U.S. Department of Transportation

Federal Railroad Administration

Reliability and Endurance Testing of Locomotive Waste Heat Recovery System

Office of Research, Development
and Technology
Washington, DC 20590

DOT/FRA/ORD-20/23

Final Report
June 2020

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 2020	Technical Report August 20, 2012–September 30, 2015

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Reliability and Endurance Testing of Locomotive Waste Heat Recovery System	FR-RRD-0035-12-01-00
6. AUTHOR(S) Claudio Filippone	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Thermadynamics Rail, LLC 8708 48th Place College Park, MD 20740	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Railroad Administration Office of Railroad Policy and Development Office of Research, Development and Technology Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FRA/ORD-20/23

11. SUPPLEMENTARY NOTES
COR: Melissa Shurland

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
This document is available to the public through the FRA website.	

13. ABSTRACT (Maximum 200 words)

From August 20, 2012, to September 30, 2015, the Federal Railroad Administration (FRA) sponsored this research for the optimization and testing of a non-invasive locomotive retrofit technology, Locomotive Waste Heat Recovery System (WHRS) dedicated to capturing and converting locomotive waste thermal energy. Optimization and testing activities were further supported via locomotive-simulator and vibration testing to validate the components' reliability, endurance, and performance. Test results indicated that retrofitting a 4,400 HP locomotive exhaust stack with High-Pressure Heat Exchangers (HiPHEXs) equipped the WHRS with the ability to capture of approximately 420 kW–1,500 kW of otherwise wasted thermal energy. Tests performed to simulate the WHRS components failure indicated that under credible design-basis worst case scenarios, HiPHEXs failure does not negatively impact locomotive engine performance and operations. Converting the captured waste thermal energy into electrical energy results in fuel savings and pollutant emissions reductions proportional to the WHRS efficiency, locomotive duty cycle and fuel price. Overall, test results validated computer models and the performance of key WHRS components, thus enabling further optimization of high-density HiPHEXs with extended surface areas to increase locomotive waste thermal energy recovery without impairing locomotive engine performance. The results of this project indicated a robust technology development pathway enabling railroad operators to lower operating costs, increase public safety by reducing pollutant emissions while decreasing thermal and greenhouse gases (GHG) emissions.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Waste Heat Recovery System, WHRS, conversion, High Pressure Heat Exchangers, HiPHEX, locomotive, greenhouse gases, locomotive, Class I railroad, rolling stock, public safety, pollutant	47
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by
ANSI Std. 239-18

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION

Inches	0	1	2	3	4	5							
Centimeters	0	1	2	3	4	5	6	7	8	9	10	11	12	13

QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

This Phase II project could not have been successfully completed without the vision, technical support, and patience demonstrated by the Federal Railroad Administration (FRA) officials, the technical and management staff at Class I locomotive facilities, and the technical staff at Transportation Technology Center Inc. (TTCI). On behalf of the entire ThermaDynamics Rail team and contracted organizations, the author expresses the deepest gratitude to all people that supported the optimization of locomotive dedicated waste heat recovery and conversion systems. This technology will enable railroad operators to lower operating costs, increase public safety by reducing pollutant emissions, and benefit the environment with decreased thermal and greenhouse-gases emissions.

Contents

Illustrations

Tables

Executive Summary

From August 20, 2012, to September 30, 2015, the Federal Railroad Administration (FRA) sponsored ThermaDynamics Rail, LLC (TDR) to conduct reliability and endurance testing of a Locomotive Waste Heat Recovery System (L-WHRS) equipped with High Pressure Heat Exchangers (HiHEX) to capture and convert wasted heat into useful energy. The purpose of the locomotive and locomotive-simulator tests executed under this project was to validate HiPHEXs performance at locomotive operating conditions and support HiPHEXs integration with power conversion components non-invasively interfaced with the locomotive engine equipment. These components include direct drive turbo-generators forming the power conversion unit (PCU), condenser heat exchangers, and positive displacement pump (PDP) providing controlled working fluid mass-flow-rates and pressure as required to obtain high efficiency of the WHRS. TDR conducted testing of a 16-cylinder locomotive engine with exhaust gases produced by 16-out-of-16 piston cylinder assemblies. The modeling, testing and results analyses validates the HiPHEX performance. Additional results supported by vibrational and locomotive simulator testing, show that substantial amounts of otherwise wasted thermal energy can be captured with no adverse effects on the locomotive turbocharger and the locomotive engine performance. HiPHEXs, PCUs, PDP and condenser, once coupled, forms the closed-loop WHRS converting waste thermal energy into electricity distributed to the locomotive bus.

Tests results indicated that by retrofitting a 4,400 HP locomotive exhaust stack with various HiPHEXs configurations, 418 kW to 1,500 kW of otherwise wasted thermal energy can be captured. Locomotive tests at all notch settings also confirmed that retrofitting HiPHEXs with the original equipment manufacturers' (OEM) exhaust gas equipment does not impair locomotive engine operations and performance.

Locomotive tests were performed with "low-density" HiPHEXs wherein the heat exchangers were equipped with reduced heat transfer surfaces to measure exhaust gas backpressure at the turbocharger discharge and to ensure unimpaired locomotive engine performance. Test results confirmed that as the exhaust gases cool-down while transferring energy to the working fluid circulating within the HiPHEXs, the pressure inside the exhaust stack decreases, thus lowering the exhaust gas backpressure at the turbocharger discharge. To simulate HiPHEXs failure during full-scale locomotive testing and ensure unimpaired locomotive operations, the HiPHEXs were temporarily operated without working fluid. Under these conditions the locomotive engine was tested at idle and at all notch settings to measure exhaust gas backpressure when the HiPHEXs did not provide cooling to the exhaust gases. Results indicate that as the notch setting is changed from idle to notch 8 with a "dry" heat exchanger (i.e., absence of working fluid), the backpressure proportionally increases and reaches the value of 10 inches of water at Notch 8. Ten inches of water corresponds to a backpressure of approximately 0.36 psi (0.025 bar). This backpressure value is comparable to the backpressure induced by the OEM flange and screen assembly normally equipping the exhaust stack. Under this worst-case scenario (e.g., no working fluid circulated through the heat exchangers and no exhaust gas cooling), there was no impact on the locomotive engine performance at all operating conditions. Based on locomotive test results, "high-density" HiPHEXs, equipped with extended heat transfer surfaces, can be retrofitted with the locomotive exhaust stack and recover up to 1.5 MW of otherwise wasted exhaust gases' thermal energy, without impairing turbocharger and engine performance.

Locomotive and locomotive-simulator test results were also utilized to estimate fuel savings by considering “low- and high-density” HiPHEXs configurations with fuel prices evaluated at 2014 and 2016 values. Accordingly, locomotives non-invasively retrofitted with HiPHEXs installed in the exhaust stack represent annual fuel savings varying from approximately $26,000 to $45,000 per-locomotive retrofitted with the “low-density” HiPHEXs, with fuel price varying from 2.211-to-3.72 dollars-per-gallon at 2016 and 2014 fuel prices respectively. When the “high-density” HiPHEXs is considered, annual fuel savings increase to approximately $91,000 per-locomotive at 2016 diesel fuel price, and to $154,000 per-locomotive when the fuel price is set to 2014 values. WHRS-induced fuel savings vary proportionally to fuel price, WHRS components efficiency, and locomotive duty cycle. The locomotive duty cycle adopted for the computation of the annual fuel saving estimates assumes “EPA Line-Haul Percent Time at Notch” (e.g., 16.2% at Notch 8). In these evaluations, the economic benefits represented by the WHRS-induced pollutant emissions reductions are not factored.

Overall, based on Phase II results, further optimizations of HiPHEXs and PCU components to increase WHRS efficiency, reliability, and to reduce pollutant emissions and component costs are recommended. Additional investigations to ensure long-term WHRS reliability by adopting an engineered organic fluid as the working fluid are also recommended. Finally, to further address pollutant emissions reductions, a portion of the energy recovered by the WHRS should be dedicated to drive “pre-combustion” pollutant-reduction systems and methodologies. These additional investigations are recommended to support compliance of EPA Tier 4 pollution reduction standards and to mitigate costs and requirements associated with after-treatment pollution reduction technologies.

TDR is committed to pursue activities to support endurance and reliability testing to accelerate market deployment of reliable, cost-effective modular WHRS optimized for locomotive applications and adaptable to various locomotive models.

1. Introduction

The Federal Railroad Administration sponsored research between August 20, 2012, and September 30, 2015, to evaluate the reliability and endurance of locomotive Waste Heat Recovery System (WHRS) equipped with High Pressure Heat Exchangers (HiPHEX). ThermaDynamics Rail LLC (TDR) developed the technology to capture and convert wasted heat from locomotive exhaust and convert it into useful power. FRA's research focused on the WHRS performance under various locomotive engine operating conditions and some worse case scenarios for the WHRS.

1.1 Background

WHRS optimized for locomotive applications represent a significant opportunity for rail operators to reduce operating cost while decreasing greenhouse gases (GHG), particulate matter, and thermal emissions. The WHRS recovers locomotive waste thermal energy and converts it into electrical power. This pollutant-free electricity can be distributed to auxiliaries, traction motors, batteries, or back to the grid for certain locomotive configurations. The locomotive-specific WHRS must comply with non-invasiveness requirements ensuring safety and unimpaired locomotive operations under credible design basis WHRS components failure scenarios.

As less fuel is consumed to produce the same traction power, the locomotive generates a proportionally lower amount of pollutants. Locomotives can further reduce pollutant emissions when a portion of the WHRS recovered energy is dedicated to drive pollutant reduction systems. In this configuration, the WHRS is equipped with features that improve fuel combustion at idle and low notch settings. Overall, locomotive-specific WHRS provide a technological platform to reduce operating cost and further reduce pollutant emissions when the locomotive is idling and at low power settings, thereby providing a technology that can reduce the requirements and costs associated with after treatment emission control technologies.

This project supported testing of locomotive engines and locomotive simulators retrofitted with optimized HiPHEX configurations coupled to various specialized components, to determine best WHRS configurations and components reliability, endurance and performance under locomotive operational conditions.

Generally, the internal combustion engines (ICE) convert approximately one-third of the fuel potential energy into propulsion power. The remaining two-thirds of the energy represented by the full fuel potential is lost as low- and high-grade thermal energy rejected to the environment by the exhaust gases and locomotive cooling system. Under normal operating conditions approximately 40 percent of the total energy of the fuel is lost through exhaust gases. WHRS captures portions of the engine heat losses and converts them to useful energy, for example, in the form of mechanical or electrical energy. Recovering at least a portion of the energy rejected to the environment provides a pollutant-free energy source that can be used to reduce fuel consumption and pollutant emissions. At the time of this writing, approximately 30 percent of all locomotives in the U.S. are 24 years old or older. For these locomotives, engine efficiency is typically lower and pollutant emissions higher when compared to recently manufactured locomotives.

Fuel savings, particulate matter emissions and thermal pollution reduction can result from retrofitting diesel-electric locomotive engines with WHRS. From a thermal-hydraulic standpoint, the HiPHEXs heat transfer performance must cost-effectively transform low- and high-grade waste heat energy into reusable energy by reliably transferring it from a primary fluid (i.e., exhaust gases) to a secondary fluid (i.e., water or EPA approved organic fluids) circulating in a closed-loop forming a Rankine power cycle. Figure 1 shows the basic principle of the WHRS.

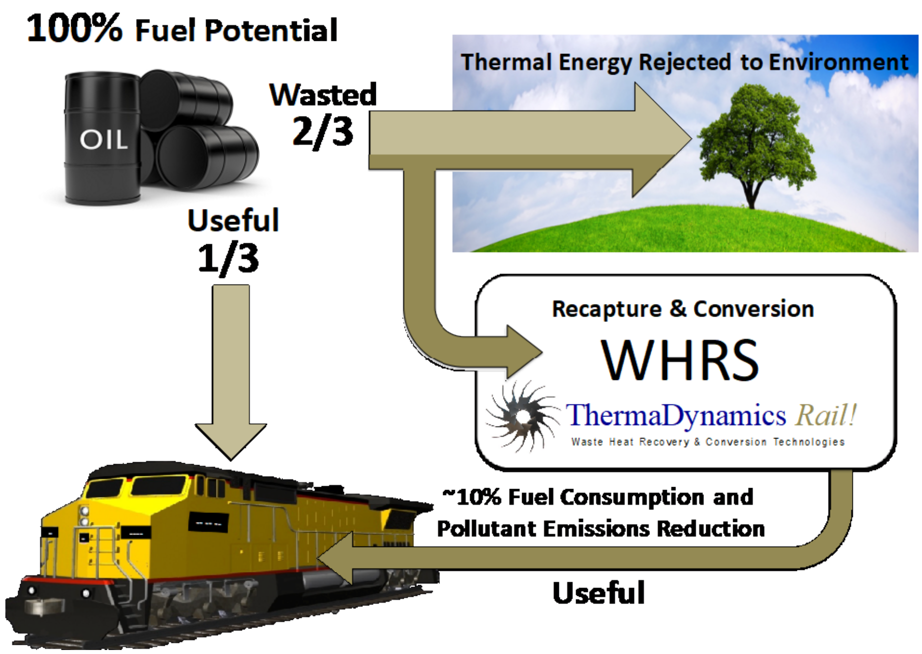

Figure 1. ThermaDynamics Rail, LLC (TDR) WHRS and conversion principles

The recovered energy can be primarily used to supply propulsion power, thereby directly reducing fuel consumption, pollutant, and GHG emissions. The advantages of retrofitting diesel-electric locomotives with dedicated WHRS include:

1. Lowering fuel consumption for unaltered propulsion power, resulting in lower operating costs
2. Reducing GHG emissions, due to reduced fuel consumption
3. Reducing criteria pollutants emissions by equipping the WHRS with pollution-reduction add-on features
4. Supporting compliance of Tier IV pollutant emissions EPA standards for new locomotives
5. Reducing thermal load on the engine cooling system
6. Enabling support of additional electrical auxiliaries entirely powered by the WHRS power conversion system

1.2 Objectives

The main objective of this project is to determine the technical performance of the HiPHEXs and ancillary equipment retrofitted to locomotives operated at all notch settings, and quantify the thermal-hydraulic parameters required to match the components forming the PCUs to recover and convert locomotive engine waste heat energy.

The overall intent of the Phase II project is to execute full-scale testing with locomotive engines retrofitted with optimized configurations of the HiPHEXs to be fully integrated with power conversion components.

1.3 Overall Approach

The overall project approach consisted of modeling the various WHRS components, followed by testing and results analyses. More specifically, thermodynamic cycle modeling was executed by using a MATLAB code of the WHRS to obtain data to optimize matching the various components forming the closed-loop WHRS based on the Rankine power cycle. The HiPHEXs were configured in agreement with the computer models and simulations performed on commercial computational fluid dynamics (CFD) software. Subsequently, the PCU, which consists of a fast rotary turbine expander and a direct-drive electric generator, were matched to the HiPHEXs. The turbine expander was configured using modeling codes and commercial CFD software. The fast-electric generator is controlled by high power electronic modules, which were configured and assembled with the assistance of a specialized contractor. The fast generator was matched to a turbine expander by selecting off-the-shelf rotor/stator pairs at various power ratings. Components simulating the PCU system underwent vibration analysis at the Transportation Technology Center, Inc. (TTCI), wherein a locomotive was retrofitted with equipment to sample acceleration data within the engine compartment during locomotive operations. To close the WHRS thermodynamic loop, a series of condenser heat exchangers were matched using the computer model and coupled to an off-the-shelf positive displacement pump (PDP).

Finally, the HiPHEXs were non-invasively retrofitted with a locomotive engine exhaust gas stack and the experimental measurements were analyzed and compared to the model predictions. Locomotive fuel saving predictions were estimated based on test results and projected to different HiPHEX configurations.

1.4 Scope

The work activities covered in this project aim at developing non-invasive, retrofittable WHRS based on Rankine power cycle technologies applied to diesel electric locomotives operated by U.S. Class I railroads. These activities are mainly focused on line-haul locomotives duty cycles. However, test results can be extrapolated to passenger locomotives, or locomotives operated under specific duty-cycles.

The project aims at:

- Performing reliability and endurance testing of locomotive engine components retrofitted with full-scale HiPHEXs and ancillary equipment
- Quantifying the recovered thermal energy under various locomotive operational conditions

- Determine whether the HiPHEXs induce off-normal backpressure within the locomotive exhaust gas system, thereby impacting the internal combustion engines (ICE) performance

The project is solely dedicated to configuring WHRS for diesel electric locomotives, and does not consider other transport or stationary diesel engines. Additionally, the project focuses on the potential fuel savings derived from retrofitting the WHRS to the engine exhaust systems, whilst it does not directly address pollutant emision reductions induced by the WHRS operations.

1.5 Organization of the Report

This report is organized as such: Section 1 offers background information on previous testing and results and how they coincide with the current Phase II reportings; Section 2 describes Phase II deliverables and work performed; Section 3 provides additional information on the cost savings of WHRS when retrofitted on the locomotive; finally, Section 4 concludes with recommendations for further work.

2. Phase II Project Activities and Deliverables

This section addresses parametric analyses to match and optimize the HiPHEXs to WHRS components configured and scaled for locomotive operations.

2.1 Waste Heat Recovery Rankine Cycle Optimization

Figure 2 shows the temperature-entropy diagram (T-S) for the Steam Rankine Cycle (SRC) and a schematic of the various components in a standard Rankine power cycle with water as working fluid. The various working fluid thermodynamic states are denoted by numbers "1," "2" and so on:

1→2 Water pressure is increased by means of a pump, from what is termed cycle bottom pressure (P_{bottom}, equivalent to the condenser pressure) to the cycle top pressure (P_{top} equivalent to the heat exchanger pressure).

2→3 The water is heated up until it reaches the liquid saturation curve in the evaporator (heat exchanger).

3→4 Water undergoes phase changes from liquid to vapor to the saturated vapor state 4)

4→5 The vapor continues to be heated and reaches a super-heated state, (i.e., a temperature above saturation); the difference between saturation temperature (at state 4) and maximum temperature (at state 5) is termed ΔT_{sh}.

5→6 Steam is expanded via expander to produce the cycle's power output.

6→1 Working fluid is returned to its initial thermodynamic conditions, via the condensation processes, thus resetting the cycle.

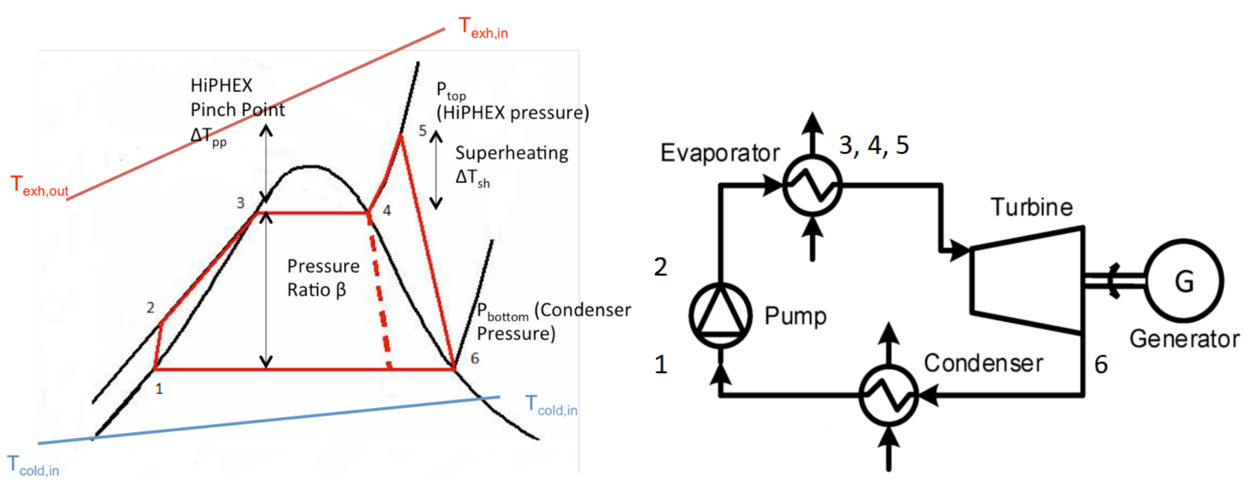

Figure 2. Steam Rankine cycle T-S diagram and thermodynamic states

The components forming a typical steam Rankine cycle include: Pump (1→ 2), HiPHEX (2→ 5), Turbine (5→ 6), and Condenser (6→ 1).

The HiPHEXs extract energy from the heat source of the WHRS. The exhaust gases characteristics referenced in this analysis are those represented by a GE Dash-9 4,400 HP 16-cylinder turbocharged locomotive diesel engine widely utilized by Class I railroad companies. The ICE exhaust gases are therefore the heat source of the Rankine cycle.

Table 1 summarizes the exhaust gas thermodynamic conditions in terms of mass-flow-rates and temperatures at different notch settings. In Table 1, the terms "T exhaust manifold" and "T exhaust stack" refer to the temperature of the exhaust gases pre-turbocharger and at turbocharger discharge respectively.

Table 1. GE Dash-9 exhaust gas conditions at different notch settings (Fritz, S. G., 2013)

	m exhausts [kg/s]	T exhaust manifold [°C]/[°F]	T exhaust stack [°C]/[°F]
Notch 1	0.585	261/502	182/360
Notch 2	0.82	359/678	271/520
Notch 3	1.72	508/946	384/723
Notch 4	2.5	513/955	393/739
Notch 5	3.84	509/948	389/732
Notch 6	4.77	511/952	374/705
Notch 7	5.49	537/999	377/711
Notch 8	6.85	609/1,128	409/768

2.1.1 Cycle Optimization Parameters

The primary objective of the WHRS is to maximize the power output of the Rankine cycle. The WHRS power is directly proportional to the amount of extracted thermal energy from the engine exhaust gases. To maximize the recoverable power, a thermodynamic analysis of the system was performed by varying several parameters that affect its performance. Following a literature survey, it was concluded that the parameters that have the greatest influence over the performance of the steam Rankine cycle include:

- β: the pressure ratio between turbine inlet and outlet
- The cycle bottom (condenser) pressure
- ΔT_{sh}: the level of super-heating (denoted by the process 4→5), expressed as the difference in temperature between the turbine inlet and saturated vapor temperatures
- The mass-flow-rate of the working fluid (m_w)

In the Rankine cycle analysis, heat is extracted from the exhaust gases flowing both in the locomotive exhaust gas manifolds and in the exhaust stack (16-out-of-16 configuration). Given the limitation on the amount of energy that can be extracted from the exhaust gas manifolds without impacting the OEM turbocharger—12 percent of the total energy represented by the exhaust gases, based on Section 2.2.1 (Naber, J., Johnson, J., Nelson, D., and Latautala, P., 2014)—the thermodynamic conditions and cycle parameters at each thermodynamic state, covering states 1→6 in Figure 2, were selected to maximize the turbine power output. From the analysis, the predicted power recoverable at different notch settings by the steam Rankine cycle were predicted and showed in Table 2.

Table 2: Maximum turbine power output comparison at different notch settings

Notch settings	SRC max power output [kW]
Notch 3	47.34
Notch 4	72.53
Notch 5	107.54
Notch 6	135.96
Notch 7	198.67
Notch 8	395.27

2.2 Optimization of HiPHEXs Components and Heat Transfer Surfaces

The "first generation" HiPHEXs were non-invasively retrofitted to 2-of-16 manifolds of a GE "Dash 9" 16-cylinder commercial diesel electric locomotive. Testing was conducted at various locomotive operating conditions. The findings from these initial investigations showed that the HiPHEXs were compliant with the non-invasiveness requirement under the exhaust gas manifolds dimensional constraints and did not produce detectable backpressure, but also performed with a relatively low effectiveness. Additional investigations aimed at determining performance of different HiPHEXs configurations by means of combustion gases generated in a combustion chamber, were executed as part of the Transportation Research Board (TRB) Innovations Deserving Exploratory Analysis (IDEA) TRANSIT-67 project.

Expanding on test results obtained in these initial investigations, the HiPHEXs were equipped with extended heat transfer surface areas and configured to non-invasively retrofit "16-out-of-16" locomotive exhaust gas manifolds corresponding to placing the HiPHEXs within streams of exhaust gases produced by the whole locomotive engine—16 exhaust gas manifolds coupled to 16 cylinders.

2.2.1 Effect of HiPHEX Back-Pressure on Turbocharger Performance

Following the initial Phase I investigations, Michigan Technological University (MTU) performed a study to estimate the impact of simplified HiPHEXs, coupled to the exhaust gas manifold under a "floating configuration" (manifold retrofitting). The study focused on determining the floating HiPHEXs impact on turbocharger performance, consequently the air-fuel ratio (AFR), and the overall engine performance (Naber, J., Johnson, J., Nelson, D., and Latautala, P., 2014).

The conclusions from the MTU study, summarized in Table 3, indicated that the effect of the HiPHEXs heat extraction $\dot{Q}_{HiPHEX}$ from the exhaust manifold gases on the locomotive engine performance remains minimal if it is below 12 percent of the total energy represented by the exhaust gases (i.e., for this particular engine).

Table 3. HiPHEXs energy removal impact on AFR at Notch 7 (Naber, J., Johnson, J., Nelson, D., and Latautala, P., 2014)

$\dot{Q}_{HiPHEX}$ (kW)	% Heat recovered/ Exhaust flow enthalpy	Calculated AFR (-)	Reduction in AFR (%)
0	0	28.5	0
25	1	28.5	0
50	2	28.4	1
100	4	28.1	2
200	8	27.7	3
300	12	27.2	5
400	16	26.7	7
800	31	24.7	12

To overcome limitations associated with the OEM turbocharger and to increase the WHRS total recovered energy, the HiPHEXs were configured to represent even lower back pressure on the exhaust gas side of the heat exchanger. The HiPHEXs were therefore equipped with "flexible" high-pressure flame-tolerant tubes configured to non-invasively retrofit the inner volume of the locomotive exhaust gas manifolds and the exhaust stack. The "manifold HiPHEXs" ($HiPHEX_{man}$) were configured to be immersed in the high-temperature exhaust gas streams pre-turbocharger. The "stack HiPHEXs" ($HiPHEX_{st}$) were then optimized to extract exhaust gas energy at the turbocharger discharge. At this location (exhaust stack) the exhaust gas temperature is lower, as a portion of the exhaust gas energy is lost due to gas expansion in the OEM turbocharger. By combining the $HiPHEX_{man}$ and the $HiPHEX_{st}$ the working fluid can be circulated to elevate its energy content via low-temperature exhaust gases at the turbocharger discharge and via high-temperature exhaust gas pre-turbocharger, thus obtaining pre-heating and super-heating of the working fluid. Figure 3 summarizes the "pre-heating to super-heating" working fluid configuration by representing the $HiPHEX_{man}$ and $HiPHEX_{st}$ non-invasively retrofitted with the GE Dash 9 locomotive engine exhaust gas manifolds and stack. In this configuration, $HiPHEX_{man}$ represents a series of heat exchangers non-invasively retrofitting the exhaust gas manifolds to extract up to 12 percent of the exhaust gases total energy at Notch 8, while $HiPHEX_{st}$ represents non-invasive heat exchangers configured to extract the remaining exhaust gas energy as the gases are discharged by the OEM turbocharger. The simplified representation of the GE Dash-9 exhaust gas piping system in Figure 3 offers a top view with respect to the 16-cylinder engine block. Accordingly, the $HiPHEX_{st}$ is positioned within the OEM stack (at the turbocharger discharge), while multiple $HiPHEX_{man}$ are positioned pre-turbocharger (within the two banks of OEM exhaust gas manifolds coupled to their corresponding cylinders).

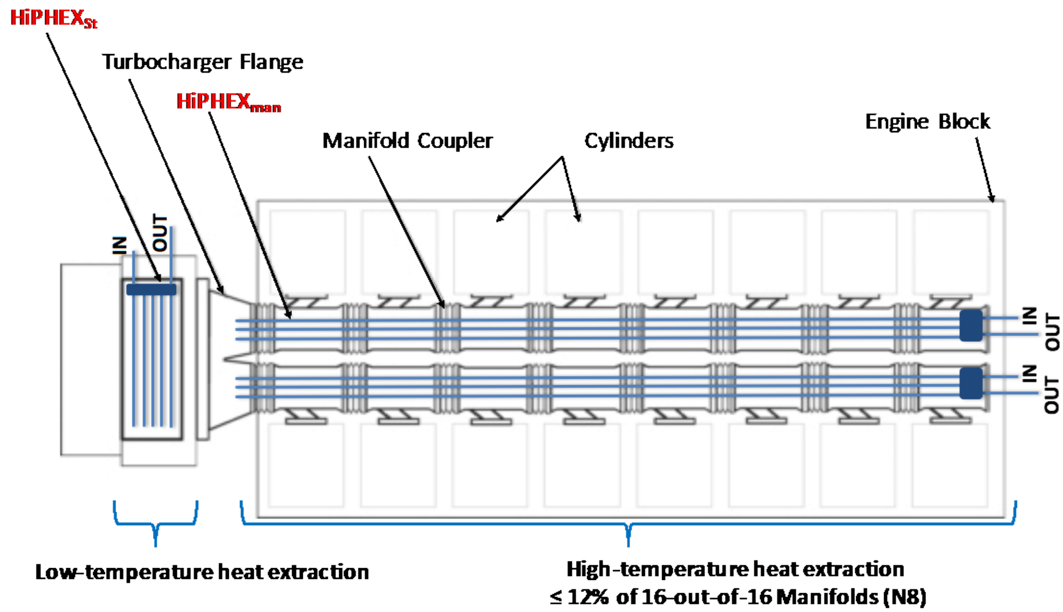

Figure 3. HiPHEXs configurations within locomotive engine OEM exhaust equipment

2.2.2 Exhaust Manifold HiPHEX (HiPHEX$_{man}$) Optimization

In the general heat exchanger design the main aim is to maximize the heat transfer between the working fluid (e.g., water or refrigerant) and its surrounding environment. The heat transfer correlates with the type of flow (laminar/turbulent), residence time (how long the working fluid is allowed to exchange heat), and surface/contact area. Both an increased surface area and high velocities of the working fluid generally increase the pressure drop (back pressure) within the heat transfer channels. Additionally, the heat exchanger optimization factors in the amount of pressurization and pumping system used to drive the working fluid within the heat exchanger. To maximize the effectiveness of the HiPHEXs, while minimizing their invasiveness in the locomotive exhaust manifolds and stack, the use of analytical tools and commercial CFD software is required. To accelerate optimization processes, TDR utilized a numerical code, which analytically solves the heat transfer mechanisms occurring within the HiPHEXs with respect to the fluids of interest. To increase resolution and obtain detailed modeling and analysis, TDR utilized licensed commercial engineering software (e.g., ANSYS, Inc.'s Fluent and Solidworks FluidFlow software).

Under the dimensional constraints represented by the GE Dash-9 exhaust manifolds, the heat exchangers were positioned in a "counter-flow" configuration.

As discussed in Section 2.1.1, the MTU study determined that to avoid impacting engine performance, only a limited amount of energy can be extracted pre-turbocharger (see Table 3 summarizing the HiPHEXs energy removal impact on the AFR). Accordingly, should the HiPHEXs be configured to extract exhaust gas energy in excess of 12 percent at high notch settings, the AFR would gradually decrease, resulting in lowering the ICE performance.

The HiPHEXs can also impact the turbocharger and engine performance if the friction pressure losses incurred by the exhaust gases result in an increased exhaust gas backpressure (EG$_{BP}$), beyond the EG$_{BP}$ values normally generated by the manifolds and couplers (see Figure 3). The

MATLAB code was used to calculate the flow dynamics of the exhaust gases traveling through the various sub-channels for varying tube numbers.

This process was numerically implemented in the MATLAB code and the EG_{BP} was determined for varying HiPHEX tube numbers to the maximum allowed within the OEM manifold dimensional constraints. Another important parameter to consider in the optimization of the $HiPHEX_{man}$ is the pressure losses experienced by the working fluid, or "working fluid backpressure" (WF_{BP}) due to friction losses developed by the working fluid circulating at various mass-flow-rates within the heat exchangers channels or tubes.

The analysis performed is summarized in Figure 4. As shown in this figure, a region of optimized HiPHEX operation with respect to the number of tubes versus several critical parameters is identified. The solid vertical black line represents the HiPHEX optimized characteristics under the various constraints. Effectively, the exhaust gas pressure drop (P_{exh}) is limited due to the exponential correlation with the number of tubes while capturing the portion of linearly increasing turbine work (W_{turb}). This analysis also factors in the varying temperature of the exhaust gases (T_{exh}).

This analysis demonstrated that further increasing the number of tubes would result in excessive EG_{BP} with only a relatively small increase in turbine work (added W_{turb} per tube).

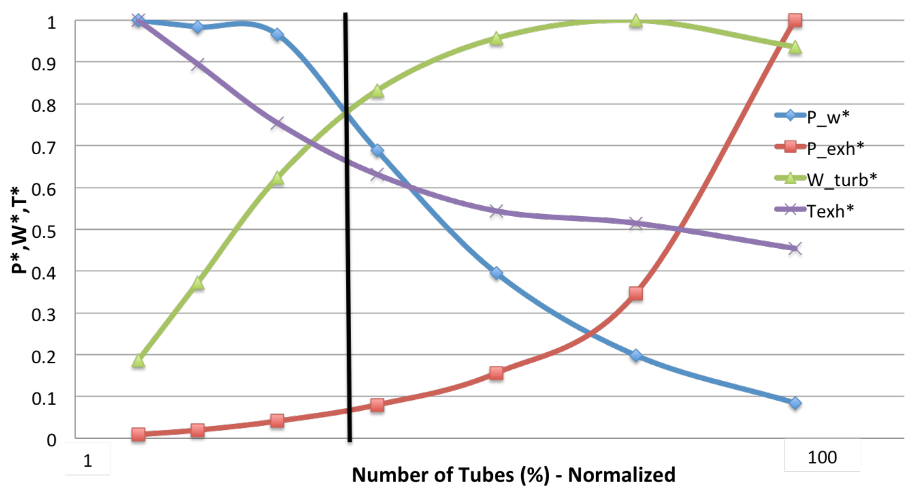

Figure 4. Normalized WF_{BP} (P_w) and EG_{BP} (P_{exh})

Based on the analysis performed with the MATLAB code, and commercial CFD software such as ANSYS Fluent and Solidworks FluidFlow, the $HiPHEX_{man}$ optimization is obtained with the heat exchanger configured to extract the required energy from the exhaust gases flowing in the manifolds pre-turbocharger (approximately 12 percent of total exhaust gas energy). Figure 5 shows the non-invasive retrofitted $HiPHEX_{man}$ optimized for the GE Dash-9 locomotive engine exhaust gas manifolds. The $HiPHEX_{man}$ are configured to be inserted from the back of the exhaust gas manifolds coupled via cylinders 1 and 9, without requiring modifications of the OEM exhaust gas manifolds (i.e., non-invasive retrofitting requirement). Each manifold is coupled to its corresponding cylinder via coupling flange "2." A similar optimization approach was executed to customize the $HiPHEX_{man}$ to non-invasively retrofit different locomotive models (i.e., passenger versus line-haul locomotives).

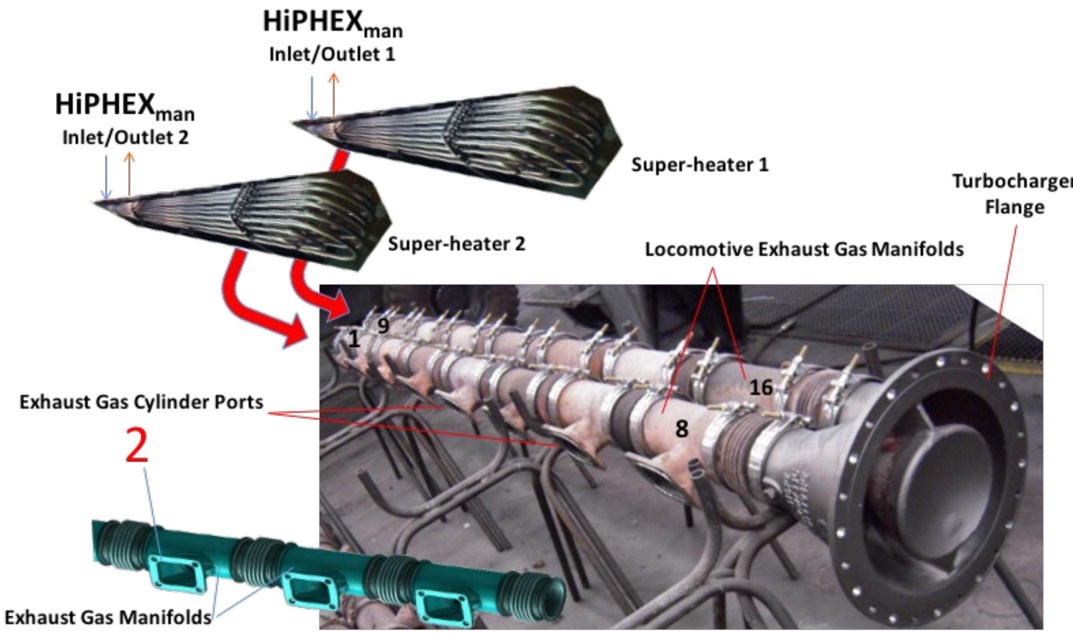

Figure 5. Non-invasive HiPHEX$_{man}$ retrofitted with 16 locomotive exhaust gas manifolds

2.2.3 Exhaust Stack HiPHEX (HiPHEX$_{st}$) Optimization

The OEM exhaust stack for the GE locomotive Dash-9 is characterized by substantially different geometry and dimensions when compared to the exhaust gas manifold geometry and dimensions represented by the exhaust gas manifolds. After expansion and loss of thermal energy through the turbocharger, the exhaust gases normally vent to atmosphere through the exhaust stack. As 16 piston-cylinder assemblies are coupled to individual exhaust gas manifolds (16-out-of-16) and they all discharge through the turbocharger, the mass-flow-rate of gases through the stack is cumulative. For the HiPHEX$_{st}$, the fluid dynamics of the gases inletting the stack is significantly different compared to the fluid dynamics mechanisms developed in the exhaust gas manifolds. For these dedicated types of HiPHEXs, the following optimization criteria was adopted:

- Maximizing heat transfer surface area in the exhaust stack
- Minimizing flow blockage to avoid EG$_{BP}$ build up at the turbocharger discharge. The stack EG$_{BP}$ due to friction is expected to be much smaller than that manifested in the exhaust gas manifolds since gas velocities are comparatively lower.
- Optimizing the HiPHEX$_{st}$ for scalability and ease of manufacturing

The MATLAB code enabled the determination of the heat transfer characteristics between the working fluid, the exhaust gases and pressure losses for varying heat exchanger parameters.

Many simulations were performed with the MATLAB code for varying geometric configurations. An optimized configuration was then selected to minimize the exhaust gas pressure losses, while enabling the desired heat transfer within the exhaust stack length.

The flow within the exhaust gas manifolds and stack is highly turbulent, chaotic and three-dimensional in nature. TDR utilized the commercial software Solidworks Fluidflow and ANSYS Fluent to perform CFD simulations of the exhaust gases traveling through varying cross-flow tubing configurations. As shown in Figure 6, from left to right, the hot gases impact the surface of the HiPHEX tubes causing increased friction/momentum exchange and consequently heat transfer. However, this occurs only at the front and sides of the upstream rows of the tubes (i.e., to the left). Increasingly in the back rows from left to right of the tubes, stagnation occurs, thus the effective heat transfer rate is reduced. The left side of Figure 6, shows areas corresponding to the bottom of the stack, wherein the exhaust gases inlet the stack after expansion in the turbocharger. The right side of Figure 6 represents areas nearing atmospheric venting regions as the exhaust gases outlet the stack.

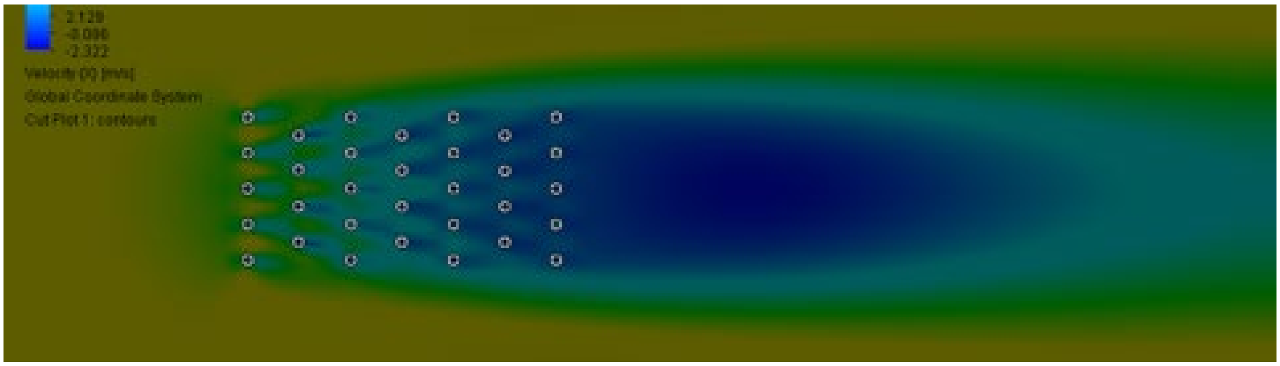

Figure 6. CFD of a cross-flow stack configuration with stagnation

Figure 7 shows the optimized CAD of the mixed cross-flow counter-flow tube configuration forming a "low-density" HiPHEX$_{st}$ customized for non-invasive stack retrofitting with minimum EG$_{BP}$. The term "low-density" indicates a HiPHEX$_{st}$ (referred hereinafter as HiPHEX$_{st\ LD}$) optimized with a minimum number of tubes. The optimization was based both on the analytical zero-dimensional MATLAB analysis and the three-dimensional CFD analyses.

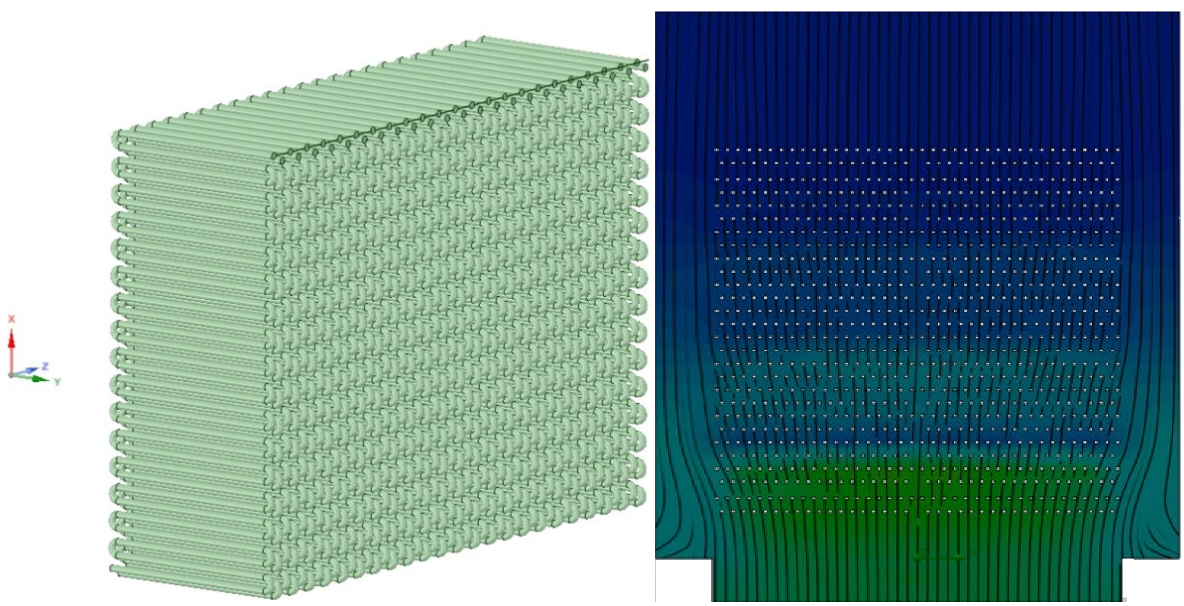

Figure 7. Simplified HiPHEX$_{st\ LD}$ CAD and CFD of the estimated EG$_{BP}$ through the stack

2.3 PDP Selection and Implementation

This section outlines the implementation and testing of the high-pressure re-circulator by customizing a PDP with variable mass-flow-rate capabilities to maximize HiPHEXs thermal output at various locomotive notch settings. Following the condensation process—thermodynamic process indicated by states $6 \rightarrow 1$ shown in Figure 2—the working fluid returns to thermodynamic State 1 at a low temperature and pressure and in a sub-cooled liquid state. The PDP must therefore execute the transition from thermodynamic states $1 \rightarrow 2$ by increasing the working fluid pressure.

An axial multi-piston pump was selected with low pulsation and performance characteristics requiring mild modifications to cover most of the targeted pressure range and mass-flow-rates. Figure 8 shows the mobile PDP system comprising the working fluid reservoir, pump hardware and instrumentation. The working fluid reservoir is also the condensate tank. The pump is driven by a three-phase frequency/vector controlled motor coupled to the PDP to pressurize the working fluid at its discharge. A pressure-reducing valve was installed to control turbine inlet pressure and a bypass line was also installed to bleed the working fluid back to the reservoir. A Hall effect sensor (i.e., detecting the position of pump rotary components) was utilized to control the motor speed and adjust the working fluid mass-flow-rate. Measurements of temperature were recorded at both the outlet (discharge) and the inlet (suction) of the pump and transmitted to the control system interface and data acquisition system.

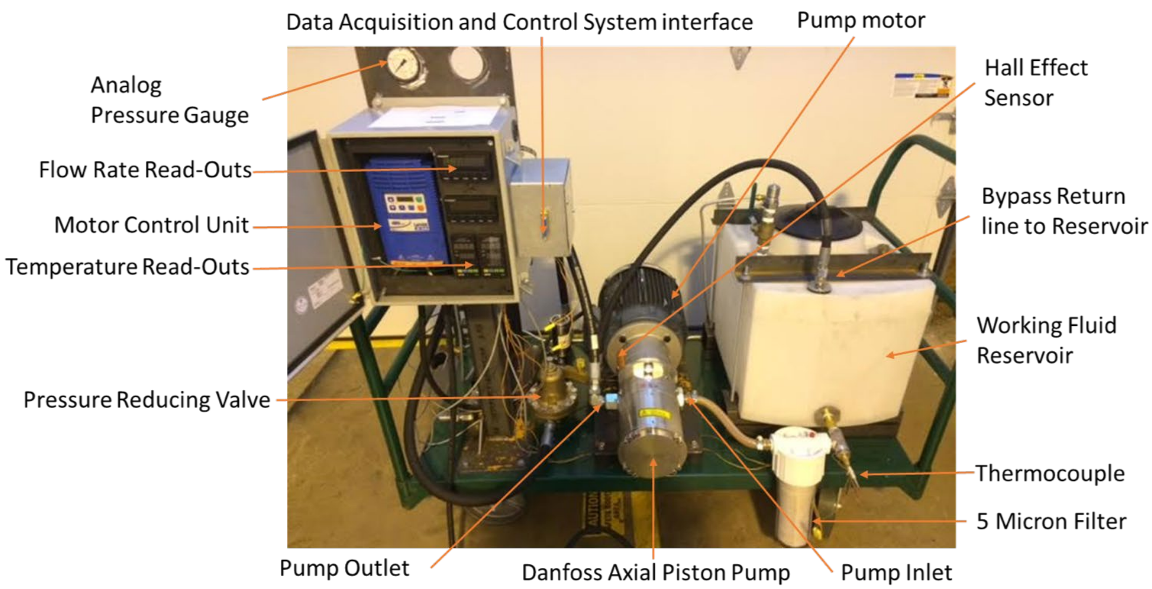

Figure 8. PDP working fluid pump and reservoir assembly

Figure 9 shows field-testing of the PDP fully instrumented and supporting full-scale HiPHEX$_{st}$ locomotive testing. Overall, the PDP assembly was configured with vibration isolators and quick-disconnect thermal hydraulic piping (Balance of Plant). Locomotive testing consisted of controlling the PDP mass-flow-rate to maximize HiPHEXs performance when the locomotive engine is operated at different notch settings. The PDP components were also installed with the option of fully integrating them with the PCU housing.

Figure 9. PDP instrumentation and connection to HiPHEX$_{st}$ retrofitted locomotive

2.3.1 Matching Turbo-machinery Components and PCU Integration

Matching the turbine expander to the SRC and HiPHEXs characteristics is critically important as the power recovered by the WHRS is directly proportional to the efficiency of the turbine. Among various contractors specialized in turbo-machinery designs, Brunel University London, UK, was commissioned to aid TDR in the optimization of the turbine expander. The results of these collaborations are presented in this section.

The turbine expander converts the working fluid thermal energy into mechanical energy. To generate electrical energy, the turbine is then coupled to a generator, which converts the turbine mechanical energy into electricity. Given the thermodynamic and geometric limitations of the locomotive-specific WHRS operating under SRC configurations, the in-flow radial (IFR) turbine was selected. Radial turbines generally develop a higher specific work output (i.e., per unit mass flow) and result in compact sizes compared to axial turbines and other types of expanders for the same power rating. A simplified methodology for the turbine optimization iteration can be summarized in Figure 10.

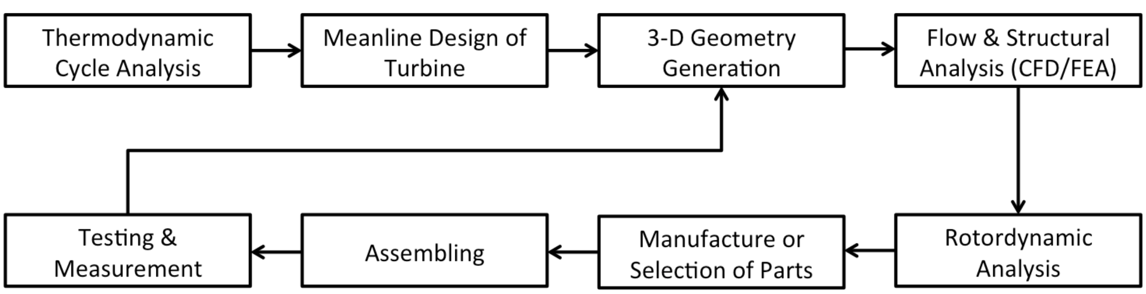

Figure 10. Simplified methodology for the turbine optimization iterations

Many methodologies were reviewed based on practical experience and a literature review conducted during this investigation. Aungier (2009) provided the most widely used analysis for IFR turbines dedicated to WHRS applications (Aungier, R. H., 2009). A modified version of Aungier's work was used to account for turbo-machinery satisfying Phase II project requirements and addressing nozzle-less IFR turbines. The implementation of this methodology was initially carried out by utilizing Microsoft® Excel. The equations from the implemented methodology were then incorporated in the program to derive thermodynamic and preliminary optimization data and the turbine efficiency.

To start the iteration, a set of input parameters are provided to the Excel code based on the turbine geometric and thermodynamic boundary conditions. As the iterative process progresses, the optimum parameters are determined and the calculations to select turbine geometric parameters can be started. A full description of the complete set of equations used for the calculation of the turbine is beyond the scope of this report. The IFR turbine resulting from these analyses complies with the non-invasiveness requirement once integrated with the PCU housing along with the PDP and condenser heat exchanger.

The preliminary results produced a conventional design with expected supersonic shock and other losses affecting the IFR turbine efficiency. To obtain accurate flow simulations—the effects of supersonic flow—and implement mitigating blade contour corrections, an extensive CFD investigation is required and is beyond Phase II budget and scope. Therefore, only a preliminary CFD simulation of a 75-kW modular IFR turbine was performed. As the CFD approach is preliminary, it only provides general information of flow distributions.

The preliminary CFD analysis of the three-dimensional turbine model was performed using ANSYS CFX followed by meshing software (i.e., ANSYS TurboGrid). More than 120 CFD simulations were performed to obtain converging solutions. Figure 11 (left), shows a screenshot of the meshing of a portion of the turbine rotor (i.e., approximately 250,000 cells were used). Figure 11 (right), shows preliminary contour plots of the working fluid angular velocity as it travels through the channels formed by the blades. As shown, regions of supersonic flow (velocity W>330 m/s) develop near the blades tips. These phenomena lead to inefficiencies, which are not accounted for by the zero-dimensional mean-line analysis.

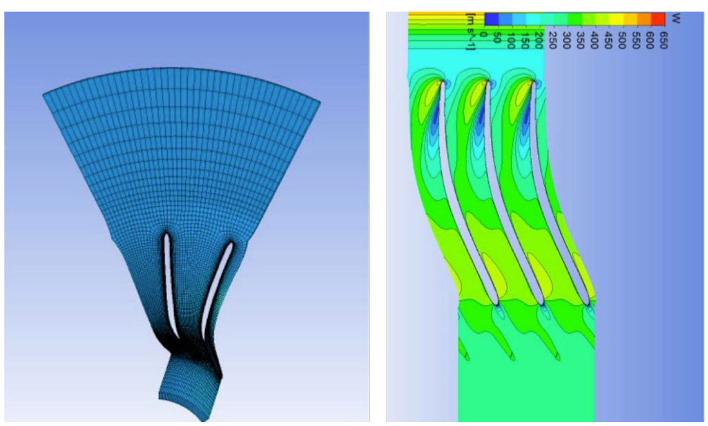

Figure 11. Meshing of a portion of the turbine, and angular velocity contour plots

The previously discussed iterative mean-line modeling, combined with the results from CFD analyses, supported the computer aided design of the solid models forming the turbine expander. Figure 12 summarizes the steps from CAD modeling (1), to rapid prototyping of the full-scale IFR turbine (2), IFR turbine manufacturing via 5-axis CNC machine (3), and assembly of the expander turbine (4) with a turbine volute.

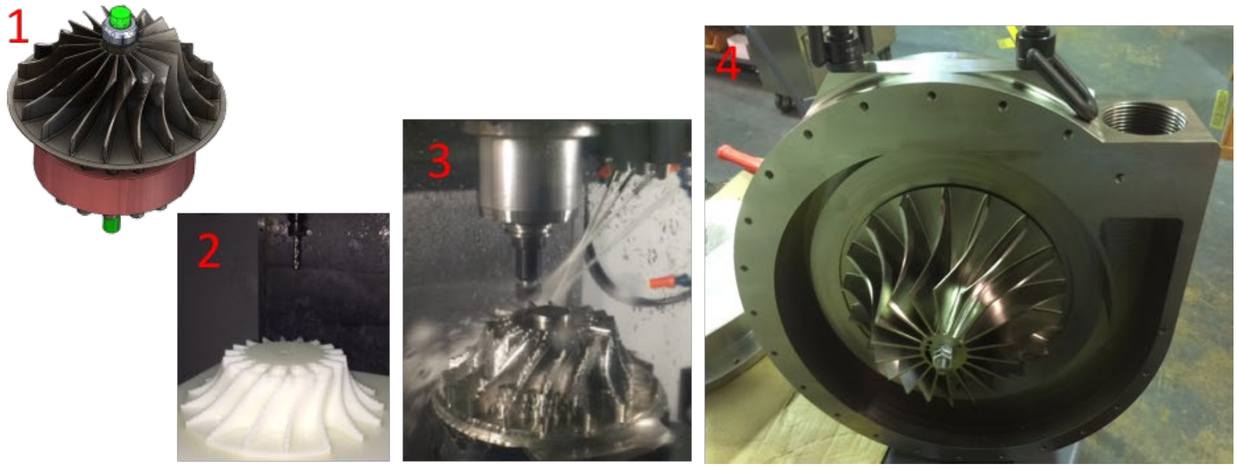

Figure 12. IFR turbine manufacturing—CAD (1), prototyping (2) and (3), final product (4)

2.3.2 Matching Electrical Components and PCU Integration

This section is dedicated to the PCU electronic and electrical components, namely the generator, dedicated control systems, and coupling to the IFR turbine. Given the relatively high-power rating represented by these components and the safety hazards associated with their interfaces in the context of untested prototype installations, a commercially available high-power motor drive was customized by a third party specialized in the production of high-power electronic controllers for locomotive traction motors, thus equipped with tested safety features.

Matching of the generator parameters with those of the IFR turbine ensures that the turbine is operated at its optimal speed to produce the highest efficiency. To ensure inherent robustness, simplicity, and reliability especially for operations at high temperatures, the selected electrical machine architecture is that of induction (asynchronous) electro-magnetic machines. As the highest IFR turbine efficiency resulting from the zero-dimensional modeling and three-dimensional preliminary CFD analyses is approximately 60 krpm of the selected induction machine rotor to match this critical parameter. A "2-pole" induction machine rotor and stator pair was procured from an OEM company with parameters to efficiently convert the IFR turbine power into conditioned electrical power. The fundamental alternating current (AC) frequency of this machine is 1,000 Hz, suitable for power electronic converter modules at the targeted power ratings.

The rotor and stator pair was then equipped with a cooling jacket for extended tests. The rotor was interference fitted with a shaft configured to provide position information to electronic transducers interfaced with the control system. Very high-precision high-speed ceramic ball bearings were employed for testing purposes. Power cables from the stator were routed through the housing and connected directly to the electronic controller. Figure 13 illustrates the assembly steps from CAD to the complete assembly of the operational induction machine of the high-speed direct drive generator. The 60 krpm generator is then coupled via a flexible high-speed coupler to the turbine shaft (Figure 12 shows the back side of the turbine).

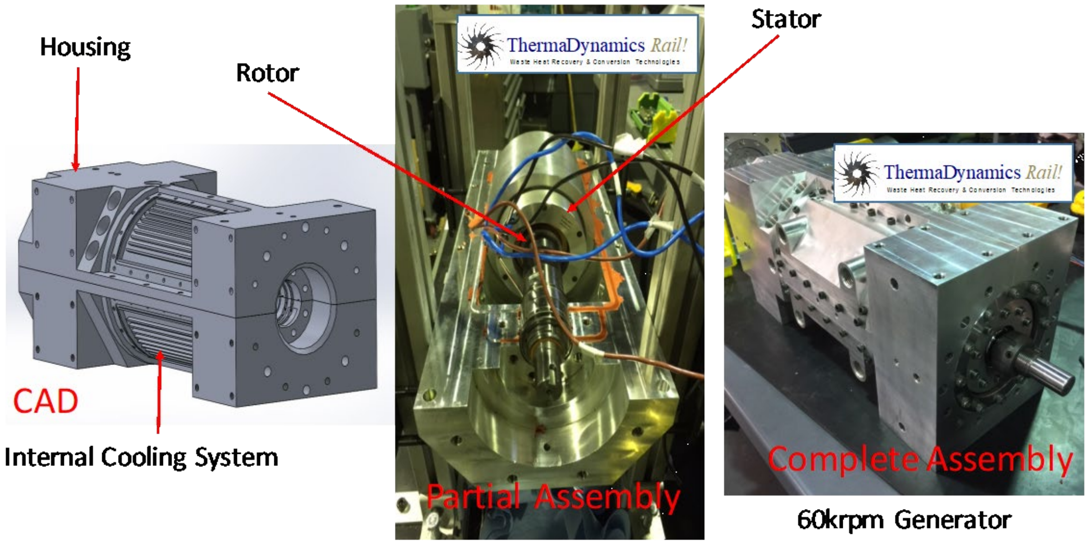

Figure 13. Direct-drive high-speed generator-motor, from CAD to final assembly

The electronic drive, converter and conditioner (referred to as "controller" for simplicity) electro-magnetically excites the generator, conditions its electrical output based on the torque and/or speed driven by the IFR turbine, and transfers the electrical energy it generates to the locomotive bus. This results in the supply of pollutant free electricity, entirely produced by converting the otherwise wasted thermal energy contained in the exhaust gases.

The power and voltage ratings developed by the WHRS are relatively high (e.g., 75–300 kWe at >1,200 VDC) as a result the fast generator-motor controllers is equipped with redundant safety features. For example, the maximum direct current (DC) link controller voltage needed to interface with one of the locomotives selected for this project operates from a relatively low voltage all the way to 1,250 VDC. To ensure reliable controller safety features, three controllers were matched to the thermal energy captured by the HiPHEXs. Two high-power controllers (HPC) with operational experience and tested safety features were customized for interfacing with TDR WHRS components for stationary motor-drive operations. An additional relatively lower power fast generator-motor controller (LPC) was customized to match different HiPHEXs configurations. The two HPCs were customized by a third party specialized in power electronics dedicated to the control and conversion of electric power to drive traction motors utilized in the rail industry. One of the HPCs is configured to convert the IFR turbine power into electricity by the fast generator-motor. The second HPC is configured to fine-tune the generator to fully simulate the torque generated by the IFR turbine when the WHRS thermal-hydraulic loop is bypassed. Therefore, one HPC drives one fast generator-motor (motoring mode), the other HPC drives the fast generator-motor to produce conditioned electricity (generator mode). All HPCs and the LPC can be configured to operate in motor- or generator-mode.

Figure 14 shows the locomotive-scale fast motors-generators configured to simulate IFR turbine operations. The locomotive-scale high-speed motor-generator test stand was assembled by coupling two electrical machines (see Figure 13) to a high-speed coupler while equipping each machine with independent water-cooling for prolonged tests.

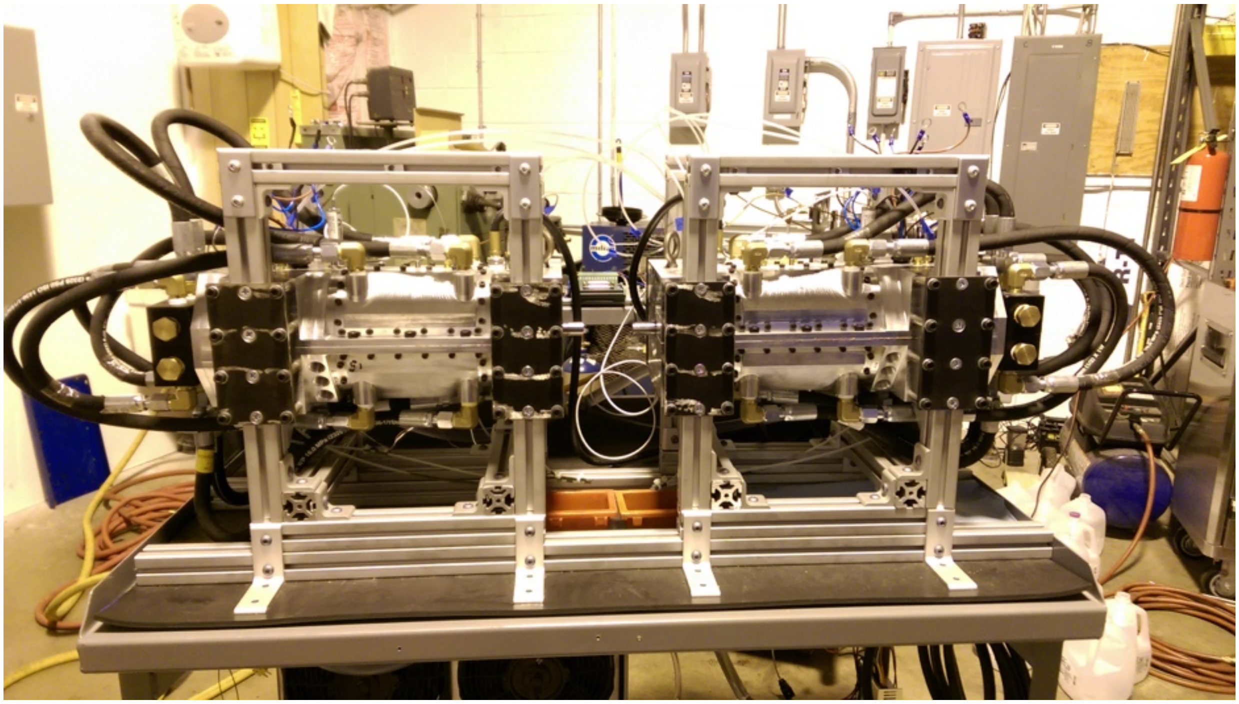

Figure 14. Locomotive-scale WHRS high-speed motor-generator testing

Commercial software Simulink was utilized to execute simulations to verify control system performance for high-power and high-speed induction generator-motor machines.

Based on these activities, TDR selected the parameters for a controller that can be matched to the IFR turbine characteristics while managing high voltages and identified commercially viable integrated power modules with gate drives protection. To connect the integrated power modules, a printed circuit board (PCB) based on a Controller Area Network (CAN) was optimized by a specialized TDR contractor to execute in-house control of the system via a low-cost laptop computer. The power module is water cooled and allows for continued testing. The electrical enclosure shown in Figure 15 contains the water-cooled integrated power module (right) and the computer interface (left).

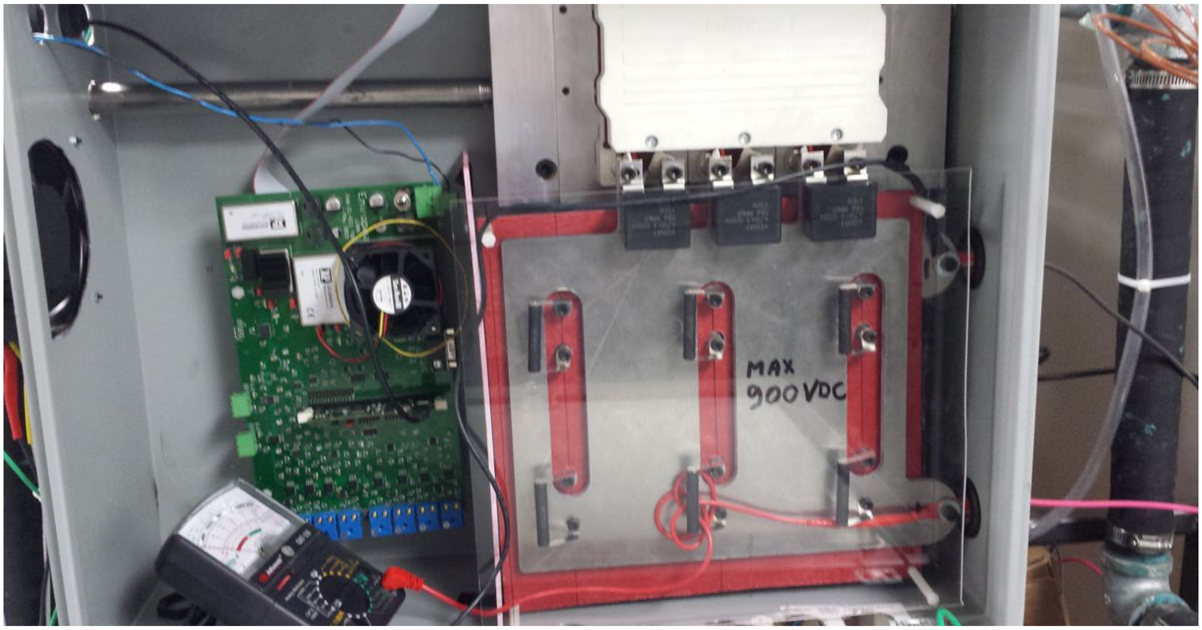

Figure 15. Integrated power module and computer interface

2.3.3 Vibration Analysis and Exoskeletal PCU Shock Absorbing System

The simulated PCU, matched to the turbo-machinery and electrical components, underwent vibration analysis by measuring the accelerations on the PCU housing in the bearings planes.

A series of tests aimed at determining the effects of impacts and vibrations on the components forming key TDR WHRS components were conducted at Transportation Technology Center, Inc. (TTCI). The locomotive model operated at the TTCI facility in Pueblo, CO, and selected for the execution of these tests was the GP40 645E3 Electro-Motive Diesel (EMD). To reduce the length of the WHRS thermal-hydraulic piping system, and for the purposes of this analysis, a series of weights simulating the total mass of the PCU was located as close as feasible and non-invasively to the locomotive waste heat sources.

Figure 16 illustrates the installation steps of a non-invasive, removable structure to support two symmetrical PCUs. For the purpose of obtaining locomotive actual operational vibration data, each fully equipped PCU would represent a total weight not exceeding 500 lb positioned above the locomotive center of mass.

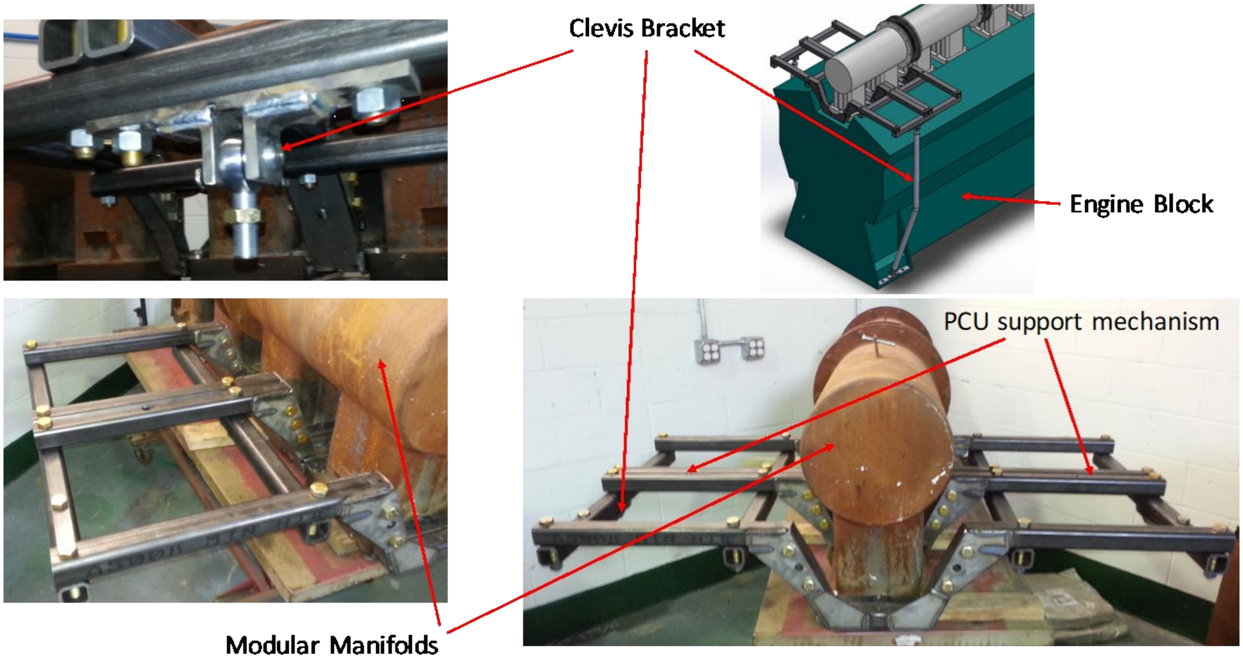

Figure 16. Non-invasive PCUs supporting structure

Figure 17 shows in greater detail the positioning of the accelerometers and PCU-simulated weights with respect to the locomotive engine block and heads within the locomotive engine compartment.

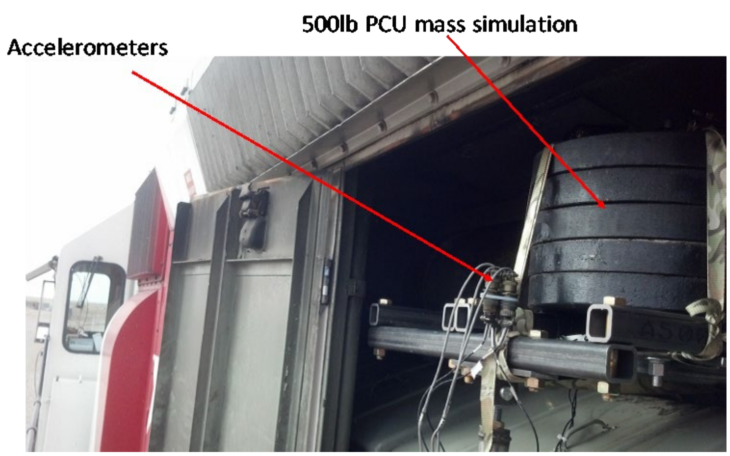

Figure 17. Locomotive testing configuration, 500 lb (x2) simulated PCUs

Locomotive testing consisted of operating the locomotive while sampling accelerations on all axes at different locomotive speeds under various locomotive operations. Various PCU configurations were considered to determine the design point for impact loads and the rates of rolling, pitching, and yawing. Additionally, the Association of American Railroads' (AAR) Manual of Standards and Recommended Practices, Section M was reviewed as it pertains to the locomotives vibration environment. The largest impact value in this section was selected as a conservative approach, this value is 6.3 G. Thus vertical, lateral and longitudinal impacts of 6.3 G were simulated on the PCU mounting frame.

The major acceleration translation to the PCU is due to vertical, lateral and longitudinal impacts, in the order of 1.2 G through 3 G. The acceleration present in the PCU as a result of the locomotive pitching, rolling and yawing is rather unimpressive and approximately a 100-fold smaller than represented by the impact loads. The main purpose of the cases considered in this section was to investigate how the locomotive pitching, rolling and yawing compares to pure vertical, and lateral and longitudinal impacts and verify whether the impact mitigating functions of the PCU suspension mounting frame would satisfactorily perform under conservative impact scenarios.

Based on the analysis results, the currently considered PCU suspension mounting frame configuration, is well designed for the larger loads resulting from vertical, lateral and longitudinal impacts. It is therefore safe to conclude that the PCU suspension mounting frame would operate satisfactorily during the angular motions (pitching, rolling and yawing) of the locomotives operating conditions.

2.4 Matching, Selection, Installation, and Testing of Condenser Components

This section is dedicated to the matching of the condenser unit to the HiPHEXs-turbo-machinery components and represents the thermal energy to be rejected to the ultimate heat sink.

The heat extracted from the superheated steam discharged by the turbine is used to change its thermodynamic state from superheated vapor to sub-cooled liquid (i.e., latent heat of condensation). To execute full-scale locomotive tests by means of a locomotive simulator at the TDR testing facility, the condenser is formed by two-closed loops wherein in the "condenser loop" cooling fluid (i.e., water from a reservoir) is pumped on the tube-side of the heat exchanger, in the "turbine loop," superheated vapor to be condensed flows on the shell-side of the heat exchanger.

For a given amount of extracted energy from the working fluid there are two options regarding the required amount of cooling fluid. The first option is to increase the outlet temperature. The second option is to increase the mass-flow-rate of the cooling fluid and maintain a certain temperature difference between the inlet and outlet of the condenser. To this end, the temperature of the cooling water at the condenser outlet was used for the selection of reservoirs and hydraulic connections. To ensure structural integrity, a target outlet temperature of the cooling water was set to be 10 °C (50 °F) less than the maximum operating temperature of the reservoirs—as generally specified by manufacturers of heat exchangers operating under similar conditions.

The condenser was configured in a manner that would ensure condensation of the working fluid at general locomotive conditions. The condenser configuration factored the dimensional constraints of the locomotive engine compartment. Moreover, cost and weight considerations were also considered and a compact condenser heat exchanger configured for non-invasive locomotive retrofitting was matched to the HiPHEXs power ratings, the IFR turbine, and PDP capabilities.

The locomotive condenser thermal load (kW_{th}) in conjunction with the mass-flow-rates (kg/s) of the working and cooling fluids were used to select low-cost off-the-shelf heat exchangers condenser components. Under the condenser thermal load requirements, a serial arrangement of two Shell and Tube Heat Exchangers (STHE) was selected and repurposed for the condensation of the superheated vapor discharged by the turbine when operated at locomotive conditions (i.e., different notch settings). The selected STHEs were connected in a series and a CAD model was used to optimize their positioning with respect to the locomotive simulator equipment. Figure 18 shows the arrangement and serial connection of the two STHE that have been repurposed for the condensation of the working fluid discharged by the turbine when operated at the stationary locomotive simulator. Figure 18 (left), shows the concept investigation, whereas Figure 18 (right) shows the final installation of the two STHEs. The condenser assembly was installed purposely at an inclination to allow for gravitational draining of the condensed working fluid.

As part of the locomotive simulator, thermocouples and flow meters were installed to measure the inlet and outlet temperatures of both the cooling and working fluid streams through the condenser.

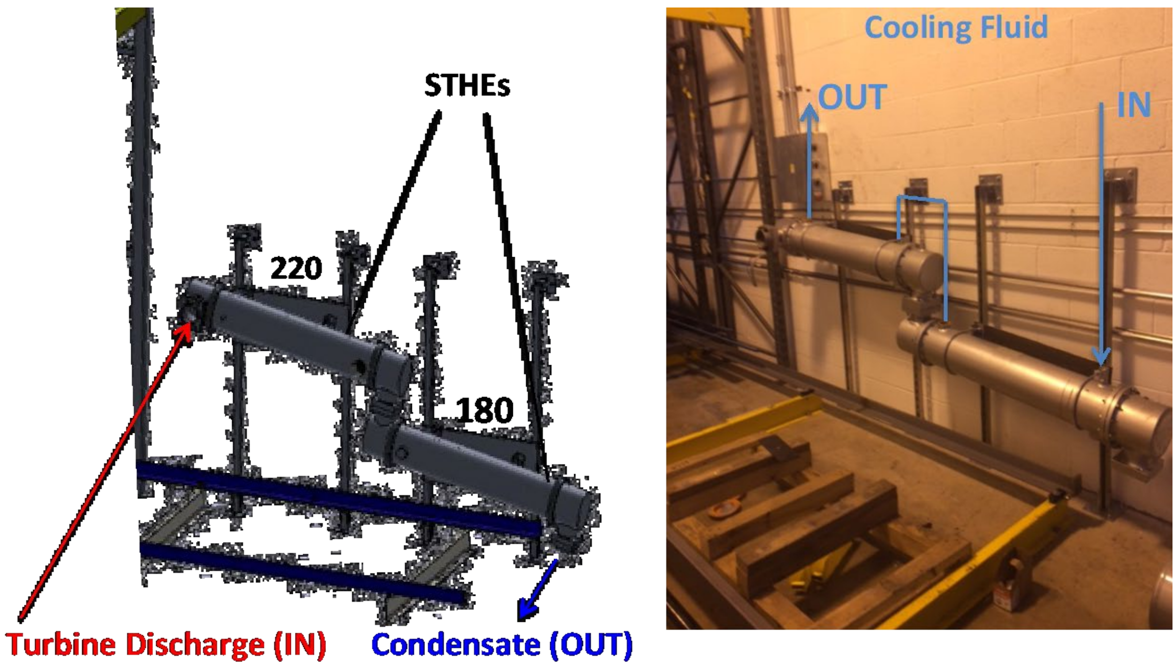

Figure 18. STHE in serial arrangement. Concept investigation and final installation

2.5 HiPHEXs Testing

HiPHEXs locomotive testing was executed at a Class I rail facility by non-invasively retrofitting a low-density $HiPHEX_{st}$ within the OEM exhaust stack of a GE Dash-9 locomotive operated at all notch settings. The full-scale locomotive test set-up and results will be discussed in this section.

2.5.1 Testing Set Up and Methodology

Thermal-hydraulic installation of the non-invasive $HiPHEX_{st\ LD}$ (i.e., stack, low-density configuration) was significantly simplified as it consisted of a few steps: (1) removal of the top flange and screen coupled to the top stack portions, (2) lowering the $HiPHEX_{st\ LD}$ from the top (i.e., removal of locomotive hood is not required), (3) securing the $HiPHEX_{st\ LD}$ to the stack structure by using the same bolts/clamps utilized to secure the top flange and screen, (4) coupling the $HiPHEX_{st\ LD}$ inlet and outlet(s).

For testing purposes, instrumentation mainly consisting of temperature, pressure, and mass-flow transducers was also installed at various locations along the working fluid and exhaust gas flow paths. Figure 19 shows the location of various transducers.

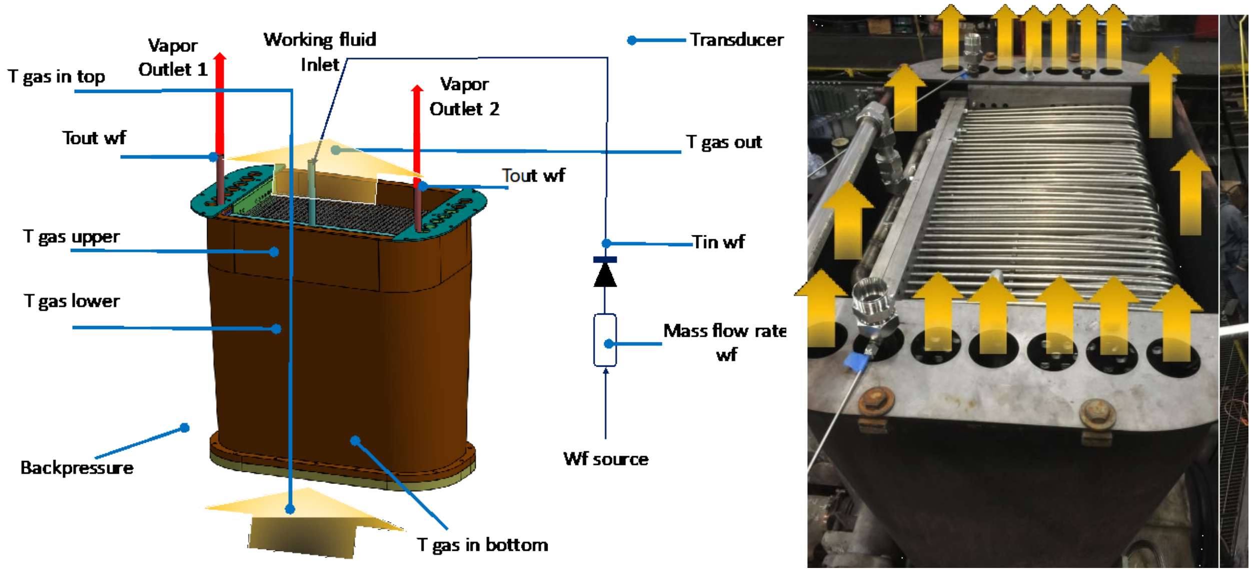

Figure 19. Measuring positions for HiPHEX testing and exhaust gases venting locations

Note that prior to the full-scale locomotive test of 16-out-of-16 cylinders, backpressure information was only predicted by simulated tests and computer analysis (see Section 2.2.3). To ensure the HiPHEX$_{st}$ would not cause excessive backpressure and possibly jeopardize the execution of the test (i.e., by negatively affecting diesel engine performance), the HiPHEX$_{st\ LD}$ was configured with side flow pathways to allow the exhaust gases to "escape" from each side of the heat exchanger as shown in Figure 19 without interacting with the heat exchanger. Mainly for this reason, the HiPHEX$_{st\ LD}$ was not configured to extract the maximum thermal energy available at the stack.

2.5.2 HiPHEXs Reliability and Endurance Pressure, and Thermal-shock Testing

The HiPHEX$_{st\ LD}$ was pressurized and kept at a pressure higher than the normal operating pressure for a testing period to verify whether the components forming the heat exchanger would undergo permanent deformations. Additionally, while the heat exchanger was pressurized, seals and hydraulic interfaces were monitored for leakages.

High-temperature and high-pressure unsteady-state testing was executed when retrofitted with the locomotive OEM stack. These tests consisted of exposing the heat exchanger to the highest operational temperature—exhaust gases produced at Notch 8—to ensure the whole heat exchanger structure reached stable temperatures of approximately 400 °C (752 °F) and establish dry tubes conditions. In this test, the pressure tubes forming the heat exchanger did not contain working fluid. While hot and dry, a large mass-flow-rate "burst" of low temperature working fluid (water) at approximately 5 °C (41 °F) was injected at the HiPHEX$_{st\ LD}$ inlet. This test was repeated by shutting off the working fluid supply to the heat exchanger, letting the working fluid evaporate, thus resetting dry conditions. The test was then repeated by re-injecting a burst of cold working fluid to ensure the heat exchanger remained reliably operational under repeated thermal- and pressure-shock conditions.

These tests verified the $HiPHEX_{st\ LD}$ ability to withstand rapid temperature changes, inducing thermal expansions and contraction cycling.

2.5.3 HiPHEXst Locomotive Testing at Operational Conditions

$HiPHEX_{st}$ testing was performed under the following sequence. After executing procedural locomotive engine warm up, the locomotive duty cycle was first varied from idle to full power (Notch 8) with the $HiPHEX_{st\ LD}$ dry—no working fluid circulated. As mentioned, this first test aimed at determining whether a failure in the WHRS (i.e., loss of working fluid accident scenarios) would impair normal locomotive operations at all notch settings. While the locomotive engine was ramped up from idle to Notch 8, a water manometer coupled to the bottom of the exhaust stack to measure EG_{BP} was monitored. At the same time, engine performance parameters during this test were compared with locomotive parameters normally obtained during locomotive servicing and without the heat exchanger equipment retrofitting the exhaust stack.

Under dry $HiPHEX_{st\ LD}$ operations, worse-case scenario, the heat exchanger merely acted as an obstruction in the exhaust gas pathway, therefore EG_{BP} (i.e., exhaust gas backpressure) gradually increased from Notch 3 reaching the maximum of 10 inches of water (0.36 psi or 0.025 bar) at Notch 8. This backpressure value is consistent with values estimated via simulations. When a test with the same notch settings was executed with the working fluid circulating within the $HiPHEX_{st\ LD}$, the EG_{BP} decreased to zero at all notch settings. This indicates that the $HiPHEX_{st\ LD}$ can be configured with a high-density core (additional tubes) and further extract thermal energy without impairing locomotive operations.

Figure 20 represents the simplified hydraulic coupling of the PDP to the $HiPHEX_{st\ LD}$, wherein the working fluid line shown represents the water supply inletting the heat exchanger. For each notch setting selected, a waiting time of approximately 30 seconds was allowed to reach steady state conditions in the exhaust gas parameters. Subsequently, the mass-flow-rate of the working fluid was adjusted and stabilized to a target value. For each batch of measurements, a minimum of 60 seconds (60 sampling points, 1 per second) were recorded. The measurements were repeated to investigate the accuracy of the test. The mass-flow-rate of the working fluid was varied to obtain steam at the outlet of the heat exchanger. The inlet and outlet temperature and pressure of the working fluid was recorded using the transducers at the positions indicated in Figure 19.

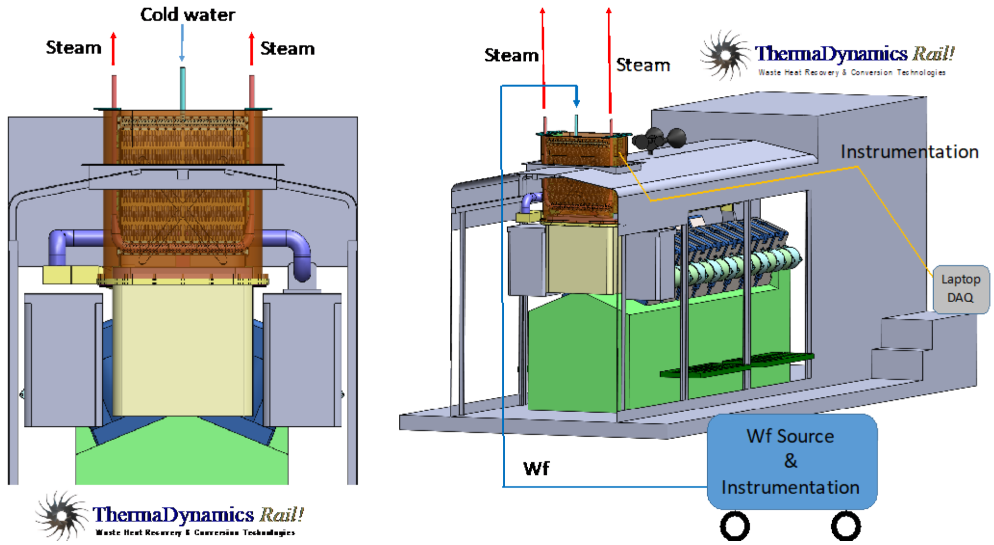

Figure 20. Locomotive test set up

2.5.4 Test Results

The analysis was performed for all notch settings. However, the most stable conditions were those corresponding to Idle, Notch 3, Notch 5, and Notch 8 (as shown in Table 4 and Figure 21 as N3, N5, and N8).

Figure 21 shows the HiPHEX$_{st,LD}$ inlet (left) and outlet (right) temperatures of the exhaust gases for various locomotive engine duty cycles. The inlet $T_{in,exhaust}$ measurements are very similar to the measurements obtained by Southwest Research Institute (SwRI) (see Table 1), which further validates the test data. The exhaust gas inlet temperature is constant for all notch conditions—except idle—but varies at the outlet depending on the energy extracted from the HiPHEX$_{st,LD}$, which is transferred to the working fluid.

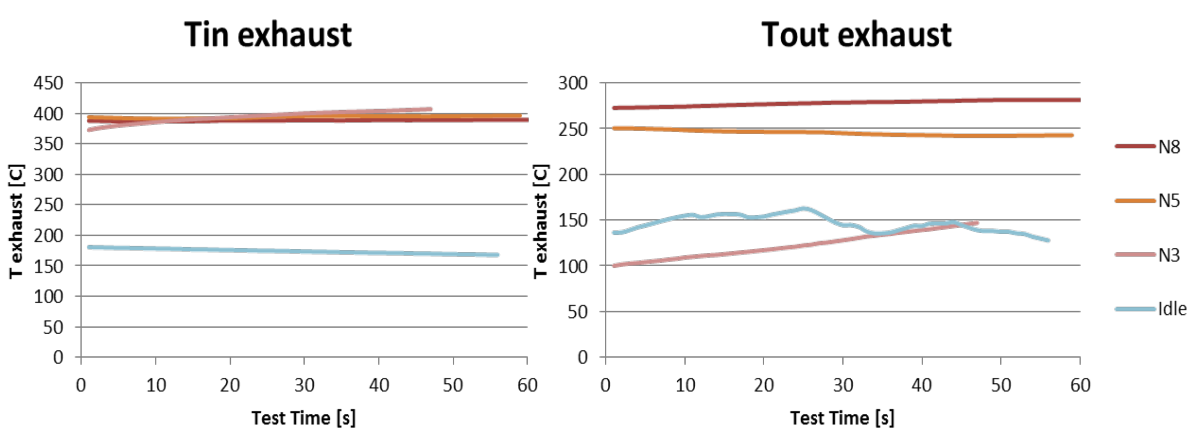

Figure 21. Inlet (left) and outlet (right) T of the exhaust gases for: idle, N3, N5, and N8

Figure 22 presents the change in temperature of the working fluid (left) and its mass-flow-rate (right) as it travels through the HiPHEX$_{st,LD}$.

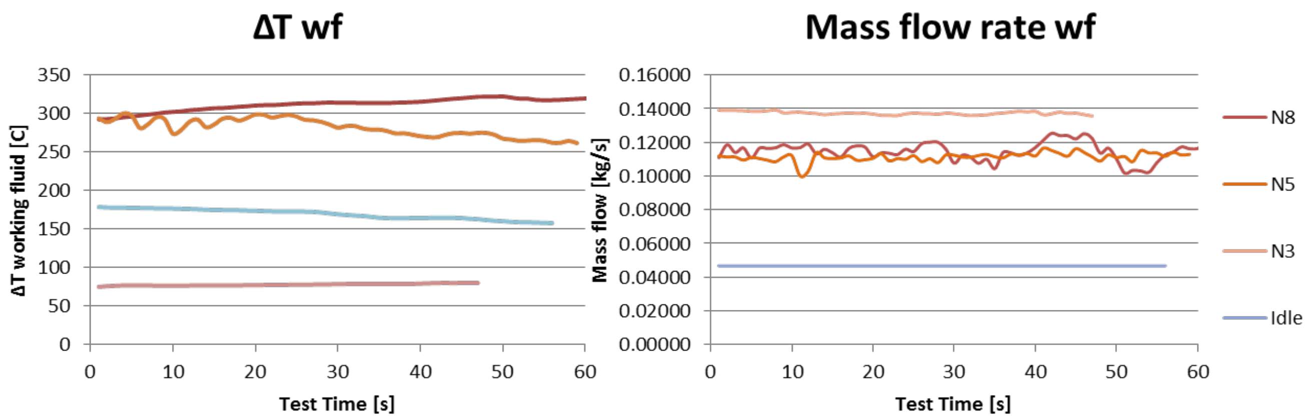

Figure 22. ΔT working fluid (left). Mass-flow-rate of working fluid (right)

From the right of Figure 22 it is noticeable that the working fluid mass-flow-rate at N5 and N8 is approximately the same. However, the energy content of the exhaust gases at N8 is higher compared to that of N5. Consequently, given a constant mass-flow-rate of ~0.11 kg/s for the working fluid in these two cases, the temperature difference is higher for N8, indicating that more energy is extracted compared to N5.

Finally, using the recorded data for the inlet and outlet temperature, a calculation was completed of the mass-flow-rate and pressure of the working fluid that the energy extracted from the exhaust gases. Table 4 summarizes the results for the various cases that were deemed most representative. The maximum power extracted in this 16-out-of-16 $HiPHEX_{st,LD}$ retrofitted locomotive test corresponds to the case of more water (referred to as N8').

Table 4. Test results summary

Variables	N3	N5	N8	N8' (more water)	Units
mass-flow-rate	0.1373	0.1113	0.1149	0.1385	kg/s
$\mathbf{T_{in\ avg}}$	12.8	12.8	13	13.1	^0C
$\mathbf{T_{out,avg}}$	90.5	294	326	301	ºC
$\mathbf{P_{in}}$	3.89	4.1	4.35	4.23	Bar
$\mathbf{P_{out}}$	1	1	1	1	Bar
$\mathbf{h_{in}}$	5.41E+04	5.42E+04	5.50E+04	5.54E+04	J/kg
$\mathbf{h_{out}}$	3.79E+05	3.06E+06	3.13E+06	3.08E+06	J/kg
$\mathbf{q_{extracted}}$	**44.63**	**334.95**	**353.04**	**418.36**	kW_{th}

The results at N3, N5, N8, and N8' are qualitatively and quantitatively consistent. As expected, the extracted energy from the exhaust gases increased as the energy content of the exhaust gases increased (i.e., for higher notch settings). Specifically, at N3 the extracted thermal energy by the $HiPHEX_{st}$ is 44.6 kW_{th}. Higher notch settings result in higher $q_{extracted}$. The maximum extracted energy recorded was at Notch 8,' when an increased mass of working fluid was delivered to the heat exchanger inlet. Note that for N8 the mass-flow-rate is 0.115 kg/s, whereas in N8' (higher mass-flow-rate) it is 0.138 kg/s, which corresponds to a 20 percent increase. A 20 percent increase in the mass-flow-rate at N8 conditions corresponds to an 18.5 percent increase in the extracted power. This also indicates that the HiPHEX$_{st\ LD}$ can be further optimized.

2.6 Low-density HiPHEX$_{st}$ Effectiveness and Optimization

In this project, the least densely packed HiPHEX$_{st,LD}$ configuration was tested to ensure that the retrofitted HiPHEX$_{st}$ would not negatively impact the locomotive ICE performance. However, test results outperformed the simulations, showing negligible backpressure on the gas side at N8 when the heat exchanger was tested dry (0.36 PSI, 0.025 bar), and there was zero backpressure when tested with the working fluid flowing through it.

To increase the extraction of thermal power from the locomotive stack, the HiPHEX$_{st}$ can be configured with a more densely packed tube core. This analysis aims at estimating the extractable thermal energy from a densely packed HiPHEX$_{st,HD}$.

Table 5 compares the results of SWRI to those retrieved from the tested HiPHEX$_{st,LD}$ retrofitted locomotive. Generally, the exhaust gas temperature measurements between the two data sources agree very well (< 5% discrepancy). The exhaust gas mass-flow-rate that was calculated from the HiPHEX$_{st,LD}$ retrofitted locomotive data can be considered as the reference amount of flow actually going through the heat exchanger.

Table 5. m$_{exh}$ and T$_{exh}$ measured by SwRI and from test results

	SwRI (Fritz, S. G., 2013)			**Test Results**	
	***m* exhausts [kg/s]**	**T exhaust stack [°C]**		***m* exhausts [kg/s]**	**T exhaust stack [°C]**
Notch 3	1.72	384.15		0.158	395
Notch 5	3.84	389.15		2.127	394
Notch 8	6.85	409.15		3.049	389
Notch 8’	6.85	409.15		3.580	390

As shown in Table 5, by comparing the mass-flow-rate data, the actual flow of exhaust gases flowing through the heat exchanger is consistently lower than the one measured by SwRI—through the entire exhaust stack—indicating that a non-negligible portion of the exhaust gases traveled through the HiPHEX$_{st}$ venting sections (see Figure 19).

As discussed, the venting sections were conservatively included to minimize potential EG$_{BP}$ generation possibly induced by the HiPHEX$_{st,LD}$. As test results demonstrated that the HiPHEX$_{st,LD}$ does not impact gas backpressure, the venting sections can be minimized to allow for a denser HiPHEX$_{st}$ tube core—effectively extending the heat exchanger surface area.

By increasing the mass-flow-rate of the working fluid, the allowable extractable energy of the high-density, with no venting, HiPHEX$_{st\ HD}$ can be determined. This analysis was performed for the conditions measured at Notch 5 and Notch 8.’ Table 6 compares the extracted thermal energy by the tested (low-density) HiPHEX$_{st}$ with exhaust gas venting features, and the maximum amount of extractable thermal energy from a high-density HiPHEX$_{st}$ occupying the whole available exhaust stack volume (no exhaust gas venting).

Table 6. $HiPHEX_{st\ LD}$ vs. $HiPHEX_{st\ HD}$ energy extraction

	m water Test [kg/s]	*m* water MAX* [kg/s]	$q_{extracted}$ Test [kW_{th}]	$q_{extracted}$ MAX* [kW_{th}]
Notch 5	0.111	**0.320**	335	**963**
Notch 8'	0.138	**0.500**	418	**1,510**

Accordingly, at Notch 5, the mass-flow-rate of the working fluid increases three-fold to achieve the same temperature difference. Proportionally, the extracted power increases from 335 kW_{th} to 963 kW_{th}. Similarly, at Notch 8,' the mass-flow-rate of the working fluid increases in excess of 3.5 times, leading to 1,510 kW_{th} of total energy extracted from the exhaust gases from the 418 kW_{th} value obtained from the $HiPHEX_{st\ LD}$ tested.

Overall, the results from testing indicate that the $HiPHEX_{st}$ are non-invasively retrofittable, can be configured to extract significant amounts of thermal energy from the exhaust gases, and do not impact locomotive performance under all operational conditions and under -abnormal WHRS scenarios (i.e., loss of working fluid accident scenarios).

2.6.1 Non-invasiveness, Retrofittability of Stack HiPHEX with Engine Components

As discussed in more detail in Section 2.2, the $HiPHEX_{st}$ was optimized to minimize or eliminate invasiveness when installed with locomotive engine equipment, and to ensure unimpaired locomotive operations under all normal and off-normal operational scenarios.

From a practical stand point, during testing at all notch settings, experienced locomotive operators did not "detect" the presence of the $HiPHEX_{st\ LD}$ retrofitted with the stack. Locomotive power, and all other parameters recorded by the on-board locomotive monitor, remained unaltered when the locomotive performance was compared.

Another very important result emerged from testing the $HiPHEX_{st\ LD}$ retrofitted locomotive is the verification that the OEM locomotive turbocharger performance was unaffected by the installation of the $HiPHEX_{st\ LD}$.

Figure 23 (left) shows a snap-shot of the locomotive control computer recording engine parameters, while at the same time, the $HiPHEX_{st\ LD}$ was tested.

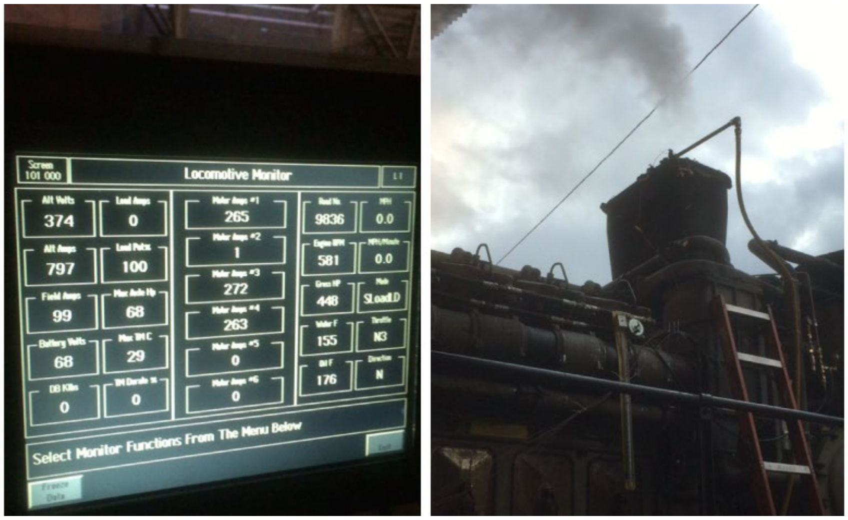

Figure 23. Locomotive monitor (left). HiPHEX$_{st}$ ejecting steam at its outlets (right)

More generally, the locomotive test shows that the HiPHEXs satisfy the requirement that the WHRS has to be "invisible" to normal locomotive operations, as failure of the WHRS equipment does not impair locomotive operations.

The HiPHEX$_{st}$ was installed onto the exhaust stack in approximately 20 minutes without interfering with engine equipment. When the HiPHEXs are configured for exhaust stack retrofitting, the installation and maintenance downtime is proportionally low. This leads to lower costs for the integration of the WHRS on the locomotive. The HiPHEX$_{st}$ can be easily maintained, cleaned, replaced and this configuration is well suited to rapidly retrofit locomotive fleets. More generally, based on experience accrued during simulation and locomotive testing activities, the HiPHEXs can be configured to non-invasively retrofit various OEM exhaust gas systems even for locomotive models with substantially different exhaust gas piping systems (i.e., see EMD locomotive manifolds and stack configurations compared to those of most GE locomotive models).

3. Fuel Saving Estimates of WHRS Retrofitted to Locomotive Stack

The WHRS coupled to HiPHEX$_{st}$ represents the simpler non-invasive retrofitting configuration. The potential fuel savings represented by the simplified WHRS will be described for configurations employing HiPHEXs retrofitted with the stack (HiPHEX$_{st}$) only.

The thermodynamic performance of the HiPHEXs, and associated WHRS, is proportional to the amount of energy extracted and the efficiency of the Rankine cycle-based WHRS. The economic performance, in terms of fuel savings, depends on the locomotive duty cycle, and the percentage of time of the year that the locomotive is in operation.

Table 7 shows the savings resulting from operating the locomotive in agreement with EPA assumptions (i.e., the locomotive is operational 60 percent of the year, and operates at averaged locomotive duty cycle or the percentage of time at given notch settings). As shown in this table, the fuel savings calculated for a low-density HiPHEX$_{st}$ is $26,605 per year factoring in the retail diesel fuel price of $2.211 (accessed January 2016, see Figure 24). The bottom portion of this table shows the fluctuation in fuel savings by factoring 2014 retail diesel fuel price of $3.730, resulting in fuel savings of $44,884 per year.

The following assumptions were made:

1. SRC efficiency was varied from 30–32 percent, in line with typical steam power plant efficiencies
2. Locomotive duty cycle was factored according to EPA assumptions. Power recovered increases for longer duty cycles at high notch settings (e.g., if Notch 8 duty cycle increases from 16.2 percent to a higher percentage, depending on locomotive actual operations)
3. The locomotive is assumed to be operational 60 percent of the year (5,256 hours per year) and power recovered and fuel savings increase proportionally with increased operation times
4. WHRS operational only for notch settings > Notch 5 (leading to underestimating the total fuel savings)
5. As the most accurate results were obtained from tests conducted at Notch 5 and Notch 8 settings, Notch 6 and 7 results were extrapolated.

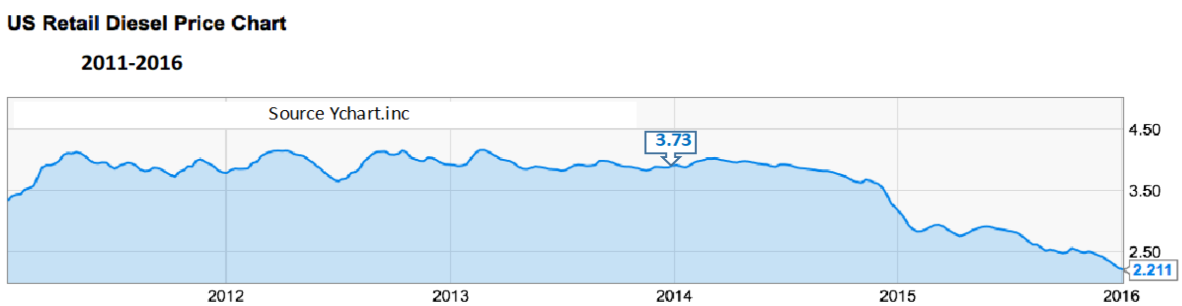

Figure 24. U.S. Energy Information Administration (EIA) retail diesel fuel price 2011–2016

Table 7. HiPHEX$_{st\ LD}$ performance, fuel savings (low-density tube core)

Phase II - Low Density High Pressure Heat Exchanger					
	Fuel Consumption	Locomotive Waste Thermal Energy Availability	HiPHEX$_{st,LD}$ Energy Extracted (Tested)	SRC Efficiency	WHRS$_{st}$ Energy Converted (Electric)
	[Kg/s]	[kW]	[kW]		
Notch 8	0.2075	3,347	418	32%	4.0%
Notch 7	0.1527	2,553	NA	31%	4.8%
Notch 6	0.1313	2,219	NA		
Notch 5	0.1067	1,798	335	30%	5.6%

	Fuel Consumption	Locomotive Duty Cycle	Fuel Price EIA Retail Diesel (01-2016)	Fuel Savings HiPHEX$_{st,\ LD}$	Pollutant Emissions Reduction
	[Gallon/yr]	[%]	[$/Gallon]	[$/yr]	[g/hp/hr]
Notch 8	198,765	16.2%	2.211	17,563	TBD
Notch 7	27,087	3.0%		2,871	TBD
Notch 6	30,279	3.9%		3,209	TBD
Notch 5	23,975	3.8%		2,963	TBD
			Total Savings	**26,605**	

Retail Diesel (2014)	HiPHEX$_{st,\ LD}$
[$/Gallon]	[$/yr]
3.730	29,629
	4,843
	5,413
	4,999
Total Savings	**44,884**

As previously mentioned the HiPHEX$_{st\ LD}$ was tested to ensure that it would not cause adverse effects on the locomotive ICE performance and operating conditions. The test results showed that the measured EG$_{BP}$ was lower than predicted. Based on the HiPHEX$_{st\ LD}$ retrofitted locomotive results, TDR will continue beyond Phase II with testing of high-density HiPHEX$_{st}$ (HiPHEX$_{st,HD}$).

Table 8 shows the increased amount of extracted energy from the stack heat exchanger (see analysis results summarized in Table 6) when the heat exchanger is configured with a high-density tube core, leading to proportionally higher fuel savings. Similarly, to the considerations and assumptions applied to the data shown in Table 7, a locomotive fitted with the HiPHEX$_{st,\ HD}$ would recover $91,308 in annual fuel savings based on the January 2016 retail diesel fuel price and $154,039 annually based on 2014 retail fuel prices.

As energy is extracted and converted, a lower amount of fuel is consumed for the same locomotive propulsion output. As a direct result, the WHRS proportionally reduces pollutant emissions, GHG emissions, and thermal emissions. The quantification of the economic benefits associated with WHRS-induced pollutant emission reductions is beyond the scope of Phase II. However, the ability of the WHRS to decrease GHG/pollutant emissions proportionally to the amount of energy extracted and recovered offers clear results in additional economic value, while contributing to compliance of increasingly restrictive pollutant reduction standards. The savings estimates reported in this section are only indicative.

Table 8. HiPHEX$_{st\ HD}$ performance, fuel savings (high density tube core)

Phase III - High Density High Pressure Heat Exchanger					
	Fuel Consumption	Locomotive Waste Thermal Energy Availability	HiPHEX$_{st\ HD}$ Energy Extracted (projected)	SRC Efficiency	WHRS$_{st\ HD}$ Energy Converted (Electric)
	[Kg/s]	[kW]	[kW]		
Notch 8	0.2075	3,347	1,510	32%	14.4%
Notch 7	0.1527	2,553	NA	31%	15.3%
Notch 6	0.1313	2,219	NA		
Notch 5	0.1067	1,798	963	30%	16.1%
	Fuel Consumption	Locomotive Duty Cycle	Fuel Price EIA Retail Diesel (01-2016)	Fuel Savings HiPHEX$_{st\ HD}$	Pollutant Emissions Reduction
	[Gallon/yr]	[%]	[$/Gallon]	[$/yr]	[g/hp/hr]
Notch 8	198,765	16.2%	2.211	63,446	TBD
Notch 7	27,087	3.0%		9,135	TBD
Notch 6	30,279	3.9%		10,211	TBD
Notch 5	23,975	3.8%		8,517	TBD
			Total Savings	**91,308**	

Retail Diesel (2014)	HiPHEX$_{st,\ HD}$
[$/Gallon]	[$/yr]
3.730	107,034
	15,410
	17,226
	14,369
Total Savings	**154,039**

4. Conclusion

The three-major qualitative and quantitative conclusions drawn from the analyses, the simulations and locomotive tests can be summarized as follows:

1. The HiPHEX$_{st}$ (stack configuration) performance indicates that a significant amount of energy can be captured from the otherwise wasted exhaust gases thermal energy, even if the energy capture occurs at the discharge of the turbocharger, thus avoiding constraints related to turbocharger performance.
2. The HiPHEX$_{st}$ does not influence the operation of the locomotive engine, therefore it achieves the non-invasive retrofittable, reversible product enabling WHRS deployment for locomotive applications.
3. The HiPHEX$_{st}$ installation involves a few easy steps, can easily be mounted and dismounted from the locomotive's stack, therefore allowing for low-cost installation and low down-times during maintenance.

The research successfully demonstrated that a significant amount of thermal energy can be extracted from the exhaust stack of the locomotive, thus bypassing the exhaust gas manifolds and turbocharger, even though this represents gases with a lower energy content when compared to the gases in the manifolds. To maximize the recoverable power, thermal energy can also be extracted from the manifolds pre-turbocharger, in a measure that does not affect turbocharger performance. The study performed by MTU (Naber, J., Johnson, J., Nelson, D., and Latautala, P., 2014) showed that thermodynamic restrictions imposed by the OEM turbocharger performance allow to extract only a fraction (i.e., 12 percent for the particular locomotive engine tested) of the total energy of the exhaust gases prior to their expansion via turbocharger.

When the HiPHEXs are configured to retrofit only the exhaust stack, the WHRS becomes simpler, safer (less tubing connecting equipment across the locomotive real estate), more reliable and there is no impact on the engine's performance even under worst case scenarios.

There is no limit in the amount of energy that can be extracted from the exhaust gas flowing through the exhaust stack as the locomotive engine and turbocharger (upstream of the energy extraction) do not "see" the HiPHEX$_{st}$. For this configuration, the PCU can be positioned adjacent to the stack, which would result in very short thermal-hydraulic connections enabling a safer and higher reliability configuration. By adopting the HiPHEX$_{st}$ configuration, the installation of the WHRS would be implemented with greater ease and consequently the downtime during both installation and maintenance would be minimized.

Additional trade-off investigations between adopting a simpler less expensive WHRS installation—only the HiPHEX$_{st}$—capturing less energy, or a more complex WHRS installation relying on heat exchangers retrofitting both the manifolds and the stack are required. These investigations need to evaluate the cost-effectiveness of simpler configurations, enhanced safety and reliability for various WHRS configurations in the context of different locomotive duty cycles and return on investment.

The results from this phase of the research also highlighted the need to investigate the adoption of recently optimized engineered organic fluids as working fluids instead of water. Organic fluids support simplified (less costly) turbo-generators components as these would operate at significantly lower speeds, thus further increasing reliability.

Phase II activities demonstrated that there is high economic, safety and environmental value in capturing and converting the otherwise wasted locomotive engine thermal energy. The results of these activities also proved feasible for all the components forming the WHRS as these were matched in agreement with HiPHEXs data obtained at operational locomotive conditions.

Testing of the HiPHEXs in various configurations demonstrated feasibility and reliability of critical elements, thus paving the way to commercial deployment of locomotive-specific WHRS.

A trade-off between system simplicity (impacting cost) against extracted energy was identified and a production-ready HiPHEX configuration was selected for fleet retrofitting.

Further investigations to determine the limits represented by exhaust gas backpressure generation (under worst case scenario—dry heat exchanger) versus the maximum energy recoverable through stack high-density HiPHEXs are required. These analyses should be performed including the option of utilizing an organic fluid for final conversion of the captured energy into electricity. Adoption of an engineered working fluid would simplify and increase turbo-generator components reliability, while reducing the overall WHRS cost.

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Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AFR	Air-Fuel Ratio
AC	Alternate Current
AAR	Association of American Railroads
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
$\dot{W}_c$	Compressor Work
CAN	Controller Area Network
DC	Direct Current
EMD	Electro-Motive Diesel
EG_{BP}	Exhaust Gas Backpressure
FMECA	Failure Mode and Effect Criticality
FRA	Federal Railroad Administration
FSLS	Full Scale Locomotive Simulator
GHG	Greenhouse Gases
$\dot{Q}_{HiPHEX}$	Heat Exchanger Heat Extraction
$HiPHEX_{st\ HD}$	High-density stack HiPHEXs
$HiPHEX_{man}$	HiPHEXs manifolds
HPC	High-Power Controllers
HiPHEXs	High Pressure Heat Exchangers
IFR	In-Flow Radial
IDEA	Innovations Deserving Exploratory Analysis
ICE	Internal Combustion Engines
LPG	Liquid Petroleum Gas
$HiPHEX_{st\ LD}$	Low-density Stack HiPHEXs
LPC	Lower Power Faster Generator-Motor Controller
MATLAB	Matrix Laboratory
MTU	Michigan Technological University
N1-N8	Notch 1 to Notch 8 (more settings)
ORC	Organic Rankine Cycle

ACRONYMS	EXPLANATION
OEM	Original Equipment Manufacturer
PCU	Power Conversion Unit
PDP	Positive Displacement Pump
PCB	Printed Circuit Board
STHE	Shell and Tube Heat Exchangers
16-out-of-16	Sixteen-out-of-sixteen Cylinders
SwRI	Southwest Research Institute
$HiPHEX_{st}$	Stack HiPHEXs
SRC	Steam Rankine Cycle
T-S	Temperature-Entropy
TDR	ThermaDynamics Rail LLC
TDR	Transportation Research Board
TTCI	Transportation Technology Center Inc.
2-out-of-16	Two-Out-of-Sixteen Cylinders
$\dot{W}_T$	Turbine Work
WHRS	Waste Heat Recovery Systems
WF_{BP}	Working Fluid Backpressure
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency