ELECTRIC POWER RESEARCH INSTITUTE

DE-FE0031762 Status Report

Andrew Howell
Principal Investigator

May 12, 2021

Project Title: Investigation of Technologies to Improve Condenser Heat Transfer and Performance in a Relevant Coal-Fired Power Plant

Project Team and Responsibilities

EPRI ELECTRIC POWER RESEARCH INSTITUTE • Principal Investigator, Andrew Howell • Economic Evaluation • Operational Assessment • Biological Evaluation • Longevity Studies	WATER Research & Conservation Center • Heat transfer and pilot-scale in-situ test facilities
Airflow Sciences Corporation • WRCC operation and maintenance • Engineering support	CleanAir • Develop attribute testing standards • Review of test plans, data analysis, and reporting
Southern Company • WRCC Site Host • Technical assistance	

Project Background

- Effective cooling of LP turbine steam exhaust is key to thermal power plant efficiency
- Conversion to liquid water generates vacuum
- Heat exchange tubes are heart of cooling process
- Impeded heat transfer is a significant limitation to power generation efficiency

Project Purpose

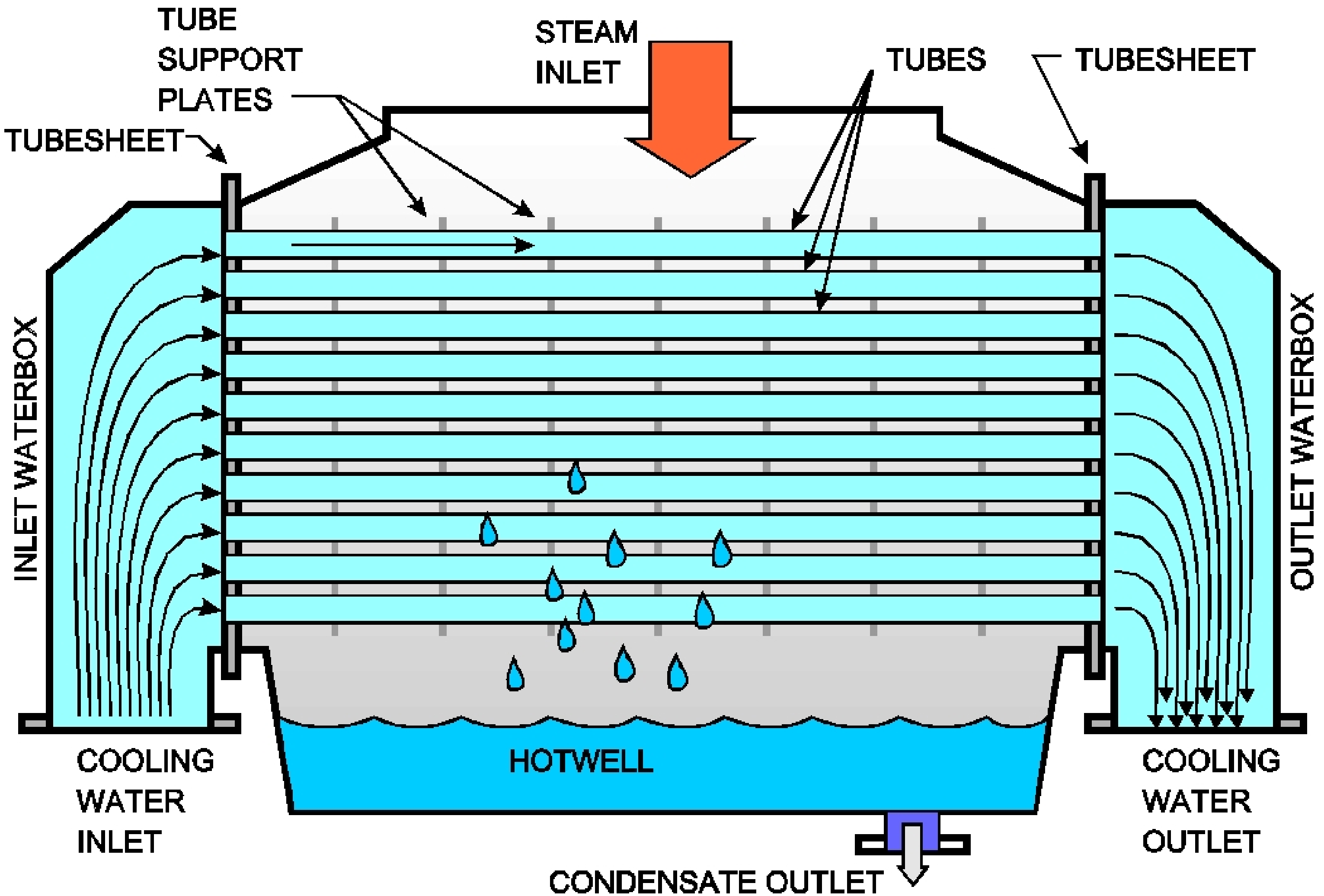
Test heat transfer and other properties of materials that

- enhance steam condensation on the tube exterior
- inhibit fouling on the interior by various materials

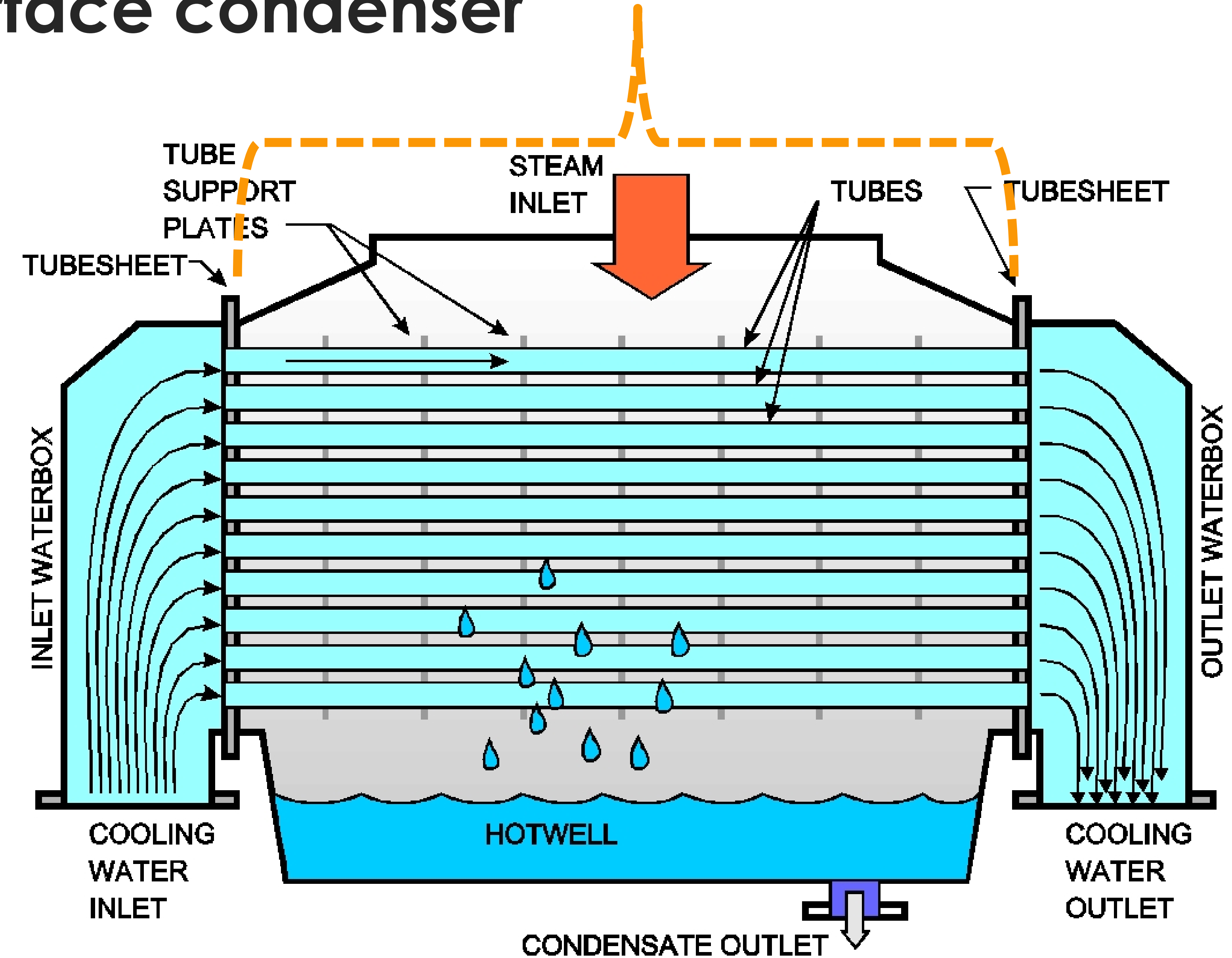
Improved performance will

- reduce fuel consumption
- improve reliability and availability of thermal power generating facilities

Steam surface condenser

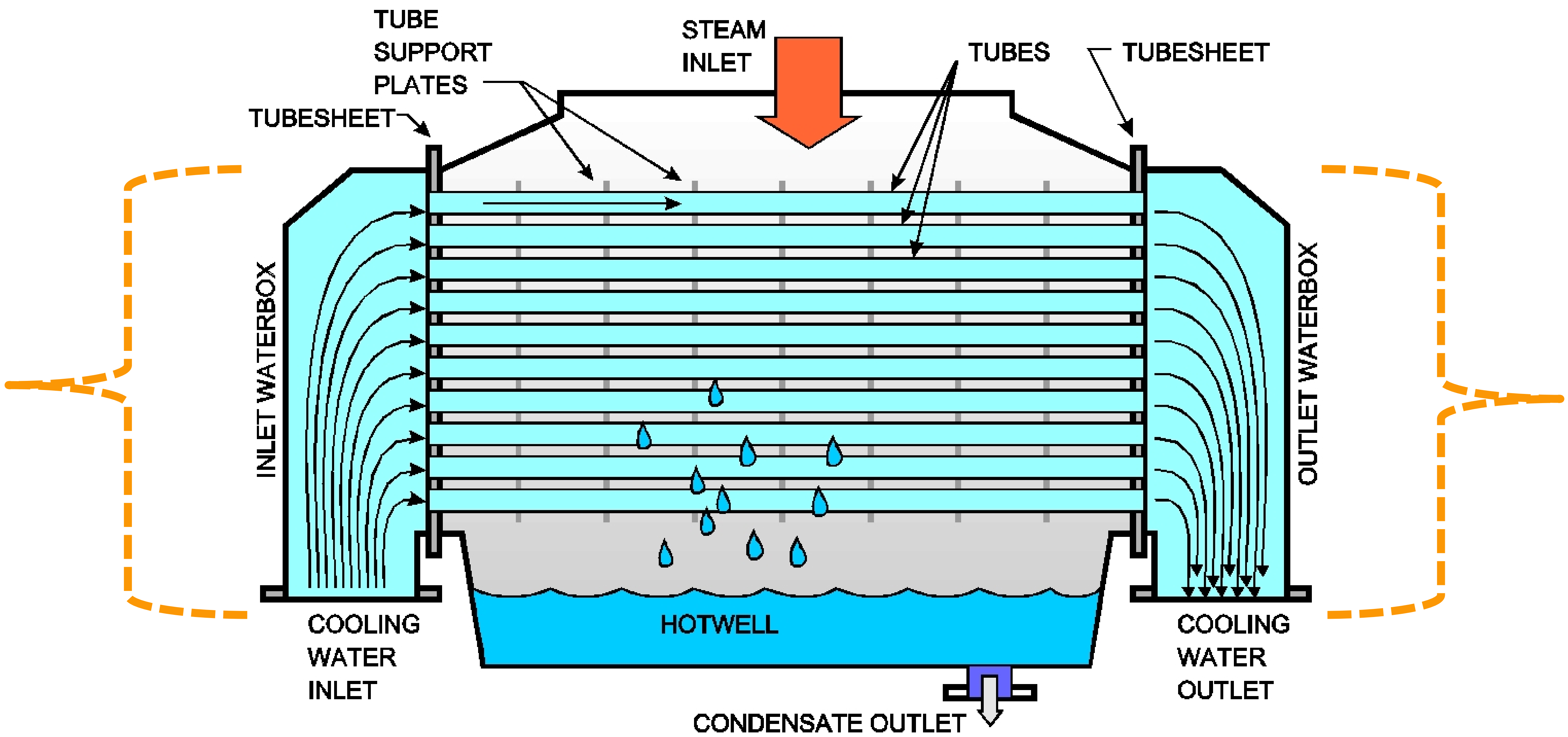


Steam surface condenser

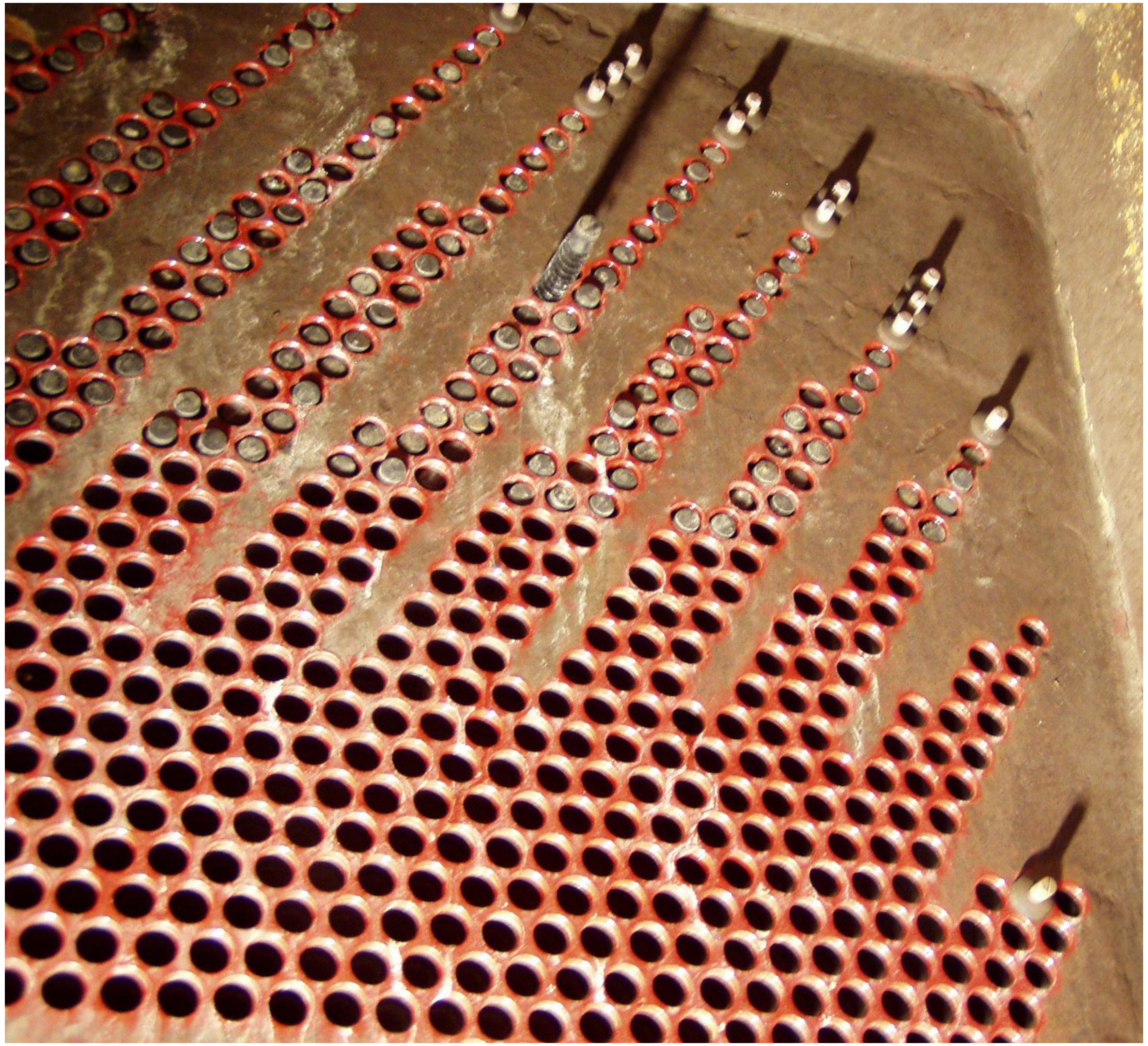


Steam surface condenser tube bundle

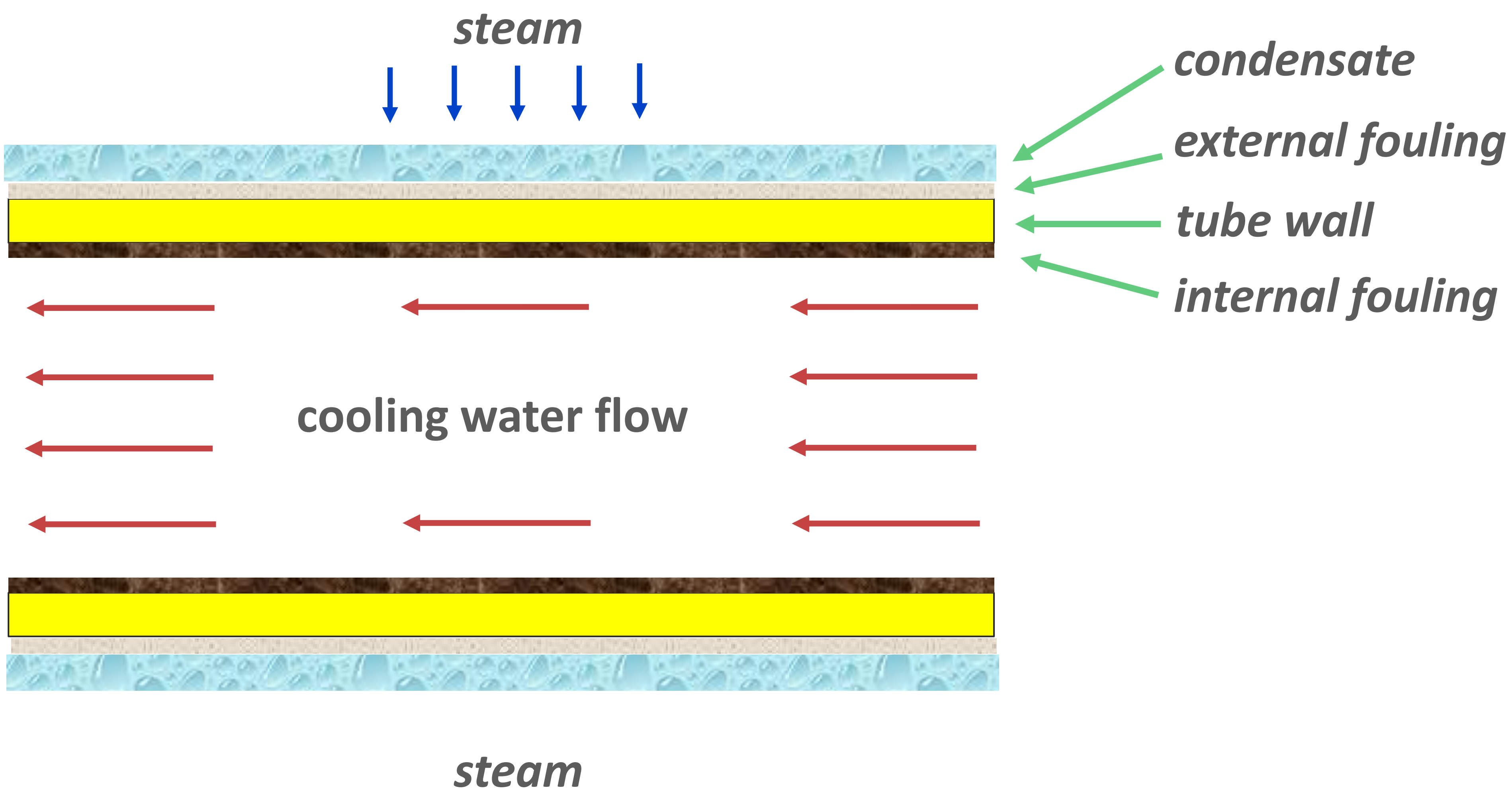
Steam surface condenser



Steam surface condenser tubesheet

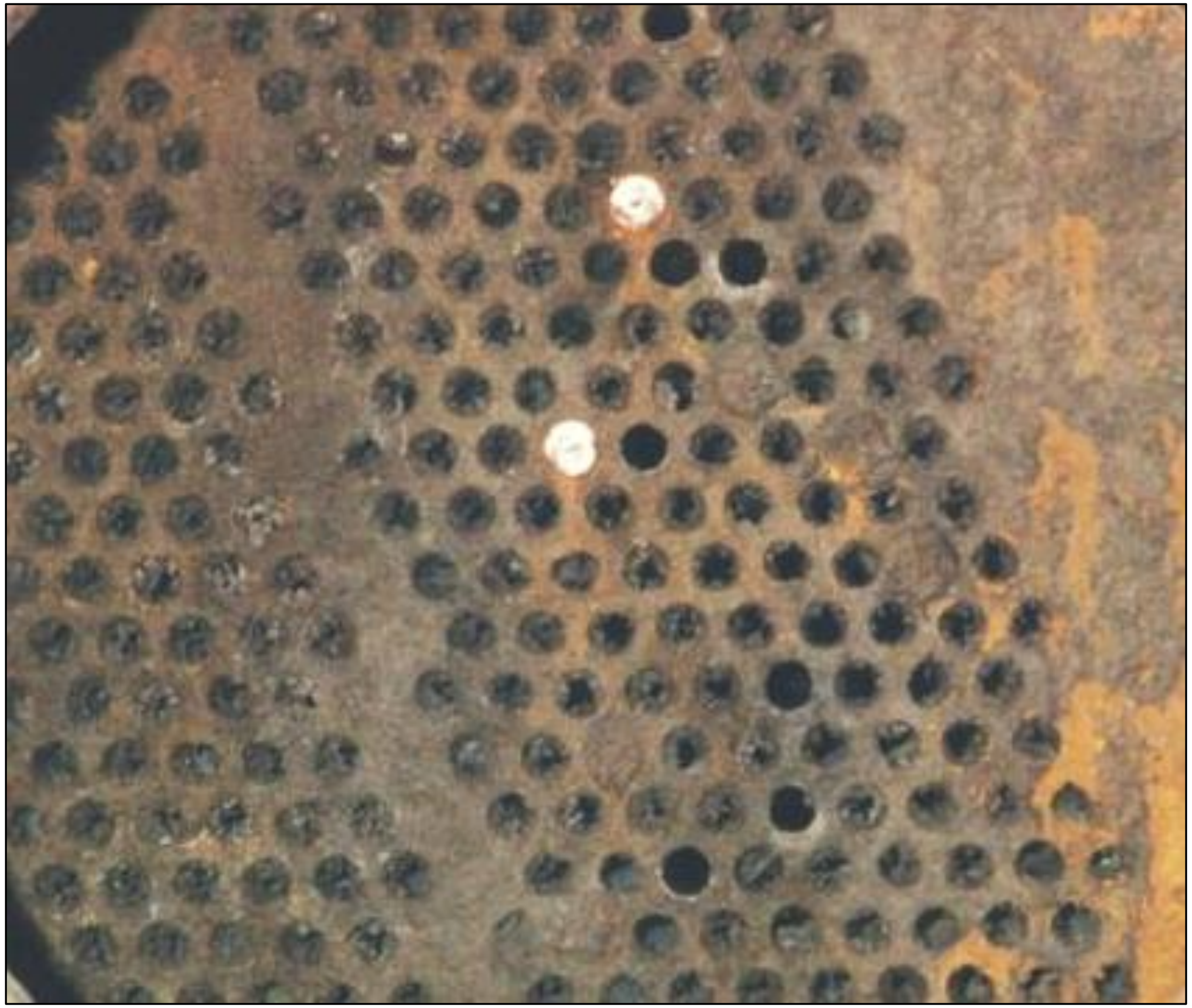


Condenser tube heat transfer

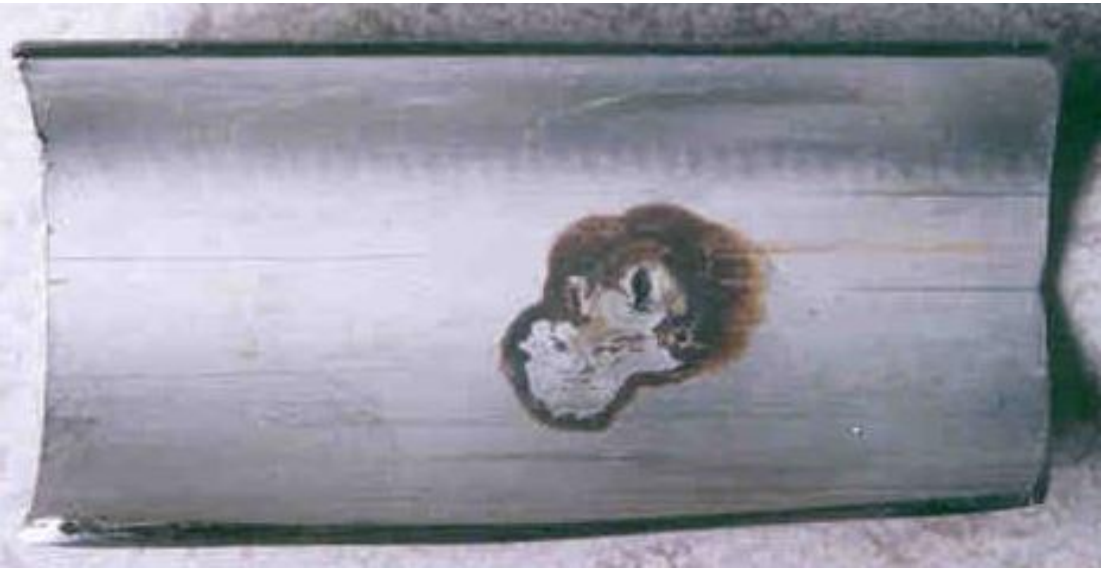


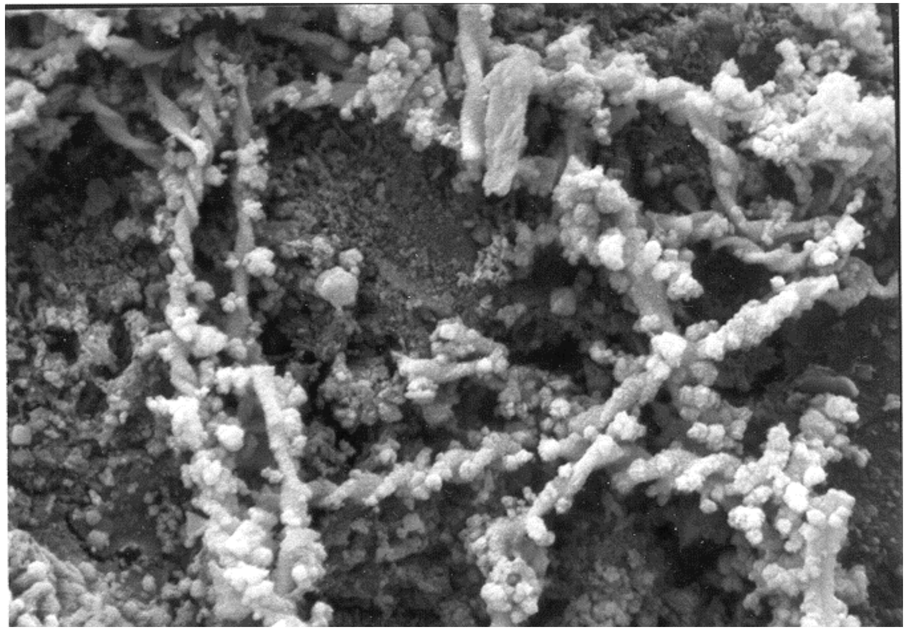
Internal Condenser Tube Fouling

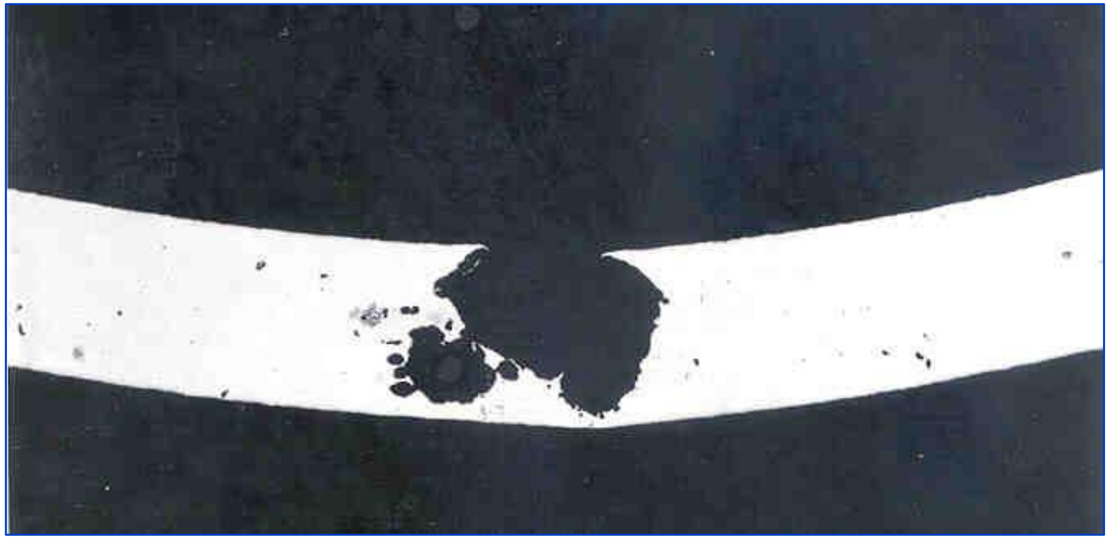
Microbiological fouling

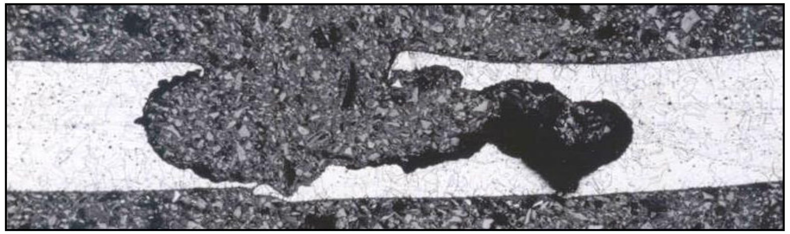


Microbiological fouling resulting in corrosion

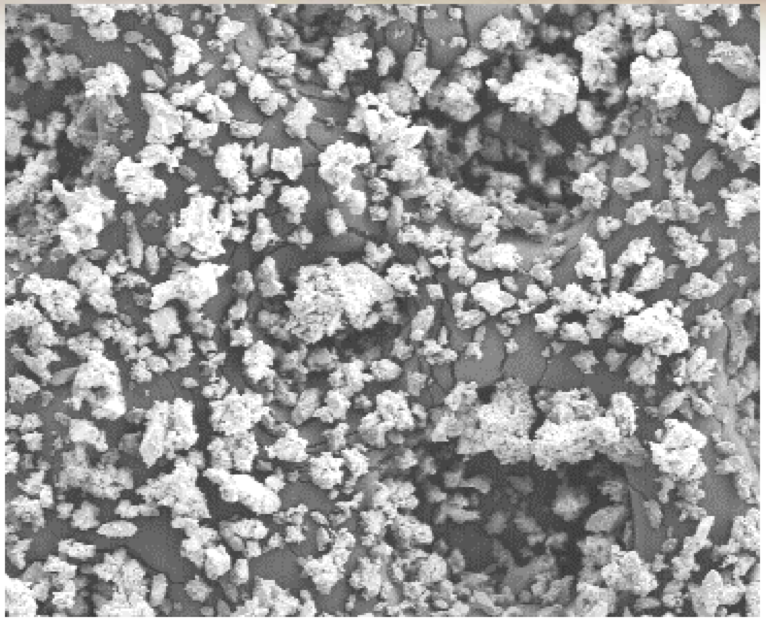


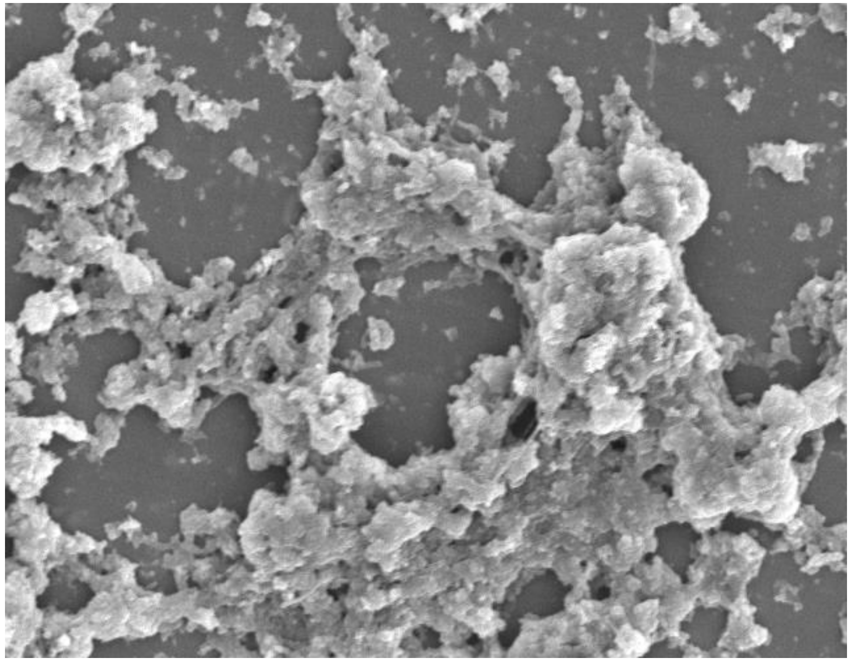


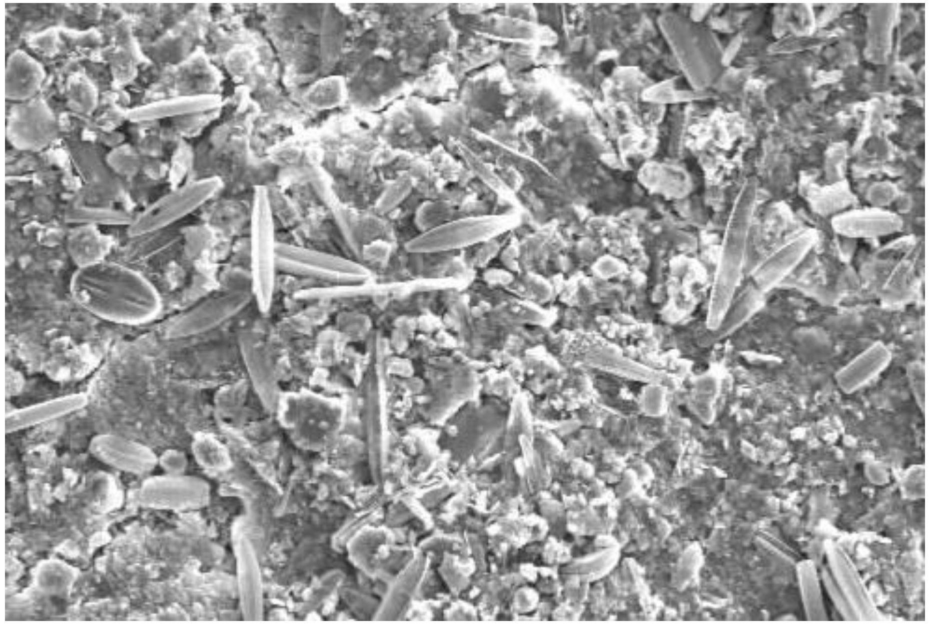




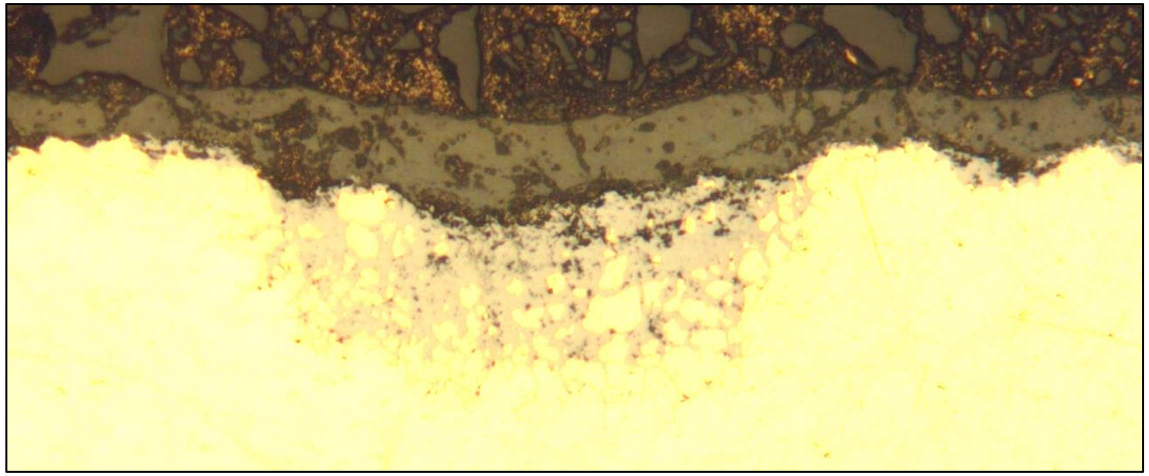
Particulate fouling

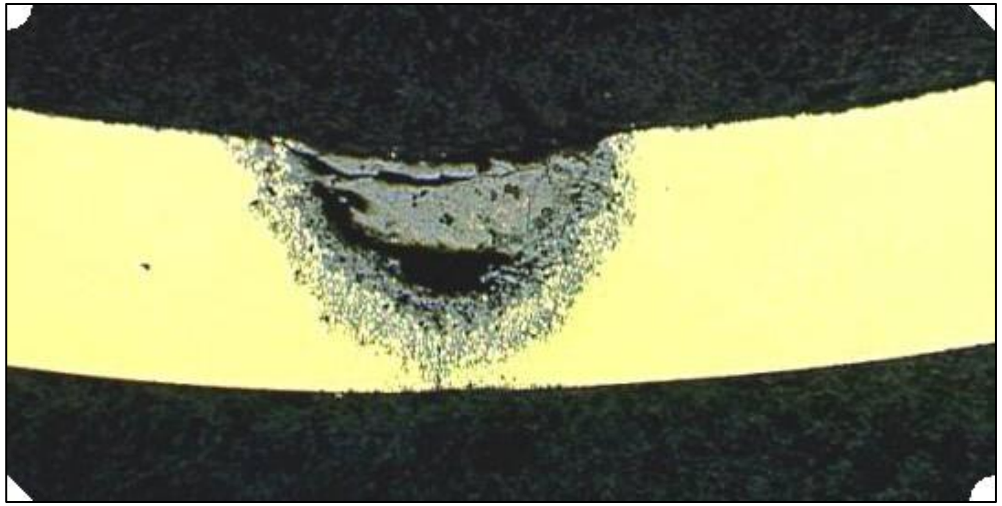






Mineral scale fouling





Condenser Tube Fouling

Source waters:
- potable
- river
- lake
- ocean
- pond
- groundwater
- recycled wastewater
- other

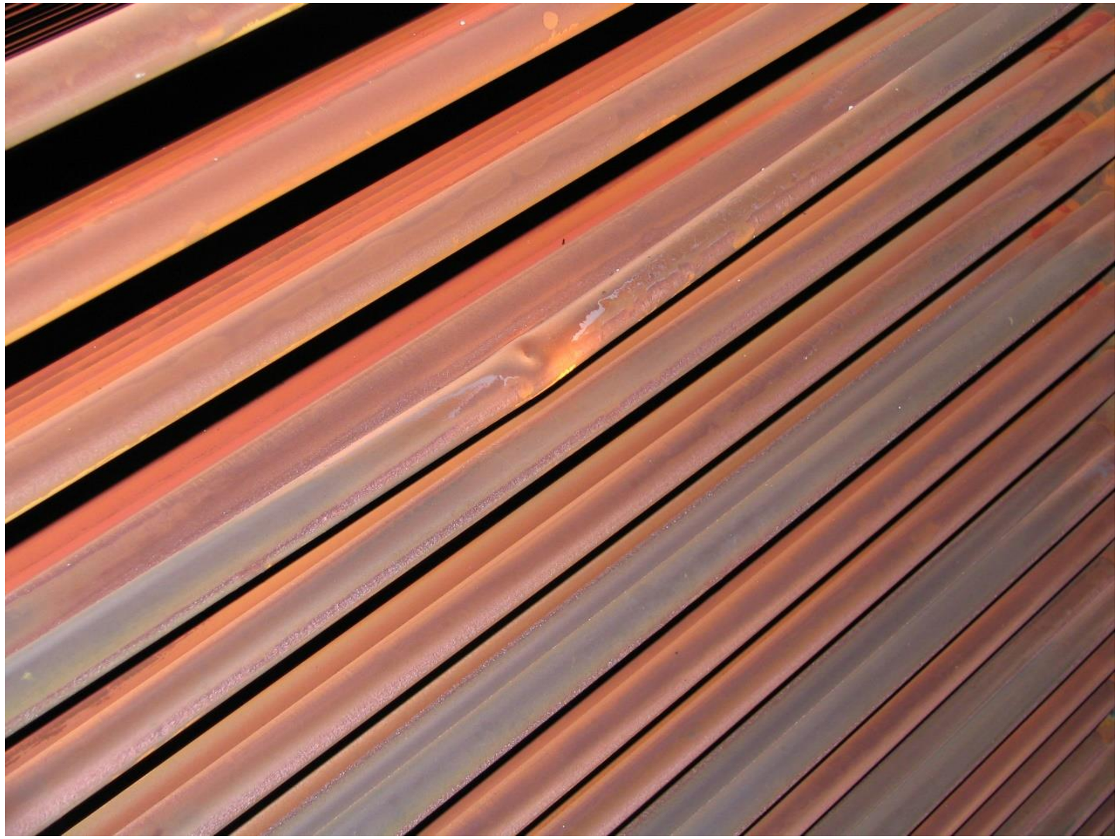
Tube cleaners

Internal Surface Modifications:

Potential to avoid some or all of these fouling options with an internal coating or other modification, thus improving heat transfer continually without having to suffer gradual performance degradation culminating in maintenance outage to “reset” cleanliness.

Steamside condensation enhancement

- steamside deposition / scale
- hydrophobicity effects



http://acc-usersgroup.org/wp-content/uploads/2016/11/Paul-Hattingh_A-Surface-Active-Metal-Passivation-Technology.pdf

Previous Work

EPRI has previously conducted research on heat exchanger tube coatings in full-scale applications. This research included the development of a list of key attributes and a compiled list and description of candidate coatings for further testing and application.

Relevant EPRI Documents include the following:

Technology Insights: Super-Hydrophobic Coatings and Surfaces for Power Generation and Delivery Applications, 3002004686 (2014)

Evaluation of Condenser Tube Nano-Coating to Improve Steam-Side Heat Transfer, 3002008260 (2016)

Evaluation of Advanced Coatings to Improve Heat Exchanger Heat Transfer, 3002013037 (2018)

Evaluation of Tube Internal Coating to Improve Condenser Cleanliness, 3002014323 (2018)

M2.1: Existing ASTM Test Standards and References Selected

- **Thermal conductivity**
- **Adhesion**
- **Abrasion**
- **Hydrophobicity / Thermal stability**
- (Fouling resistance)
- (Corrosion protection)

M2.2: Technologies and Modifications Selected and Prioritized

- **Anticipated 5 modifications for tube interior (limiting fouling adherence with minimal effect on heat transfer)**

- **Anticipated 3 modifications for tube exterior (modification that promotes dropwise condensation)**

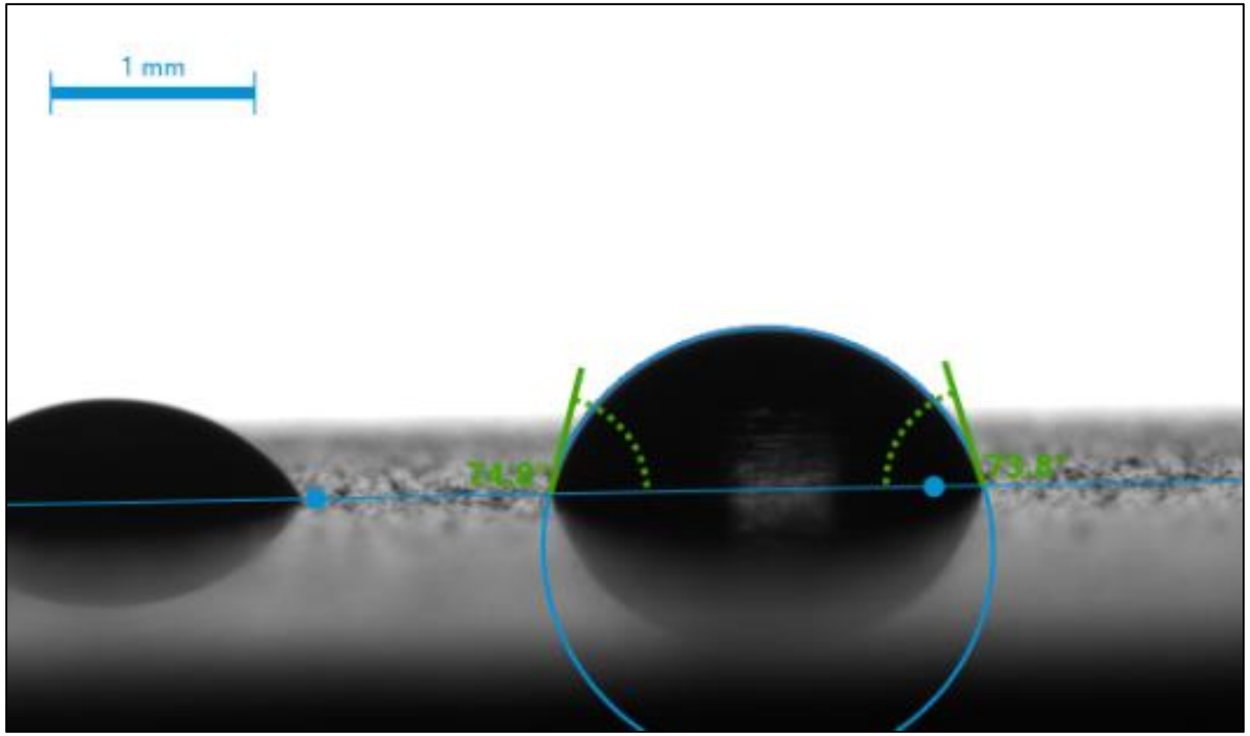
Additional modifications will be identified in the event that higher priority options prove inadequate after rigorous testing

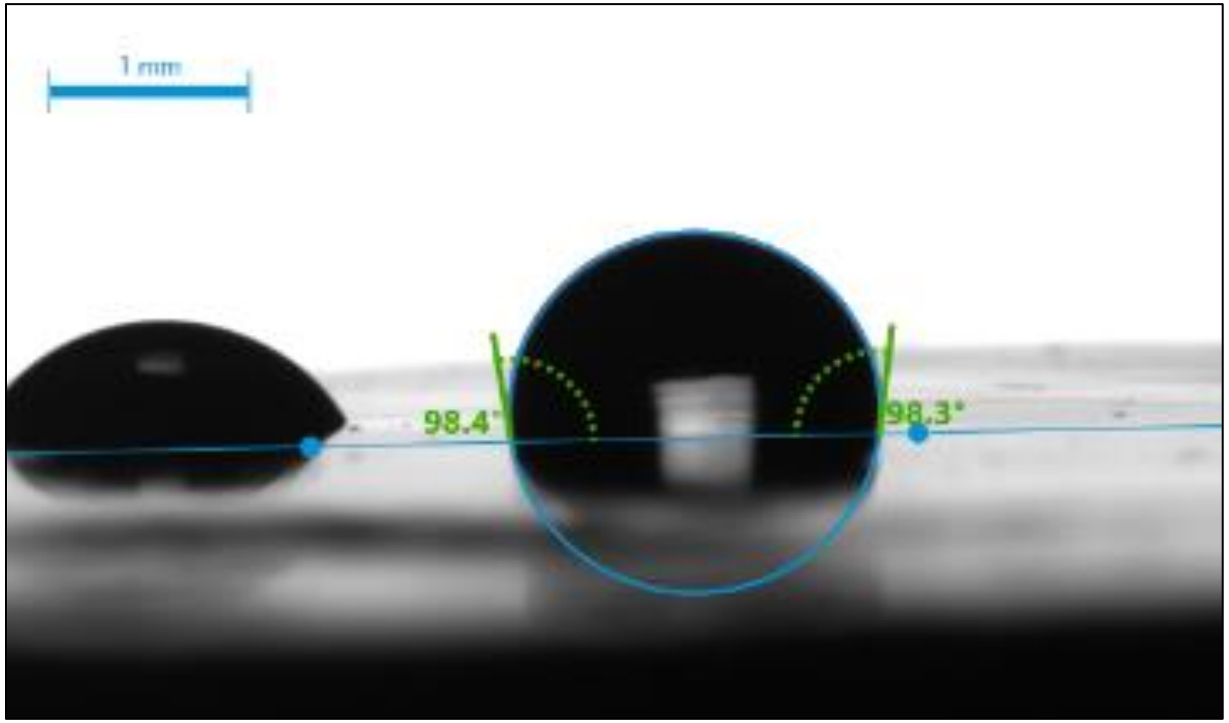
M2.2: Technologies and Modifications

Internal Tube Modifications	External Tube Modifications
Surface modification type	Surface modification type
hybrid epoxy with nanocomposite	physical surface modification
chemically functionalized silicon oxide	functionally graded superhydrophobic coating
epoxy with copper oxide	fluoro-molecular surface treatment
thin-film nanocomposite (polymer base + additive)	functional polymer
nano surface treatment	
functional polymer	

ASTM test results

Hydrophobicity Contact Angle: ASTM D-7334





ASTM Test Results: Hydrophobicity

Internal

Specimen	Contact Angle
A	74.5
B	90.5
C	108.8
D	86.0
E	109.3
F	90.3
U	82.5

External

Specimen	Contact Angle
F	95.3
G	110.8
H	118.2
W	98.6
Microtexture	**101.6**

ASTM Test Results: Abrasion

Internal

Specimen	mm^3
A	0.030
B	0.015
C	0.372
D	0.284
E	0.093
F	0.018
U	N/A

External

Specimen	mm^3
F	0.018
G	0.299
H	0.378
W	N/A

ASTM Test Results: Thermal Diffusivity

Internal

Specimen	mm²/sec
A	8.154
B	5.794
C	8.441
D	8.475
E	7.968
F	8.431
U	8.708

External

Specimen	mm²/sec
F	8.431
G	8.608
H	8.613
W	8.708

ASTM Test Results: Adhesion

Internal

Specimen	mN/um
A	115.2
B	118.2
C	N/A
D	197.4
E	24.6
F	36.2
U	N/A

External

Specimen	mN/um
F	36.2
G	69.1
H	302.4
W	N/A

Test Condenser Operation

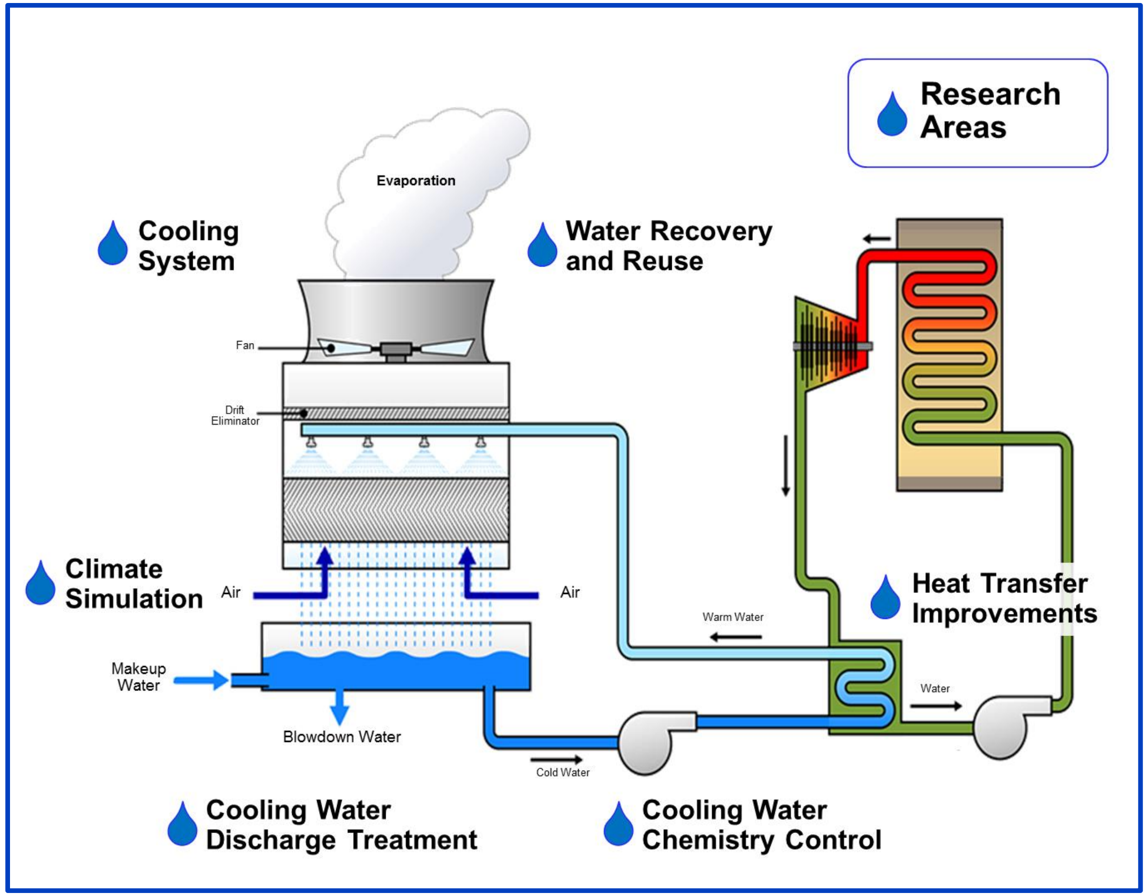
WRCC (Water Research and Conservation Center)

Objectives and Scope

- Recently complete R&D test center to address mid- to long-term needs in power plant cooling applications
- Cooling R&D focused on advanced and alternative cooling systems, cooling water chemistry control, and heat transfer improvements

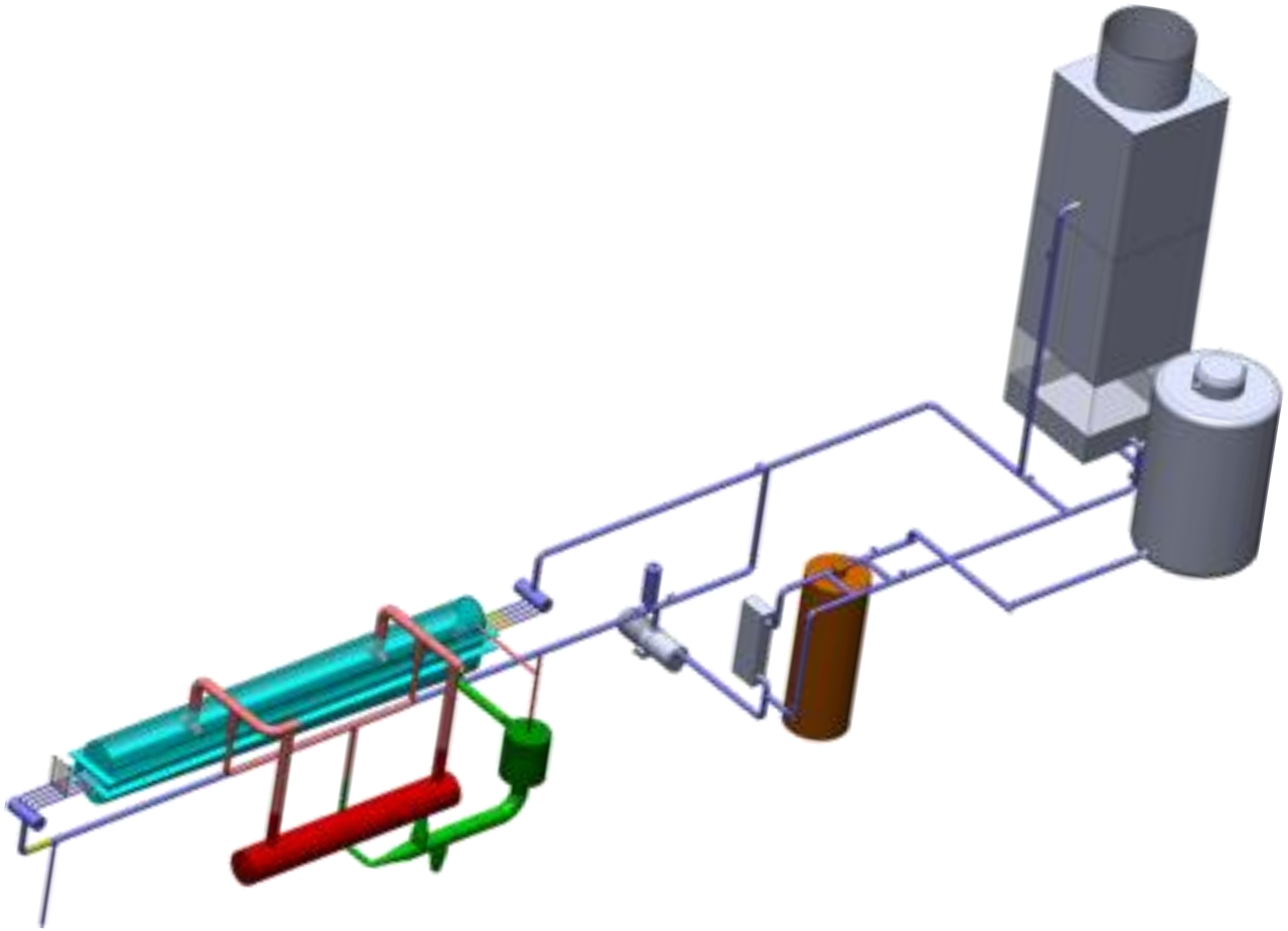
Value

- Accelerate technology development to meet anticipated future needs
- Address research gaps to facilitate development of technologies that provide cost-effective solutions
  - Reduced water withdrawal and consumption for thermoelectric cooling
  - Improved heat transfer and plant efficiency



Comprehensive test center to expand cooling system and heat transfer research

WRCC Test Condenser

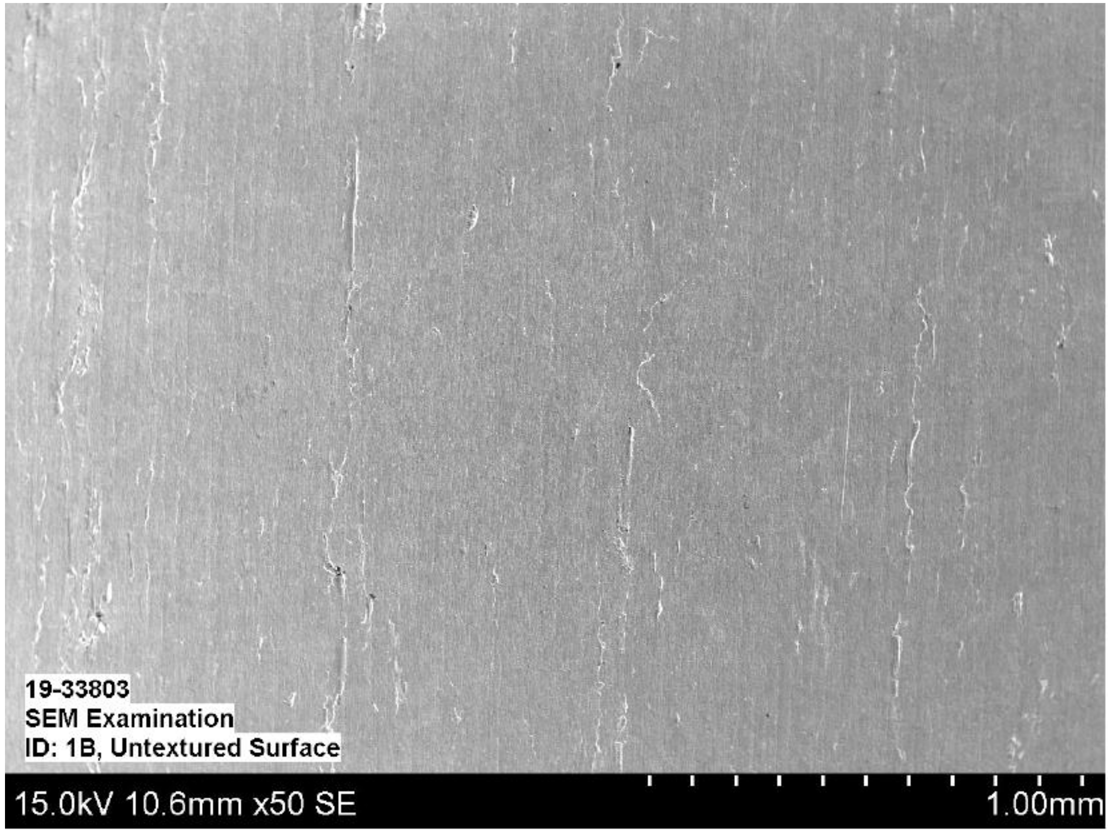


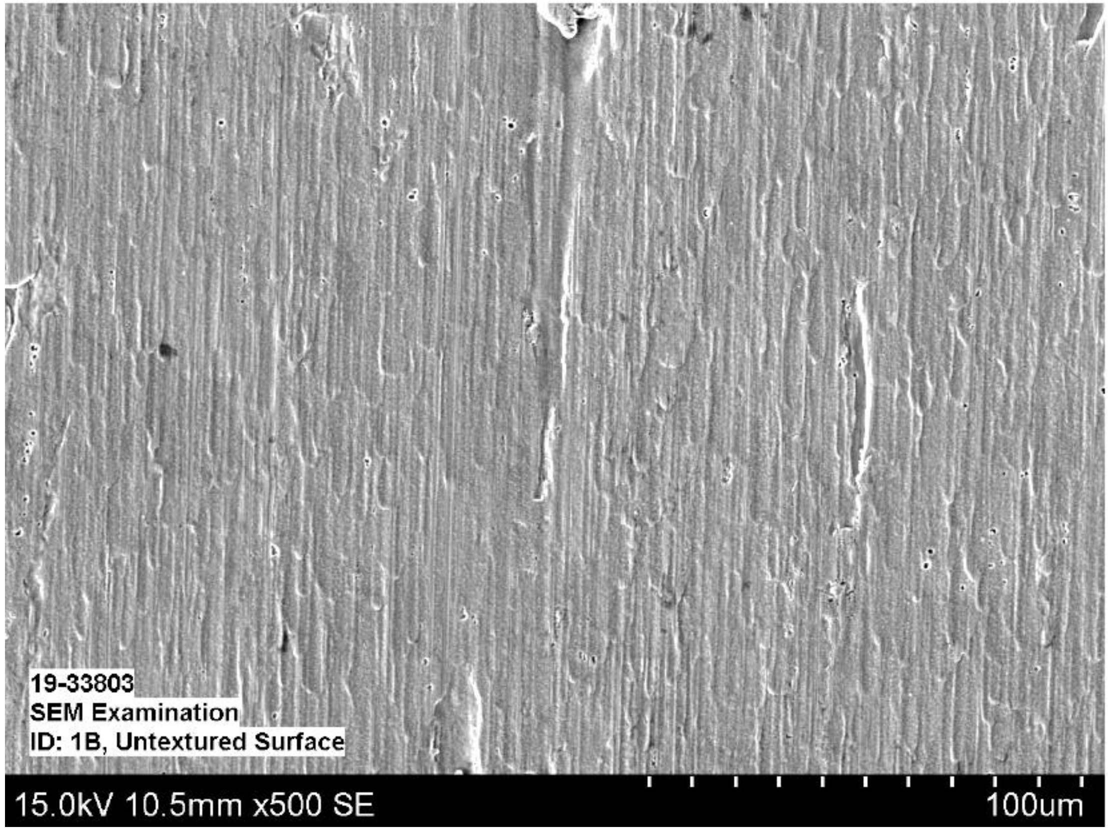
WRCC Test Condenser

Test #1: Physical Modification of Steamside Surface

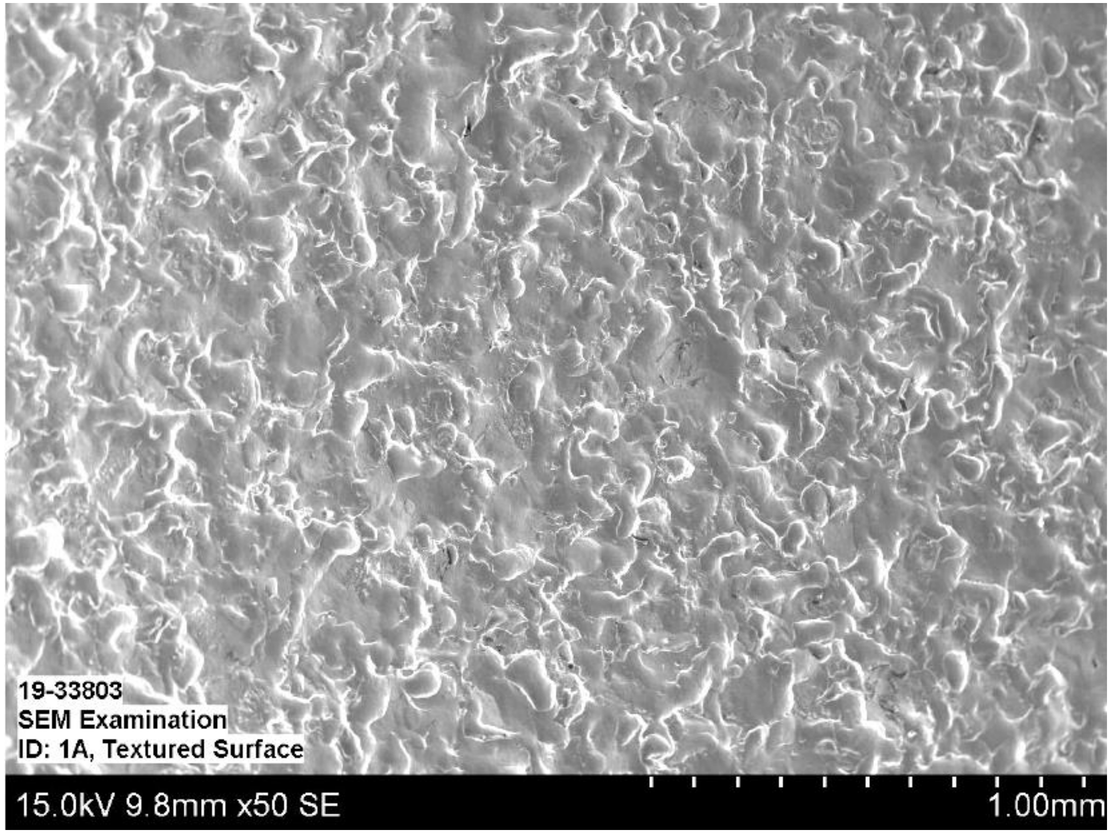
microtextured surface

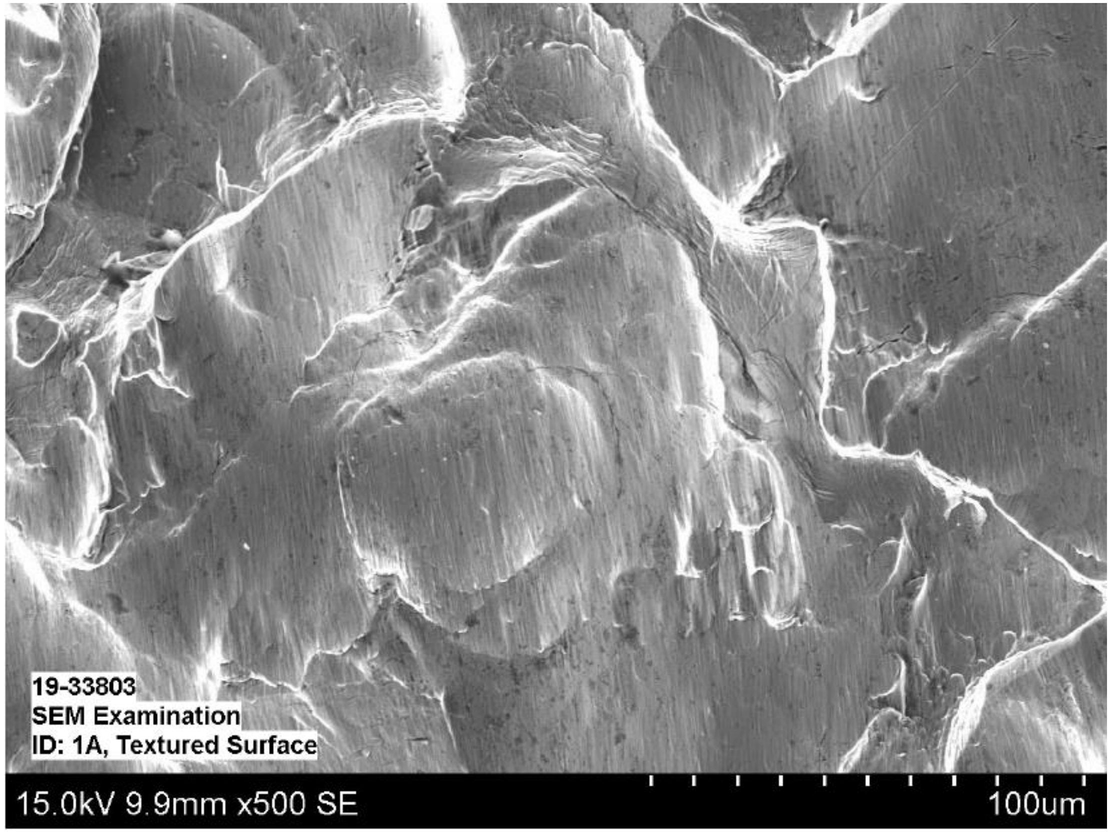
Stainless Steel tube surface untexturized



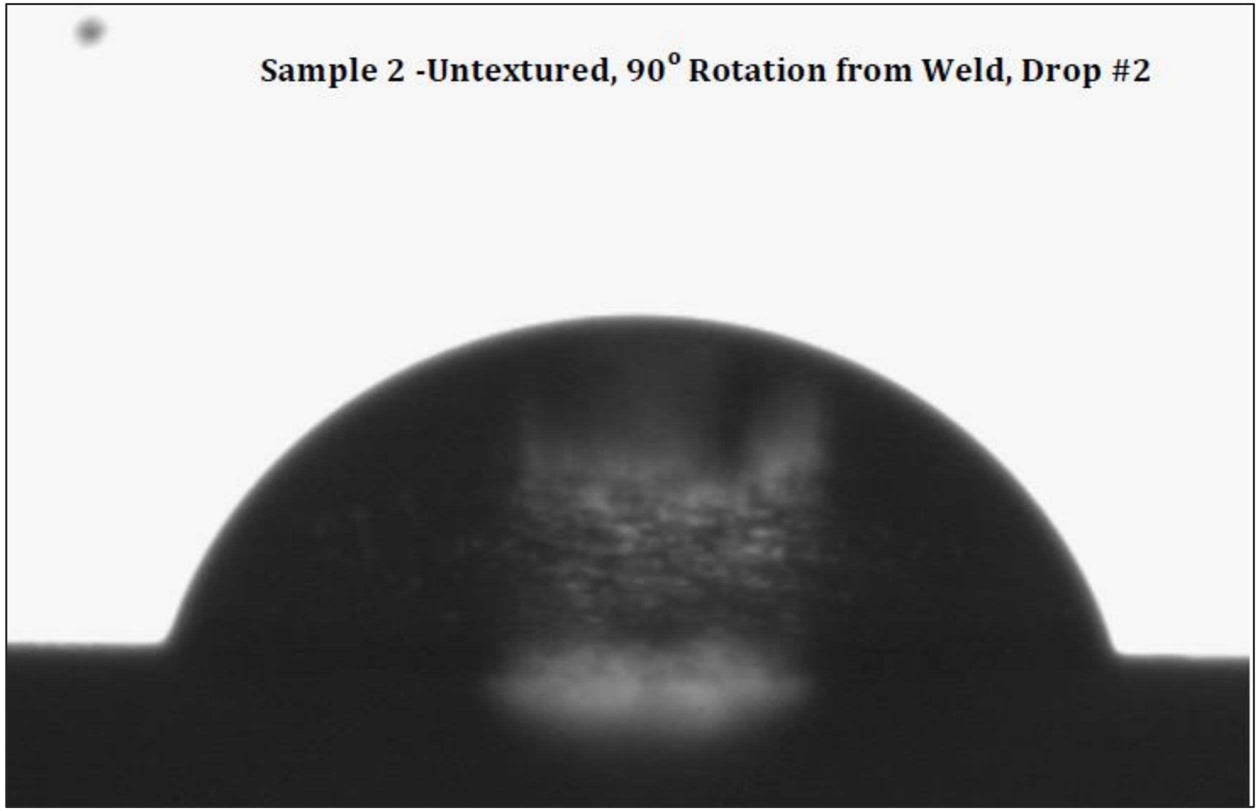


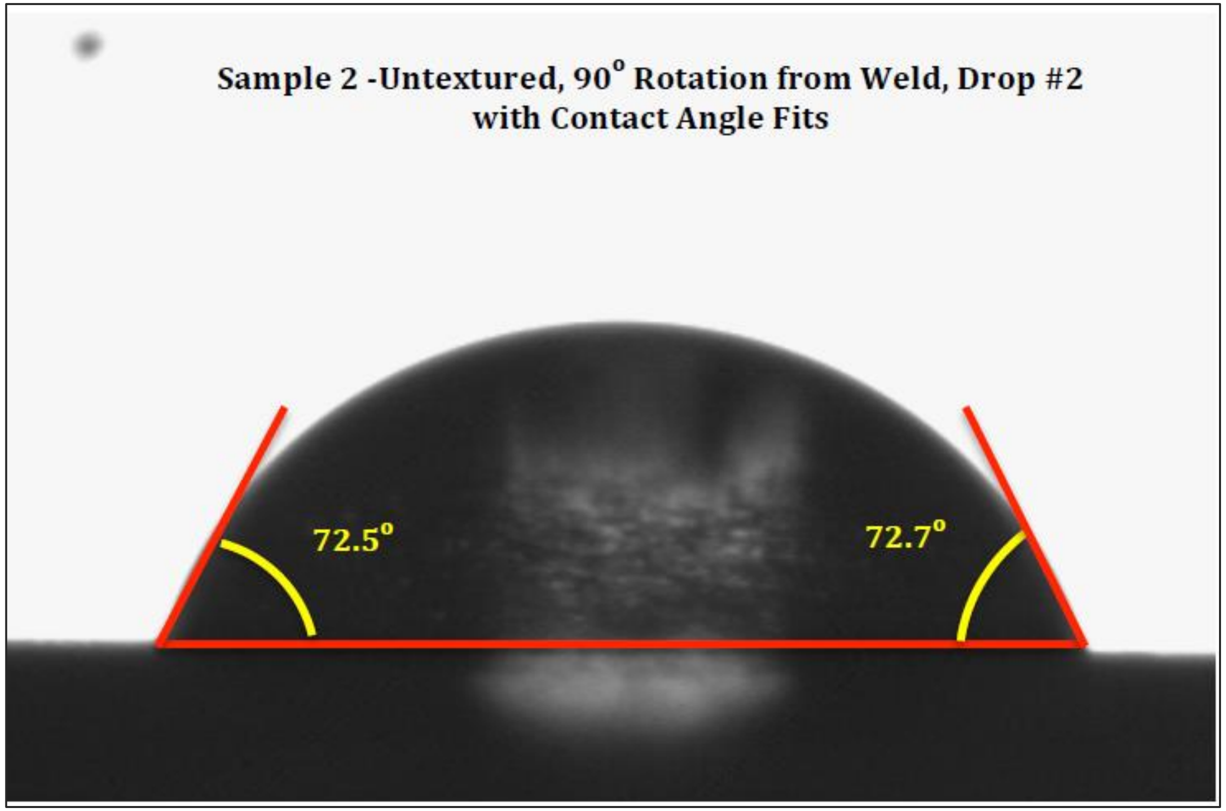
Stainless Steel tube surface texturized



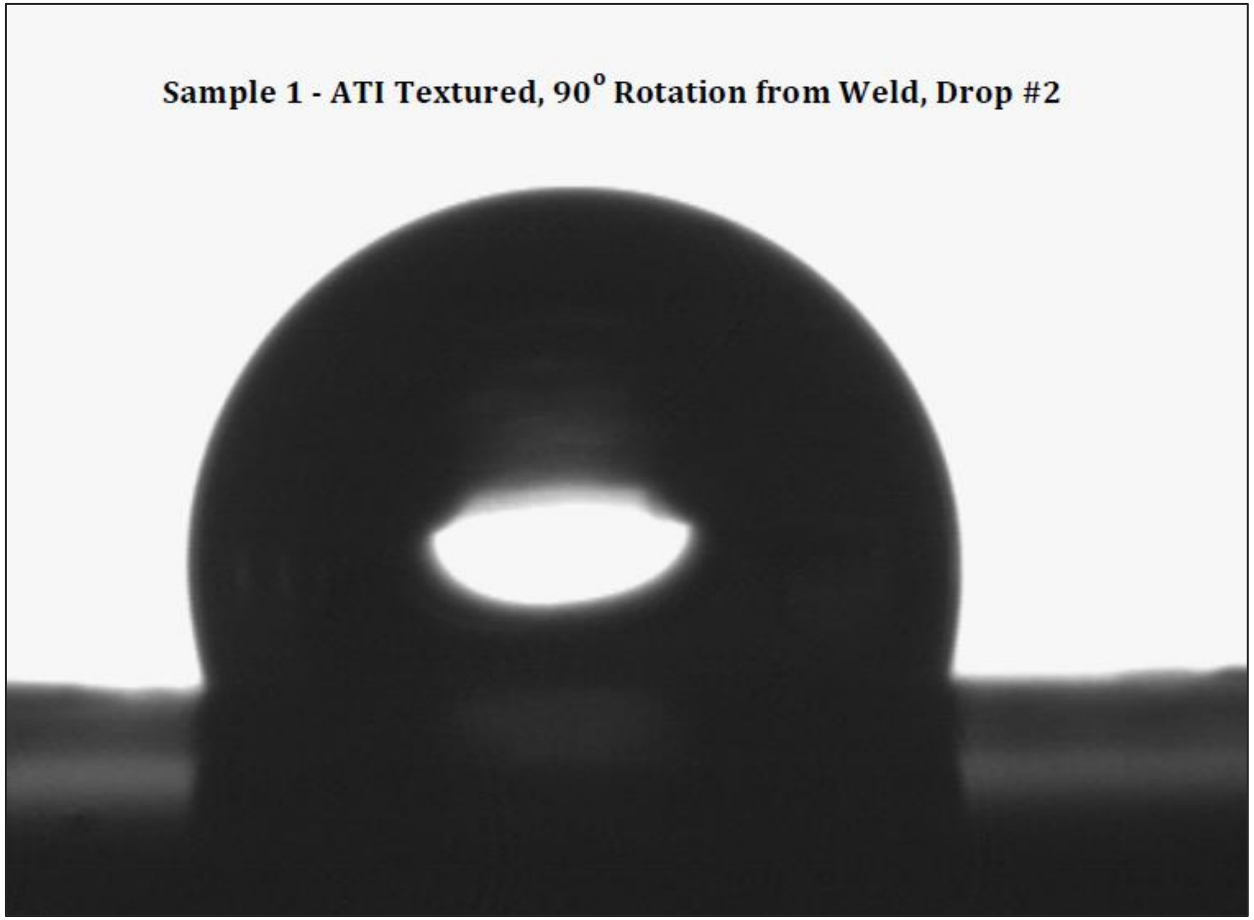


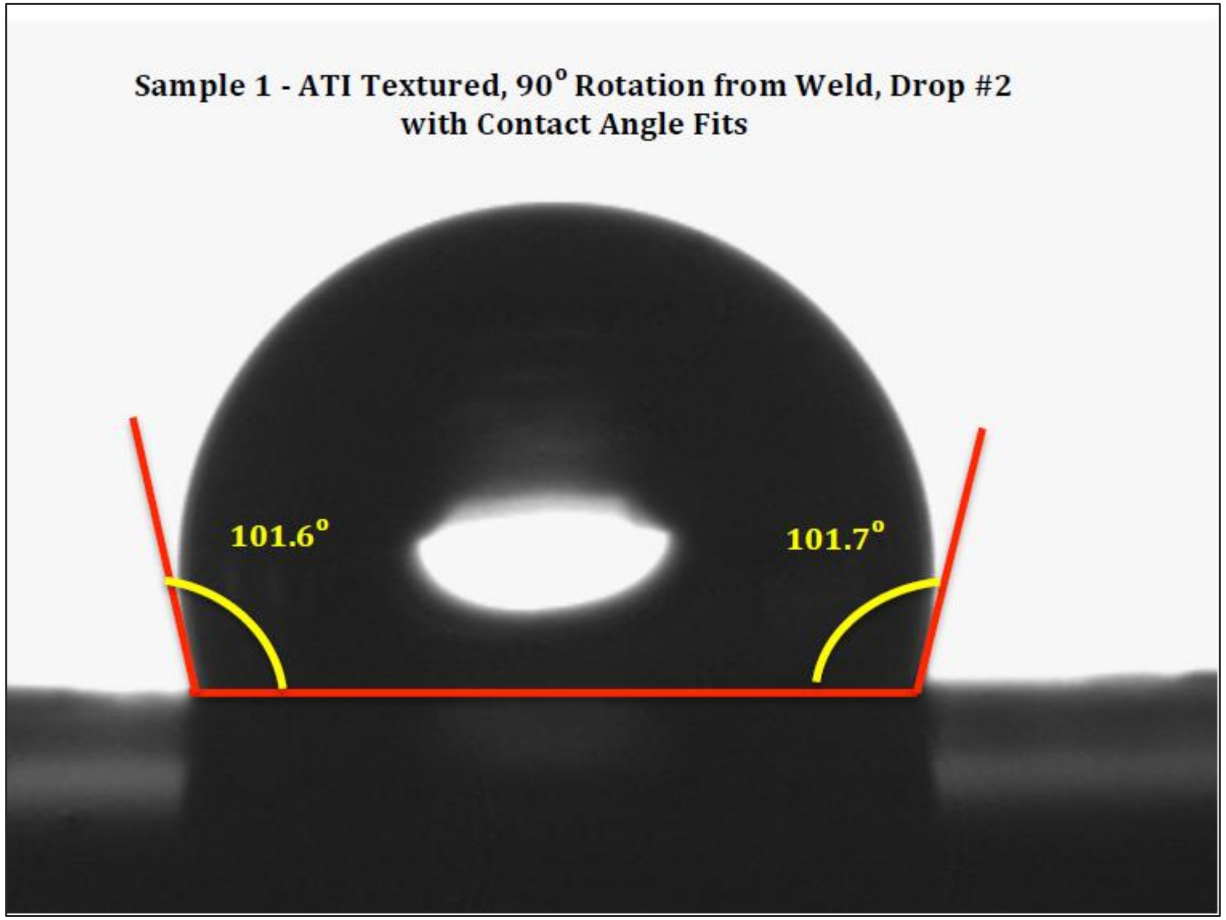
Hydrophobicity Testing: Untextured tube surface



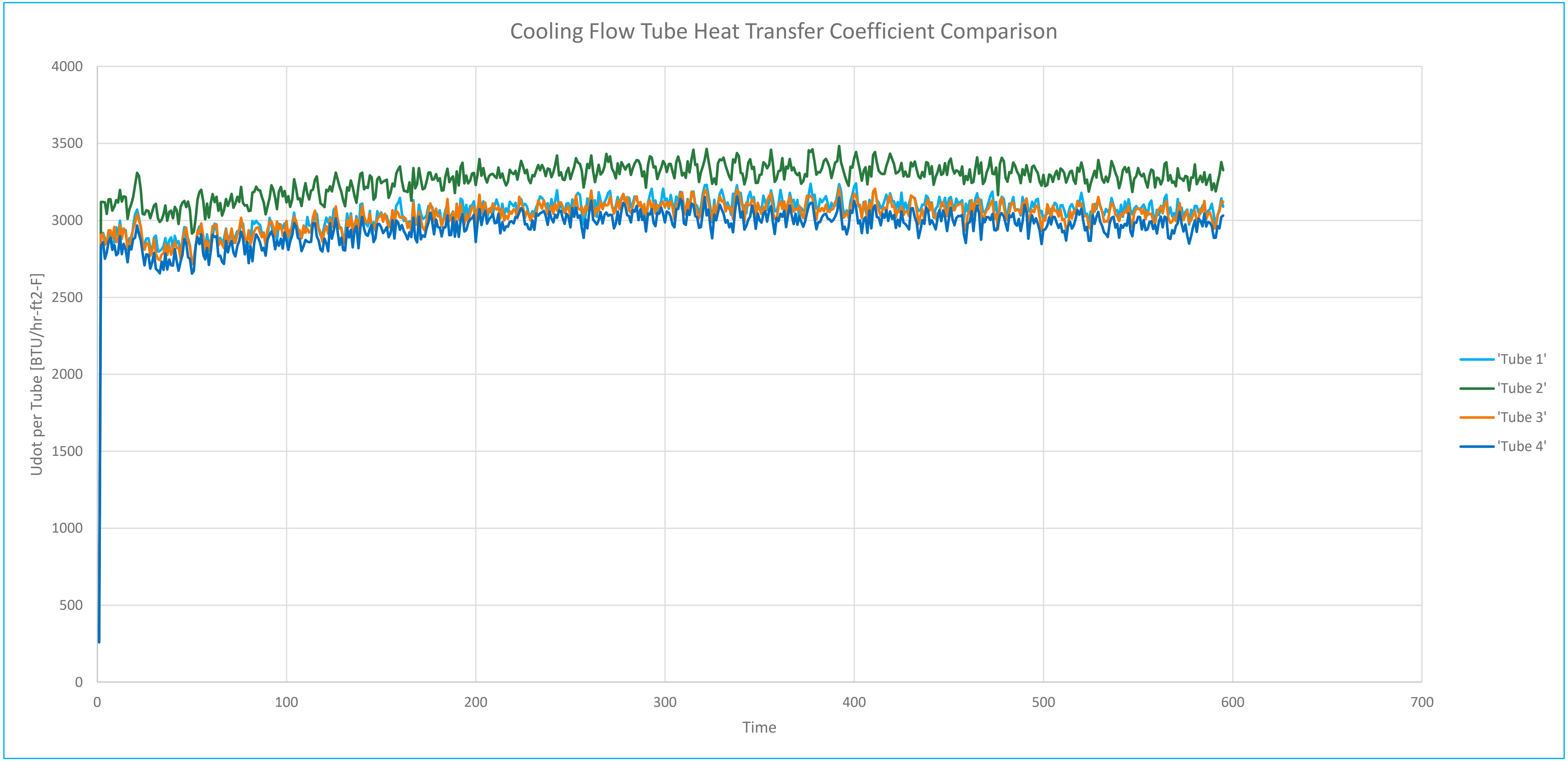


Hydrophobicity Testing: Textured tube surface

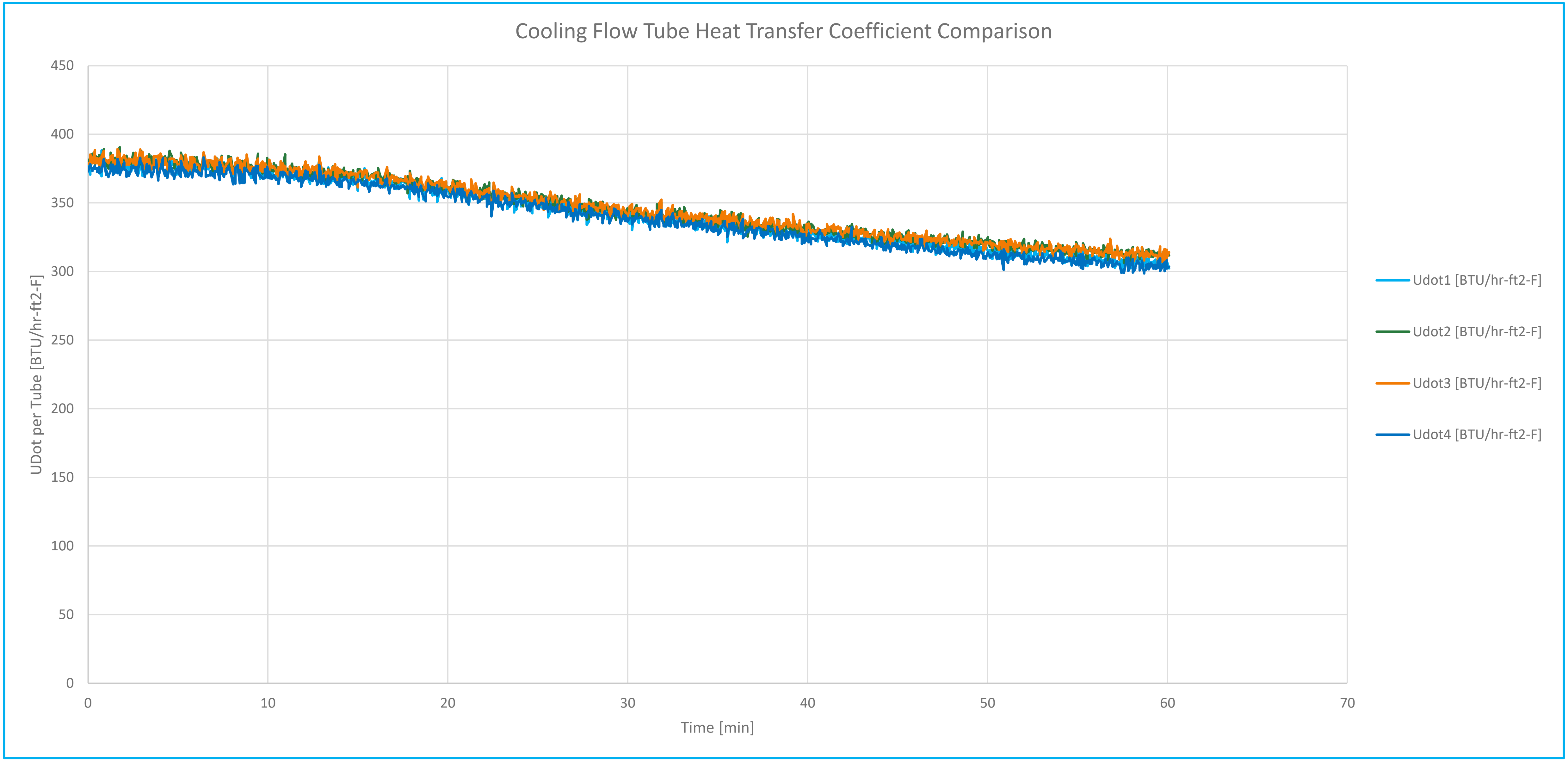




Physically Modified tube #2a: Heat Transfer Coefficients 11.02.2020



Physically Modified tube #3b: Heat Transfer Coefficients 01.28.2021



Results, Test Run #1: Physically Modified Tubes (Steamside Condensation)

4 test runs, 3 identical tubes in each run (triplicate)

As-manufactured physically modified tubes demonstrated lower heat transfer compared with an unmodified tube. Two different modifications were applied.

Post-manufacture high-temperature anneal of the same tube modifications showed similar heat transfer compared with an unmodified tube.

Conclusion: The physical modification applied to the tubes received did not improve heat transfer (presumably did not promote drop-wise condensation). Modified tubes subjected to high-temperature anneal showed improved heat transfer compared with non-annealed tubes.

Test #2: Internal (waterside) Tube Coating

epoxy with copper oxide (Epoxy-CuO_x)

Test Run #2: Internal Tube Modification (Epoxy-CuO_x coating) (Waterside fouling mitigation)

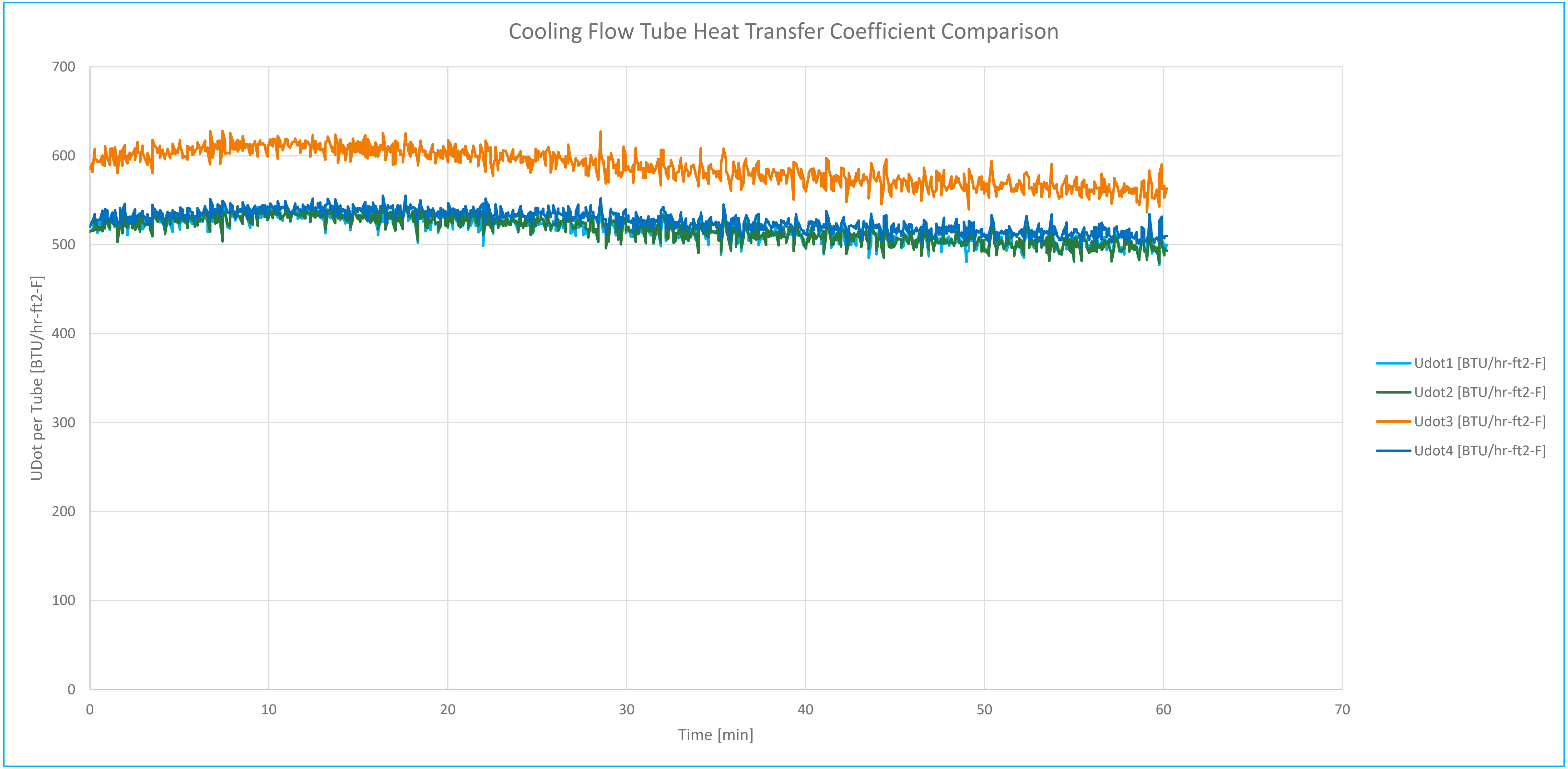
4 test runs, 3 identical tubes in each run (triplicate)

Titanium tubes were supplied to a tube coating company for internal application of a coating with potential anti-fouling characteristics. These tubes were returned to EPRI's Water Research & Conservation Center (WRCC) and the second test run was initiated.

Results thus far:

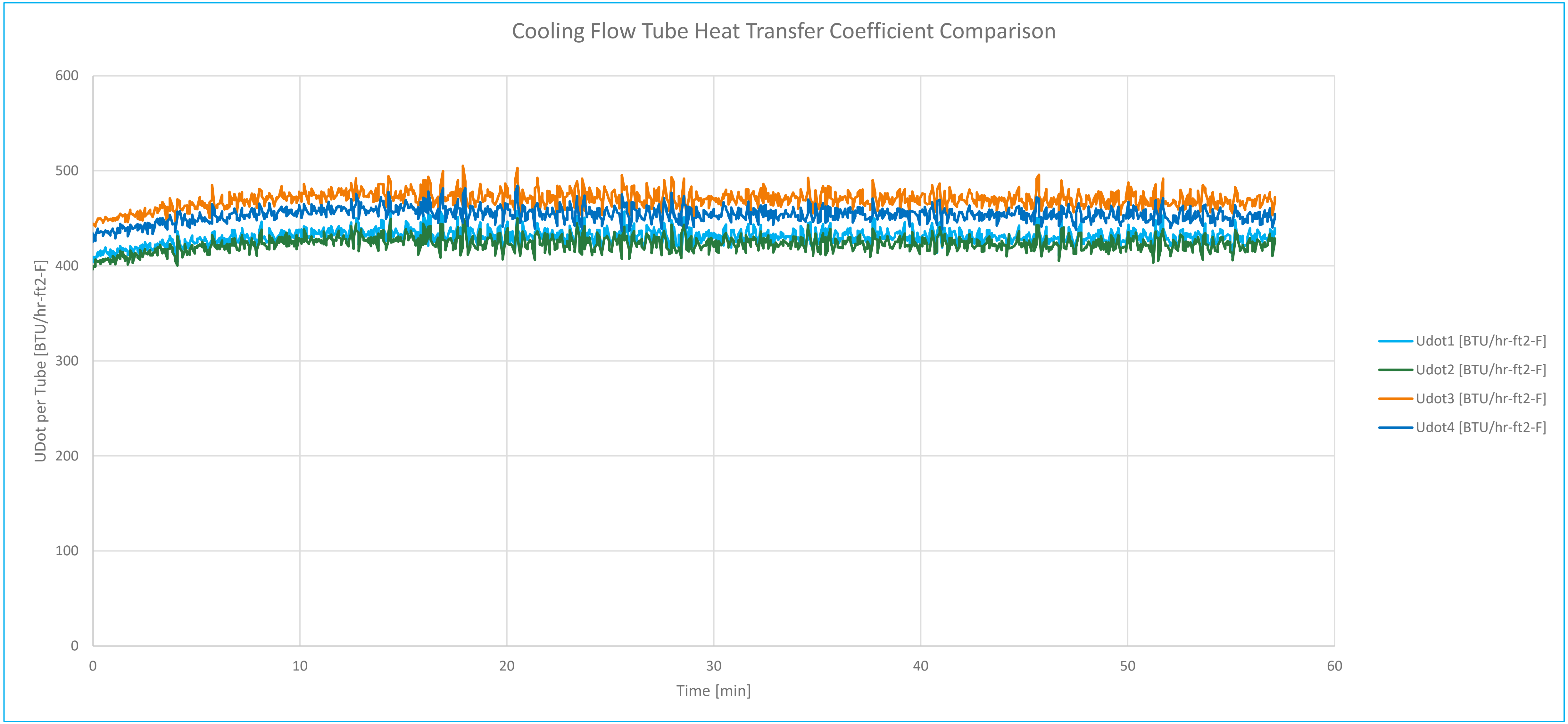
- Heat transfer testing of as-received tubes showed significant impedance to heat transfer for the coated tubes compared with an un-coated tube.
- Efforts to induce microbiological fouling has produced some results that indicated that heat transfer across the unmodified tube degraded more rapidly with biofouling compared with the modified (coated) tube.

Epoxy-CuO_x Modified Tubes: Initial Heat Transfer Coefficients 03.08.2021

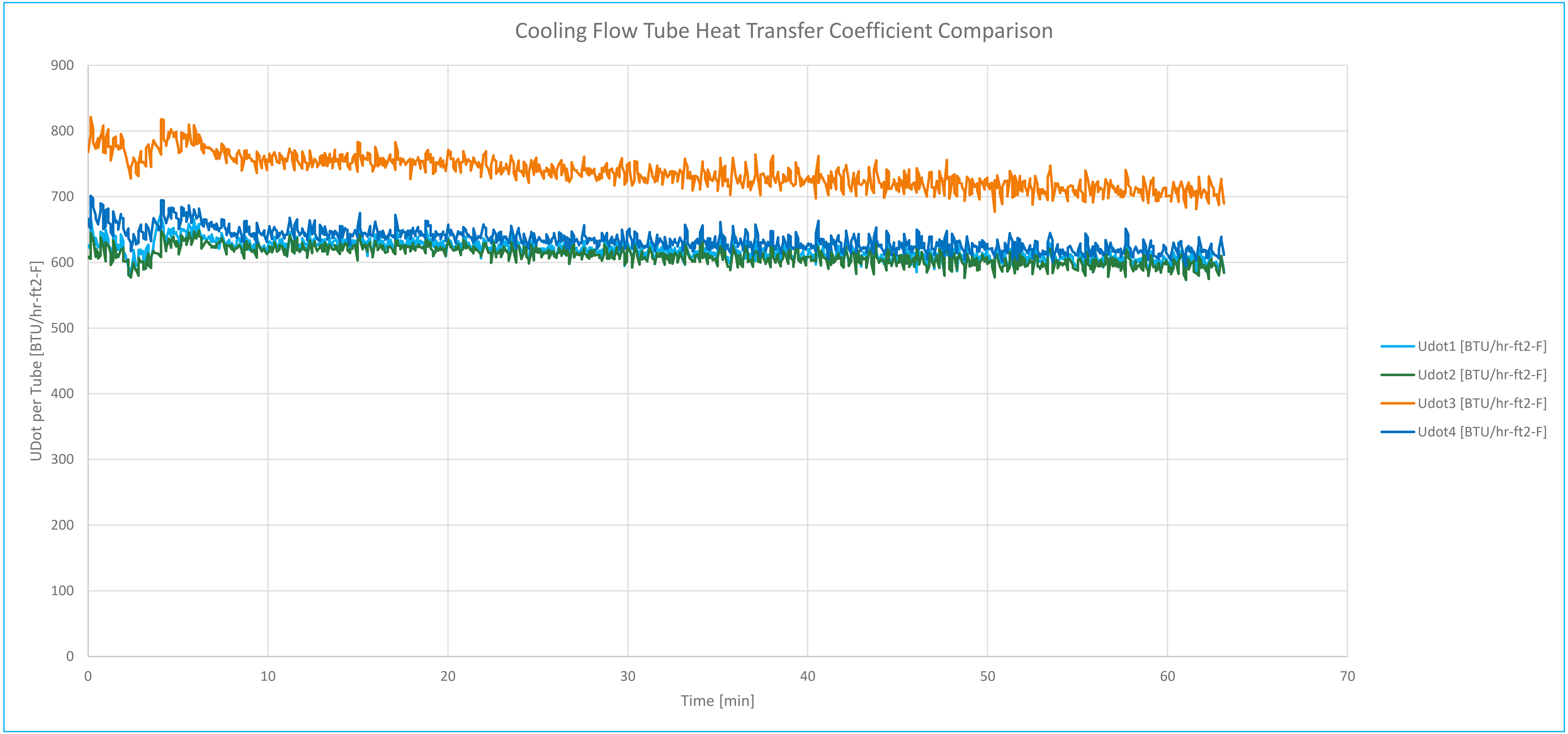


Epoxy-CuO_x Modified Tubes: Heat Transfer Coefficients 03.22.2021

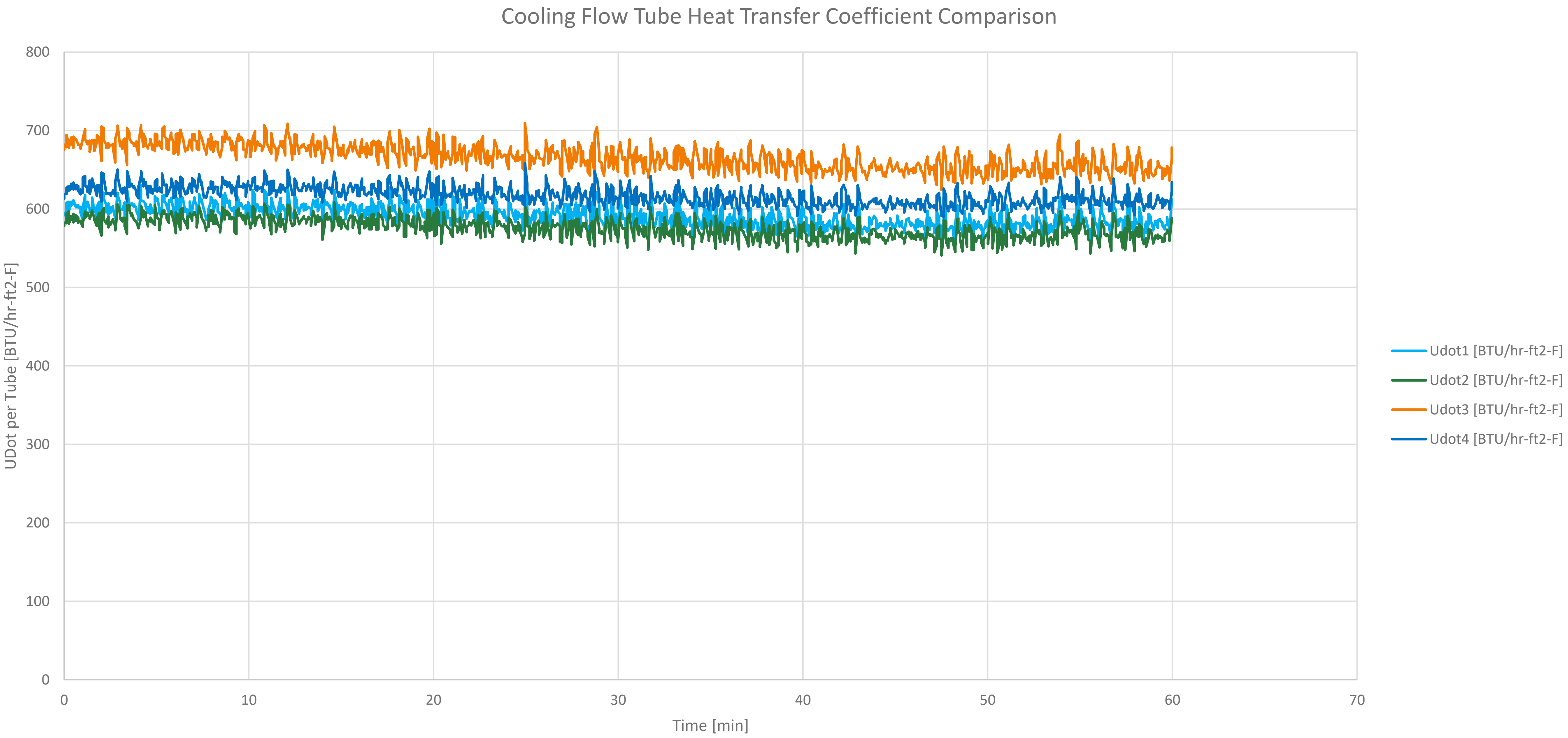
Bio-Fouling Initiated



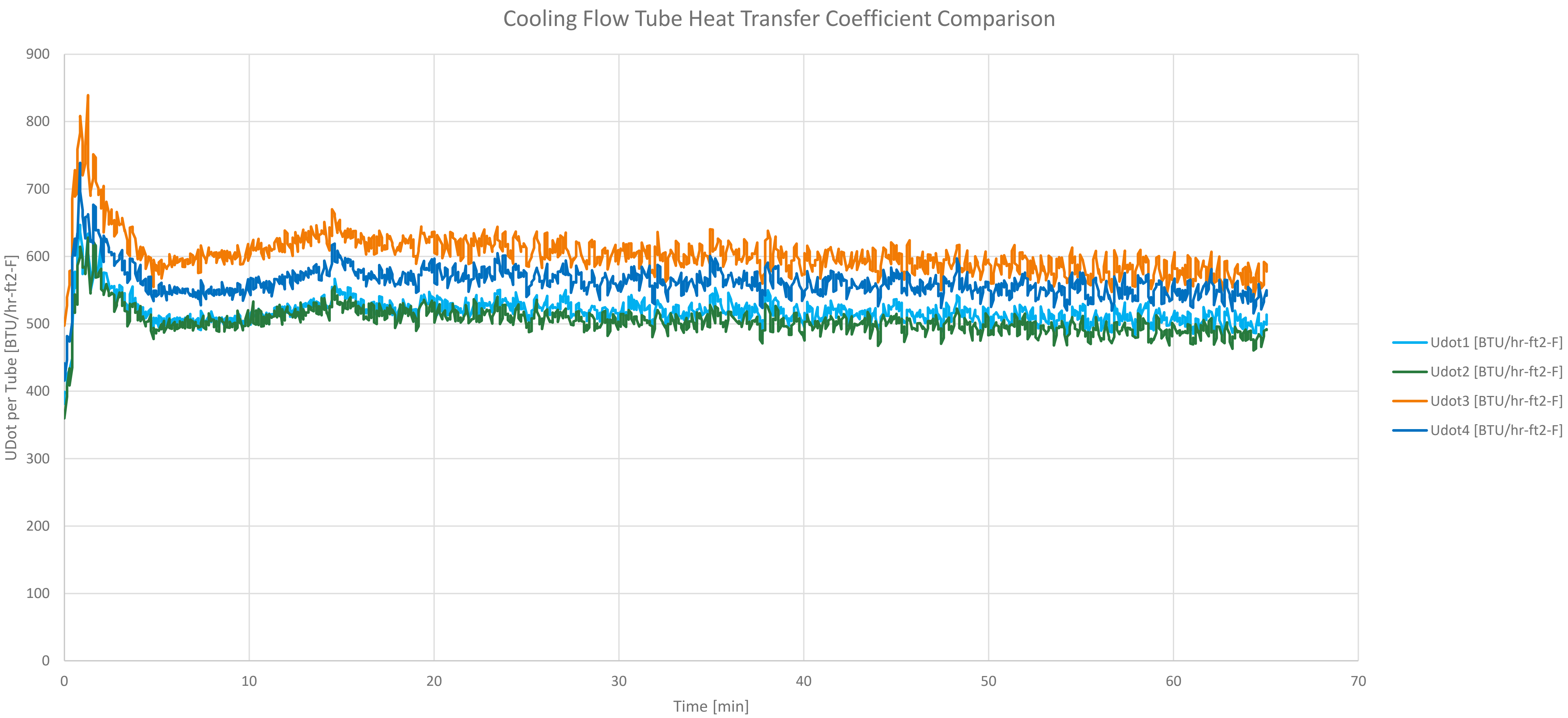
Epoxy-CuO_x Modified Tubes: Heat Transfer Coefficients, Half Bleach 03.17.2021



Epoxy-CuO_x Modified Tubes: Heat Transfer Coefficients, Half Bleach 3hr daily 04.05.2021



Epoxy-CuO_x Modified Tubes: Heat Transfer Coefficients, No Bleach, ½ flow rate 04.16.2021



Test #3: Internal (waterside) Tube Coating

hybrid - epoxy with nanocomposite

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FE0031762.

Q&A

Together…Shaping the Future of Electricity

Standard Operating Conditions

1. Target tube velocity of 7 ft/s (+/- 0.25 ft/s during an "official" test run)
2. Target average cooling water temperature rise of 15F (+/- 1F during an "official" test run)
3. Sand filter in use
4. UV filter not in use
5. Blowdown of 3% cooling water flow rate (+/- 2% aside from PLC-controlled blowdowns and additions required to maintain CT basin level during an "official" test run) OR controlled to CIC04 (CT basin conductivity) set to meet at target level as decided in planning stage.

Standard Operating Conditions

6. CT fan adjusted to maintain a condenser inlet temperature between 80-100F, with a variance of +/- 2F during an "official" test run.
7. Cooling water chemistry will only use:
    a. Sodium hypochlorite (bleach) to 0-3 ppm (exact level TBD during planning stage based on coating)
    b. Sulfuric acid to adjust to pH of 6.5-8.5 (exact level TBD during planning stage based on season and test-specific adjustment needs)
8. Monitor chemistry as needed via grab samples
9. Test run of 1 week for tests that do not include fouling
10. Test run of up to 90 days for tests that involve fouling. Each week, times for a 1-hour segment will be recorded where all conditions were near-optimal. These will be used as the official test runs.

Condenser Tube Fouling

Problems:

- reduces heat transfer
- can lead to corrosion and tube failure and consequently
  - contamination of high-purity steam cycle water
  - requires an outage to address the leak
- can require outage to remove foulant(s)

Common Foulants:

- microbiological films
- particulates
- scale

Project Objectives

- Evaluate application of various surface modification technologies on coal-fired power plant condenser tubes to enhance heat transfer properties and overall performance
- Coating technologies and materials will be applied to heat exchanger tubes to modify and enhance the heat transfer characteristics
- Testing of full-scale modified tubular components will be performed in a simulated environment relevant to coal-fired stations
- Supporting objectives include:
  - identification of potentially suitable coatings/modifications to test
  - laboratory testing to identify key modification characteristics both pre- and post- environmental exposure
  - heat transfer testing and performance evaluations

Project Objectives and Key Activities

M2.2: Technologies and Modifications

Coating name / company	AAA / BBB
Coating type	etc.
Coating thickness	
Coating process (location)	
Suitability for test condenser (15’ length)	
Suitability for field condenser	
Expected durability to 200 ^{o}F?	
Compatibility with common alloys	

ASTM Qualification Testing

1. Procurement of titanium coupons
2. Apply surface modification to coupons
3. ASTM testing

- hydrophobicity
- abrasion (wear)
- microscratch (adhesion)
- thermal conductivity (thermal diffusivity)

Titanium Coupons

1. rectangular 1” x 3” x 1/8”, 600-grit finish

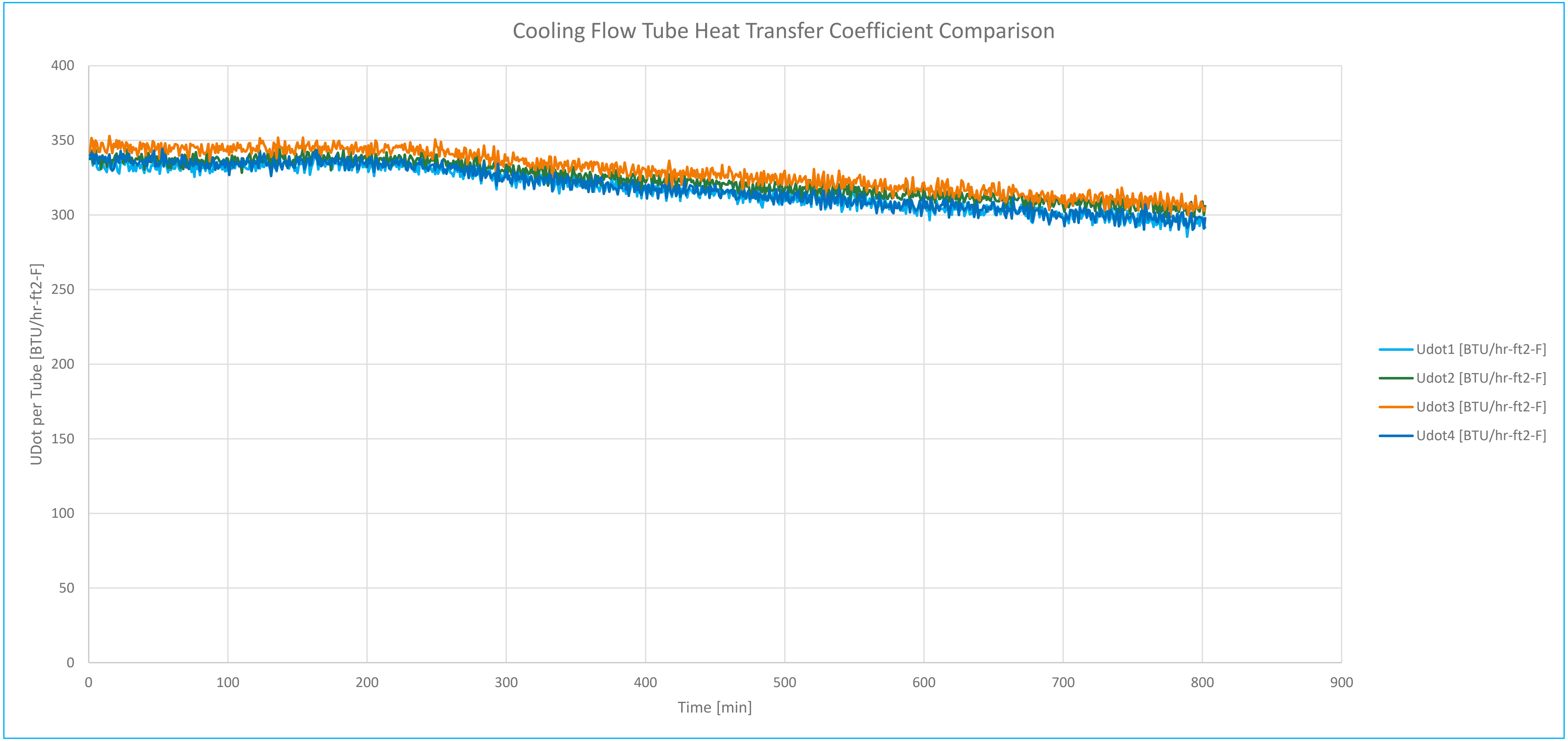
   - hydrophobicity, abrasion, microscratch

2. circular 0.500” diameter x 1/16”

   - thermal conductivity (thermal diffusivity)

- Provided for testing in duplicate after coating
- Non-modified coupons provided for each test

Physically Modified tube #5c: Heat Transfer Coefficients 02.10.2021



Physically Modified tube #4c: Heat Transfer Coefficients 01.12.2021