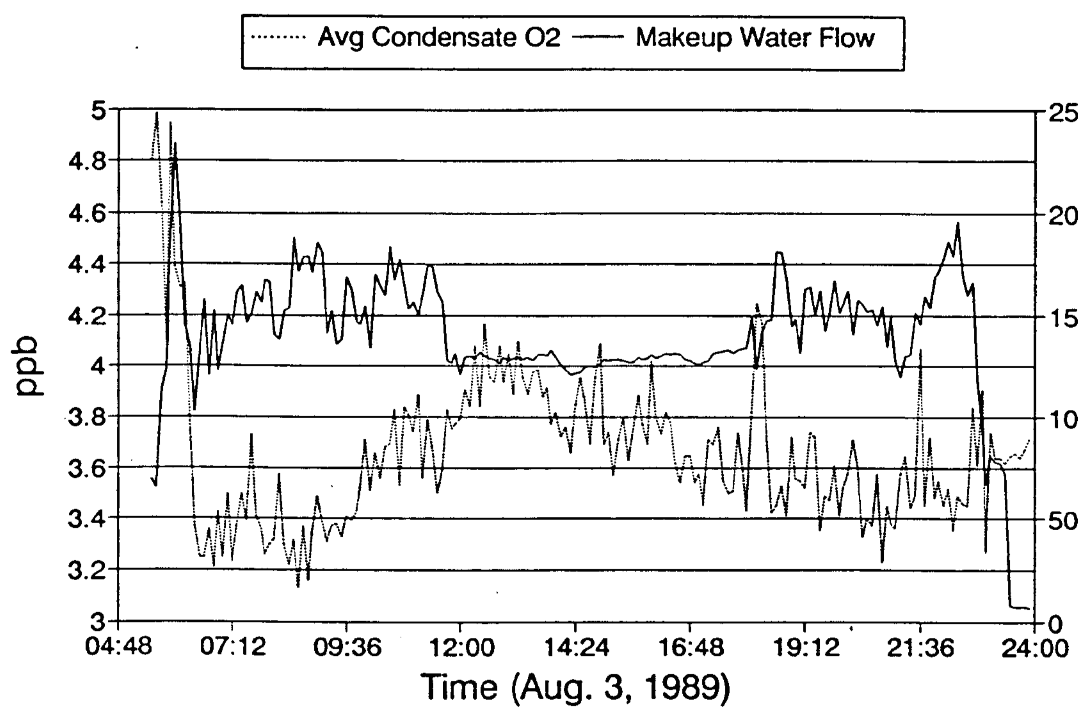


Figure 10

DEAERATING CONDENSER PERFORMANCE AS MAKEUP FLOW TO THE SYSTEM CHANGES

SUMMARY

The deaeration of water to a dissolved oxygen level of 0.005 cc/liter is difficult. However, this level of deaeration can be achieved through a combination of methods. Individual component tests verify that dissolved oxygen can be reduced by using a unique design for the vacuum deaerator/condenser/venting system in a cogeneration plant. Highly oxygenated condensate or makeup water can be deaerated to desired oxygen levels by means of a vacuum deaerator using only turbine exhaust steam, coupled with enhanced venting of the noncondensibles, and a segregated reheat hotwell. A cogeneration steam condenser system has been designed without a conventional deaerator to consistently provide condensate dissolved oxygen levels of 7 ppb under the most adverse operating conditions. Portions of this oxygen removal system can be retrofitted to existing condensers in either conventional or cogeneration systems in a relatively cost effective manner.

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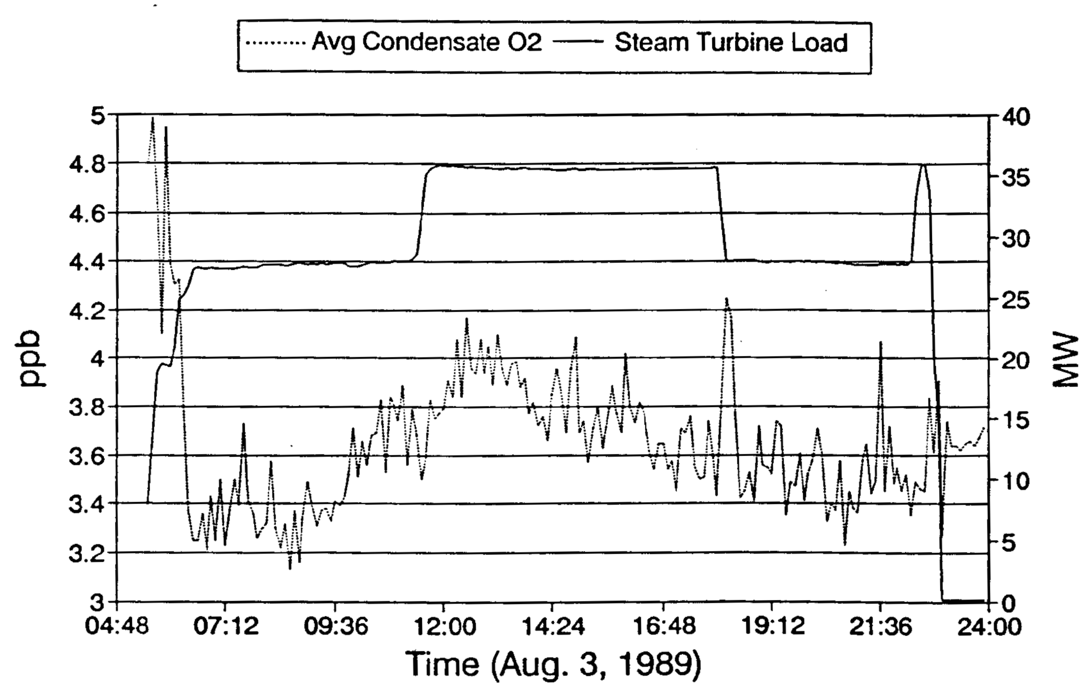

DEAERATING CONDENSER PERFORMANCE AS POWER OUTPUT FROM THE SYSTEM CHANGES

Figure 11