

Solving Heat Exchanger Tube Problems with Thin Film Thermally Conductive Coating Applications and Novel Tube and Pipe Cleaning as a Precursor to Coating Application and NDT

BEST MAINTENANCE PRACTICE EXTENDS THE LIFE OF HEAT EXCHANGER TUBES INDEFINITELY, ELIMINATE SCALING DEPOSITION SOLVES AGGRESSIVE EROSION AND CORROSION PROBLEMS, AND MAINTAINS OPTIMUM HEAT RATES.

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Abstract

Corrosive and mineral laden fluids leave deposits on the water side surface areas of condenser and exchanger tubes; contributing to regular maintenance needs of tubular equipment and is a major economic event for operations. Operational disruption to find tube leaks or clean tubes for efficiency improvements contribute to higher operational margins, lower unit availability, and higher energy costs.

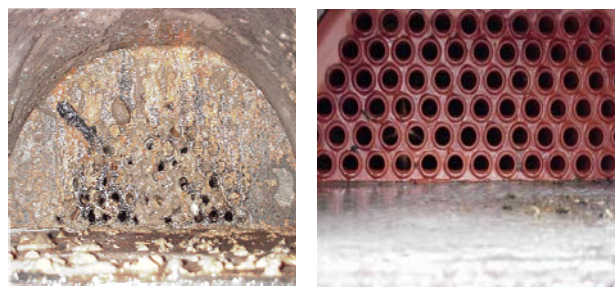


Figure 1

Cooling water exchanger bundles, uncoated and coated, after one year in same service. Coated exchangers improve the release properties of steel, reducing or eliminating scale and fouling deposits. Thin film coatings have been used to improve performance of carbon steel cooling water exchangers for more than 50 years.

Heat exchanger fouling is a major economic problem, and maintenance costs are estimated to account for 0.25% of the world GDP. To remain competitive and reduce energy costs power plant operators must pay attention to the small details involved in the proper maintenance of tubular systems in condensers, heat exchangers and other heat transfer equipment to realize significant savings. By utilizing the best available technology reliability, and energy efficiency gains can be realized.¹

Another method 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. This process developed in the 1980's has matured into a viable, low cost procedure to solve heat exchanger tube fouling and corrosion problems.

History

Shop applied tube ID coatings have been in use since the 1950s and account for millions of coated tubes in service for decades. Applied by a "fill, drain, rotate" method in specialized coating shops, the IDs of tubes in heat-transfer equipment have been successfully protected from scaling and corrosion typically associated with cooling water in heat transfer systems. During the mid 1980's an Italian power plant had been experiencing extremely high fouling rates in its condensers. Effluent discharge being pulled into the cooling water inlets produced a rich broth of bacterial and mineral components at several power stations. The resulting excessive fouling in the main steam condenser tubes, adversely affected condenser efficiency and power-generation capacity. A local engineer with shop applied tube coating experience developed an in-situ air-atomized spray applications of ambient cured epoxy phenolic to help solve this problem. By coating the copper-nickel tube interior with the epoxy phenolic compound, the Italians achieved excellent results of fouling and corrosion resistance to the main condensers, and restored the generating units to normal operating capacity.

In the late 80's a Florida generating station with a recent retube began experiencing through wall leaks. They began searching for alternatives to retubing which led to a collaborative effort to investigate tube ID coatings with EPRI. The EPRI project TR-107068 researched coating material, heat transfer resistance, wear resistance, back pressure, and other related quantitative variables. A trial application in 1993 of 6,000 tubes of a 12,000 tube condenser provided performance data for more than three years and demonstrated better heat transfer performance from the coated condenser tubes, proving the viability of the process. A final EPRI report was published in 1997 with the coated tubes still in operation.

As a result of the EPRI study commercial in situ applications began operations in the USA in 1995. Cleaning methods, coating materials, thermal conductivity, and application equipment have evolved over the last 15 years to become an on going industry that cleans and coats millions of tubes per year.

Methods

Technology Improvements: Surface Preparation of Tube IDs

In EPRI and earlier attempts to clean small diameter tubes for coating, little was known about effective cleaning practices. Earlier systems used standard sandblasting nozzles which consumed vast amounts of time and cleaning grit. At times the middle third of the tubes would not clean to a satisfactory standard for coating application. Achieving a NACE 1 specification to full length tube IDs required long dwell times, impacting overall project efficiency. Trials to lance blast tubes were effective, but for in-situ projects improbable because of the need for water box removal.

A gas dynamics lab at a Northeastern University had previously researched the grit-blast nozzle design and optimization of design for maximum grit velocity. 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 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 nozzle has since become the standard cleaning method for tubes prior to coating.

Unlike hydroblasting, this cleaning process is highly predictable in achieving the cleanliness results acceptable for the varied inspection methods utilized in condenser tubes. Video probe inspections also verify tube cleanliness and surface profile, helping project managers comply with NACE/SSPC standards demanded by the industry.



Figure 2

Carbon steel scaled tube on the left and again after a 30 second grit cleaning session

Grit blasting has proven so effective that it is now widely used to clean tubes with tenaciously adhered deposits that UHP (ultra-high pressure, 2000+ bars) water jetting could not remove. (Table 1) An entire industry has grown out of the need to clean tubes prior to LOTIS, IRIS, RFET, and other NDT inspections.

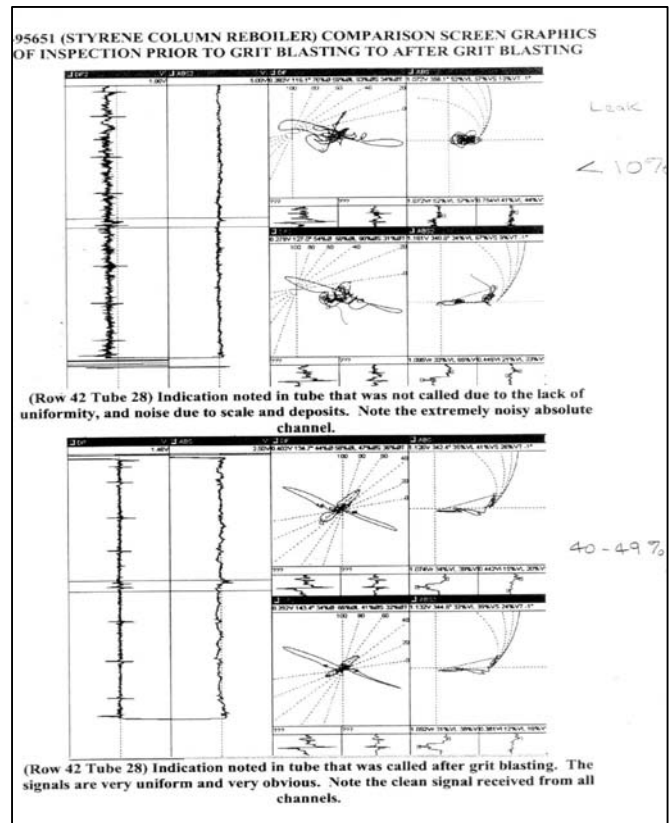


Figure 3

Images were captured by NDE company performing RFT evaluation of carbon steel tubes for a Houston area chemical plant. The same tube was inspected after hydroblast cleaning, the top record, and dry abrasive cleaning. The inspector noted the "extremely noisy absolute channel" due to scale and deposits post hydroblasting. The dry abrasive cleaned the tube of all scale and deposits, making for a "clean signal from the probe. As tubes are cleaner, a larger "fill factor" is enabled.

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 several end users and initially by EPRI. Using 90/10 Cu/Ni (copper/nickel) tubes to test for benchmarking; tubes were abrasive blasted up to 3 minutes with no measurable wall loss. We have repeated the test with up to 8 minute dwell time on carbon steel tubes and again no measurable wall loss. These findings were verified by direct micrometer measurement and IRIS inspection. Average dwell time for cleaning tubes to NACE 1/SSPC 5 which is the standard for white metal cleanliness, is 30 seconds.

Another 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 it easier to spot residual scale and confirm surface cleanliness.

Application Development

Earlier application methods by fill, drain and rotate worked well enough and continue to be practiced, but could not be done 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, these systems will have a limited future without reformulating the coatings.

Air atomized applications left uneven distribution of coating as pumps cycled the coating was distributed on the tube wall in rings of high and low coverage

The best application method for tube id spray application utilizes high pressure airless pumps which apply a reliable, uniform layer of coating. Current application equipment can coat 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. This equipment with greater than 99% reliability, coats millions of tubes annually and has been key in development of the industry since organic coatings are not normally applied to blind areas

Coating Materials

Polymer materials for condenser tubes as a group are limited generally by materials that are functional at less than 100 microns DFT to avoid impacting heat transfer. Common coatings falling into this category for condenser tube ID coating include epoxy phenolic, novolac epoxy, baked phenolics, fluoropolymers, 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 or whether it is heat cured or ambient cured. Table 2 describes the most common groups and their service temperatures.

Coating Material	% Solids	Temperature Limits – water/steam	Catalyst
Epoxy Phenolic	67%	120C	Amine cured
Novolac Epoxy	100%	120C	Amine Cured
Baked Phenolic (2)	65%	150C	Heat Cured – 200C
Thermoplastics	100%	200C	Heat Cured – 325C
Bisphenol A	100%	80C	Amine Cured

Table 2

Typical heat exchanger applications have been with epoxy phenolic, epoxy novolac, and bisphenol A resins. Formulations have included PTFE, carbon based pigments, pure fluoropolymers, and other pigments to further enhance foul release properties.

Thermal Conductivity

Polymer tube linings have always suffered from an initial perception of heat transfer penalties due to their lower thermal conductivities vis-à-vis metallurgy but quantitative data and strong long term case history has demonstrated just the opposite. Decades of service history have shown that tube coatings can enhance heat transfer and overall performance to a significant degree. While the thermal conductivity of the coating is much less than the parent tube, this factor is mitigated by inherent properties of the coating. There have been four major studies performed on coated condenser tubes. Two by universities and two by commercial vendors. In each case the impact to overall thermal conductivity was nil or minor. Table 4 details the results from the University of Stellenbosch, that compared the 75 micron coating to a 150 micron layer of scale. The University of Thailand study determined that when relating the coating to the actual tube wall, that when new and not oxidized or scaled, is 2% of the overall HTR equation (Table 3) the coated tube wall resistance increased to just 2.38% of the total HTR which again is minimal

Another factor covers normal design considerations. Generally, HEI and TEMA design condensers to operate 85% capacity, or with 15 % of the tubes plugged without effecting turbine performance. Fouling factors are also built into the equation to add additional performance hedging into the 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. (table 3) 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, to 30 - 40 dynes per cm² compared to metallurgy (1200 dynes/cm²) in a non-oxidized or new condition. Tube wall oxidation or scaling would increase this friction by multiples. 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. This increased flow at the tube wall also inhibits nucleation site for micro and macro scaling deposition to begin. An added benefit and energy saving is the reduction of energy needed to power circulation pumps.

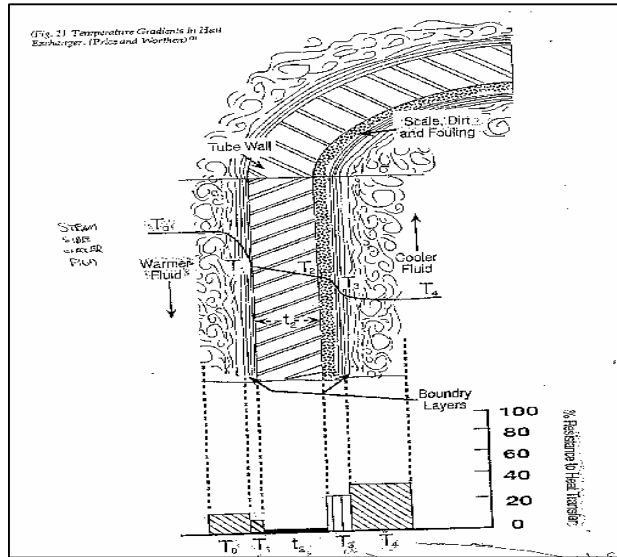


Figure 4

The EPRI study contributed significant thermal conductivity studies of various polymer coating resins. Significant differences were identified even between resin groups. By utilizing the best of these earlier identified resins and adding newer pigments that were not available during the EPRI study thermal conductivity of polymer coating has been significantly improved to 4x the level achieved during the study

21 mm brass tube x 2.3 mm wall - conditions	Thermal conductivity w/mK
Average 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 – proprietary pigment loading	14.764

Table 3

Quality Control

Tube interior coatings can be inspected with similar tank lining methods adapted specifically for small ID tubes. Blotter tests or 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 1 meter 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

Results

Since 1995 over 20 million tubes have been coated. The following are general heat exchanger problems that coatings have solved.

Under deposit corrosion.

Copper alloyed tubes have been the mainstay of condenser metallurgy because of their superior heat transfer and resistance to sea and lake water corrosion. Scale accumulation, however can be detrimental to the tube with resulting under deposit corrosion. Removal of the scale and application of coating has eliminated under deposit corrosion.

Fouling.

Smooth polymer linings both promote flow velocities at the tube wall to eliminate fouling nucleation sites and act as a dielectric barrier to ionic bonding between the tube wall and the mineral laden cooling water. Coated tubes have eliminated all cleaning cycles or greatly extended the cleaning cycle times. Any deposits are generally removed easily by brushes or 200bar water pressure.

Copper ion discharge.

Coating of the condenser tubes prevents the tube wall from oxidizing and leaching Cu^+ into the cooling water.

Chemical attack.

Polymer coatings are resistant to H_2S and other organic acids that can quickly through wall copper alloyed tubes. Case histories include remediation of corrosion rates of 2mm/yr

MIC or Manganese attack

Polymer coatings preferentially wick into pitting by capillary action. Case histories have shown penetration into MIC or manganese pitting and have provided multi-year protection against further tube leaks and corrosion

Erosion

Tubes operating in high suspended solid or high velocity fluids continually have the lightly bonded protective oxides removed. Polymer coatings eliminate the oxidation process plus pigmenting with ceramics create a hard abrasion resistant barrier. Multi year case histories with 5m/s flow rates and high suspended solids provided complete erosion protection

De-alloying

Aged Copper alloy tubes are subject to de-alloying from continual preferential ion release into the cooling fluid. Polymer coating is a barrier to ion exchange and has multi-year case histories for elimination of any further alloy loss and subsequent tube leaks.

Through wall leaks

Through wall leaks have been repaired using polymer coating. Holes up to 1.5mm have been sealed and returned to service in condensing service. Case history of 8+ years in service.

CASE STUDIES

Chemical Attack in the Caribbean

A generating facility on a Caribbean Island had been experiencing severe corrosion in their 7 small TG condensers. A new retube had experienced several through wall leaks within three months. Eddy current revealed more than 50% of the new tubes had wall loss greater than 60%. Failure analysis revealed. SO₂ discharged from the plants smoke stacks was being carried into the inlet area by trade winds and elevated levels of H₂S.. A decision was made to retube with the same metallurgy for heat transfer reasons but coat the condenser and hydrogen coolers for corrosion protection. After five years of service the condenser and hydrogen tubes are still in service. The remaining condensers and hydrogen coolers were all coated.

Tube leak elimination

A Midwest power station had been experiencing an accelerated leak rate in sections of its condenser. Large areas had been plugged but continual leaks were affecting unit reliability and generation. Eddy current reports identified areas of greatest wall loss in the 20+ year old tubes. The sectional areas were coated within a 12 day shutdown. The condenser then operated for an additional 3 years with no leaks.

Coatings a Steam 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 and has received 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.

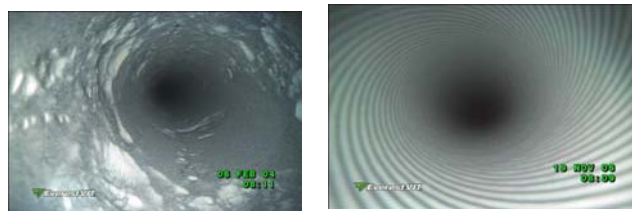


Figure 5

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.

"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.

Acknowledgements

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