Proceedings of the 2012 20th International Conference on Nuclear Engineering
collocated with the
ASME 2012 Power Conference
ICONE20-POWER2012
July 30 - August 3, 2012, Anaheim, California, USA

ICONE20POWER2012-50000

GRAY & IMPAIRED WATER COOLING IN SURFACE CONDENSERS AND HEAT EXCHANGERS

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ABSTRACT:

In recent years, concern over the continued use of limited fresh water supplies or similarly, cooling towers and their essential makeup, high maintenance and associated chemical treatment requirements has spawned a clever, yet dramatic change in powerplant surface condenser and heat exchanger cooling. The paradigm shift away from the established and typical toward the unconventional has produced an innovative and non-traditional cooling water source for surface condensers and heat exchangers.

Pundits suggest water shortages will increase the amount of water reuse (Chart 1) in the US from a current estimated 1.7 billion gallons to an estimated 12 billion gallons by the year 2015 [2].

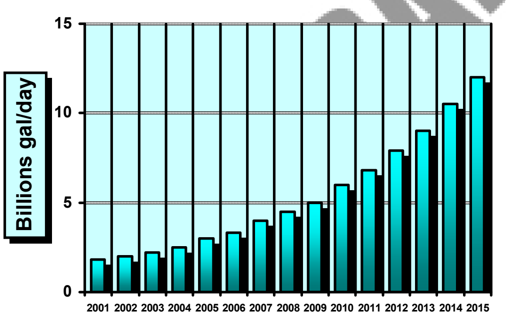


Chart 1
Projected Water Reuse

Given this dramatic prediction, water reuse, or the reclamation and treatment of impaired or gray water will be driven by and emerge as market incentives joined at the hip by emerging or mandated effluent discharge standards.

Without a clear understanding of the legislative and political landscape, regulative complexities that deal with this type of cooling water could conceivably lead to an unattractive environmental legacy.

Having duly noted the “trend or aberration” dilemma, this paper will further identify efforts by the municipal wastewater treatment plants to economically process a usable product. We will investigate the impact of ancillary add-on costs absorbed by the electric utility such as secondary filtration and examine an actual case study involving the extensive use of gray water.

Finally, the paper will evaluate new operational conditions, emerging new corrosion issues with suggested abatement, metallurgical changes, pollution considerations, maintenance issues and other mechanisms which have forced utilities to develop innovative solutions when employing impaired cooling water sources for the main surface condenser and other heat exchangers.

OVERVIEW

By definition, gray water is cooling water where all or part of the flow stream is made up of either partially or fully treated sewage effluent. The use of sewage effluent provokes a plethora of new issues. They are led by the voluminous unknowns that flow from society to the sewage treatment plant and the economics of processing and transporting this impaired water from the municipal host to the ultimate user. The application of this relatively new cooling medium suggests the potential impact of this “water” on plant metallurgy, chemical treatment requirements, corrosion abatement and other physical plant system needs, can become a blueprint for both the speculative and the unproven.

BACKGROUND

Of the 24,000 municipal wastewater treatment plants in the U.S., it is estimated that only about 1,500 employ water reuse facilities. Indeed, more glaring is the fact that only 6% of the total municipal wastewater volume is presently reused. This percentage is even less when applied to power generation facilities.

Economic, legislative and logistical impediments to wholesale expansion of water continue to be the high cost associated with medium transport, biological nutrient removal, macro and mircofiltration, ultraviolet disinfecting and corrosion abatement activities.

In addition, the "relative" abundant supply of fresh water, be it destined as make-up or once-through, poses even greater challenges to the increased use of impaired water. Even though legislative action, albeit confusing, is currently underway to curtail the use of this "fresh" water, current regulative issues, high transport cost, interruptible shortages, wastewater disposal and inconsistent quality contribute to any dramatic increase in the use of impaired water.

In stark contrast, the relatively stable and predictable cost of fresh water undermines, in many cases, the unpredictability of sourcing to impaired water. Given this operational and economic conundrum, it should be noted that a number of utilities and utility consortiums have successfully made the transition from fresh to impaired. This has been accomplished by maintaining a successful economic return – both within the operating utility itself and the community at large.

Costs

Chart 2 [2] identifies the comparative raw cost of water worldwide. You will note the United States enjoys a relatively low cost when compared to other locations. One could speculate that this low, first cost poses economic roadblocks to the usage enlargement of impaired water. In many areas of the country, this is a truism.

The first or raw cost of the water is not however, the final cost of treated water. Chart 3 identifies the add-on costs to treat a variety of waters using both "conventional" (chemical) and MF/RO (micro filtration/reverse osmosis) processes.

Chart 2

COUNTRY	WATER COST ($/1,000 gal)	Water Cost ($/m^3)
Germany	$6.70	$1.78
Puerto Rico	$5.00	$1.32
Netherlands	$4.31	$1.14
Italy	$2.75	$0.73
Finland	$2.43	$0.64
S. California	$2.27	$0.60
United States *	$2.06	$0.54
Canada	$1.42	$0.38

Note: Costs west of the Mississippi River can be well above the national average

Chart 3

BASE COST U.S.	CONVENTIONAL TREATMENT	MF/RO TREATMENT
$2.06/1000 gal	$2.84/1000 gal	$2.68/1000 gal

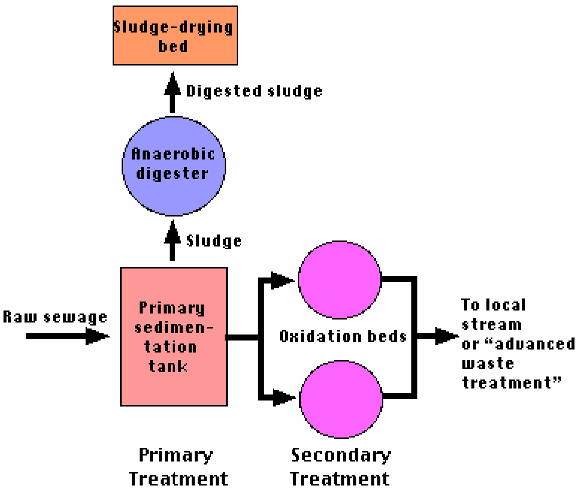
The Process

Each day, U.S. industries consume 25 billion gallons of water all while generating about 20 billion gallons of wastewater. Furthermore, each day, thermoelectric plants in the U.S. consume 186 billion gallons of water. Given the voluminous flows and declining resources, gray or impaired water, as an alternate cooling medium, has emerged as a viable option.

Should sewage effluent be considered as the cooling medium, a first or initial treatment typically takes place at a municipal sewage facility [13] (Graphic 1 & Photos 1 & 2). It is here that raw effluent is processed and treated to physically separate solids from liquids and purify the liquid and includes the following.

> ***Preliminary Treatment***: Solids, such as wood, rags and plastic are removed by screens. This debris is washed, dried and removed for safe disposal. Grit and sand are similarly removed.

Graphic 1
Typical Sewage Treatment Process



Primary Treatment: Remaining solids are separated from the liquid using large, settlement tanks. The settled solids, referred to as sludge, are further treated for use as fertilizers.

Secondary Treatment: Biological or percolating filters break down organic material and purify the liquid. The process can be speeded up using aerating tanks. Further separation to isolate sludge is also required during this treatment phase.

At this point, the sewage or gray water is suitable for transport to the user facility. If further or tertiary treatment is required, final "polishing" may be required before the water is returned to the environment.

Photos 1 & 2
Tolleston, Arizona Wastewater Treatment Facility

Chart 4
Typical Condenser Cooling Water Analysis

Chart 4-1

Parameter	Effluent (mg/l)
Sodium	139
Hardness	320
Calcium	71.6
Magnesium	34.4
Alkalinity	97.2
Carbonate	0
Bicarbonate	119
Chloride	65.2
Fluoride	0.67
Sulfate	312
TDS	730

Chart 4-2

Parameter	Effluent (mg/l)
Fecal Coliform	13
BOD (Biochemical 0xygen Demand)	5.5
TSS (Total Suspended Solids)	5
COD (Chemical Oxygen Demand)	47.3
Nitrate+ite	21
Ammonia	<0.1
TKN (Total Kjeldahl Nitrogen)	2.66
T Phosphorus	2.23
Potassium	10.8
pH	7.49

Chart 4-3

Heavy Metals (total)	Effluent (mg/l)
Aluminum	0.15
Antimony	<0.001

Arsenic	<0.001
Barium	<0.1
Beryllium	<0.001
Boron	0.3
Cadmium	<0.001
Calcium	73
Chromium	0.002
Cobalt	<0.001
Copper	0.01
Iron	0.1
Lead	<0.001
Magnesium	34
Mercury	<0.0002
Molybdenum	0.003
Nickel	<0.01
Selenium	<0.005
Silicon	7.1
Silver	<0.001
Strontium	0.7
Thallium	<0.001
Tin	<0.1
Uranium	0.002
Vanadium	<0.001
Zinc	0.07

Note: The use of sewage effluent represents a dramatic departure from the more historically benign water used for cooling in the past. Chart 4-1 presents an abbreviated water analysis that would typify effluent components that would not present immediate concern to the designer. However, the addition of sewage effluent to the mix (Chart 4-2) dramatically changes not only the water quality but introduces biological considerations tied directly to BOD, COD and TKN requirements. The addition of heavy metals and radioactive materials to the effluent noted in Chart 4-3 further compound treatment requirements.

Once the effluent arrives at the power plant site, it undergoes a series of further treatments (Photos 3 & 4). Initially, trickling filters are employed to reduce ammonia and alkalinity. Additional multi-phase, biochemical treatment processes typically employ clarifiers where phosphates, magnesium, silica and some calcium are removed. A second stage removes much of the calcium-carbonate ($CaCO_3$) using several chemical treatment options. Calcium carbonate, if not addressed, can be a significant source of scale buildup and corrosion concern. Sulfuric acid may be added at this point to reduce pH and chlorine is added to control biological growth. A final gravity filtration will remove remaining suspended solids.

Photos 3 & 4
Palo Verde Wastewater Treatment Plant

Photos 5 & 6
Palo Verde Plant Site & Storage Reservoir

At this point the treatment is complete and the gray water is transferred to storage reservoirs (Photos 5 & 6) and used as tower makeup. In other cases, the treated effluent can be used directly as the main cooling water.

Corrosion Discussion

Calcium Carbonate

The transformation of sewage effluent to gray water – water suitable for use in a powerplant surface condenser produces unusual issues that deserve special attention. The first, which was noted previously, is the identification and reduction of phosphates or calcium carbonate (CaCO3). A recent Xcel Energy study and subsequent ASME [8] paper demonstrated that calcium carbonate can initiate formation after only 1.5 cycles of concentration.

Having duly noting this low level of initiation, typical CaC03 values found in gray water suggest ranges from 68 ppm (City of Amarillo, TX) to 71 ppm (Raton, NM). Xcel Energy [8] has noted in their study that CaCO3 becomes a problem at levels around 15 ppm. Higher cycles of concentration in the tower or the effluent itself could exceed the 15 ppm threshold and precipitate in the form of deposits on the condenser tube ID surface opening up the potential to underdeposit pitting in susceptible tube materials. To minimize the fouling buildup, several solutions are can be employed (Chart 5).

Chart 5

- Ferric sulfate
- Lime
- Soda ash & carbon dioxide gas
- Continuous on-line cleaning
- Oligomers (scale inhibitors)

In many locations, selection of the lime dosing proved the most economical. Others have selected the soda ash/carbon dioxide treatment. Evaluation of scale inhibitors classified as oligomers show promise as they are chlorine resistant [1]. An on-line cleaning system will also prove beneficial if already in place. However, the capitol expenditure of a new unit may prove prohibitive.

Chlorine

A highly effective measure to prevent biocidal growth in all treatment areas typically includes the use of chlorine. This is especially true in pipelines and areas of the treatment that are highly susceptible to the spread of fecal coliform staff infection. Some utilities will use gaseous chlorine sparingly and have eliminated all forms of chlorine shock due to reasons of safety, regulatory and public relations moving instead to bleach/bromide combinations. The use of chlorine in gray water applications is particularly troubling. If the cooling water contains amines or ammonia, chloroamines are formed which consume chlorine increasing the dosage amount to achieve the desire effectiveness.

Manganese

Manganese can also contribute significantly to corrosion concern. Recent research articles identified what they refer to as one of the most interesting and insidious corrosion issues relating to underdeposit pitting in impaired water cooling systems. It has to do with corrosion that is caused by manganese oxide - a phenomena that causes severe pitting on the tubes. The corrosion mechanism is not completely understood, however, it appears that soluble manganese precipitates as manganese dioxide on the condenser tube surface. Indeed, the manganese may be naturally occurring in river or lake water, or in sediments. If sediments become anaerobic, the manganese in them can solubilize. The soluble manganese subsequently oxidizes and precipitates as manganese dioxide on condenser tubes. It can be concluded from the research [5] that the austenitic family of stainless steel tube materials appears particularly susceptible to the phenomenon of manganese induced and under deposit pitting.

Another possible explanation that has been postulated for the corrosion is that oxidizing biocides - such as chlorine - oxidize the manganese oxide to soluble permanganate. This destroys the passive layer on stainless steel and creates cathodic and anodic areas that generate severe pitting. Some researchers also theorize [5] that biofilms themselves can concentrate manganese oxide. When the biofilm contains iron and manganese-oxidizing bacteria, they can create manganese-oxide deposits on the tubing. These deposits may work in conjunction with sulfate-reducing bacteria, creating corrosion cells.

Given the few economic choices and resulting high incidence of chorine usage in impaired or effluent water systems, the chlorine itself may actually exacerbate the corrosion problem. Should the cooling water contain amines or ammonia – clearly present in gray water, chloroamines are formed which consume chlorine and thus increase an ever increasing amount of chlorine required to produce the desired results.

An additional problem with manganese is that it induces pitting by changing the potential of the exposed material. In the case of surface condensers, titanium is immune to this type of attack because it has such a very high pitting potential (on the order of +10V) [6]. Stainless steel, on the other hand, has a pitting potential very close to its rest potential (less than +1V) and can be susceptible to pitting attack when oxidizing compounds are present that raise the potential. Because all stainless materials are susceptible to their own PRE or critical pitting temperature number [11], care must be exercised in the proper material selection when manganese-oxide conditions are present or suspected.

MIC

Invariably, Microbiologically Influenced Corrosion (MIC) must be addressed when employing impaired or gray water. The bacteria present will predictably place susceptible materials in harms way.

The susceptibility of stainless steels to MIC is well documented [6,9,10]. In particular, 304/304L and 316/316L are at risk. Indeed, batch culture tests indicate that all alloys examined at the time (316L, 904L, Al-6X, 254 SMO & 625) are susceptible to MIC attack [10]. Later tests suggest the "N" grade of AL-6X exhibited good resistance to MIC [6]. Considerable testing by the Naval Research Lab [6,11] suggests titanium is immune to MIC – even at elevated temperatures (55 – 70°C).

Floaters and Sinkers

Effluent water quality can vary a great deal from city to city and from source to source. Plastic materials (floaters) can accompany the effluent water floating on the top of clarifiers potentially plugging heat exchanger equipment. Suspended solids and debris (sinkers) tend to form sludge in the cooling tower basin. Initially, chlorine was used to reduce the biological fouling identified as sulfate reducing bacterial. However, heavy chlorine dosing can cause damage to system metallurgy – particularly the brass family of condenser and heat exchanger tubing. Other methods may be employed as a result of this damage potential. Similarly, high concentrations of ammonia will cause harm to copper bearing materials. High BOD also tends to exacerbate the problem.

A Case Study

Over the past several years, an increasing number of new generating facilities have employed the use of gray water in some form of cooling. Typically, the gray water is used either as the principal cooling medium in a tower or similarly, as makeup to same. In some cases, although rare, the impaired water is used in direct, once-through cooling. Delta Energy, Millennium Power Project, Bosque Energy, The City of Lakeland, Florida, Londenderry and PSE&G are just a few of the subscribers to this latest trend. Because of the highly corrosive nature of the cooling medium (treated sewage effluent), PSE&G, Bergen & Linden stations, replaced their new 316 stainless condenser tubing with titanium. Xcel Energy and SWEPCO have employed effluent cooling in some form at their Nichols and Jones Generating stations for almost 40 years

Historically, the recent spate of impaired water usage has been employed for small to mid-size generating units. The Arizona Public Service Palo Verde Generating Station (APS-PV) is the glaring exception in terms of sheer size and historical precedence. Palo Verde is a three-unit, PWR facility generating a total of 3,875 MW and provides electric power to 4 million people in the Southwest. The station has been in operation since 1986 and uses gray water exclusively for cooling. See Chart 6 for plant statistics.

Cooling Water

Raw sewage, received from the greater Phoenix area, is initially treated at the Tolleston, AZ Municipal Sewage plant before transport approximately 45 miles via a 96" diameter line to Palo Verde. Additional treatment is completed at the APS-PV facility and purified water is pumped to the on-site storage reservoir for use in the closed loop condenser/tower circuit.

Note: The nearby Redhawk CCGT merchant power plant also uses a partial flow of the effluent produced by the APS-PV generating station.

Photos 7 & 8
Palo Verde Storage Reservoir & Cooling Towers

Three (3), APS-PV mechanical forced-draft cooling towers service each generating unit (Photos 7 & 8). As a result of the impaired water usage over time, corrosion of exposed rebar and spalling of the concrete into a gelatinous substance has occurred over the operational years due to the continuous wet/dry cycling. Chlorinating has been used to successfully combat the algae growth. The tower operates at 25 concentration cycles resulting in salinity approaching and in some cases, exceeding seawater. Once this concentration is reached, the water is discharged to evaporation ponds.

Chart 6

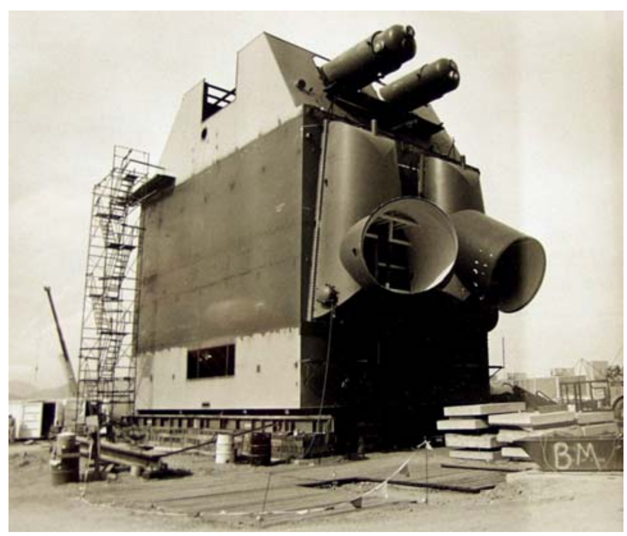
DISTANCE SEWAGE PUMPED	**45 MILES**
DIAMATER OF PIPE	**96"**
SEWAGE PLANT FLOW	**58 MILLION GALLONS/DAY**
APS-PV WATER RECLAMINATION CAP	**90 MILLION GALLONS/DAY**
STORAGE RESERVOIR	**670 MILLION GALLONS 80 ACRES**
TOWER EVAPORATION (av.)	**14,000 GAL/MIN/UNIT**
TOWER BLOWDOWN (av.)	**865 Gal/min/unit**
EVAPORATION POND	**250 ACRES – 2 PONDS**
TOWER CONCENTRATION CYCLES	**≥ 25**

Condenser

A Marley, 3-pressure, 3-shell surface condenser was field erected and tubed (Photo 9) at the APS-PV site. In classic multi-pressure, variable tube length configuration, the CIRH20 is series connected in a parallel path (allowing bundle isolation) from the LP to IP to HP shell (Graphic 2). The cycle is completed with shell C discharging to the cooling tower. Because of the corrodents present in the cooling water, the tube material was changed from stainless steel to titanium after cage assembly/fabrication but prior to tubing. The tube bundles were later staked to prevent the onset of damaging vibration due to the excessively large support plate spacing. The tubesheets are Al. Bronze with mechanically expanded tube joints. The tubesheets are coated at the inlet end but not at the discharge. All 12 water boxes are coated with presumably, an epoxy coating.

It is of keen interest to examine the overall performance and integrity of this condenser given its considerable service life, after-the-fact tube material selection, galvanically dissimilar tubesheet material, tube-tubesheet joint configuration, coating philosophy and above all, the aggressive water chemistry. Let us consider the following after nearly 20 years of service life.

Photo 9
On-site Surface Condenser Erection (1 of 6 shells)



(Circa 1985)

1. No titanium tubing corrosion has taken place.

2. The integrity of the tube-to-tubesheet joint appears to remain viable.
3. Coating the inlet tubesheet has apparently halted some initial erosion of the Al. Bronze material. The initial erosion may have been galvanically induced.

4. Some fatigue failures of the titanium tubes were attributed to excessive support plate spacing. Staking successfully addressed this issue.

5. Several tube failures resulted from poor design of the cold water discharge spargers.

6. Some minor steam erosion has been detected on the tube OD at the top of the bundle.

7. Mechanical scrapers are used to keep the tubes clean. Little to no ID buildup has been observed using this cleaning method.

Conclusion

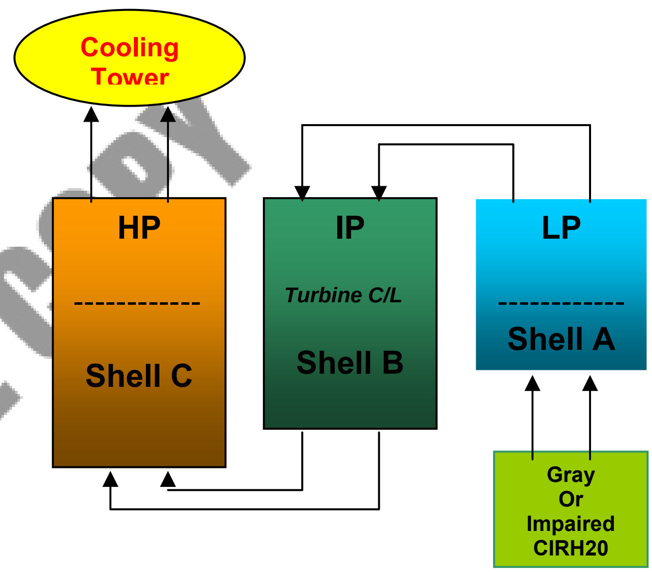
The remarkable and increasing use of sewage effluent to cool powerplant component systems including main surface condensers and ancillary heat exchangers has been successfully demonstrated at many locations where fresh water is unavailable, not usable or too costly. Impaired or gray water, given proper treatment, has emerged as an economically viable and highly sustainable resource. As a result, it becomes clear that water reuse will increase dramatically over the next 10 years notwithstanding the invasion of regulatory complexities that could derail this continued growth pattern.

The paper followed the transformation process from effluent to potable water taking on the nuances of multi-phase treatments, attendant corrosion mitigation and metallurgical “red flags”. Considerable dialog was spent on the manganese and chlorine issues – issues that can dramatically impact the operational competency of the system.

User experience suggests chemical treatments and material selections should be implemented based solely on good engineering practice. Engineers need to take a highly pragmatic view when considering material options, limitations and selection within the operating environment.

Finally, a brief case history study of the APS - Palo Verde experience demonstrated that these practices can be successfully implemented on a long-term basis within the operating environment. Proven technologies and good engineering practices, not myopic speculation must be employed when operating in such a volatile system.

Graphic 2
SIMPLIFIED CONDENSER SCHEMATIC



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