Application of Heat Transfer Enhancement (HTE) System for Improved Efficiency of Power Plant Condensers

Final Technical Report

U.S. Department of Energy, Office of Fossil Energy

DOE Award: DE-FE0031561

Executive Summary

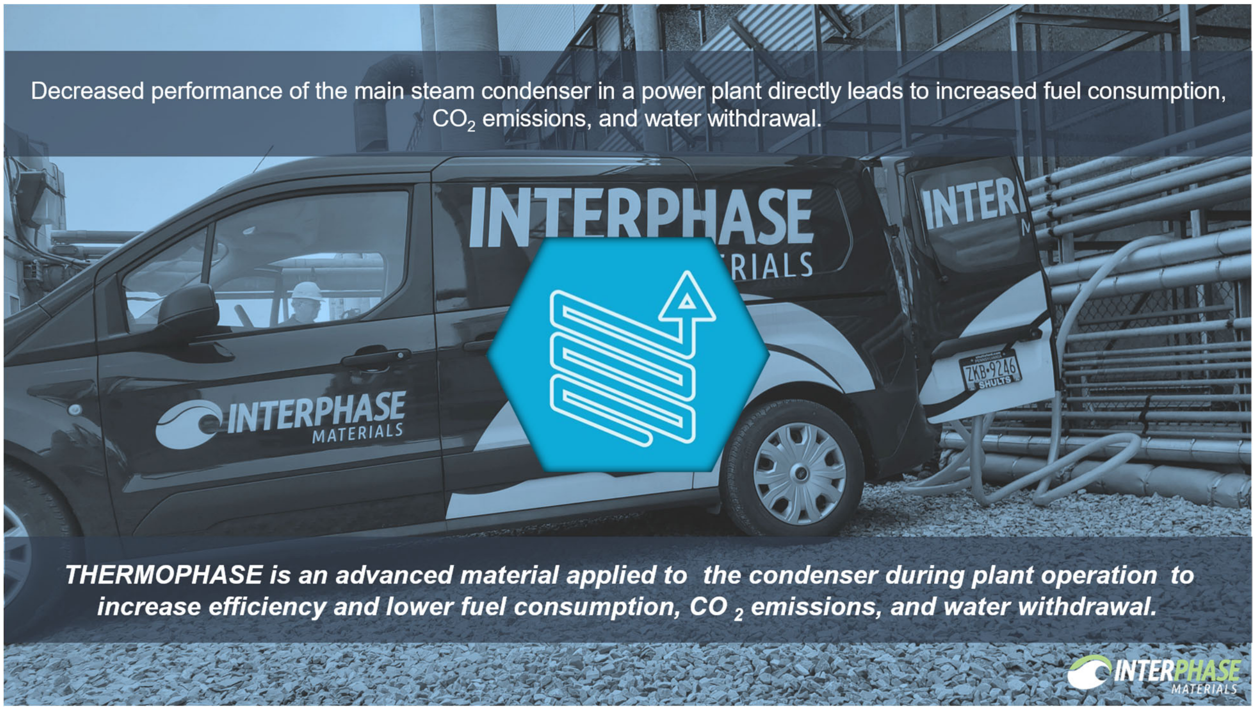

Figure 1. THERMOPHASE Problem-Solution Statement.

The mission of the National Energy Technology Laboratory (NETL), a U.S. laboratory under the Department of Energy, is to drive innovation and deliver solutions for an environmentally sustainable and prosperous energy future. Through the U.S. Department of Energy (DOE)/Fossil Energy's (FE) Crosscutting Research Program, NETL funded Interphase Materials to develop and demonstrate a technology to improve power plant condenser efficiency. From 2018 through 2021, Interphase Materials developed THERMOPHASE, an advanced material applied to the condenser during plant operation to increase efficiency and lower fuel consumption, CO_2 emissions, and water withdrawal. THERMOPHASE was evaluated in controlled environments where improvements to heat transfer and a reduction in fouling were observed. THERMOPHASE was also applied to the main condenser of the Longview Power plant and changes to the plant performance were monitored. After two years following application of THERMOPHASE, a reduction in condenser back pressure of 0.26 ± 0.13 inHg was observed resulting in an estimated $3.35M in fuel savings, 136 million lbs. of decreased CO_2 emissions, and 1,287 million gallons reduced water withdrawal.

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Acknowledgements

We would like to thank the National Energy Technology Laboratory (NETL) and the Department of Energy (DOE) for funding this work. This effort would not have been possible without their support. We especially would like to thank the U.S. taxpayers that enable the DOE and NETL to support technology advancements, like the work in this report, in the energy sector. We are grateful to have worked with tremendous partners at Longview Power who provided us with a continuous flow of data and allowed Interphase Materials to demonstrate THERMOPHASE on the plant's main steam condenser. Finally, Interphase Materials is appreciative of our employees, shareholders, and supporters that make the work we do possible.

Introduction

Energy is a necessary requirement of life. Prior to the modern era, organisms survived by directly consuming energy and converting that energy via metabolic processes into usable work. Organisms such as plants relied on light; whereas animals consumed other organisms to provide the chemical energy necessary for sustenance. In the modern era, energy also became a requirement for the tools that form the foundation of human society. In the United States, our habitats, modes of transportation, communication capabilities, and sources of sustenance are no longer functional without a constant supply of electrical energy of their own. The production of a constant source of electrical energy is now a requirement for human life in the modernized world.

However, the conversion of chemical energy from fossil fuels to usable electrical energy at power plants is resource expensive, produces CO_2 emissions, and consumes high volumes of water. The increased CO_2 emissions and water consumption by power plants threatens the biological requirements to have sources of clean air and water.

To produce the electrical energy necessary to sustain a technology-dependent human society; while balancing the biological needs of life on this planet, humans will need to overcome the current day technical limitations of energy production to enable sustainable production of clean energy.

The Steam Ranking Cycle

The Steam Rankine Cycle is a water-reliant process by which fossil fuel and nuclear power plants convert energy from fuel into usable electrical energy (Figure 2). In the boiler of a power plant, water is converted to steam by releasing the energy from the fuel input. In a fossil fuel plant, this occurs through the burning of coal or natural gas; whereas, in a nuclear plant this occurs via nuclear fission. The heat generated by the fuel consumption (Q_{in}) produces high pressure steam that flows through the steam turbines of the power plant causing them to rotate, converting the energy from the steam into usable work (W_{out}). The rotation of the turbines is coupled to the generator which contains a large electromagnet that produces electrical energy as it rotates. The second half of the Steam Rankine Cycle is about efficient recovery of the steam to provide a source of water back to the boiler. It is more energetically favorable to boil hot water as opposed to cold water. Therefore, the steam from the turbine (now at low pressure after going through the turbines) is condensed back into high temperature water at the main steam condenser. The heat removed from the steam during the condensation is transferred to cold water that is piped into tubes within the main steam condenser (Q_{out}). A constant supply of cold water is supplied to the condenser either from an array of cooling towers (known as a recirculating system) or a natural water source like a large lake or ocean (known as an open system). The high temperature water from the condenser, i.e. the condensate, is pumped back to the boiler to restart the process by the main condensate pump(s) (W_{in}).

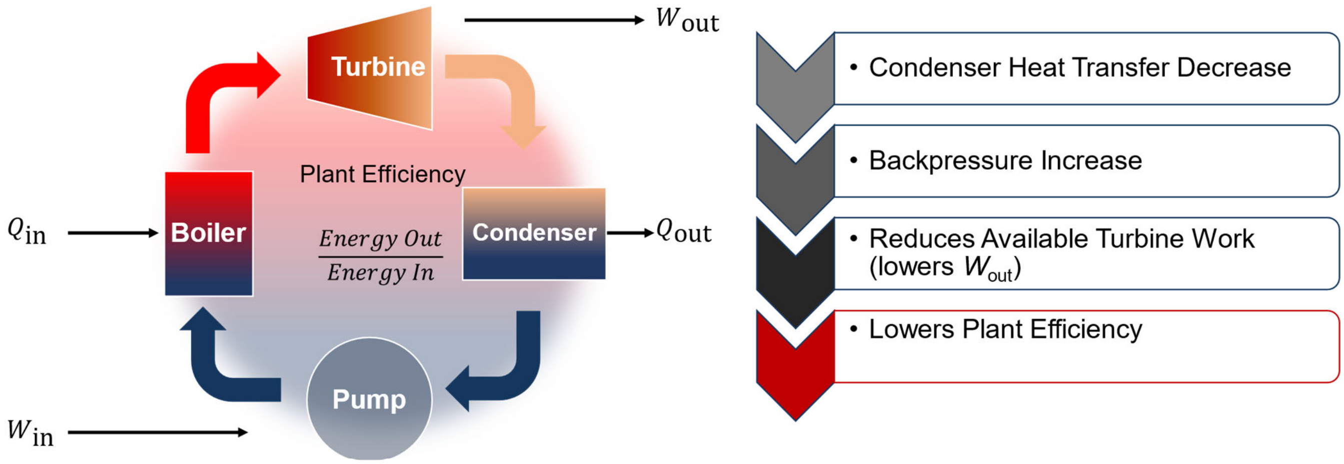

Figure 2. The condenser is one of four key components of the Steam Rankine Cycle. A decrease in efficiency of the condenser results in an increase in the turbine backpressure. The increase in backpressure reduces the available work to the turbine. To achieve a desired output, the operational response is to increase the Q_{in} by consuming more fuel.

The overall plant efficiency is defined as the ratio between the total energy input and the total energy output from the Steam Rankine Cycle. Each of the main four components (the boiler, turbine, condenser, and pump) can greatly impact the overall plant efficiency. An improvement in plant efficiency directly impacts the total amount of fuel used, the CO_2 emissions, and water withdrawal of the power plant.

Project Background

The mission of the National Energy Technology Laboratory (NETL), a U.S. laboratory under the Department of Energy, is to drive innovation and deliver solutions for an environmentally sustainable and prosperous energy future. In 2018, the NETL awarded projects under the Fossil Energy's (FE) Crosscutting Research Program (FOA DE-FOA-0001686), with the goal to bridge between basic and applied research by targeting concepts that offer the potential for transformational breakthroughs and step-change benefits in the way energy systems are designed, constructed, and operated. Interphase Materials, with its mission to restore and reinforce biological needs, was awarded one of these projects (Award No. DE-FE0031561) to increase plant efficiency by improving performance of a power plant steam condenser using its novel heat transfer enhancing advanced material, THERMOPHASE (Figure 3).

NETL Mission To drive innovation and deliver solutions for an environmentally sustainable and prosperous energy future	The U.S. Department of Energy (DOE)/Fossil Energy's (FE) Crosscutting Research Program FOA (DE-FOA-0001686) To bridge between basic and applied research by targeting concepts that offer the potential for transformational breakthroughs and step-change benefits in the way energy systems are designed, constructed, and operated.
Interphase Materials Mission To restore and reinforce global biological needs with sustainable biointerfaces	Project Objective (DE-FE0031561) To determine the condenser efficiency improvements coal-fired power plants could realize by utilizing the Recipient's HTE system* as well as the reduction of continuous feed water treatment technologies

Figure 3. Project Objective. This project was funded via the U.S. Department of Energy (DOE)/Fossil Energy's (FE) Crosscutting Research Program (DE-FOA-0001686).

*THERMOPHASE was referred to as the HTE System at the time Interphase Materials' submitted the original proposal.

THERMOPHASE Background

THERMOPHASE is an advanced material developed by Interphase Materials to improve the function of heat transfer surfaces. While the technology is sometimes referred to as a 'nano-coating', it is not a true coating. THERMOPHASE is comprised of multiple proprietary components that chemically bind to heat transfer surfaces, as opposed to cross-linking polymers like traditional coatings. In the laboratory setting, THERMOPHASE behaves like a monolayer with a thickness ~ nm. However, monolayer thickness in the field is often challenging to observe. In addition, due to the non-pristine nature of field materials, it's quite possible that THERMOPHASE performs more like a thin film in the field.

Functionally, THERMOPHASE works by impacting heat transfer surfaces in two manners (Figure 4). Firstly, the technology increases the surface energy of the material and interferes with attachment of both inorganic and biological fouling, reducing the fouling thermal resistance (R_{F}). Secondly, the technology is hypothesized to reduce the laminar boundary layer on heat transfer surfaces, reducing the boundary layer thermal resistance (R_{B}). The impact to the boundary layer is immediate; while, the impact to the fouling resistance is preventative. Therefore, THERMOPHASE increases heat transfer immediately by lowering the boundary layer thermal resistance and maintains improved heat transfer performance by reducing chronic fouling.

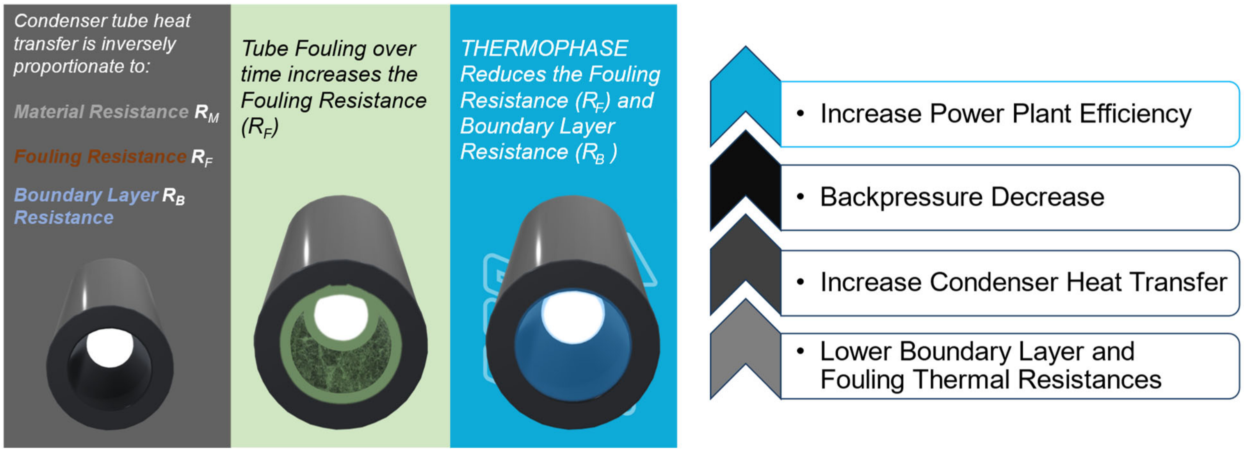

Figure 4. THERMOPHASE Mechanism of Action. THERMOPHASE is an advanced material technology applied to the inside of heat exchanger components, such as condenser tubes, to lower the thermal resistance of the material by either reducing fouling or the boundary layer.

THERMOPHASE has been in development by Interphase Materials since 2016 (Figure 5). Interphase Materials was founded in 2015 in Pittsburgh, PA after launching from the University of Pittsburgh. The first technology Interphase Materials developed was originally created with the intent to reduce biofouling on brain implants to improve neural prosthetic technology.

In 2016, the U.S. Navy awarded Interphase Materials a Phase 1 Small Business Innovative Research (SBIR) contract to develop a solution for reducing biological fouling in marine heat exchangers (Topic # N161-41-0110, Contract # N00024-16-P-4092). During the Phase 1 SBIR, Interphase Materials created THERMOPHASE, a biocide-free chemical material that covalently binds to the surface of heat exchanger components to reduce the accumulation of biological organisms. Interphase Materials discovered early during heat transfer testing that THERMOPHASE appeared to increase the heat transfer of heat exchangers, even those free from fouling. Due in part to this discovery, the U.S. Navy awarded Interphase Materials a Phase 2 SBIR contract in 2017 to continue the development of THERMOPHASE.

Following the initial success of the U.S. Navy SBIR development, Interphase Materials began transitioning the technology to land-based commercial applications. In 2018, Interphase Materials applied THERMOPHASE to a land-based chiller plant at the Carnegie Museum of Natural History in Pittsburgh, PA. Since that application, Interphase Materials has continued applications to land-based chillers in several states including Pennsylvania, New York, Illinois, Texas, Nebraska, Massachusetts, and Louisiana.

In 2019, as part of a Phase 3 SBIR awarded by the Rapid Reaction Technology Office, Interphase Materials applied THERMOPHASE to the seawater cooling system of a Caterpillar engine onboard the M-80 Stiletto. This marked the first time THERMOPHASE had been applied to an operating marine system. The following year, the Department of Energy funded the effort described in this report to Interphase Materials to apply THERMOPHASE to the first power plant condenser system at the Longview Power Plant in Maidsville, West Virginia. Most recently, Interphase Materials applied THERMOPHASE to the first marine chiller onboard the TS KENNEDY using a practical commercial application system.

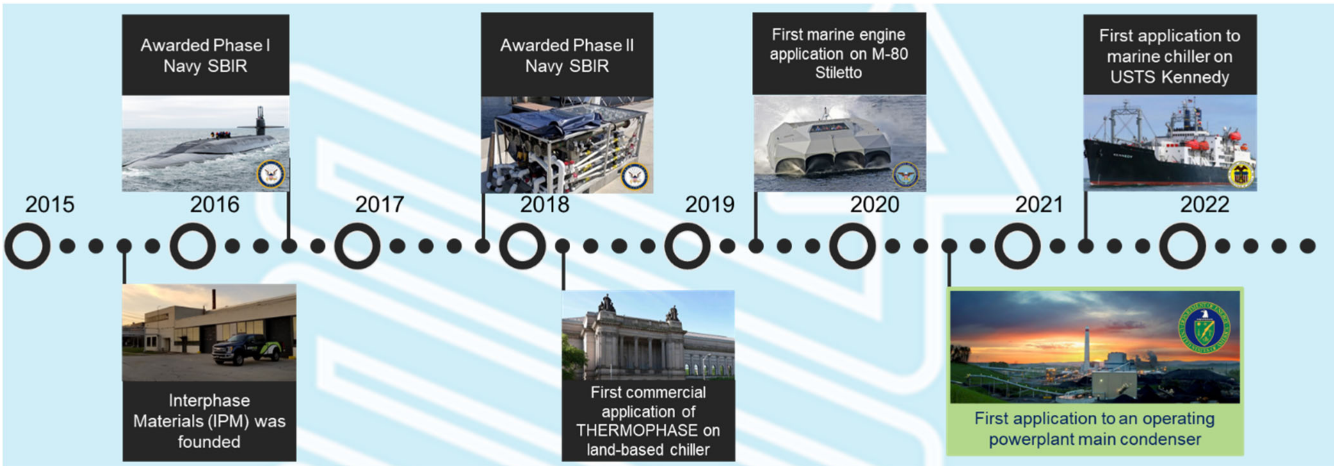

Figure 5. THERMOPHASE Development Timeline. THERMOPHASE has been in development since Interphase Materials was founded in 2015 and has been funded from a variety of sources including the U.S. Navy Small Business Innovation Program (SBIR), the Rapid Reaction Technology Office (within the Department of Defense), the U.S. Department of Transportation Maritime Administration (MARAD) and the Department of Energy. THERMOPHASE has been available commercially for building cooling systems since 2018.

During the recent application to the USTS Kennedy, a clear visual reduction in fouling was observed in chiller tubes treated with THERMOPHASE compared to standard untreated tubes (Figure 6). However, to achieve the goal of improving sustainable energy production by existing power plants, Interphase Materials would need to demonstrate performance improvements in an operational power plant. That was the mission of this effort, and the results are described herein.

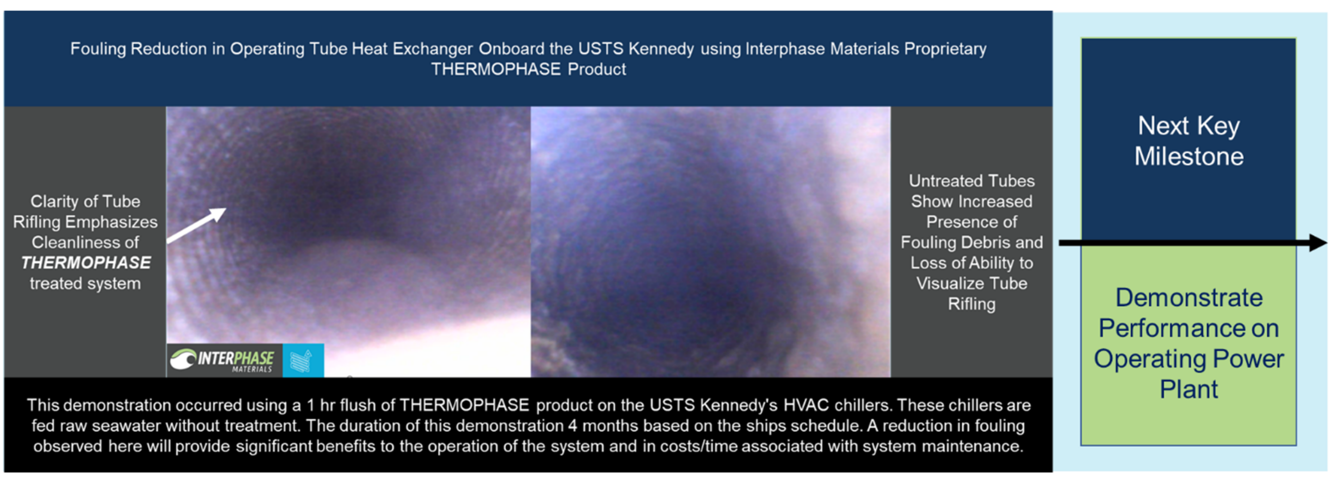

Figure 6. THERMOPHASE Field Demonstration and Next Key Milestone. THERMOPHASE reduced chiller tube fouling on the USTS Kennedy (DOT MARAD Project #693JF71850005, https://www.maritime.dot.gov/sites/marad.dot.gov/files/2022-09/Interphase%20Materials%20MMA%20Final%20Report.pdf). The next key technical milestone for THERMOPHASE is to demonstrate performance improvements in an operating power plant.

Pre-Application Testing

Before applying THERMOPHASE to the condenser of an operational power plant, Interphase Materials optimized the application conditions in controlled environments. Firstly, THERMOPHASE was evaluated for immediate heat transfer increases in the laboratory setting (Figure 7). A small heat transfer loop was constructed comprised of a heater and pump to supply high-temperature water to the shell-side of a test heat exchanger, a chiller and pump to supply cold-temperature water to the tube-side of a test heat exchanger, and the test heat exchanger itself. In some instances, the test heat exchanger was a single tube with a PVC shell. Using a stainless-steel heat exchanger, THERMOPHASE was shown to improve heat transfer by ~ 5.8% in the laboratory.

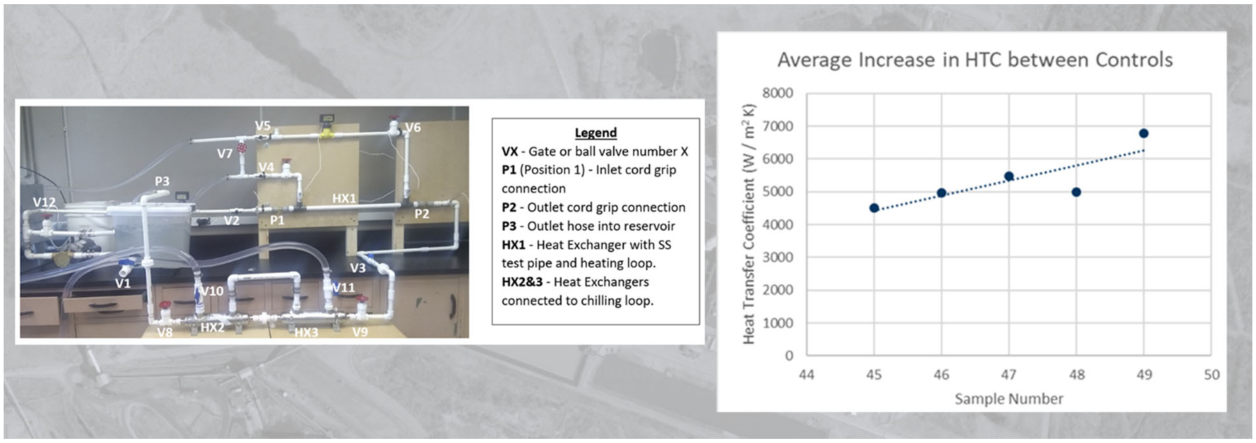

Figure 7. THERMOPHASE Benchtop Heat Transfer Results. THERMOPHASE increases the heat transfer coefficient by 5.8% in benchtop testing.

Two semi-controlled field tests were performed prior to the THERMOPHASE application on a power plant condenser. In the first test, cooling towers were installed at the water treatment facility serving the Longview Power plant (Figure 8). The water treatment facility withdraws water directly from Dunkard Creek and serves to provide clean water to the Longview Power plant. The test cooling towers were installed prior to water treatment to examine how quickly the raw water would foul the test fill. To determine the impact of THERMOPHASE on plastic-based cooling tower fill, one of the cooling towers was treated with THERMOPHASE by circulating the material through the tower. During the 2019 fouling season and over a time-frame of four months, the THERMOPHASE treated cooling tower showed a reduction of fouling weight by 18%.

Figure 8. THERMOPHASE Cooling Tower Fill Reduction. THERMOPHASE treatment reduced dry weight by 18%. Small-scale cooling towers installed at water treatment station, circulating raw untreated water over the 2019 fouling season. Towers treated with Interphase technology showed increased fouling resistance, accumulating 18% less dry weight fouling.

In the final semi-controlled field test, Interphase Materials evaluated the performance of THERMOPHASE on a custom-built test rig installed next to the Longview Power plant cooling towers (Figure 9). Within this test rig were four stainless steel heat exchangers. Each heat exchanger was fed cooling tower water from the Longview Power plant towers through the tube-side of the heat exchangers. The shell-side heat exchangers were supplied with heated water. One set of the heat exchangers were treated with THERMOPHASE. In the Fall of 2019, THERMOPHASE treated heat exchangers maintained a stable terminal temperature difference compared to the gradual rise observed in the untreated heat exchangers. Heat transfer calculations were inconclusive, and the test rig was abandoned in 2020 for multiple reasons. Firstly, following the COVID-19 pandemic, access to the rig was restricted. Secondly, the Longview Power plant staff were comfortable with the progress of THERMOPHASE and ready to begin testing on the main steam condenser, making the test rig superfluous.

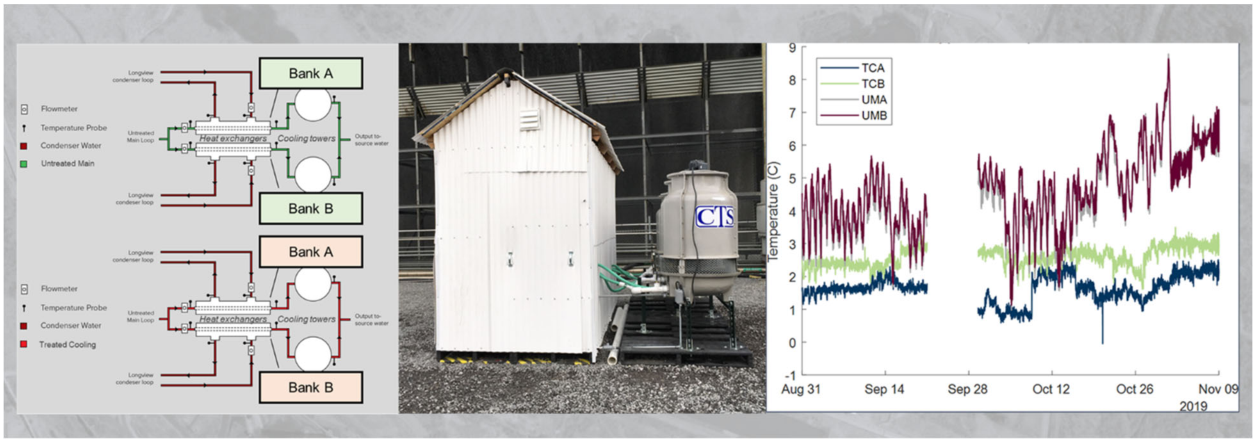

Figure 9. THERMOPHASE Pilot Skid Results. THERMOPHASE treatment prevented observed rise in terminal temperature difference. Interphase Materials custom built a heat transfer skid and pumped cooling water from the Longview Power Plant through the system. Two heat exchangers in the skid were treated with THERMOPHASE and two were not. During the brief operation there was an increase in the terminal temperature difference in the untreated heat exchangers.

THERMOPHASE Application to Longview Power Plant

Longview Power Plant

The Longview Power plant is one of the most efficient coal power plants in the world on a basis of plant heat-rate (Figure 10). The plant is equipped with an HMNN 770 MW turbine system, a SGen6-3000W, and a SCon6000 condenser, all products of Siemens. Interphase Materials was fortunate to partner with Longview Power for the THERMOPHASE demonstration.

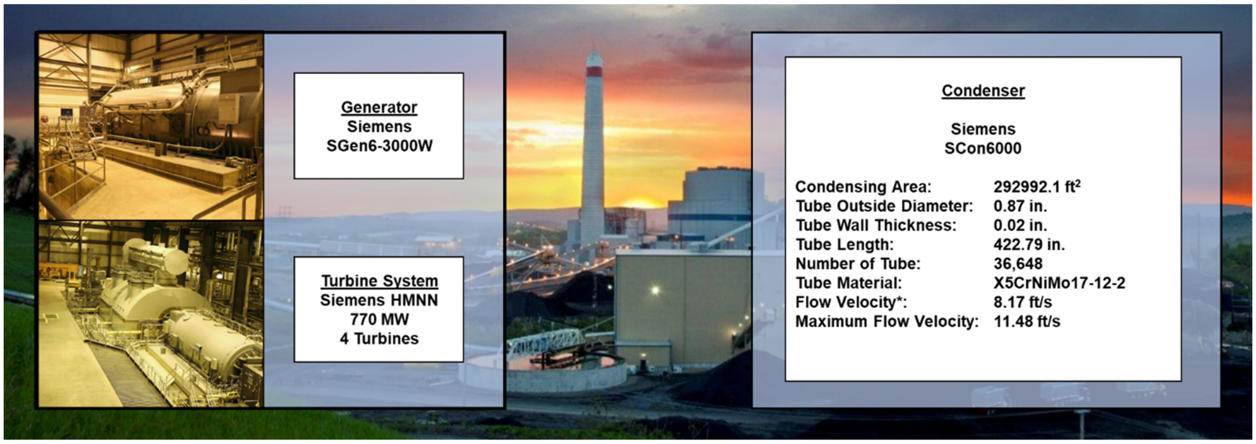

Figure 10. Longview Power Plant Overview. *Flow velocity at rated temperature rise

Source: The Future of Reliable Clean Coal Power. Retrieved December 13, 2022, from https://longviewpower.com/clean-coal-power

The location of the Longview Power plant also made the effort more feasible. The plant is located just south of the Pennsylvania-West Virginia border in Maidsville, WV (Figure 11) within a 2 to 3 hour drive from Interphase Materials headquarters in Pittsburgh, PA..

Figure 11. Longview Power Plant Location. The Longview Power Plant is located in Maidsville, WV.

Operationally, the Longview Power plant runs near maximum capacity with an average power output of 755 MW (Figure 12). Plant operation was mainly consistent between 2017 and 2022; however, during the COVID-19 pandemic, Longview did increase low-load operations for a brief period. During low-load conditions, the plant would operate closer to 500 MW.

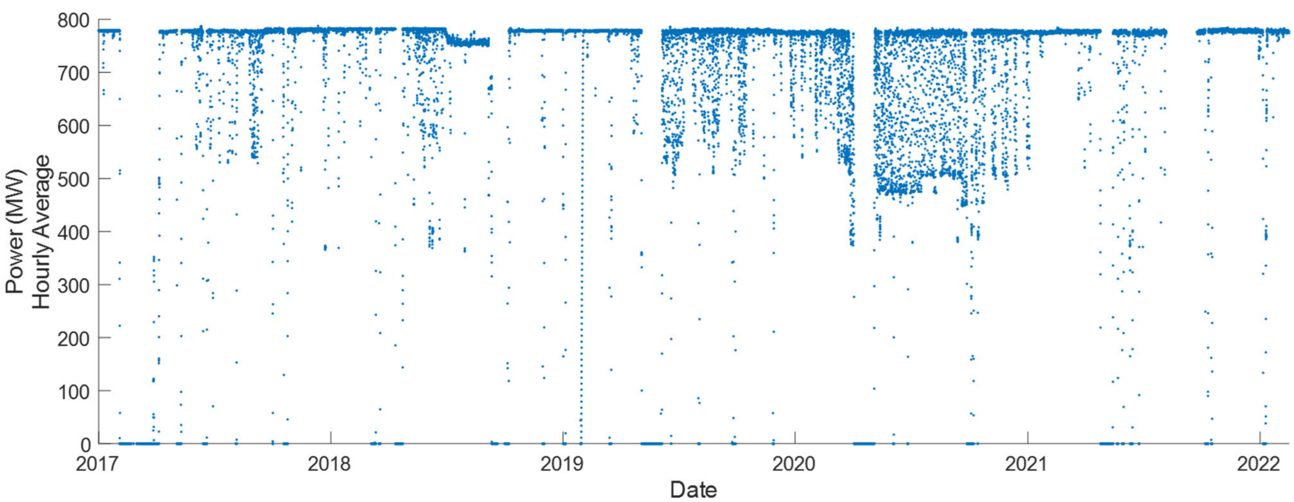

Figure 12. Longview Power Plant Output. The average power output of the Longview Power plant is ~ 755MW. The daily average of the hourly MW output is plotted above. The output is an instrument value recorded in the Longview Power historian (variable 10MKA01CE903.XQ02).

Table 1. Longview Power Plant Output Summary Table. The plant power output is an instrument value recorded in the Longview Power historian (variable 10MKA01CE903.XQ02).

Longivew Power Plant Operation Summary

Daily Average Output (MWh)	Capacity	Percent of Total Days	Percent of Operational Days
500+	65%	83%	100%
539+	70%	82%	99%
616+	80%	80%	97%
693+	90%	74%	90%
731+	95%	65%	78%

Based on data set from 01-JAN-2017 through 15-FEB-2022

Between January 1st 2017 and February 15th 2022, the Longview Power plant was operating at above 500 MW for 83% of all possible days. For 78% of these operational days, the plant was outputting more than 731 MW, which is at 95% full capacity (Table 1).

THERMOPHASE Application

THERMOPHASE was applied to the Longview Power plant three separate times (Figure 13). The first application occurred on September 2nd, 2020. For the first application, THERMOPHASE was applied over the course of two weeks by direct injection into a port before the main condenser inlet. The material was prepared in two 275-gallon chemical storage totes and slowly pumped in, with concentrations never exceeding 6 ppm. THERMOPHASE was added slowly in this manner so that Interphase Materials and Longview Power plant staff could closely monitor the plant performance for any undesirable effects. THERMOPHASE was added directly to the cooling tower sump in under one hour during the second application on July 27th 2021. Interphase Materials injected THERMOPHASE via a more concentrated 50-gallon tank loaded onto a company truck for this application. Finally, 50-gallons of material were delivered to the Longview Power staff to add by staff members for the third and final application on Augusts 11th, 2022.

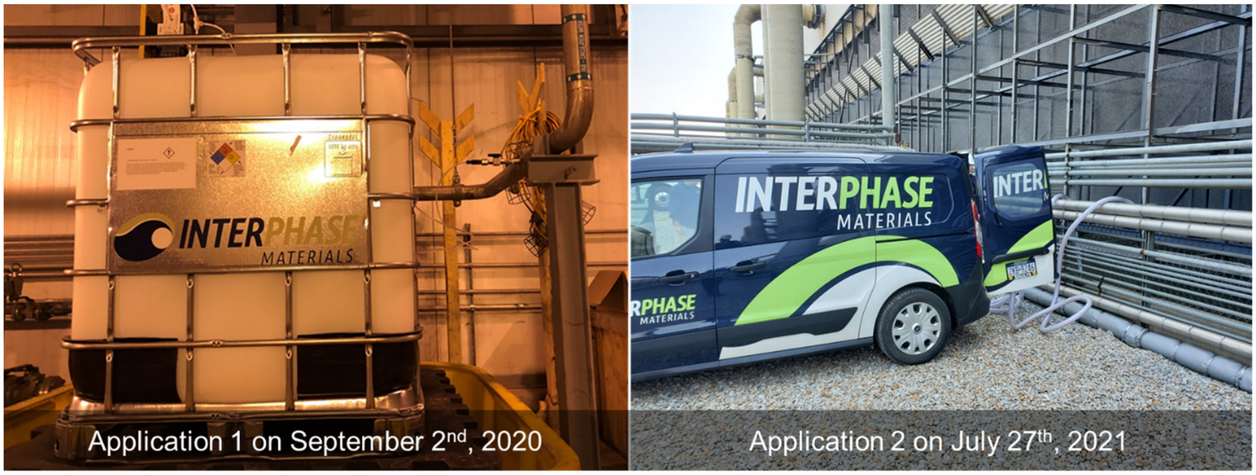

Figure 13. THERMOPHASE was applied to the Longview Power plant beginning on September 2nd, 2020. The second and third applications were on July 27th, 2021, and August 11th, 2022. In the first application, THERMOPHASE was slowly added over two weeks with the system concentration not exceeding 6 ppm (based on an estimated 2 million-gallon system volume). The second and third applications were performed by adding the material directly into the cooling tower sump with a peak concentration of ~ 25 ppm. The tubes of the condenser were not cleaned before or after THERMOPHASE application.

Data Collection and Analysis

All Longview Power plant data were sent from Longview Power staff directly to Interphase Materials. The data was extracted from the plant historian. Some of the data are instrument values and others are online calculations completed by the historian. These online calculations were setup by the Longview Power plant staff in collaboration with the OEM manufacturers and power plant contractors during the power plant's construction.

Interphase Materials has been developing and evaluating THERMOPHASE since 2016. Our scientists and engineers have been inside countless facilities including power plants, district energy plants, and shipping vessels. The plants are complex, dynamic, and unique. Creating generalized conclusions about the impact of a single technology is a very challenging task for a single plant, let alone attempting to extend these conclusions to the general. To reduce the complexity of the systems, advanced statistical tools can be deployed; however, an increase in statistical complexity is often at odds with interpretability. Therefore, our goal is to use simple statistical methodology combined with transparency in our methods to enable plant experts to interpretate and apply the results to their own unique circumstances.

To create a simple analytical approach that could be easily communicated to plant experts, Interphase Materials chose to utilize interrupted time series analysis to evaluate several key performance metrics. The performance metrics were based on several key industry metrics, including condenser back pressure, Heat Exchanger Institute (HEI) Cleanliness Factor, terminal temperature difference, and the overall heat transfer[1].

To evaluate the change in these performance metrics over time, Interphase Materials used Interrupted Time Series Analysis, a quasi-experimental comparative analysis tool. This methodology is often employed in economic, medical, and psychological studies that are evaluating the impact of an intervention on a time-series[2]. The end result of the analysis is output of four key statistical coefficients. The lines and fit for each of these curves are displayed in the data figures. In addition, when combining results to determine net changes, the propagation of error was performed based on standard methods.

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THERMOPHASE Application Results

Heat Exchanger Institute (HEI) Cleanliness Factor (%)

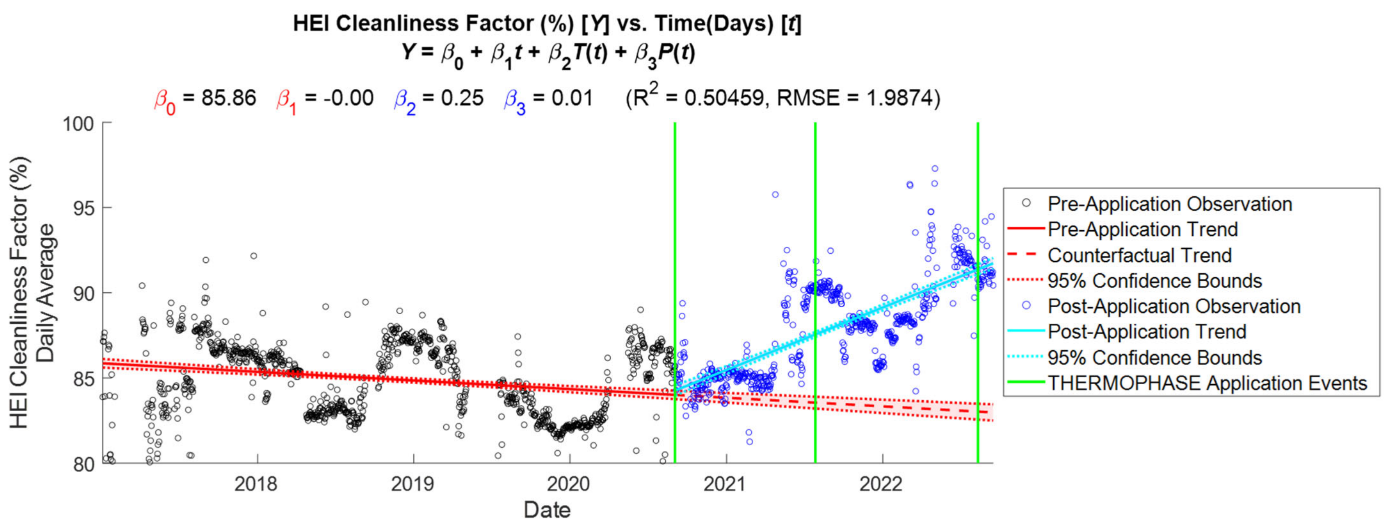

Figure 14 The daily average of the HEI Cleanliness Factor is plotted above through September 16th, 2022. The HEI Cleanliness Factor is a historian calculation recorded in the Longview Power historian (variable 1OPM.CONDENSER:Cleanliness). The HEI Cleanliness Factor is defined as $\frac{U_{\text{Observed}}}{U_{\text{Expected}}} \times 100$.

Table 2 There was a statistically significant immediate and sustained decrease in the HEI Cleanliness Factor after the THERMOPHASE application on September 2nd, 2020. The HEI Cleanliness Factor is a historian calculation recorded in the Longview Power historian (variable 1OPM.CONDENSER:Cleanliness). The HEI Cleanliness Factor is defined as $\frac{U_{\text{Observed}}}{U_{\text{Expected}}} \times 100$.

HEI Cleanliness Factor (%)	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	85.86 ± 0.26	%	0.00
Pre-Application Slope (β_1)	-0.51 ± 0.12	% per Year	0.00
Immediate Change Post-Application (β_2)	0.25 ± 0.39	%	0.21
Sustained Change Post-Application (β_3)	4.17 ± 0.29	% per Year	0.00
Net Change After 2 Years	9.60 ± 0.74	%	

The upper and lower limits for analysis were 80.00 and 100.00 %.

Condenser Backpressure

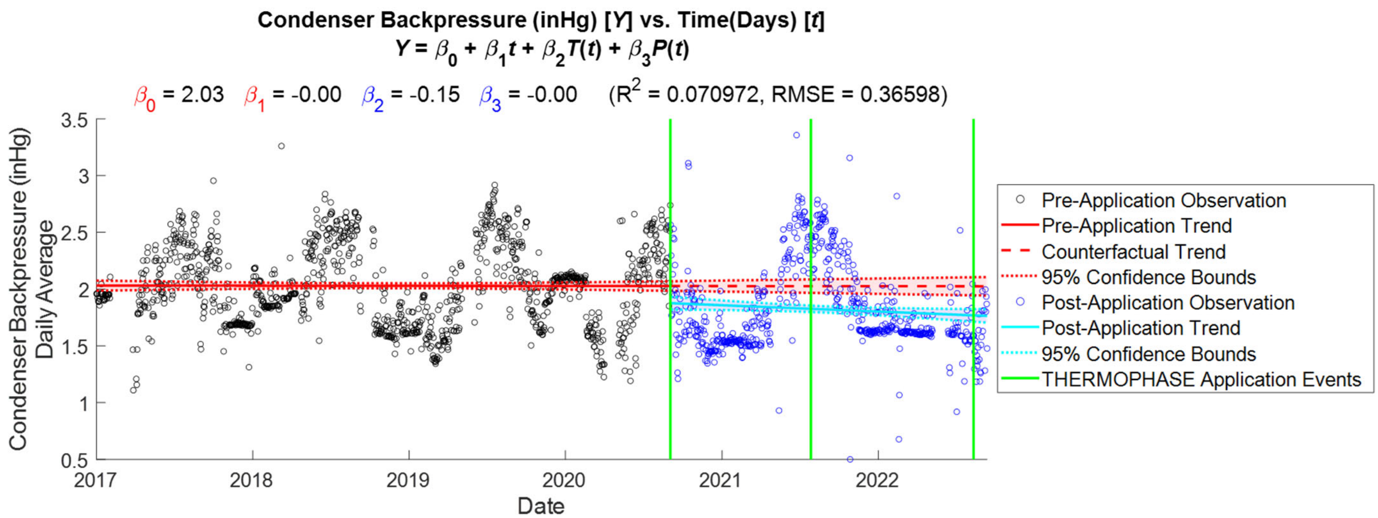

Figure 15. The daily average of the condenser backpressure is plotted above through September 16th, 2022. The condenser backpressure is an instrument value recorded in the Longview Power historian (variable 10MAG10CP002.XQ01).

Table 3. There was a statistically significant immediate and sustained decrease in condenser backpressure after the THERMOPHASE application on September 2nd, 2020. Condenser backpressure is an instrument value recorded in the Longview Power historian (variable 10MAG10CP002.XQ01).

Condenser Backpressure (inHg)

	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	2.03 ± 0.04	inHg	0.000
Pre-Application Slope (β_1)	0.00 ± 0.02	inHg per Year	0.916
Immediate Change Post-Application (β_2)	-0.15 ± 0.07	inHg	0.000
Sustained Change Post-Application (β_3)	-0.054 ± 0.054	inHg per Year	0.047
Net Change After 2 Years	-0.26 ± 0.13	inHg	

The upper and lower limits for analysis were 0.50 and 3.50 inHg.

Terminal Temperature Difference

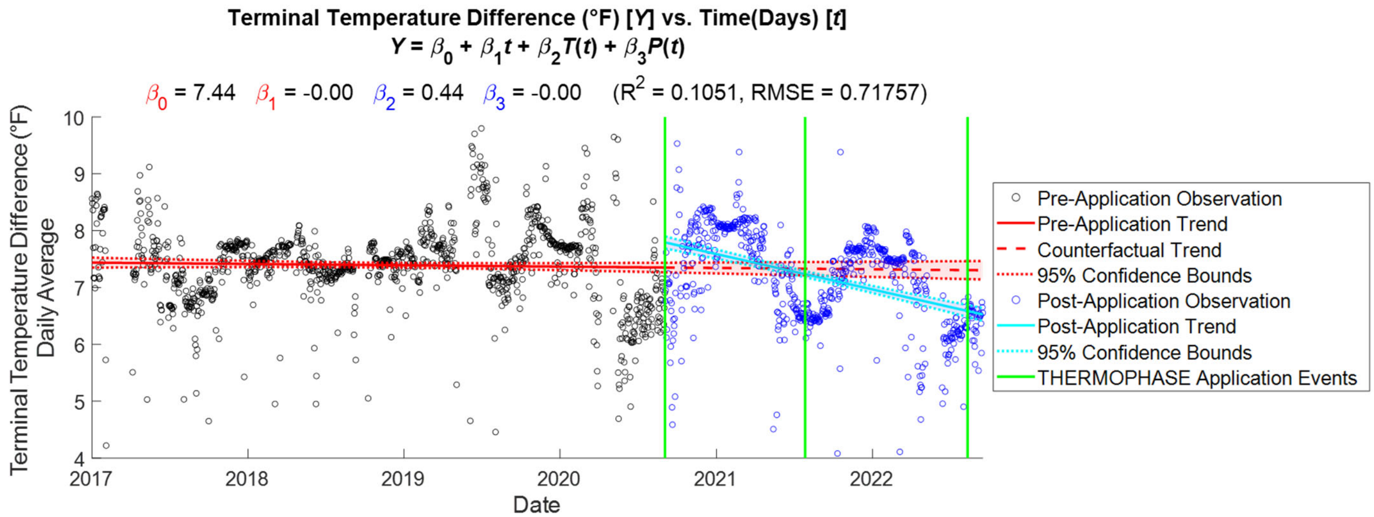

Figure 16. The daily average of the terminal temperature difference is plotted above through September 16th, 2022. The terminal temperature difference is a historian calculation recorded in the Longview Power historian (variable 1OPM.CONDENSER:TTD). The terminal temperature difference *(TTD)* is defined as, $TTD = T_{\text{Steam}} - T_{\text{CWout}}$.

Table 4. There was a statistically significant immediate increase and a sustained decrease in terminal temperature difference after the THERMOPHASE application on September 2nd, 2020. The terminal temperature difference is a historian calculation recorded in the Longview Power historian (variable 1OPM.CONDENSER:TTD). The terminal temperature difference (TTD) is defined as,

Terminal Temperature Difference (°F)

	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	7.44 ± 0.09	°F	0.00
Pre-Application Slope (β_1)	-0.02 ± 0.04	°F per Year	0.26
Immediate Change Post-Application (β_2)	0.44 ± 0.14	°F	0.00
Sustained Change Post-Application (β_3)	-0.60 ± 0.10	°F per Year	0.00
Net Change After 2 Years	-0.71 ± 0.26	°F	

The upper and lower limits for analysis were 4.00 and 10.00 °F.

Condenser Heat Duty

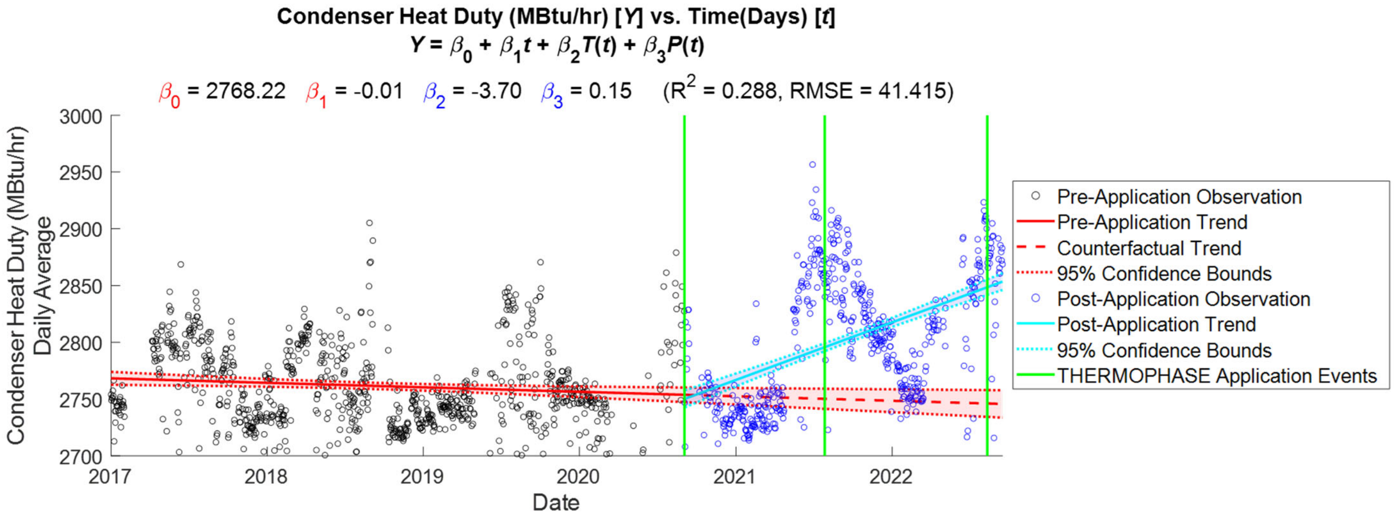

Figure 17. The daily average of the condenser heat duty is plotted above through September 16th, 2022. The condenser heat duty is an instrument value recorded in the Longview Power historian (variable 1OPM.CONDENSER:DUTY).

Table 5. There was a statistically significant sustained increase in condenser heat duty after the THERMOPHASE application on September 2nd, 2020. The condenser heat duty is a historian calculation recorded in the Longview Power historian (variable 1OPM.CONDENSER:DUTY).

Condenser Heat Duty (MBtu/hr)			
	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	2,768.22 ± 5.69	MBtu/hr	0.00
Pre-Application Slope (β_1)	-3.95 ± 2.93	MBtu/hr per Year	0.01
Immediate Change Post-Application (β_2)	-3.70 ± 9.88	MBtu/hr	0.46
Sustained Change Post-Application (β_3)	54.71 ± 7.11	MBtu/hr per Year	0.00
Net Change After 2 Years	113.54 ± 18.28	MBtu/hr	
The upper and lower limits for analysis were 2,700.00 and 3,000.00 MBtu/hr.			

Temperature Rise

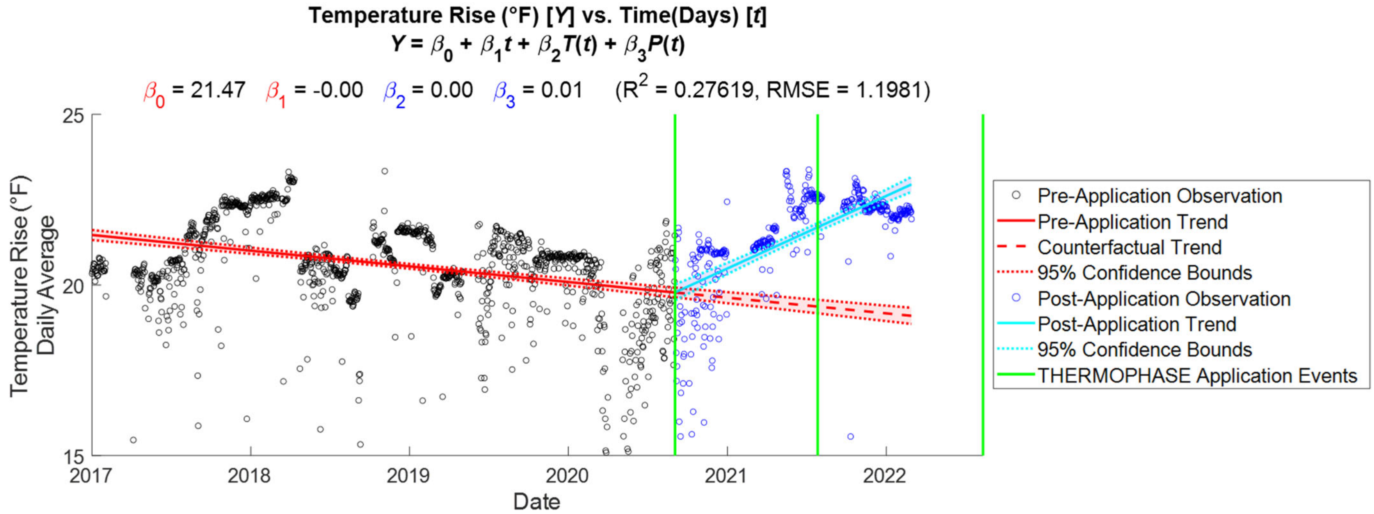

Figure 18. The daily average of the temperature rise is plotted above through February 12th, 2022. The temperature rise is an offline calculation. The temperature rise (*TR*) is defined as, $TR = T_{CW_{out}} - T_{CW_{in}}$.

Table 6. There was a statistically significant sustained increase in temperature rise after the THERMOPHASE application on September 2nd, 2020. The temperature rise is an offline calculation. The temperature rise (*TR*) is defined as, $TR = T_{CW_{out}} - T_{CW_{in}}$.

Temperature Rise (°F)

	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	21.47 ± 0.15	°F	0.000
Pre-Application Slope (β_1)	-0.46 ± 0.07	°F per Year	0.000
Immediate Change Post-Application (β_2)	0.00 ± 0.28	°F	0.993
Sustained Change Post-Application (β_3)	2.59 ± 0.27	°F per Year	0.000
Net Change After 2 Years	6.09 ± 0.62	°F	

The upper and lower limits for analysis were 15.00 and 25.00 °F.

Log-Mean Temperature Difference

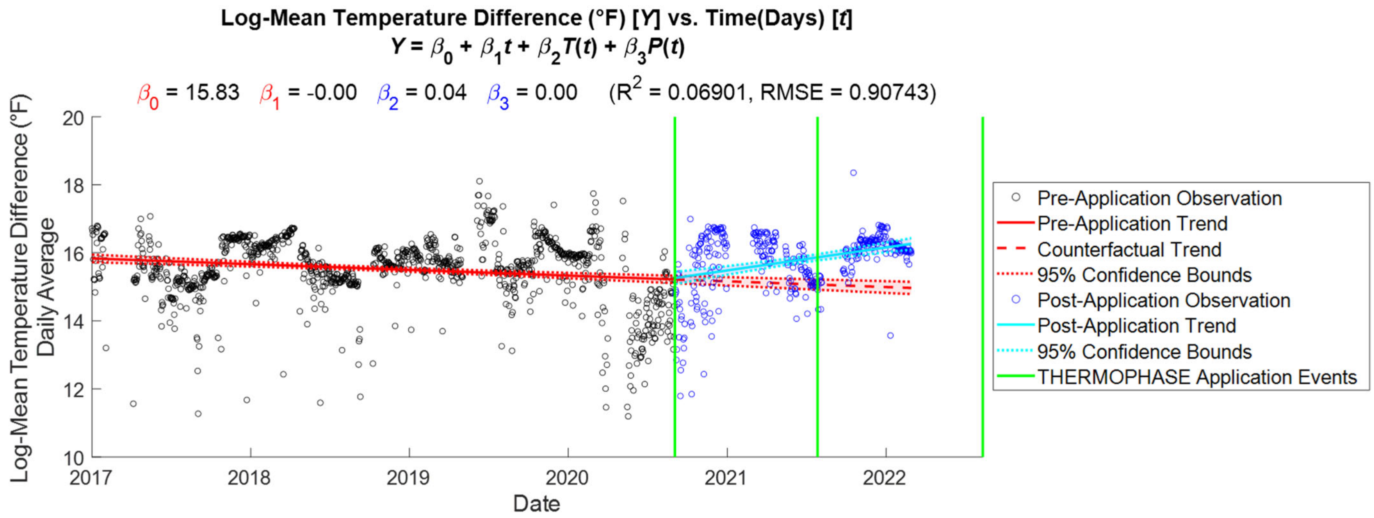

Figure 19. The daily average of the log-mean temperature difference is plotted above through September 12th, 2022. The log-mean temperature difference is an offline calculation. The log-mean temperature difference (LMTD) is defined as, $LMTD = \frac{TR}{\ln\left(\frac{TR+TTD}{TTD}\right)}$.

Table 7. There was a statistically significant sustained increase in log-mean temperature difference after the THERMOPHASE application on September 2nd, 2020. The log-mean temperature difference is an offline calculation. The log-mean temperature difference (LMTD) is defined as, $LMTD = \frac{TR}{\ln\left(\frac{TR+TTD}{TTD}\right)}$.

Log-Mean Temperature Difference (°F)			
	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	15.83 ± 0.11	°F	0.000
Pre-Application Slope (β_1)	-0.17 ± 0.05	°F per Year	0.000
Immediate Change Post-Application (β_2)	0.04 ± 0.21	°F	0.699
Sustained Change Post-Application (β_3)	0.84 ± 0.21	°F per Year	0.000
Net Change After 2 Years	2.06 ± 0.47	°F	
The upper and lower limits for analysis were 10.00 and 20.00 °F.			

Heat Transfer Coefficient

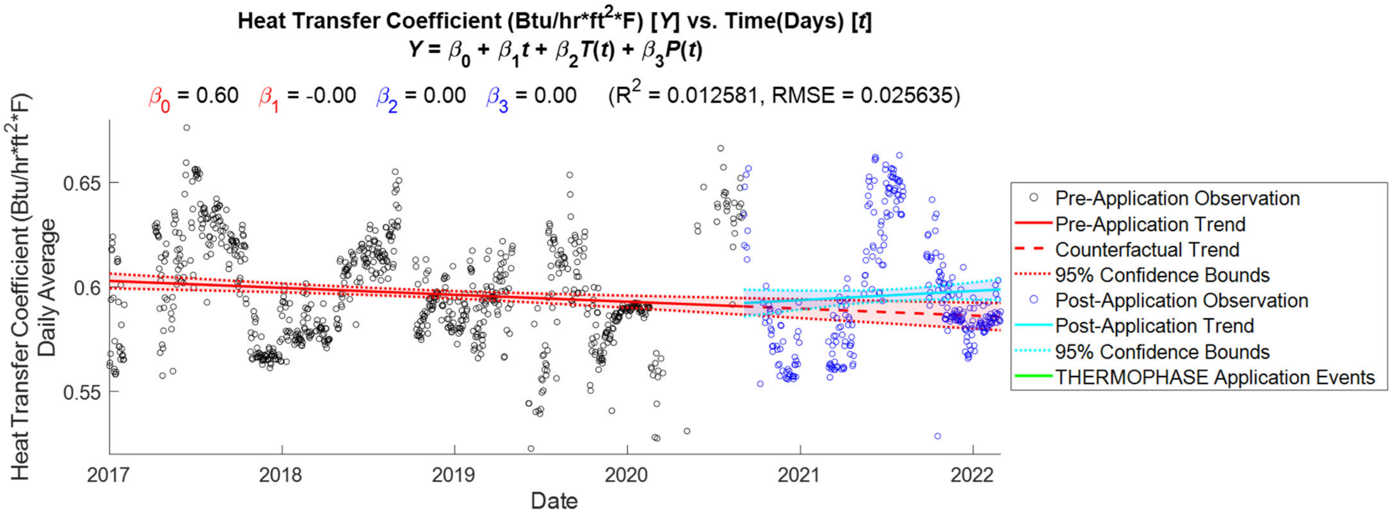

Figure 20. The daily average of the heat transfer coefficient is plotted above through September 12th, 2022. The heat transfer coefficient is an offline calculation. The heat transfer coefficient (U) is defined as, $U = \frac{Q}{A \cdot LMTD}$.

Table 8. The daily average of the heat transfer coefficient is plotted above through September 12th, 2022. The heat transfer coefficient is an offline calculation. The heat transfer coefficient (U) is defined as, $U = \frac{Q}{A \cdot LMTD}$.

Heat Transfer Coefficient (Btu/(hr·ft2·°F))

	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	0.60 ± 0.00	Btu/(hr·ft2·°F)	0.000
Pre-Application Slope (β_1)	0.00 ± 0.00	Btu/(hr·ft2·°F) per Year	0.000
Immediate Change Post-Application (β_2)	0.00 ± 0.01	Btu/(hr·ft2·°F)	0.684
Sustained Change Post-Application (β_3)	0.008 ± 0.007	Btu/(hr·ft2·°F) per Year	0.029
Net Change After 2 Years	0.024 ± 0.016	Btu/(hr·ft2·°F)	

The upper and lower limits for analysis were 0.50 and 0.70 Btu/(hr·ft2·°F).

Mass Water Flow

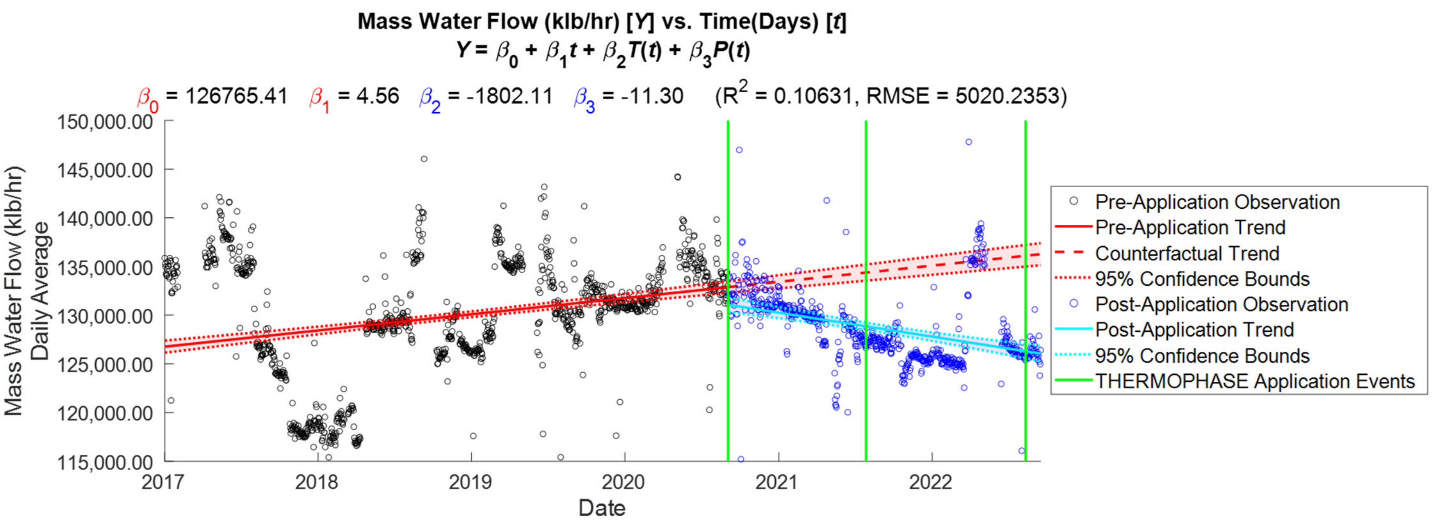

Figure 21. The daily average of the mass circulation water flow is plotted above through September 16th, 2022. The mass circulation water flow is a historian calculated value recorded in the Longview Power historian (variable 1OPM.CIRC_WATER_IN:FLOW).

Table 9. There was a statistically significant immediate increase and sustained increase in the mass circ water flow after the THERMOPHASE application on September 2nd, 2020. The mass circulation water flow is a historian calculated value recorded in the Longview Power historian (variable

Mass Water Flow (klb/hr)			
	Estimate ± 95% C.I.	Units	p-Value
Y-Intercept (β_0)	126,765.41 ± 621.59	klb/hr	0.000
Pre-Application Slope (β_1)	1,664.36 ± 288.15	klb/hr per Year	0.000
Immediate Change Post-Application (β_2)	-1,802.11 ± 959.59	klb/hr	0.000
Sustained Change Post-Application (β_3)	-4,126.962 ± 720.784	klb/hr per Year	0.000
Net Change After 2 Years	-13,376.829 ± 1824.218	klb/hr	
The upper and lower limits for analysis were 115,000.00 and 150,000.00 klb/hr.			

Conclusions

The size and dynamic nature of power plants makes it challenging to determine how one change impacts the entire system. However, by evaluating several key metrics dependent upon the condenser we can see several changes in the plant and condenser performance following the first application of THERMOPHASE on September 2nd, 2020.

The overall heat transfer coefficient of the condenser should be, by definition, fundamental to the performance of the condenser. Following the THERMOPHASE application on September 2nd, 2020, there was a statistically significant sustained increase in each of the heat transfer coefficient components (condenser duty, LMTD, and the overall heat transfer coefficient) (Table 10).

Table 10.

Heat Transfer Components			
	Condenser Duty (Q)	Log-Mean Temperature Difference (LMTD)	Oveall Heat Transfer Coefficient (U)
Source	Online Calcultion	Offline Calculation	Offline Calculation
Immediate Change Post-Application	-3.70 ± 9.88MBtu/hr	0.04 ± 0.21°F	0.00 ± 0.01Btu/(hr·ft2·°F)
Sustained Change Post-Application	54.71 ± 7.11MBtu/hr per Year	0.84 ± 0.21°F per Year	0.008 ± 0.007Btu/(hr·ft2·°F) per Year
Net Change After 2 Years	113.54 ± 18.28MBtu/hr	2.06 ± 0.47°F	0.024 ± 0.016Btu/(hr·ft2·°F)

In addition, when evaluating the key condenser performance, following the application of THERMOPHASE there were observable improvements. Following the THERMOPHASE application on September 2nd, 2020, there was a statistically significant sustained increase in each of the condenser performance metrics (terminal temperature difference, backpressure, overall heat transfer coefficient, and HEI cleanliness factor). There was a statistically significant increase in terminal temperature difference and a decrease in backpressure (Table 11).

Table 11

Condenser Performance				
	TTD	BP	U	CF
Source				
Immediate Change Post-Application	0.44 ± 0.14°F	-0.15 ± 0.07inHg	0.00 ± 0.01Btu/(hr·ft2·°F)	0.25 ± 0.39%
Sustained Change Post-Application	-0.60 ± 0.10°F per Year	-0.054 ± 0.054inHg per Year	0.008 ± 0.007Btu/(hr·ft2·°F) per Year	4.17 ± 0.29% per Year
Net Change After 2 Years	-0.71 ± 0.26°F	-0.26 ± 0.13inHg	0.024 ± 0.016Btu/(hr·ft2·°F)	9.60 ± 0.74%

The alignments in the improvements observed on the Longview Power bring power to the observations, even given the dynamic nature of plant operation. The confidence of the improvements in the terminal temperature difference and backpressure associated with THERMOPHASE are strengthened by the corroborating improvements observed in the overall heat transfer coefficient and HEI cleanliness factor. Industry and academic reports suggest an improvement in condenser backpressure of 1.0 inHg results in 2-3% improvement in plant efficiency[3]–[5]. Assuming a decrease of 0.26 inHg ± 0.13 inHg in condenser backpressure following THERMOPHASE combined with the average water withdrawal, CO_2 emissions, and fuel cost reported by U.S. Energy Information Administration, an overall impact can be calculated (www.eia.gov). The improvements by MWh can be seen in Table 12 and the improvement after 2 years can be seen in Table 13.

Table 12.

THERMOPHASE 2-Year Savings per MWh		
	Estimate ± 95% C.I.	
Savings Type	Coal Plant	Natural Gas Plant
Water Withdrawl	139 ± 69.6 gal/MWh	18 ± 9.1 gal/MWh
CO_2 Emissions	15 ± 7.3 lb/MWh	6 ± 3.2 lb/MWh
Fuel Cost	$0.36 ± 0.2 per MWh	$0.33 ± 0.2 per MWh

Table 13.

THERMOPHASE 2-Year Savings per Plant					
	Estimate ± 95% C.I.				
Savings Type	Longview Power Plant	Average Coal Plant	Average Natural Gas Plant	All U.S. Coal Plants	All U.S. Natural Gas Plants
Water Withdrawl	1,287 ± 750.8 Mgal	972 ± 486.1 Mgal	29 ± 14.4 Mgal	222,622 ± 111,311 Mgal	58,094 ± 29,047 Mgal
CO_2 Emissions	136 ± 79.3 Mlbs	103 ± 51.3 Mlbs	10 ± 5.0 Mlbs	23,504 ± 11,752. Mlbs	20,176 ± 10,088 Mlbs
Fuel Cost (in Millions)	$3.35 ± 1.68	$2.53 ± 1.27	$0.53 ± 0.26	$579.76 ± 289.88	$1,062.15 ± 531.08

Note: There are 229 coal plants with an average combined annual output of 800 million MWh and there are 2,020 natural gas plants with an average annual output of 1,600 million MWh. Longview Power Plants annual output is estimated to be ~ 5.4 million MWh and is more efficient than the average plant by 15%.

In summary, the heat transfer coefficient improvements at Longview (4%) were consistent with laboratory results (5.8%) and consistent with condenser performance improvements (TTD, U, and HEI CF%). Based on a net decrease of 0.26 inHg after two years (13% reduction), the water, emissions, and fuel cost savings are significant and in support of the DOE/NETLs mission to provide solutions for an environmentally sustainable and prosperous energy future.

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