Final Technical Report for DOE/EERE

"Energy Efficient Clothes Dryer with IR Heating and Electrostatic Precipitator"

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Executive summary:

The project goal was to develop a revolutionary energy saving technology for residential clothes drying. The team developed an IR (infrared) heating system and NESP (Nebulizer and Electro-Static Precipitator) for integration into a ventless clothes dryer. The proposed technology addresses two of the major inefficiencies in current electric vented dryers by providing effective energy transfer for the removal of the water and recapture of the vapor latent heat. The IR heaters operating in the mid wave (2.5-10um) are very efficient as they target the 3-micron peak absorption of the water molecule. This allows direct energy absorption, unlike conventional element heaters where heat is transferred by convection. The low power NESP removes water vapor from the exhausted stream and recaptures the latent heat in the ESP (Electro-Static Precipitator) exchanger section. This allows the warm dry air to be recirculated back into the drum for additional efficiency savings. The remaining majority of the dryer hardware stays the same. Summing the efficiency gain from the two subcomponents we anticipated the EF (Efficiency Factor) to exceed the goal of 4.04. EF is obtained by dividing the weight (lbs) of water removed by the energy (kWhr) used, where the test load size is 8.45 lbs of bone dry clothing wetted to 57.5% or 4.8lbs of water, and dried to a remaining moisture content of 2.5-5%. Additional benefits include not having to recondition (heat or cool) the large amounts of make-up air to replace the air exhausted by a vented dryer. It was anticipated that the NESP/heat exchanger would be the most challenging and highest risk element in the program. Therefore, the team focused their efforts during Phase 1 of the program on the design, construction, testing, and optimization of the NESP/heat exchanger. At the end Phase 1, the team compared the performance of the NESP/heat exchanger with the system level requirements and made a Go/No-Go decision on proceeding with the second portion of the program. Phase 2 of the program was structured to develop the IR heating system and then integrate it and the NESP/heat exchanger into a residential clothes dryer prototype for final testing. A depiction and summary of the program is shown in Figure 1 “Program Summary”

The proposed technology utilizes heat recovery which is known to have the biggest impact on dryer efficiency. The two current mainstream recovery approaches are air to air exchangers and heat pump condenser systems. Air to air exchanges can be very efficient but require large surface areas which are prone to fouling from uncaptured lint. Dryers based on heat pump condenser recovery systems have shown efficiency improvements of 20–60% and are commercially available. The issue with a heat pump condenser approach is the added cost, as typical prices are twice that of standard vented dryers and they are only available in small to medium capacities. The energy factor (EF) for these systems is 5.50 to 6.88 pounds/kWh compared to conventional dryers at 2.75 to 3.67 pounds/kWh. The efficiency improvements for the proposed technology come from the use of IR heating and the NESP. As the concept is in its infancy, and these improvements were difficult to predict without experimental data, assumptions were made based on available literature. IR radiant drying times, when compared to convection, are typically 30% less. This is a result of the fact that radiant energy heats directly and is absorbed at and below the surface, unlike convection heating, that must conduct the heat through the boundary film of air at the clothes

surface and rely on wicking of the moisture to the surface. The second area of improvement comes from the NESP. The NESP operation is as follows:

1. Highly charged, micron sized, droplets of water are injected into the dryer exhaust by the Nebulizer.
2. These charged droplets attract water molecules and continue to grow in size, until losing their charge. During this process, latent heat is rejected back into the air stream.
3. The large droplets enter the ESP, where they are recharged and drawn to the ESP wall, to be extracted at the bottom of the ESP. The warm dry air is then recirculated back into the dryer.

Figure 2 shows the energy audit comparison between a conventional vented electric dryer and the proposed technology. The proposed technology, at the time of the proposal submission was estimated to have an EF of 4.79.

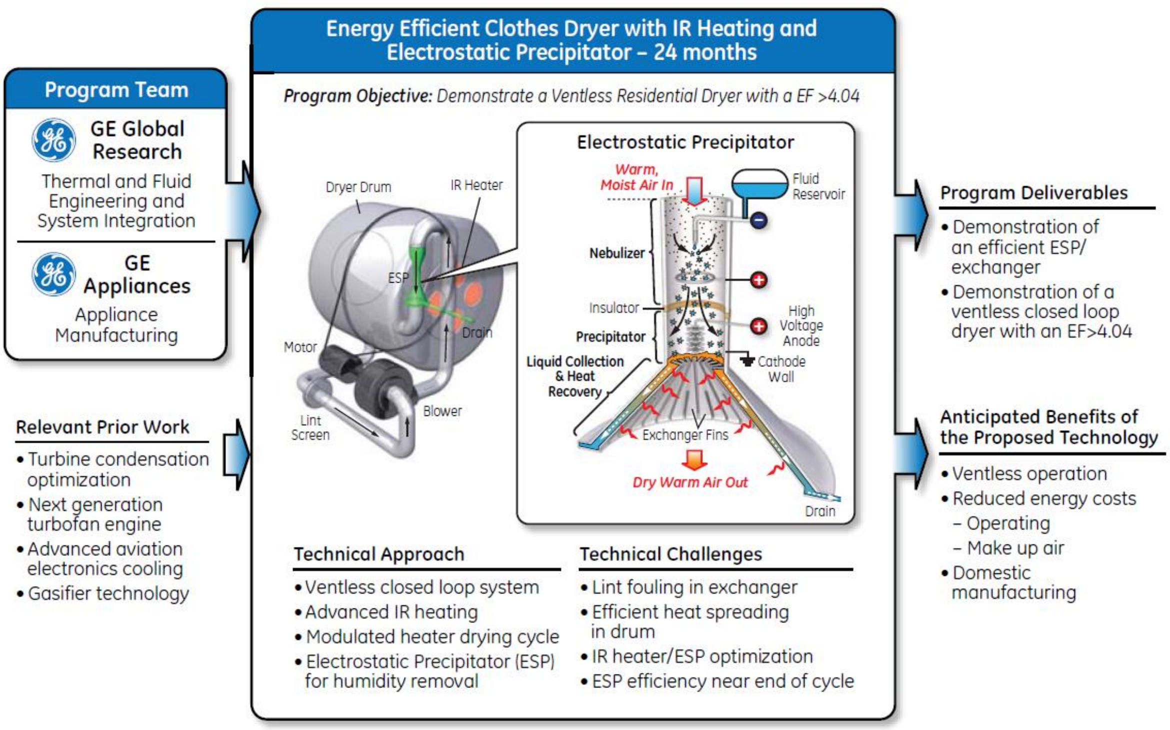


Figure 1 Program Summary

At program completion we have designed, built, tested, integrated and optimized the proposed technologies into a prototype "high efficiency" residential clothes dryer. Testing of the integrated prototype dryer provided insight into the technical effectiveness and economic feasibility of the proposed technologies. The program has the potential of greatly impacting energy savings. The predicted EF of the proposed technology is 4.79, yielding an energy savings of 42% when compared to conventional electric vented dryers. Given there are approximately 84 million dryers in the US consuming ~64 billion kWh per year, a net savings of 27 billion kWh per year or 0.092 quads could be realized. Since the dryer is not vented, make up air from the room is not needed, adding an additional savings of ~1kWh per load, or 23.8 billion kWh per year. In addition, it is envisioned that the proposed ESP, when successful, would potentially find applications in industrial and residential dehumidification.

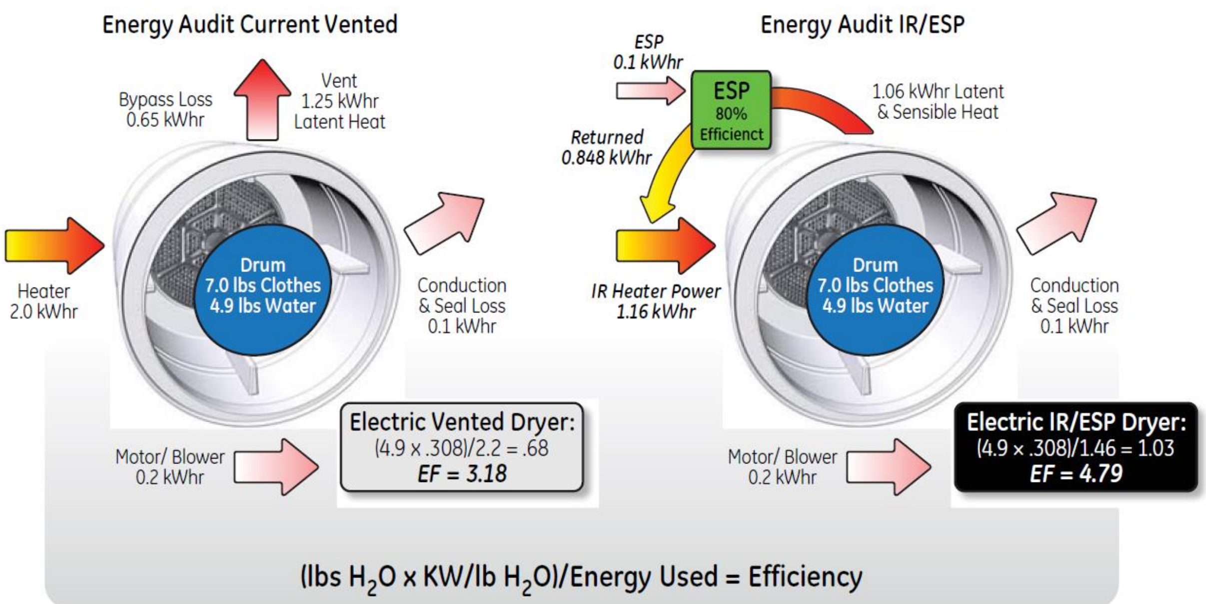


Figure 2 Energy audit of current versus proposed dryer from proposal

Comparison of actual accomplishments with goals and objectives of the project:

The table in figure 3 shows the planned goals and actual accomplishments for the project.

Task/Subtask Number and Title	Milestone Type (Milestone or Go/No-Go Decision Point)	Milestone Number* (Go/No-Go Decision Point Number)	Milestone Description (Go/No-Go Decision Criteria)	Actual Accomplishment/result
1.Dryer System Level Design	Milestone	M1.0	Report summarizing the dryer design and required subcomponent performances to exceed an EF of 4.04	Summarized in figure 2 "Energy audit comparison" Predicted EF of minimum of 4.79 and maximum EF of 6.25 with IR credit.
2. Design and Testing of the ESP and Exchanger	Milestone	M2.1	Demonstration of an ESP meeting the system Task 1.1 requirements	ESP was demonstrated with a total power consumption of less than 0.1kWhr
2. Design and Testing of the ESP and Exchanger	Milestone	M2.2	Report summarizing the ESP design and performance	Q2, 2016 report submitted to DOE summarizing optimized ESP performance
2. Design and Testing of the ESP and Exchanger	Go/No-Go 1 No-End Program	Go/No-Go 1	Measured efficiency of the ESP must meet system requirements from task 1.1	Phase 1 EF goal of 4.04 was met based on experimental results and modeling predictions. The total drying cycle time is predicted to be ~1.5hrs falling short of the 1hr goal. We believe that running 2 ESPs in serial would reduce total cycle time back to 1hr with minimal cost impact
3.Design and Testing of the IR heater system	Milestone	M3.1	Demonstration of IR dryer assembly meeting requirements of Task 1.2	IR heater design complete and capable of a minimum 4150W at 208V. Heater produced by Emitted Energy
3.Design and Testing of the IR heater system	Milestone	M3.2	Report summarizing the IR heater design and performance	Q2, 2017 report submitted to DOE summarizing IR heater performance
4. Integration, testing and optimization of the IR/ESP clothes dryer	Milestone	M4.1	Demonstration of integrated dryer exceeding 4.04 EF	Integrated IR/ESP prototype dryer measurements demonstrating an EF of 6.23, exceeding the target goal by 54% and nearly matching the modeled goal of 6.4
4. Integration, testing and optimization of the IR/ESP clothes dryer	Milestone	M4.2	Report summarizing the integrated dryer performance	Q3, 2017 report submitted to DOE summarizing the integrated prototype dryer performance
5. Technology to Market	Proceed to NPI with GE Appliances	Project End	Demonstration of integrated dryer with an EF exceeding 4.04 at acceptable costs	Integrated prototype dryer measurements demonstrating an EF of 6.23. A full high-volume cost estimate was not completed. With the sale of GE Appliances, we are now pursuing licensing opportunities and other technology applications relevant to GE.

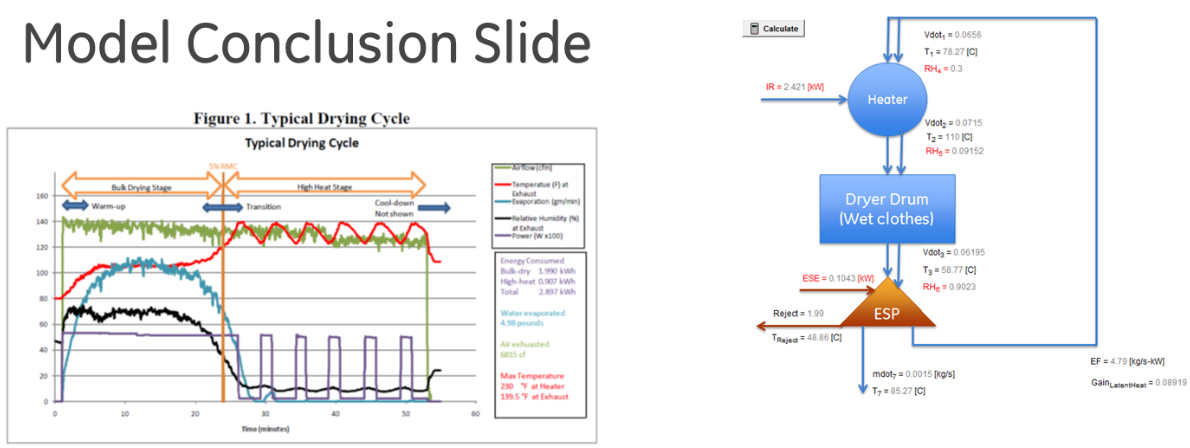
Figure 3 Summary of proposed versus actual results

Summary of project activities:

<u>Phase 1</u>

Early in the program a more refined EES (Engineering Equation Solver) system level analysis was developed showing the proposed technology can demonstrate a residential ventless dryer with an EF of >4.04. The summary of the EES analysis results can be seen in figure 4. In addition, a variable heated air/water vapor generator was designed and constructed. The output of the generator was designed to simulate dryer exhaust. The generator design allows temperatures up to 300°F, 95% relative humidity and flows of 200cfm. The generator adjustability will be crucial as it is anticipated that the NESP peak efficiency may not align with current typical vented exhaust conditions. Figure 5 shows the layout of the dryer test generator. The future position of the Nebulizer and ESP are shown next to the clear acrylic tube.

Following completion and testing of the dryer test generator, efforts were focused on designing, building and integrating the NESP with the test generator.



Stage	Time		Conventional		Ventless ESP		Ventless ESP with IR	
	[mins]	[hrs]	[kWh]	[kW]	[kWh]	[kW]	[kWh]	[kW]
Bulk Drying	23	0.38	1.99	5.19	0.968	2.53	0.678	1.77
High Heat	30	0.50	0.91	1.81	0.907	1.81	0.635	1.27
Total	**53**	**0.88**	**2.90**	**7.01**	**1.875**	**4.34**	**1.313**	**3.04**
EF			**2.91**		**4.50**		**6.4**	

Figure 4 Summary of EES modeling results

A high-level analysis of the Nebulizer and ESP was conducted to identify the crucial parameters and trends. Results from the Nebulizer analysis suggested that an increased density of smaller (<10um) highly charged droplets leads to higher efficiency.

The ESP analysis provided guidance for the required electric field/corona current, length and flow regime for the ESP to be effective at removing water droplets.

Initial stand-alone Nebulizer experiments looked at what parameters would result in the smallest size drops with the highest charge. The parameters varied were voltage, orifice size, flow, and electrode design and spacing. Several techniques were investigated to measure droplet size and charge coming from the Nebulizer. For droplet size measurement, two techniques were investigated. The first being high speed imaging, which was found to be highly susceptible to vibration induced errors. The vibration induced distortion reduced the resolution of the high-speed imaging system beyond a usable point, and this technique was abandoned. The second technique was the use of a commercial Malvern Spraytec laser droplet size analyzer. A lot of time was also spent trying to get relevant measurements with the Malvern analyzer, eventually these efforts were also abandoned. The two main reasons for the ineffectiveness of the Malvern

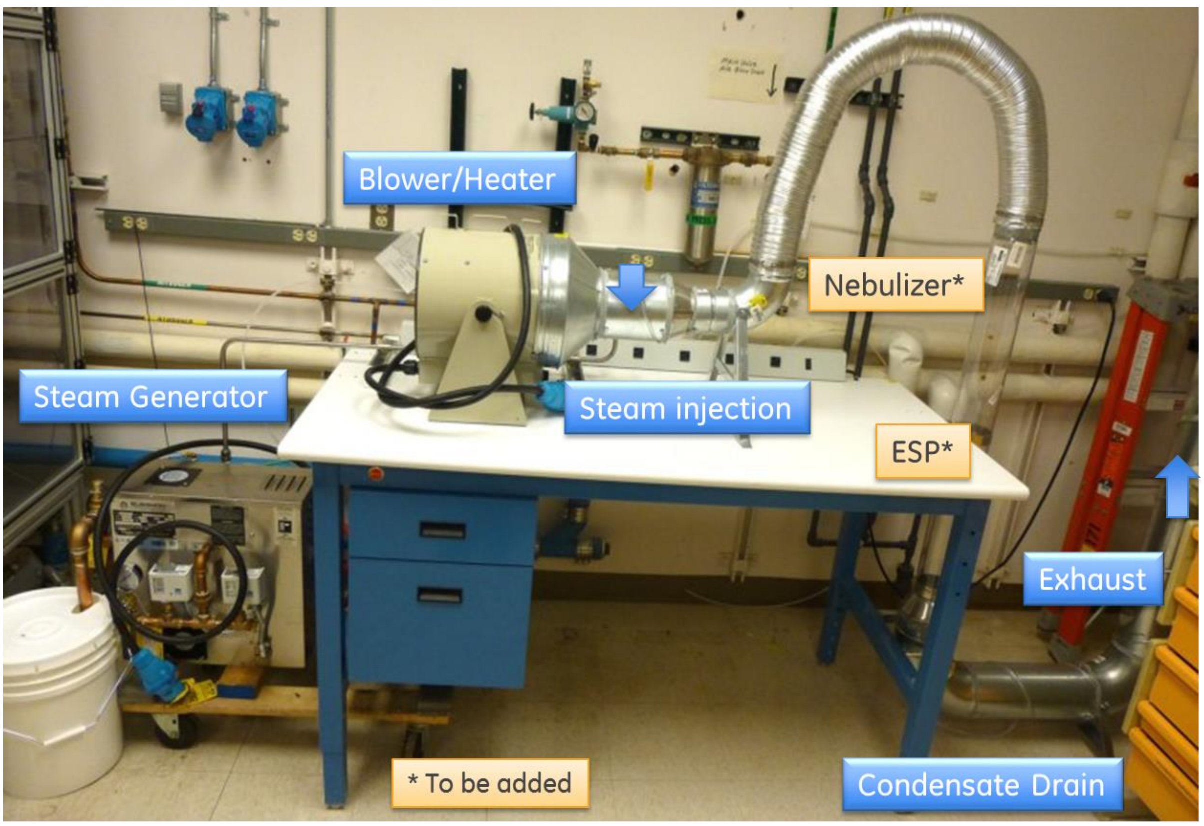


Figure 5 Overview of dryer test generator

were insufficient density of the droplet stream and collection of droplets on the quartz viewing window. To measure droplet charge, a commercial charge plate monitor was used measure the charge transfer, as a function of time, at the output of the nebulizer. Although the droplet size and charge transfer measurements were not perfect they did give insight into operational trends of the ESP. Going forward efforts were focused on

NESP optimization through in system water extraction efficiency measurements. A photo of the integrated test system with the Nebulizer and ESP can be seen in figure 6. The system was fully instrumented to allow data collection of all pertinent operating parameters.

Optimization of the extraction efficiency was done through "Design of Experiments" (DOEs). Parameters that were investigated are shown in figure 7. One of the major issues encountered during testing was breakdown and arcing of the ESP. The main arcing path was along the ESP electrode holders at the top and bottom of the ESP. These holders are required to center the anode within the ESP diameter. Several design iterations of the holder were required to get sufficient water shedding along the holder arms. A robust design was eventually realized that allowed wet operational standoff voltages of greater than 12kV/in.

Figure 6 View of fully instrumented, integrated test system with enlargement of nebulizer and ESP to right (orange mixers removed)

Test Section	***DOE Parameters investigated***				
Nebulizer	Voltage	Water flow	Injection orifice size/#'s	Electrode design/spacing	Nebulizer mixers
Precipitator	Voltage	Anode design	Anode holder design	Water extractor design	
Steam Injector	Steam injection rate	Air flow			

Figure 7 Test section and parameters varied to increase water extraction efficiency

A graph of water extraction efficiency improvements with time is shown in figure 8. Extraction efficiency is calculated by the following formula:

Extraction Efficiency = Steam input (gr) / water extracted (gr) – Nebulizer input (gr)

As noted on the graph the major contributors to efficiency improvements are Nebulizer droplet size reduction, ESP enhancements (increased voltage, heat extraction), adjusting exhaust flow to the laminar regime and increased Nebulizer droplet flow/density. Droplet size reduction is optimized through Nebulizer voltage and more directly through the Nebulizer orifice diameter. Various Nebulizer designs were examined looking at reduced orifice size. The down side of reduced orifice size is that multiple orifices are required to meet the desired flow, and clogging of the nozzles is more prevalent even with pre-filtering. The main clogging issue came from mineral deposits in the orifice openings.

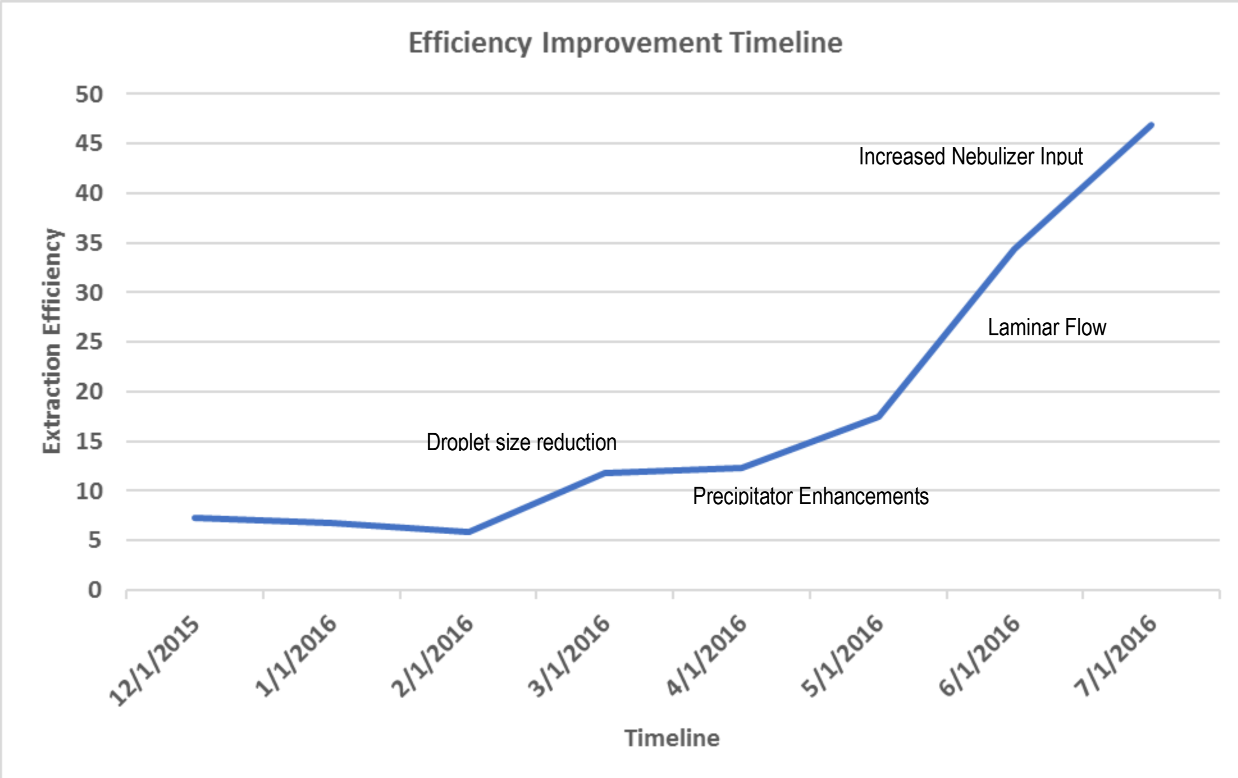


Figure 8 Graph of water extraction efficiency versus project timeline

Various Nebulizer head designs were evaluated, these included orifice diameters ranging from 10-200um and orifices numbers from 1 to 40. Head designs were built using simple hypodermic needles to complex designs using laser drilled metal discs.

The ESP enhancements were largely driven by the ability to increase the ESP voltage/ corona current thus allowing capture of smaller droplets at higher exhaust flow levels.

The largest enhancement in efficiency was gained by reducing the exhaust flow such that the flow became laminar. Operating in the laminar regime allows for a higher density of charged droplets as well as longer reaction times. Lastly increasing nebulizer flow showed enhancement and again is related to the increase in droplet density.

The extraction efficiency of near 50% demonstrated the viability of the NESP and the program was awarded Phase 2. One item of concern around the 50% extraction efficiency would be that the total drying time would not meet the 60min goal. To address this issue the team proposed multiple NESPs in series or increasing the exhaust humidity level through higher bulk drying temperatures.

Phase 2

The major efforts in phase 2 concentrated on the IR heater design and construction, followed by integration of the IR heater and NESP into a minimum viable dryer prototype demonstrating an EF>4.04.

The IR heater specifications including wavelength, total wattage and physical size were determined. Several IR heater vendors were identified and Emitted Energy was down selected based on their ability to meet the required specifications. The custom IR heater was received and paired with a PID (Proportional Integral Derivative) controller and SCR (Silicon Controlled Rectifier) power controller. This combination allowed control of the IR heater based on feedback from the dryer exhaust temperature.

Various dryer brands were evaluated for the prototype demonstration. Two key criteria for selection were a model with a fixed drum back, to allow simple installation of the IR heater, and manual controls for easier modification. A Speed Queen Model: ADE3SRGS-173TW01 electric vented dryer was chosen. The EF of the Speed Queen dryer as received was measured, using DOE guidelines, and found to be 2.89 for timed mode operation for 50 minutes.

Modifications were then made to the dryer to allow installation of the custom IR heater and controllers. Figure 9 shows the mounting of the IR heater in the dryer drum and its associated controller. Basic operation of the heater was verified, and then a series of dryer runs were made to adjust the PID controller parameters to optimize the dryer EF. All EF measurements were made in vented mode operation to compare the modified IR dryer EF to the as received EF. Under optimum controller conditions the EF of the IR dryer was demonstrated at 6.0, for an efficiency improvement of 54%, exceeding the Go/No Go goal of 30%.

Integration of the existing NESP with the modified IR dryer was completed next. The dryer exhaust was connected to the input of the NESP and the output of the NESP connected to the air inlet to the drum closing the system, now making the dryer non-vented. Additional modifications to the dryer blower assembly were also necessary to allow varying the exhaust flow from laminar to turbulent regimes for optimization studies.

Testing was again performed using DOE’s guidelines with the integrated dryer prototype to optimize the EF of the system. The same Nebulizer and ESP parameters identified in figure 7 were varied, along with the exhaust flow. An optimum system EF of 6.23 was demonstrated, exceeding the program goal by 54%. An image of the integrated system can be found in figure 10. No long-term reliability studies have been conducted on the system, however operation over several months showed no major failures of the components.

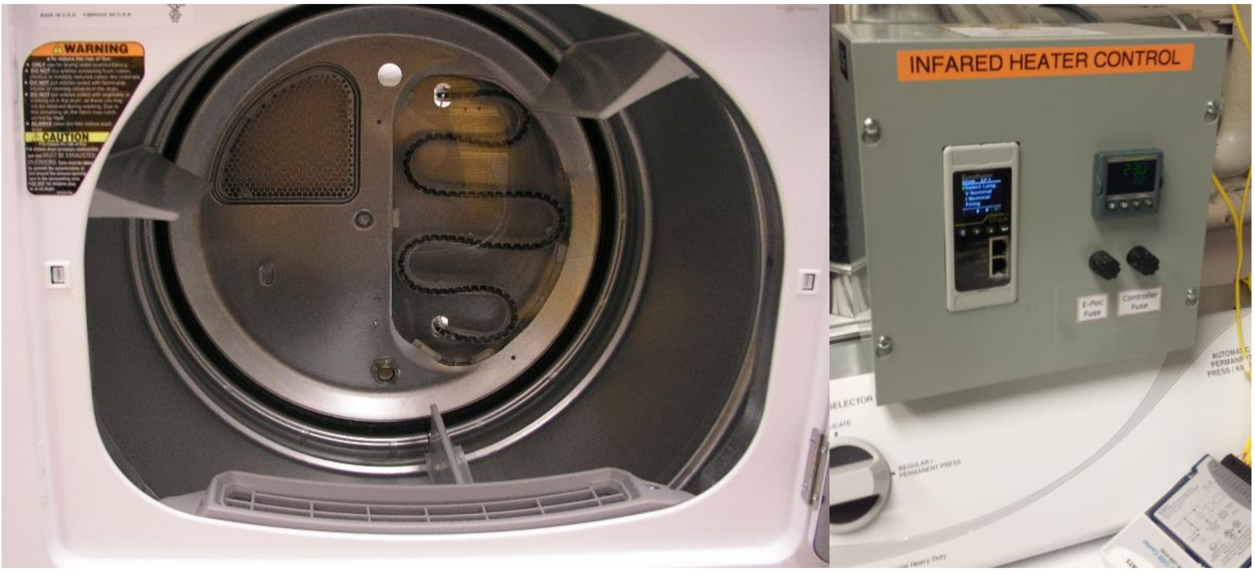


Figure 9 Installed IR heater in dryer drum left, IR heater controller right.

Products developed under the program

Due to the sale of GE Appliances during the program execution, product development was not pursued and no products have been developed. GE is however pursuing opportunities through its licensing division. Concurrently GE is investigating alternate applications of the technology that are relevant to its business operations.

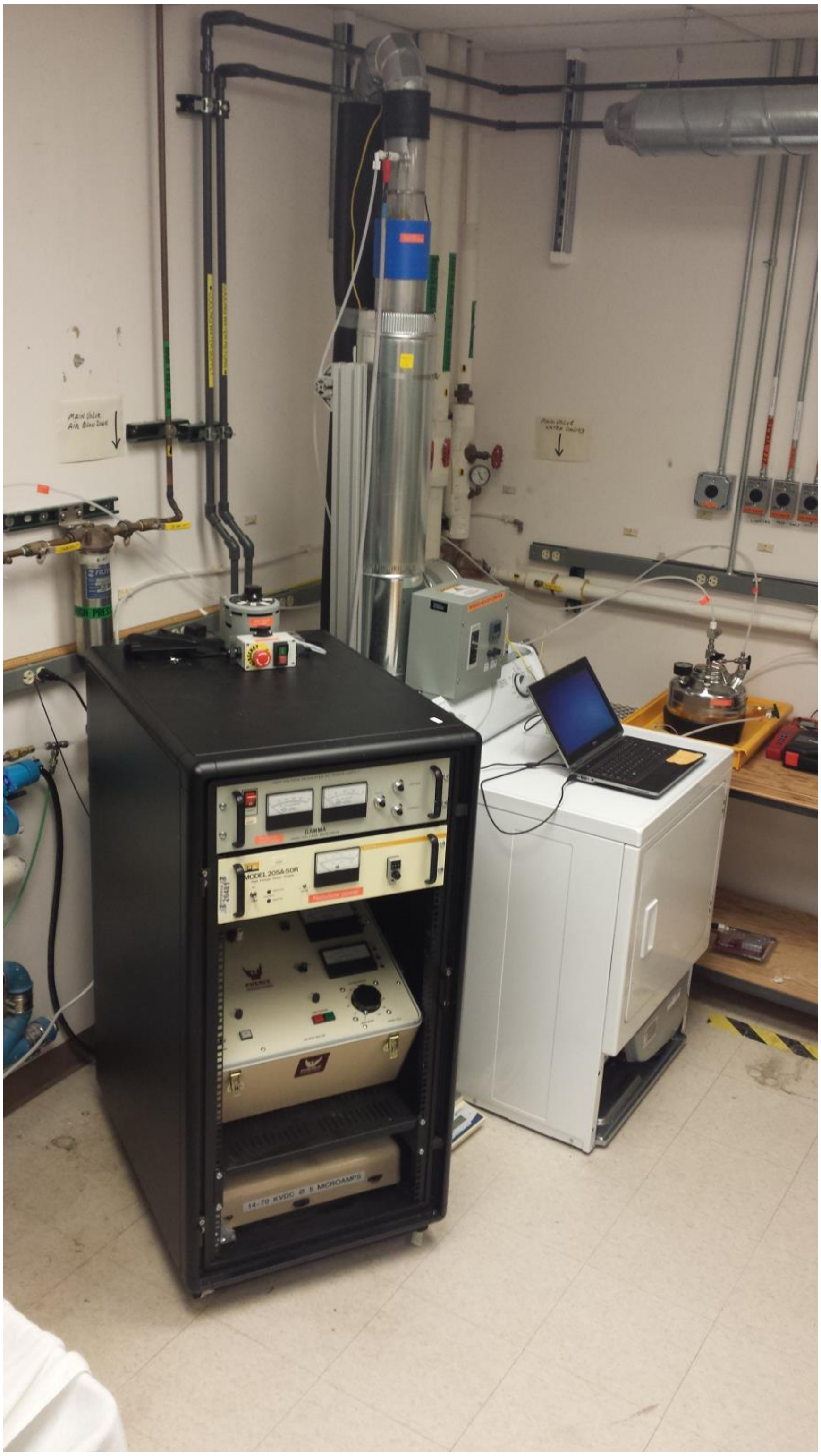


Figure 10 Image of integrated prototype dryer.