Protective Thin Film Coatings Applications for Tubular Equipment

Best maintenance practice extends the life of the equipment, and improves plant asset utilization, production reliability and operational excellence

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Operational disruption, equipment downtime and unscheduled, unplanned maintenance contribute to lower operational margins and regular maintenance expense. Corrosive and mineral laden fluids leave deposits on the water side surface areas of condenser and exchanger tubes; regular maintenance of tubular equipment is a major economic event for operations. Chemical treatment in water discharge systems have become more restrictive and in some cases less prevalent in recent years.

Power plant operators who pay attention to the small details involved in the proper maintenance of tubular systems in condensers, heat exchangers and other heat transfer equipment can realize significant cost savings. By minimizing downtime, increasing energy efficiency and minimizing turbine backpressure, plant operations are more predictable. Heat exchanger fouling is a major economic problem, and maintenance costs are estimated to account for 0.25% of the world GDP.[1]

An innovative way to cut plant and equipment downtime, recover energy efficiency, and achieve fewer stoppages for routine maintenance is by using thin film polymer coatings applied to full length tube IDs. Alloy materials were is short supply during vast infrastructure rebuilding after World War II when engineers at Dow/Bayer Chemicals first developed phenolic materials for tube ID coatings in the 1950s. Applied by a “fill, drain, rotate” method in specialized coating shops, the IDs of carbon steel tubes in heat-transfer equipment, such as heat exchangers, were protected from scaling typically associated with cooling water in heat transfer systems. The advantages of coating metallic tubing rather than leaving it bare in these conditions are numerous, providing long term benefits in corrosion control and fouling protection for heat-exchanger maintenance.

Since those formative years, advances in application technology, surface preparation, and the continued use of ambient cured phenol epoxy materials have promoted this as a viable “in-field” application. It took decades of trial and error to find the right solutions for each ID, bare metal, and chemical coating compound to optimize the practice for each and every application. Today, ID coatings are considered a best practice for extending the performance and lifecycle of a heat-transfer system.

Corrosion, Deposition, and Fouling

Microorganisms that draw nutrients from cooling water inside tubes cause bacterial build-up and fouling, and represent the most common way that corrosion cells are created inside condensers and heat exchangers. The bacteria breed quickly in the nutrient-rich environment, enhanced by certain chemical processes and the lack of light inside the tubes.

Each corrosion cell creates a pit – a place for bacteria to further multiply and hide – that leads to intricate bacterial structures that rapidly advance corrosion to inefficient and even dangerous blockages. Such bacterial pits can cause electrochemical changes inside tubes that exacerbate the damage.

The interactions of various cooling waters with the materials used to create these cooling water systems have spurred larger numbers of water chemists and cleaning services contractors that now thrive in our industries.

Fouling typically falls into the following discrete categories:

- Micro and macro biological fouling — aerobic and non-aerobic—bio-fouling
- Particulate—silt, mud, and sand—insoluble products, suspended solids, sediment or silt accumulation
- Crystalline— calcium carbonates, sulfates
- Corrosion—metals are oxidized, metal fluid reactions

- Chemical reaction—petroleum refining and polymer production interactions.[2]

Fluids, by their very nature, have always posed a difficulty for efficiently running heat-exchanger equipment as they come into contact with the metallic tube surfaces. Traditionally, water treatment and periodic cleaning by hydroblasting managed the cleaning process, but the results were not always optimal. Increasingly, users are applying polymer coatings to the tubular inner and outer diameters (ID and OD) of the heat-transfer apparatus. Table 1 shows the effects of flow on relative fouling when the temperature is constant and the effects of surface temperature on relative fouling when the flow is constant.

Table 1:

Type of Fouling	Effect of Temperature	Effect of Flow
Crystalline fouling	Increases with temperature	Deceases >0.5 m/s
Biological fouling	Decreases at >50C, no effect at >140C	Decreases > 0.7 m/s, stops >2.2 m/s
Particulate fouling	Increases with temperature	Stops >1.7 m/s
Corrosion fouling	Decrease slightly at >50C	Decreases >1.2 m/s

[3]

Generally, tube fouling and pitting can be corrected in several ways: cleaning, chemical treatment and retubing. But none of these options is as viable or cost-effective as coatings.

Cleaning

Because of the bacterial component of pitting, removal of tube deposits and adoption of better methods for tube cleaning can halt deterioration, or at least stabilize the rate. Deep pits can be identified through eddy testing and preventatively plugged prior to cleaning. Rough cleaning can be accomplished by brushes and scrapers, or by using hydrolyzing or sponge balls. Tubes need to be decontaminated as well. Low chloride potable water that has been demineralized, or water conditioned with a chloride neutralizer can flush out contaminating chlorides. Finally, abrasive blasting to remove the last vestiges of contamination in the tubing should then be deployed.

Chemical Treatment

Biocides or oxidizing agents can be used on the tubes to control biological activity. Biostats can be used after a biocide treatment to control future growth, a milder form of chemical control. In recent years, chemical treatment has fallen out of favor due to the toxic nature of the chemicals used.

Retubing

If severe pitting cannot be alleviated, complete retubing of the heat exchanger may be called for, particularly in older equipment that has run for consecutive years. Choosing a more appropriate tube material or accelerating maintenance can stave off recurring fouling and corrosive conditions; however, this option is extremely costly and may have to be done several times to prolong the working life of the apparatus. The bare tube surface will inevitably sustain pitting and bacterial build-up as long as they remain uncoated.

Surface Preparation of Tube IDs

In early attempts to clean small diameter tubes for coating, little was know about effective cleaning practices. The systems used standard sandblasting nozzles, attempts to lance tubes was ineffective, and for in-situ projects improbable. Achieving a NACE 1 specification to full length tube IDs required long dwell times, impacting overall project efficiency.

A gas dynamics lab at a university in the Northeastern U.S. had previously researched the grit-blast nozzle design. They were provided data to develop a new design for a grit-blasting nozzle specifically to clean tube IDs. Typical sandblast nozzles attained an air speed of 340 m/s and grit velocity of 130 m/s, which was inadequate to maintain the grit velocity (kinetic energy) needed to clean tubes more than 3-meters) long. The new design increased air speed to 680 m/s, or “Mach II”,” and grit velocity to 243 m/s. This increased the kinetic energy in the grit particles by 81 percent, and proved highly effective as a tube

ID cleaning method. Grit blasting using this special sandblast nozzle has since become the standard cleaning method for tubes prior to coating.

Unlike hydroblasting, this cleaning process is highly predictable in getting the cleanliness results acceptable for the varied inspection methods. Video probe inspections also verify tube cleanliness, helping companies comply with the rigorous standards demanded by the industry. Inspections have always sought reliable, verifiable and predictable methods to ensure these cleanliness standards are met and applied consistently. **See supplemental image #1 at end of document.**

Grit blasting has proven so effective that it is now widely used to clean tubes with tenaciously adhered deposits that UHP (ultra-high pressure) water jetting could not remove. An entire industry has grown out of the need to clean tubes prior to LOTIS, IRIS, RFET, and other NDT inspections.
While the grit cleaning method has been widely adapted for heat-exchanger tube cleaning, the question of tube wall erosion due to the cleaning procedures has also been raised and studied by certain end users and initially by EPRI. Using 90/10 Cu/Ni (copper/nickel) tubes to test the benchmark; the average dwell time is 30 seconds for grit-cleaning tubes to NACE 1, which is the standard for white metal cleanliness. After repeated tests of up to 10 minutes dwell time, no measurable wall loss occurred.

A helpful advance in surface preparation occurred in the use of high-resolution video probes to verify tube interior cleanliness for grit blasting. The latest video probes can now identify extremely small surface imperfections, making is easier to spot residual scale and confirm surface cleanliness, matching it to the industry standard.

History of Polymer Tube Coating

Corrosive and mineral-laden fluids that come into contact with heat transfer surfaces have always left unwanted residue and resulted in longer term ill effects that break down the surface of tubing in heat-exchanger equipment. Historically, water treatment and periodic cleaning by hydroblasting could usually stave off such deterioration, but the results were not always optimal.

More often than not, today's power plants and electric utilities operators are applying polymer coatings to the tubular inner and outer diameters (ID and OD) of their heat-transfer apparatus. This practice has evolved and matured into a cost-effective remedy to reduce typical fouling and corrosion problems intrinsic to such equipment. Improvements in coating materials, surface preparation, application and thermal conductivity, plus owner-operator data collection and analysis, have propelled tubular coatings toward viable heat transfer equipment problem solving.

Since the early years when a German chemical supplier first developed heat-catalyzed phenolic materials for tube ID coatings in the 1950s in Germany much progress has been made in application techniques. Traditional "fill, drain, rotate" methods were performed in specialized shop, this was the industry's best option until the mid-1980s. Companies in Italy began experimenting with air-atomized spray applications of ambient cured epoxy phenolic; they hoped tube coating of condensers would alleviate the huge volume of effluent discharge contaminating the cooling water inlets with a rich broth of bacterial nutrients at several power stations. This was causing excessive biological fouling in the main steam-condenser tubes, adversely affecting condenser efficiency and power-generation capacity. By coating the copper-nickel tube interior with the epoxy phenolic compound, the Italians achieved excellent results and improved fouling and corrosion resistance to the main condensers, which actually restored the generating units to normal operating capacity.

Across the Atlantic, a Florida-based utility was experiencing rapid-through wall leaks two years after a retubing. In 1990, in collaboration with the Electric Power Research Institute (EPRI), they initiated a joint study to investigate alternatives to expensive retubing. Together, both organizations experimented with coating the tube ID with epoxies as a best practice. They brought the Italian engineers to Crystal River, Florida, to demonstrate their technology at a corporate power-generation site. The joint testing revealed some invaluable findings about tubular coating materials, surface preparation and cleanliness. It also confirmed that a uniform layer of coating was an effective solution. Over the years, this practice has evolved and matured into a cost-effective remedy to reduce typical fouling and corrosion problems intrinsic to this equipment. Improvements in materials, surface preparation, application techniques and thermal conductivity, plus owner-operator data collection and analysis, have established tubular coatings as viable heat-transfer equipment (HTE) problem solvers.

Application Development

Earlier application methods by fill, drain and rotate worked well enough but could not be done on-site, in situ. These also required high-solvent loading to control thickness and prevent coating set-up before solvent flash-off. Since solvents are recognized as being hazardous environmental contaminants, such practices are being phased out.

Application method refinements with the spray application approach apply a reliable, uniform layer of coating. Current application equipment can actually coat up to four tubes at a time at speeds of 2 meters/second. Spray methods also allow for application of different coatings and solids content to 100 percent. Using this spray method has yielded less than 37.5-microns differential in dry-film thickness (DFT) for the tube ID circumference. Coatings can be applied to a pinhole-free condition and verified with a full-length holiday test designed specifically for tube ID. Curing of the amine epoxy may be accelerated by using commercially available heat. **See supplemental image #2 at end of document.**

Coating Materials

Polymer materials for heat-transfer equipment as a group are limited generally by materials that are functional at less than 300 microns DFT to avoid impacting heat transfer. Common coatings falling into this category and used for the heat exchanger ID coating include epoxy phenolic, novolac epoxy, baked phenolics, and thermoplastics. Coatings are chosen according to the service temperature and conditions in which they are to be applied, and how the application will occur -- for example, whether it is field or shop-applied.

Coating Material	% Solids	Temperature Limits – water/steam	Catalyst
Epoxy Phenolic	67%	135C	Amine cured
Novolac Epoxy	100%	135C	Amine Cured
Baked Phenolic (2)	65%	150C	Heat Cured – 200C
Thermoplastics	--	250C in low pH, 150C in acidic brine	Heat Cured – 250C
Bisphenol A	100%	80C	Amine Cured

Tube interior coatings can be inspected with similar tank lining methods adapted specifically for small ID tubes. Blotter tests of black light examination can confirm or eliminate the presence of hydrocarbons. Chloride testing is also viable, but usually on tube sheet areas. The most limited QA issue concerns DFT readings. Current instrumentation can only reach six inches (150mm) into the tube-end to verify adherence to the specification. If additional verification is needed, sample tubes can be coated, split and measured for verification of minimum DFT throughout the tube. Holiday testing can then be accomplished with high or low-voltage methods, adapted to reach all the way through the tube, with the sponges/brushes sized to fit snugly into the tube ID.

Thermal Conductivity

Polymer tube linings have always suffered from a perception of heat transfer penalties due to their lower thermal conductivities vis-à-vis metallurgy but case history has demonstrated just the opposite. Decades of service history have shown that tube coatings can actually enhance heat transfer and overall performance to a significant degree. While the thermal conductivity of the coating is much less than the parent tube, its impact is offset by several factors.

The first factor covers normal design considerations. Generally, heat exchangers in petrochemical and refinery operations are designed with a fouling factor of .001 or .002 inches. Adding a coating to the tube ID impacts the thermal duty by a factor of .0006-8 inches at full-dry film thickness, which is well below the pre-calculated design. Applying the coating either totally eliminates the subsequent fouling or greatly reduces the accumulation of typical micro-/macro-fouling, mitigating the initial design consideration.

The second major factor is the boundary layer-drag reduction. Fully 70 percent of total heat transfer resistance (HTR) across a heat exchanger tube is the slow-moving fluid coming into contact with the tube wall. Tube wall friction reduces this flow and creates an insulating barrier of low velocity fluid. Polymer coatings reduce the surface tension at the tube wall substantially, by a factor of 30 to 40 dynes per cm^2 compared to metallurgy in a non-oxidized or new condition. Reducing friction reduces the boundary layer drag and substantially opens up the flow profile. Two separate studies show flow rate improvements of 80 to 100 percent with polymer coatings compared to new uncoated tubes in the same fluid train. This increase in flow and low surface energy of the coating contributes to the improved overall thermal efficiency of the heat exchanger in fluid service.

The opportunity to optimize heat transfer performance of thin film epoxy coatings shows potential; by loading pigments in epoxy material heat transfer performance may improved almost 2X. Tubes coated with thermal enhancing pigment loaded in the epoxy phenolic using spray applied method were evaluated by a South Africa power company.[4]

21 mm brass tube x 2.3 mm wall - conditions	**Thermal conductivity w/mK**
Heavily scaled - <0.150 mm	14.9
100% solids – applied at 75 microns average	2.737
Epoxy phenolic – applied at 75 microns average	8.82
Epoxy phenolic – 3% pigment loading	14.764

Best Practices

Applying polymer coatings to the ID of heat transfer equipment can provide benefits such as increased heat transfer duty, eliminating corrosion, reducing micro- and macro-fouling and associated cleaning cycles, increasing process throughput, and providing perpetual equipment life with recoating.

Certain extreme chemical exposures, temperatures, and high fluid or gas velocities can limit the efficacy of coatings. However, great benefits can be realized through applying coatings in the acceptable temperature and exposure that corresponds to the coating properties, guided by quality assurance (QA) techniques. Coating the ID of small-diameter and long-length tubes is working effectively, a full QA of every phase of surface preparation, coating application, and holiday testing can be adapted from today's current immersion lining standards.

The methodology is now well proven and utilized by the world's largest companies. Now there are more approaches to produce the desired outcomes and reduce the losses incurred through inefficient heat transfer in power generation and petrochemical refining. The best approach is to consider the various conditions and use the most efficient method to clean and coat the tubular systems.

CASE STUDIES

Coatings a Ship Condenser, In-Situ

A steam freighter sailing the Pacific experienced frequent downtime due to aggressive pitting and through-wall corrosion of its main 90/10 Cu/Ni (copper-nickel alloy) steam condenser tubes supporting steam turbine propulsion in the engine room. The corrosion came mainly from under-deposit corrosion developing beneath many layers of scale. The Cu/Ni tubes in the condenser are used to condense the steam that is created by boiler heat. The more efficiently the condenser can convert the steam to liquid, the greater is the pressure differential across the turbine, and the more energy-efficient is the power plant in the ship.

With corroded tubing in the condenser, the ship's operations were becoming less reliable, the vacuum was suboptimal tube leaks and plugging, and maintenance was more frequent than the ship's captain and crew had planned. Traditional sawdust injection was maintaining the condenser leaks from port to port but an enormous amount of water treatment was needed to maintain boiler water purity.

As a result, they were spending more time in port to get the tubes cleaned, perform eddy current testing and subsequent tube plugging than they anticipated, eking out as much turbine efficiency as possible under the circumstances. When the ship finally docked at its home port in the US, the maintenance crew knew that something had to be done. The tubes were more than 20 years old and had served the vessel well. The ship owners wanted to operate this ship another five years and were faced with a decision to retube the condenser or try an new approach that had been successful in power plant condensers since 1990, epoxy coating of the full length tube ID.

The problem was complicated because the condensers were located deep in the ship's bowels near the boiler room, where space is limited. Alternatively, it would be extremely difficult, at best, to physically remove the huge condensers and bring them to a repair facility for cleaning and renovation. Many factors played into in the decision to repair the condenser tubes, not least was the potential impact of ship maintenance on transport schedules and the financial considerations of putting the ship out of commercial commission for an extended period of time.

Project Evaluation

Sample tubes pulled from the condenser showed spherical cavities containing crystalline chlorides, calcium, and sulfides along the tubing's inner diameters. Substantial pit fields surrounded multiple through-wall pits in one of the specimen tubes, and there were active under-deposit corrosion cells where scale was partially removed. Ship management preferred to avoid a costly retubing, which would run close to $1 million for a ship that might only be in service for another five years.

Each condenser bundle was about 6 meters long, and the entire interior diameters (IDs) of each separate tube was to be treated with the special formulated, thermally conductive, protective coating of an epoxy material. The coating scope was for 6,000 tubes x 17.5mm x 6 meters long, all work to be performed below the ship's decks. Tube IDs and tubesheets were grit-blasted clean to NACE 1 (white metal) standards so that all soluble contaminants were removed from full length IDs and tubesheets prior to coating. The full-length tubes were prepped and fully coated with a thin-film epoxy 50-75 microns. Forced curing of the application readied the condenser for service in less than 9 days.

Since returning to service the ships engineer reported a 25 percent improvement in "overboard" sea temperature change, as well as an improvement in condenser/turbine vacuum, brought about by a significant drop in steam pressure caused by the efficient cooling tube bundles of the condenser. Boiler chlorides remained at steady measures. The ship was sailing again after only an abbreviated stopover for repairs.

Economics

Most ship operators are familiar with metallic inserts installed in either the inlet or outlet tubes. This has been a common method for "life extension" of ship heat transfer equipment. Epoxy coatings can provide the same type of protection but can now be extended full length of the tube. In the last several years, new technology has made it possible to perform polymer epoxy tube ID coating without the full removal of the condensers. By adapting the equipment to apply a uniform layer of epoxy even in tight areas, coatings can be applied with minimum time and within a fraction of the cost of retubing.

Retubing a ship board condenser is estimated at 5x the cost of performing the coating application, according to some industry sources. "In-situ" project capabilities also give coatings a significant edge when evaluating comparable schedules of retubing versus coating. Using stainless or copper alloy tubes the cost for tubing alone will be 3X the cost of coating. After more than three years of service, the ship has not experienced a single tube leak nor has its condenser had to be opened for tube cleaning. The client had since coated two more steam ships in its fleet, citing the benefits of coating.

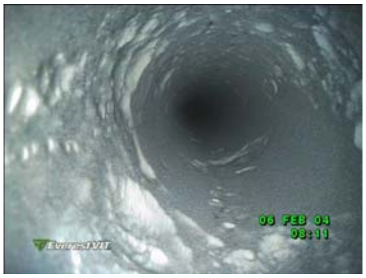
Petrochemical Refinery learns "It Pays to Coat Tubes"

At a petrochemical refinery, six heat exchangers in the catalytic cracker recovery unit's refrigeration section required maintenance. They were not operating efficiently, and upon examination, the diagnosis was severe tube corrosion and pitting. Two of the six exchangers required complete retubings due to age and damage over time. The four remaining exchangers had only been operating for three years, but still had telltale wear and tear, corrosion and pitting.

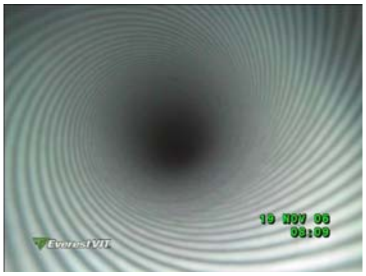
The refinery management opted to apply coatings to all six exchangers to prevent further damage and to decrease fouling from sulfate-reducing bacteria. By coating all the equipment, preventive maintenance in future would suffice to reduce stoppages, leak repairs, replacements and the need for any retubings – and the unit would see better performance from the equipment in the refrigeration area.

The results the refinery realized in taking the preventive measure of coating the tubes in six of their heat exchangers included improved pressure, measured in PSI. The two older heat exchangers ran at more than 230 PSI before retubing and coating. Afterwards, the coolant fluid pressure dropped 10% and remained steady within a range of 190 to 200 PSI, a desirable metric in its consistency. The additional cooling eliminated all gas recycling and kept the unit at a 96% recovery rate, even in the hottest summer months. Additional recovery netted 1000 BPD. Previous cleaning cycles for each exchanger averaged six months at 4 months each, and lost production of 10,000 BPD. During their first three years of "bare" pipe service, the four younger exchangers experienced an increase of pressure drop by 15 psi per year. Once the tubes were coated, the pressure performance stabilized.

The refinery expects a 10-year minimum coating life for the exchangers, barring some minor tube-sheet touchups during maintenance periods. After a decade, the tube bundles may need to be grit-blasted and recoated if needed, but the life expectancy of the heat-transfer equipment is expected to exceed 20 years, conservatively, and the maintenance required is extremely minimal compared to the bare pipe alternative.



Supplemental image #1: Image taken down tube, 0.20mm OD tube x 6 meters long; exchanger in cooling water service, tube ID heavily pitted as a result of cooling water.
Tube ID surface prep cleaned tube ID to NACE 1 "white metal" for full length ID coating application.



Supplemental Image #2: "Enhanced" chiller tube, 0.20mm OD, image taken after surface prep and coating application of ~75 microns DFT. Homogenous film of epoxy phenolic material was spray applied to full length tube IDs, all work was performed "in-situ" at the client location.

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References

1-3 "Coatings in Power Plants: Controlling Fouling and Corrosion in Tubing," JPCL November 2005, by Bruce Woodruff, Corr-Coat Consulting.

4. Thermal-Flow Performance Characteristics of Condenser Tubes,” W. Honing and D.G. Kruoger, Institute for Thermodynamics and Mechanics, Department of Mechanical Engineering, University of Stellenbosch, Stellenbosch, South Africa, January 2006.