

**Innovations Deserving
Exploratory Analysis Programs**

Transit IDEA Program

**Advanced Locomotive Exhaust Gas Simulator to Fine-Tune
Energy Recovery and Conversion Systems**

Final Research Report
for Transit IDEA Project 81

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Acronyms and Notes

DR	ThermaDynamics Rail LLC
WHRS	Waste Heat Recovery Systems
IDEA Program TRANSIT-67	Project TR67 or TR67
IDEA Program TRANSIT-81	Project TR81 or TR81
High-Pressure Heat Exchangers	HiPHEX
ECC	Extended Combustion Chamber
CFD	Computational Fluid Dynamics
PCU	Power Conversion Unit
EGMs	Exhaust Gas Manifolds
GE	General Electric
CAD	Computer Aided Design
MW	Mega-Watt
kW	Kilo-Watt
TC	Thermocouple
DAQ	Data Acquisition System
EES	Engineering Equation Solver (software)
EMD	Electro-Motive Division
SW	SoildWorks (software)
SOW	Statement of Work
PT	Pressure Transducers
PLC	Programmable Logic Controller

Thermodynamic main parameters

Q	Extracted energy
$P_{subscript}$	Pressure
$T_{subscript}$	Temperature
$m_{subscript}$	Mass-flow-rate
$AFR_{subscript}$	Air-to-Fuel Ratio
$U_{subscript}$	Velocity

Notes

The acronyms “High-Pressure Heat Exchanger (HiPHEX)” and “Waste Heat Recovery System (WHRS)” may be used to describe both singular or multiple systems.

The term “non-invasive” is generally used to describe retrofitting assemblies and components that do not require irreversible modifications of the Original Engine Manufacturer (OEM) equipment. Thus, should the retrofitting components or equipment be uninstalled, the OEM equipment is reconfigured to operate identically as prior to the retrofitting installation.

Executive Summary

ThermaDynamics Rail (TDR) is optimizing Waste Heat Recovery Systems (WHRS) to recover and convert otherwise wasted thermal energy represented by locomotive exhaust gases and cooling fluids. The recovered energy is converted into electrical energy distributed to the locomotive traction motors and/or to locomotive electrical loads. The investigation being conducted under the Transit IDEA Project 81 (TR81) expands on the findings obtained in the technical and economic performance analysis of WHRS applied to locomotive engines executed under the Transit IDEA Project 67 (TR67). The results of TR67 confirmed technical feasibility and economic attractiveness of energy recovery and conversion components optimized for non-invasive locomotive equipment retrofitting, and indicated that 10% to 17.5% in fuel savings and pollutant emission reductions can be achieved. Project TR67's successful results opened the way to the activities conducted under TR81 dedicated to the development of a cost-effective, locomotive-scale, exhaust gas simulator to fine tune WHRS' components customized for operation at locomotive conditions. WHRS optimized for non-invasive locomotive retrofitting can reduce locomotive operating cost and support compliance of emission standards applied to old and recently manufactured locomotives.

Project TR81 accomplishments include the successful implementation of a scaled Extended Combustion Chamber (ECC) to enable low-cost testing of various High-Pressure Heat Exchangers (HiPHEX) configured to non-invasively retrofit locomotive equipment. Data collected from the ECC coupled to different HiPHEX configurations were used to increase the accuracy of computer codes to estimate the HiPHEX effectiveness when operated under various dimensional, operational, and thermodynamic constraints characteristic of different locomotive models. The locomotive scale ECC resulting from this investigation is capable of reaching in excess of 5MW of thermal energy represented by the locomotive exhaust gases.

Results indicated that the computer codes predicted the HiPHEX and the exhaust gases thermodynamic characteristics with satisfactory accuracy, thus enabling further scaling-up of the ECC to generate exhaust gases at conditions replicating actual locomotive exhaust gases at all notch settings. In one of the testing configurations, the HiPHEX was non-invasively retrofitted within the exhaust gas stack equipping a widely deployed commercial locomotive. As the heat exchangers were tested via locomotive exhaust gas simulator and in the field at maximum locomotive power for the first time, the HiPHEX were equipped with features to allow a portion of the exhaust gases to "escape" from the sides of the heat exchanger. The results confirmed that the HiPHEX induce negligible backpressure with respect to the exhaust gases flowing through the locomotive exhaust stack, even when the locomotive is operated at Notch 8 (maximum engine power) and can safely perform.

Tests enabled by the locomotive-scale exhaust gas simulator confirmed that the adoption of HiPHEX does not affect the performance of the locomotive engine as the HiPHEX do not negatively impact the performance of the turbocharger at all locomotive operating conditions. Locomotive simulator results, verified by locomotive field tests, confirmed the predictions obtained through Computational Fluid Dynamics (CFD) simulations, which accurately quantified the portions of exhaust gases bypassing the HiPHEX and venting through the side walls of the exhaust stack, thereby reducing the heat exchanger effectiveness. Test results demonstrated that even with large portions of exhaust gases bypassing the HiPHEX, approximately 590 kW can be recovered from a 4,400 HP locomotive engine operated at Notch 8. At these conditions, CFD simulations confirmed by test results indicated that the exhaust gases pressure loss caused by the HiPHEX reached approximately 20 millibar (0.29 psi), which is negligible and lower than the backpressure normally produced by the screen normally equipping the locomotive stack. Due to the exhaust gas bypass features, the HiPHEX effectiveness was 30% (approximately one-third of the total thermal energy represented by the locomotive exhaust gases flowing through the exhaust stack). Based on these results, CFD simulations indicated that by decreasing the spacing between the exhaust gas stack inner walls and the HiPHEX components, the HiPHEX effectiveness can be increased to approximately 66%, corresponding to a total recovered energy of 1,200 kW (1.2 MW). This confirms that substantial fuel savings and pollutant emissions reductions can be achieved via WHRS optimized for non-invasive retrofitting of old and new locomotives, without impairing locomotive operations at all notch settings.

Overall, the locomotive exhaust gas simulator developed under TR81 can reliably and repeatedly produce exhaust gases with energy content equivalent to locomotives dissipating up to 5 MW of thermal energy. The locomotive exhaust gas simulator performed as projected by enabling low-cost, full-scale prolonged testing and fine-tuning of various WHRS components. Thanks to project TR81, TDRs as well as third parties developing WHRS' components can fine tune various components by testing them at variable power ratings replicating locomotive exhaust gas conditions from low notch settings to Notch 8 in a controlled laboratory environment.

Low-cost testing of WHRS components at actual locomotive-scale provides validation data to support further optimization of these components and accelerates deployment of these technologies, which have the greatest potential to effectively decrease fuel consumption and operating cost, while reducing pollutant emissions and supporting compliance of pollutant reduction standards applied to old and new locomotives.

Project TR81’s impact on practice manifests as improved transit capital operating efficiency, while protecting public safety and the environment, in addition to promoting energy independence.

TDR plans to continue the optimization of the locomotive exhaust gas simulator to execute long-term reliability and endurance testing of WHRS components and to further investigate features targeting more aggressive pollutant emissions reduction methodologies enabled by the retrofitting of WHRS with locomotive equipment.

Background

The HiPHEX are scalable, non-invasive, specialized heat exchangers designed to reliably operate when exposed to streams of high-temperature fluids (i.e., exhaust gases). Figure 1 shows TDR’s waste heat recovery closed-loop Rankine power cycle diagram, wherein specialized heat exchangers are coupled to a positive displacement pump on the “cold side” and to a Power Conversion Unit (PCU) on the “hot side.” The power conversion unit is formed by a turbine expander directly coupled to an electric generator.

As shown in Figure 1, a working fluid (i.e., water or an organic fluid) is pressurized by means of a high-pressure pump from a reservoir. Once pressurized, the working fluid flows into the HiPHEX whose surfaces are exposed to the exhaust gases generated by the locomotive diesel engine. The objective of the HiPHEX is to transfer thermal energy from the exhaust gases to the working fluid circulating within the heat exchanger to increase its energy content. As energy from the exhaust gases is transferred within the HiPHEX, the working fluid changes its thermodynamic state to reach superheated vapor properties. At these conditions, the working fluid expands in a turbine coupled to an electric generator. The electricity produced by the generator is then electronically conditioned, distributed to the locomotive power train (i.e., traction motors, electric loads), and, in some configurations, converted into pollutant-free propulsion power, thereby reducing fuel consumption and emissions proportionally to the engine duty cycle.

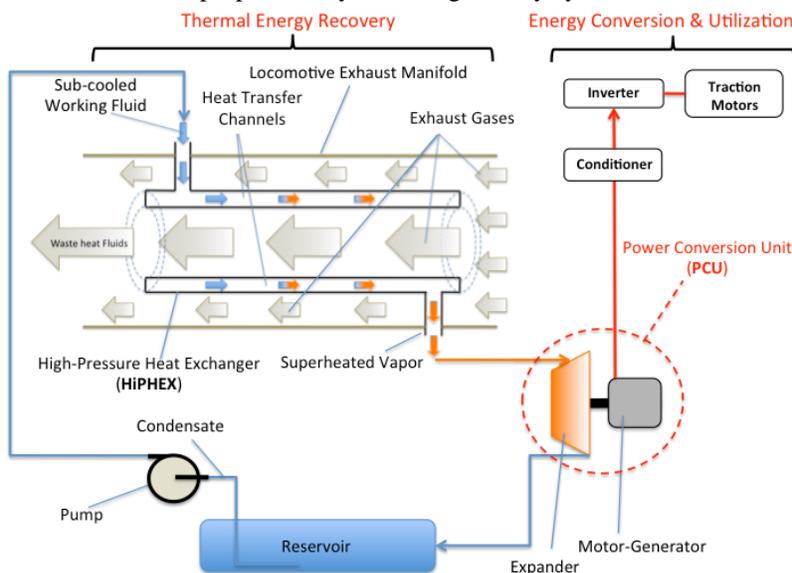


Figure 1: Closed loop cycle of ThermoDynamics Rail components.

To complete the closed-loop power cycle of the waste heat recovery system, low-energy vapor at the turbine discharge is condensed through thermal exchange with a recuperator and condenser heat exchangers (not shown in Figure 1) prior to accumulating back into the reservoir.

Tasks Performed in Stage I

Project TR81 is divided into two stages. The main activities of TR81 Stage I addressed the design, manufacturing, assembly, and testing of an ECC to closely simulate the behavior of locomotive exhaust gases and to validate computer codes.

Stage I Tasks

Stage I groups a total of nine tasks addressing the activities required to support the operations of an advanced locomotive simulator and the validation of a dedicated computer code to project the performance of various HiPHEX configurations and their performance when subjected to different streams of exhaust gases produced by locomotive engines. Stage I tasks are summarized as follows:

- T81-1: Design and Manufacturing of Extended Combustion Chamber (ECC)
- T81-2: Electric Air Fan and Fuel Burners Installation (to support the ECC)
- T81-3: First Generation HiPHEX Optimization and Testing on GE Dash-9 Exhaust Gas Manifolds (EGMs)
- T81-4: First Generation HiPHEX Optimization and Testing on EMD 645 EGMs
- T81-5: Optimization of EES-based Computer Codes
- T81-6: Development of Computer Codes for Detailed Simulation of HiPHEX Performance
- T81-7: Second Generation HiPHEX Optimization
- T81-8: Testing of Second Generation HiPHEX Design
- T81-9: General Accounting and Stage I reporting

Task T81-1: Design and Manufacturing of Extended Combustion Chamber (ECC)

Task T81-1 involved the design and manufacturing of the ECC based on testing data and design requirements and emerged from completing T67 Stage II. The ECC was designed with the following main objectives:

1. Provide a controlled scaled combustion system with an extended volume and increased residence time for atomized fuel and air to properly mix and fully burn; thus, simulating exhaust gases as if they were generated by locomotive engines.
2. Enable the proportional scaling of the ECC to support design and manufacturing of a full-scale (locomotive-scale) ECC to simulate exhaust gases generated by different locomotive models when operated at various duty-cycles.

Task T81-1 included design and manufacturing of an intake air compressor to supply a controlled quantity of air to the ECC. During testing of the “first-generation” combustion chamber, developed as part of T67, poor combustion was observed. To briefly recap T67 findings, Figure 2 shows the flame resulting from mixing and igniting diesel fuel and air at the outlet of General Electric (GE) Dash-9 locomotive exhaust manifolds non-invasively retrofitted with a combustion chamber developed as part of T67. In this first configuration, the combustion chamber was formed by modified oil burners coupled in a manner that the exhaust gases discharged directly inside a series of modular locomotive exhaust gas manifolds (EGMs). Figure 2 shows one of the oil burners coupled to the combustion chamber. From analysis conducted under T67, the flame characteristics, temperature, and color indicated poor combustion mainly caused by un-optimized coupling of the combustion chamber with the locomotive manifolds. Specifically, the main problems identified were:

- Poor fuel combustion and burnout due to insufficient combustion chamber volume.
- Delayed flame forming downstream of the locomotive EGMs where the HiPHEX are located, leading to exhaust gas temperatures in excess of 1,000°C (1,832°F). Under these conditions, the exhaust gas temperature values were too high compared with those produced by locomotive operations. Accurate testing was not achievable as the flame reached the highest intensity in the regions where the HiPHEX were located.
- Limited mixing of air mass-flow-rate (kilogram/second or pound/second) to be bled and mixed prior to entering the EGMs.
- Limited ability to tailor data and scale combustion parameters to closely mimic duty cycles corresponding to various locomotive models.

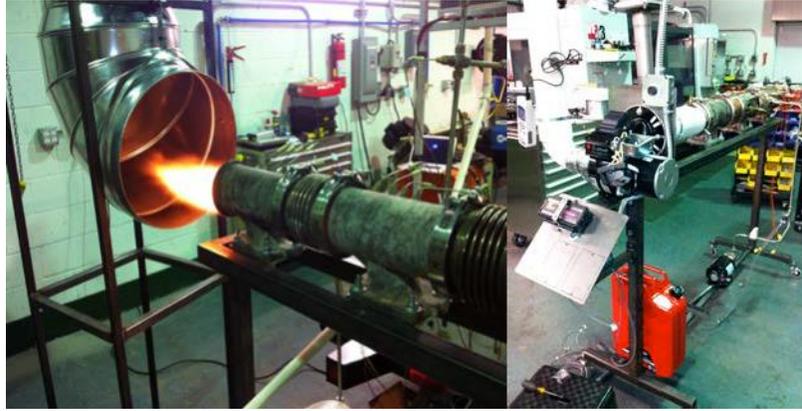


Figure 2: TRANSIT-67 Exhaust gassimulator.

Based on lessons learned from T67, task T81-1 was dedicated to the design and manufacturing of an ECC with higher control of the combustion parameters. The first step in the configuration of the ECC was dedicated to performing a combustion similarity analysis to study a portion of exhaust gases with the same thermodynamic conditions of exhaust gases sampled from a line-haul locomotive. The locomotive utilized as reference was the GE Dash 9 locomotive model providing 4,400 HP at Notch 8 (maximum power). Subsequently, the combustion similarity analysis was used to support the optimization of the ECC and to enable scaling of the combustion system to produce exhaust gas mass-flow-rates at locomotive scale.

Table 1 summarizes GE Dash-9 locomotive exhaust gas parameters at different locomotive notch settings. These data were used as reference for the combustion similarity analysis. In this table, T_{exh} represents the temperature of the exhaust gases in the EGMs prior to entering the locomotive turbocharger; $m_{fuel,loc}$ is the locomotive fuel consumption, AFR_{loc} is the locomotive Air-to-Fuel Ratio, and $m_{exh,loc}$ is the mass-flow-rate of the exhaust gases as generated by the referenced locomotive diesel engine. When considering the total energy content represented by the fuel consumed to operate locomotives, only a portion of the fuel energy is actually transformed into locomotive propulsion (approximately 30%–35% of the total fuel energy). The remaining energy is transported by the exhaust gases and locomotive cooling system and lost to the environment. Therefore, when considering the total energy availability for the purpose of waste heat recovery, only a portion of the total fuel energy can be captured. A diesel burner with a 5 gal/h capacity, as the one used for the execution of T67, was selected as the energy source for the analysis to support optimization of the ECC. The main objective of the similarity analysis was to determine the necessary mass-flow-rate of air to be bled in the simulator’s combustion chamber to obtain exhaust gases temperatures at locomotive-scale mass-flow-rates, and to closely mimic the exhaust gases sampled in the EGMs of a GE Dash-9 locomotive.

Notch	T_{exh} °C	$m_{fuel,loc}$ kJ/s	AFR_{loc} kg/s	$m_{exh,loc}$ kg/s
8	608	0.208	32	6.85
7	537	0.153	35	5.49
6	511	0.131	35.4	4.78
5	510	0.107	35	3.84
4	512	0.0752	32.4	2.51
3	508	0.054	30.8	1.72
2	360	0.0206	39.1	0.83
1	260	0.00966	59.5	0.59

Table 1: GE Dash-9 exhaust gas test measurements

Table 2 shows the mass-flow-rates of cold air ($m_{air, simu}$) required to mimic the thermodynamic conditions found in the referenced locomotive exhaust manifolds.

Notch	T_{exh} °C	AFR_{simu} --	$m_{air,simu}$ kg/s	$m_{air,simu}$ CFM
8	608	53.11	0.61	1,300
7	537	60.42	0.43	910
6	511	64.44	0.29	612
5	509	64.44	0.29	606
4	512	64.44	0.29	606
3	508	65.02	0.29	606
2	360	96.67	0.27	569
1	260	138.1	0.24	417

Table 2: Scaled ECC exhaust gases thermodynamic properties

The scaled ECC utilized a 55-gallon oil barrel to support burners and compressor components while containing the refractory elements forming the combustion chamber. As shown in Figure 3, a metal barrel was utilized to structurally support the refractory materials needed to insulate the scaled ECC. The refractory materials selected were capable of withstanding temperatures in excess of 1,600°C (2,912°F) and the metal barrel inner walls were used to support a low-cost, ceramic-lined, cylindrical combustion chamber. Figure 3 shows the CAD, manufacturing, and assembly stages developed for the implementation of the ECC. The scaled ECC was also equipped with two low-temperature air and fuel inlet ports configured to support high-pressure fuel injectors, and one high-temperature outlet for a ceramic coupler to hydraulically mate and seal the locomotive EGMs (as shown in Task T81-2). These activities concluded T81-1 and provided information needed to scale-up the ECC to locomotive-scale.



Figure 3: Transit-81 Scaled Extended Combustion Chamber.

Task T81-2: Electric air fan and fuel burners installation

The air source coupled to the ECC was supplied by electrically driven power fans that provided pressurized air for fuel mixing. This air source was also utilized to cool down the exhaust gases by “injecting air” during combustion. Control of the injected air mass-flow-rate was achieved through valves adjusted by monitoring the air speed via anemometer probes. In this manner, the AFR observed in the diesel-electric locomotive operated at various notch settings and used as reference (see Table 2) was replicated. The electrically driven power fans were electronically controlled to compensate for the backpressure generated within the combustion chamber and for the additional backpressure generated by the locomotive EGMs. Additionally, on the “cold side” of the ECC, through the inlet ports, high-pressure fuel lines were coupled to a fuel pump that could support multiple burners to obtain a wider range of fuel mass-flow-rates, and proportional thermal power in the resulting exhaust gases. To execute this task, gas data at the outlet of the ECC, at various AFRs and fuel mass-flow-rates, were sampled in real time. Before retrofitting the ECC to a set of the GE Dash-9 EGMs, preliminary qualitative experimental measurements were performed to ensure that complete fuel combustion was obtained. Figure 4 (left) shows the scaled ECC in operation prior to being retrofitted to the GE Dash 9 EGMs. Figure 4 (left) also shows that the great majority of the combustion processes occur within the combustion chamber itself; thus, the resulting exhaust gases are properly conditioned prior to inletting the locomotive manifolds shown in Figure 4 (right). These activities supported scaling of the ECC for locomotive-scale HiPHEX testing.

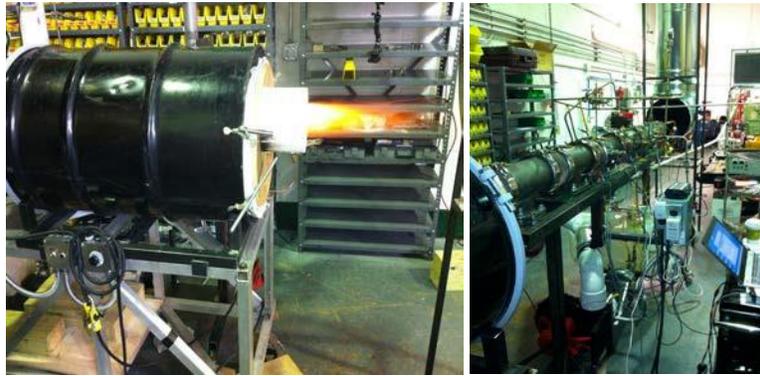


Figure 4: (left) Operating ECC and (right) Locomotive EGMs fitted to the ECC.

Figure 5 shows the scaled ECC with the air-injection system coupled to locomotive EGMs during calibration testing.

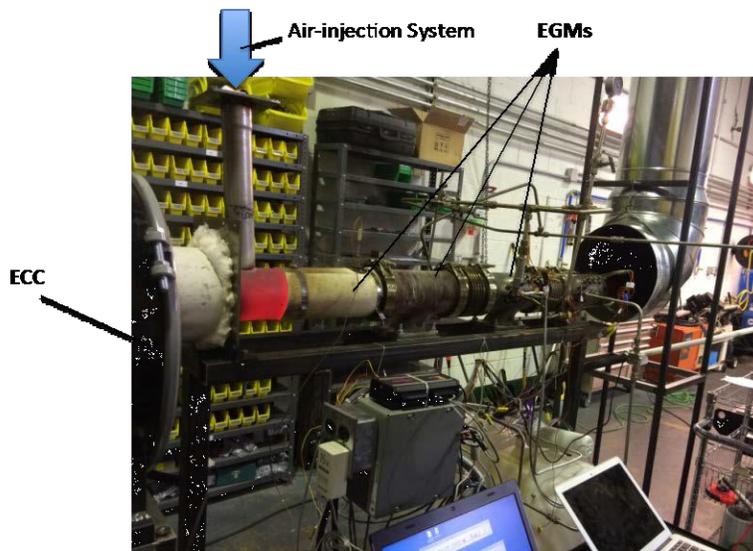


Figure 5: ECC coupled to exhaust gas manifolds in operation.

The activities conducted in Tasks T81-1 and T81-2 enabled fine-tuning of the parameters needed to design a locomotive-scale ECC capable of providing exhaust-gases with adjustable mass-flow-rates and energy content to mimic locomotive operations at various duty cycles. The schematic provided in Figure 6 illustrates the basic features of the scaled ECC and those represented by a combustion chamber producing exhaust gases at actual locomotive conditions (locomotive-scale ECC). As it will be shown in detail in the following tasks, the scaled ECC produced exhaust gases with energy contents in the kW range and utilized “off-the-shelf” low-cost compressors. The ECC developed for the locomotive simulator required multiple compressor stages to produce exhaust gases with substantially larger mass-flow-rates and energy contents in the megawatt range as produced by locomotive engines.

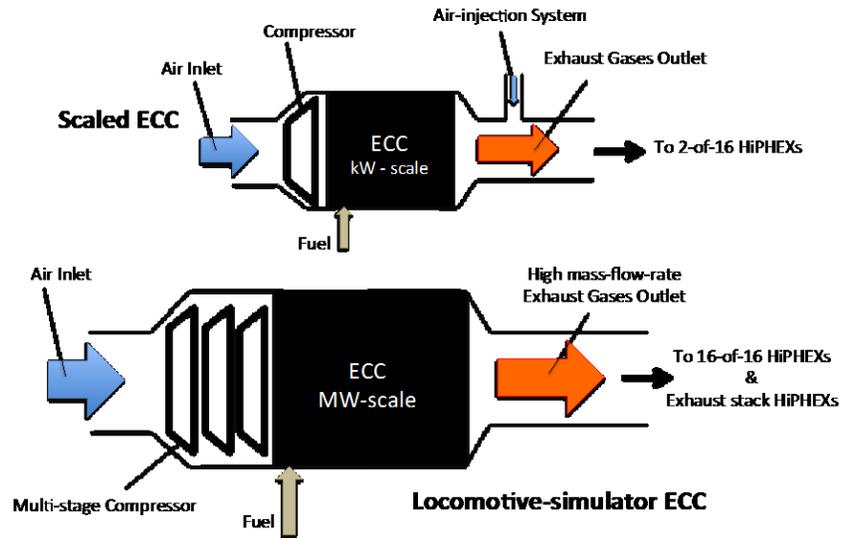


Figure 6: kW-to-MW ECC scaling.

Task T81-3: First generation HiPHEX optimization and testing on GE Dash-9 EGMs

Coupling of 8 x GE Dash 9 EGMs to the ECC corresponds to simulating the exhaust gases produced by 8 of 16 cylinders for this particular locomotive engine. Based on the results obtained through T67, the first generation of HiPHEX was fitted to 8 x GE-Dash 9 modular EGMs. Figure 7 illustrates a simplified schematic of the locomotive 8 x EGMs wherein two of the EGMs were retrofitted with HiPHEX 1 and HiPHEX 2 and instrumentation. To fully characterize the working fluid and exhaust gases temperature profiles, the EGMs and HiPHEX were fitted with K-type thermocouples (TCs).

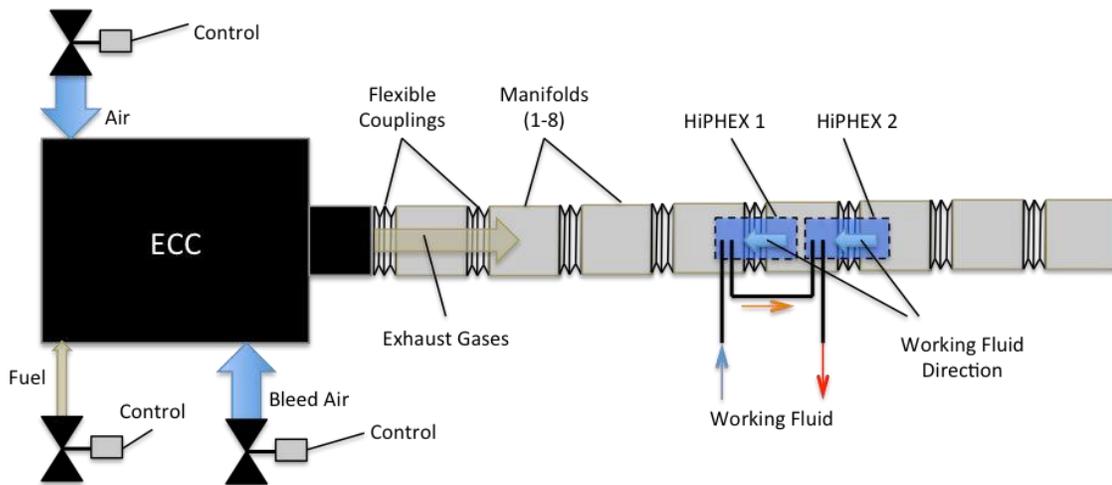


Figure 7: T67 locomotive EGMs with HiPHEX non-invasive retrofit.

The description and location of the TCs are outlined in Table 3. In this configuration, the working fluid temperature was measured at the inlet of the HiPHEX ($T_{w,in}$), in the middle between the two HiPHEX ($T_{w,mid}$) and at the outlet of the HiPHEX ($T_{w,out}$). The exhaust gas temperatures were measured at the outlet of the EGM ($T_{g,f}$) opposite to the ECC coupling flange, at the outlet of both HiPHEX (T_0, T_1, T_2), on the outside surface between the HiPHEX and the manifold wall (T_3, T_4), between the two HiPHEX (T_5, T_6), and at the inlet of the HiPHEX post ECC combustion chamber ($T_{g,in}$). The mass-flow-rate of the water (m_w) was measured by an analog-to-digital flow meter, and the water pressure (P_w) by a pressure transducer that supplied real-time digital information to a Data logging and Acquisition System (DAQ). Finally, the air-flow-rate (via U_{air}) utilized to estimate the total mass-flow-rate of the exhaust gases was measured by utilizing a hot wire anemometer.

Name	Description
$T_{g,f}$	Temperature of exhaust gases exiting EGM—manifold 6
T_0	Last TC inside of manifold post heat exchangers—manifold 5
T_1	Second TC inside manifold post heat exchangers—manifold 5
T_2	First TC inside manifold post heat exchangers—manifold 5
T_3	TC on the outside surface of HiPHEX 2 (inlet side of water)
T_4	TC on the outside surface of HiPHEX 2 (outlet side of water)
T_5	TC of exhaust gasses between HiPHEX 1 and HiPHEX 2
T_6	TC of exhaust gasses between HiPHEX 1 and HiPHEX 2
T_7	TC on the outside surface of HiPHEX 1 (outlet side of water from HiPHEX 2)
$T_{g,in}$	TC of the exhaust gas entering the HiPHEX, after combustion chamber
$T_{w,in}$	TC of water going into the heat exchangers
$T_{w,out}$	TC of water at the outlet of the two heat exchangers
$T_{w,mid}$	TC of water between HiPHEX 1 and HiPHEX 2
m_w	Mass flow of water
P_w	Pressure of the water
U_{air}	Inlet air velocity, which gives a measure of the exhaust gas mass-flow-rate

Table 3: Name and description of sensors on the EGMs and HiPHEX

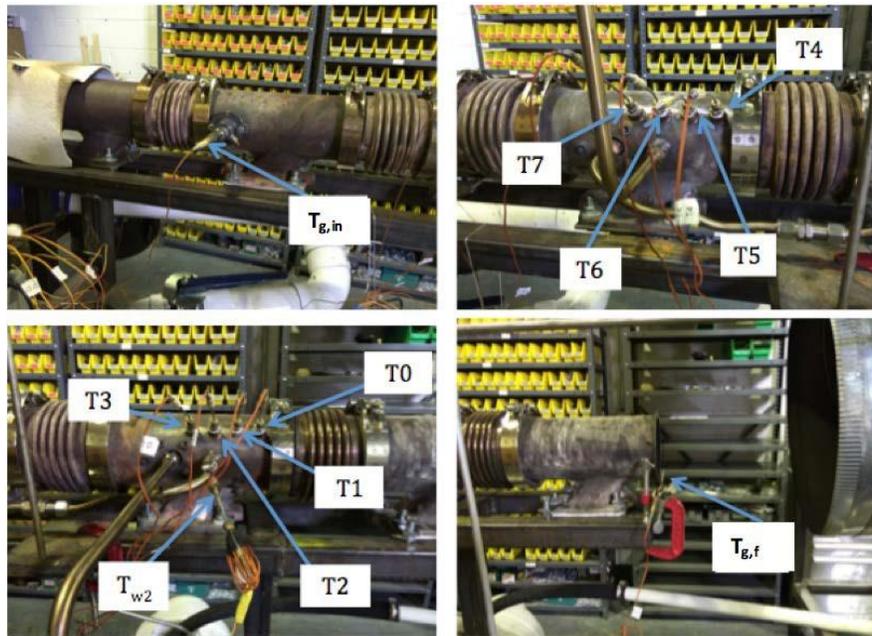


Figure 8: Thermocouple locations on EGMs and retrofitted HiPHEX.

Testing was performed on the retrofitted HiPHEX using the exhaust gases produced by the scaled ECC. In this test, the working fluid was represented by water pumped through the HiPHEX in a counterflow configuration with pressure and mass-flow-rates varied to obtain superheated vapor at the outlet of the second HiPHEX. Measurements were recorded and the results are discussed in the following analyses.

The exhaust gas temperature measurements varied between 605°C and 650°C, which is comparable to the temperatures observed in the GE Dash-9 locomotive at Notch 8 conditions (608°C). This validates the combustion similarity analysis implemented in Task T81-1, and shows that the scaled ECC can replicate the exhaust gases characteristics as if the exhaust gases were produced by the locomotive engine. Figure 9 depicts the variation of mass-flow-rate and pressure of the working fluid.

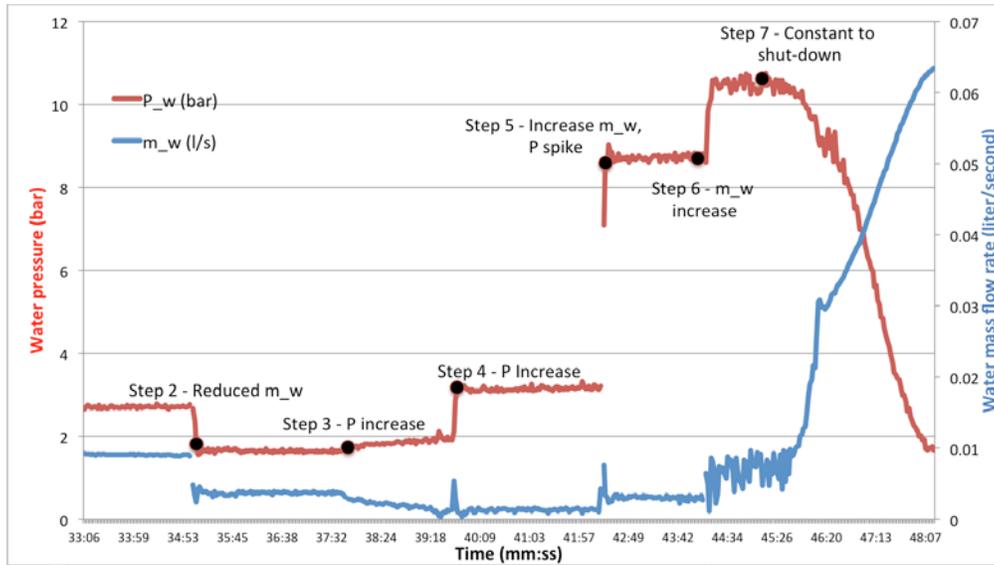


Figure 9: Mass-flow-rate of water and pressure of water at the various test stage.

Figure 10 shows the corresponding working fluid temperature change at the outlet of the HiPHEX. Note that by increasing the pressure of the working fluid at a given mass-flow-rate, the temperature at the heat exchanger outlet increases as expected. At a given pressure, as the mass-flow-rate of the working fluid increases, the outlet temperature drops correspondingly. Throughout the test the working fluid was pressurized into HiPHEX 2 inlet ($T_{w,in}$, - blue line) at the constant temperature of 30°C.

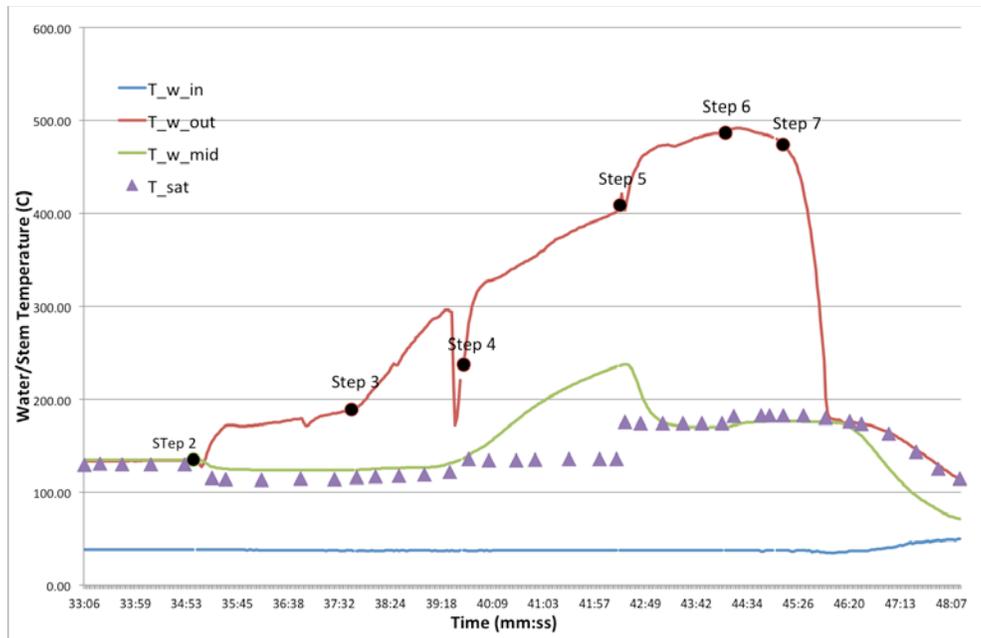


Figure 10: Water temperature at inlet ($T_{w,in}$), outlet ($T_{w,out}$), and saturation (T_{sat}).

The measurements recorded during this test were divided into six main steps, which are illustrated in Figures 9 and 10 and outlined in greater detail in Table 4.

Test Step	Change in m_w and P_w	Effect on water temperature
Start (Step1) – Step 2	Initial conditions	The working fluid (water) outlets both HiPHEX 1 and 2 as wet steam. $T_{w,mid} = T_{w,out} = T_{sat}$
Step 2 – Step 3	Mass-flow-rate (m_w) and pressure P_w are reduced	The working fluid now outlets HiPHEX 1 as superheated steam, while at the outlet of HiPHEX 2 its still wet steam. $T_{w,mid} = T_{sat}$, while $T_{w,out} > T_{sat}$
Step 3 – Step 4	The mass-flow-rate (m_w) reduced at a constant rate	The superheated steam at the outlet of HiPHEX 1 increases at a constant rate. The water remains wet steam at the outlet of HiPHEX 2.
Step 4 – Step 5	P_w is increased, while the m_w remains mostly constant	The water exits both HiPHEX 1 and 2 as superheated steam. $T_{w,mid} > T_{sat}$, while $T_{w,out} > T_{sat}$
Step 5 – Step 6	m_w increased (pressure spike)	The water leaves HiPHEX 2 as wet steam and HiPHEX 1 as superheated steam. $T_{w,mid} = T_{sat}$, while $T_{w,out} > T_{sat}$
Step 6 – Step 7	m_w highly fluctuating (pump instability)	The water leaves HiPHEX 2 as wet steam and HiPHEX 1 as superheated steam. $T_{w,mid} = T_{sat}$, while $T_{w,out} > T_{sat}$

Table 4: Summary of various test stages

Overall, T81-3 HiPHEX optimization, testing, and data collection were successfully performed by non-invasively retrofitting specialized heat exchangers with the GE Dash-9 exhaust gas manifolds. The working fluid was successfully superheated from a saturated liquid to a superheated vapor according to test steps summarized in Table 4. This task provided data that can be used to validate the EES- and MATLAB-based codes further discussed in Task 81-6.

Task T81-4: First generation HiPHEX optimization and testing on EMD 16-645 EGMs

Task T81-4 consisted of coupling the locomotive model EMD 16-645 EGMs to the ECC and retrofit first generation HiPHEX to perform tests under conditions simulating locomotive operations. This task included data analysis obtained in Task T81-3 and data obtained from Task T81-7, which was conducted in parallel to develop sets of correlations. Using these correlations, the optimal HiPHEX tube size, thickness, and orientation were selected. Accordingly, the optimized HiPHEX design for the EMD locomotive exhaust gas manifolds (EGMs) configuration consisted of arranging sets of tubes with an outer diameter that allows fitting of the largest number of tubes in the EGMs, thus enabling an overall increase in the total energy extracted from the exhaust gases. To validate the analysis a Computational Fluid Dynamic (CFD) analysis using ANSYS software was carried out. The main aim of the CFD analysis was to support HiPHEX optimization to extract the maximum amount of thermal energy from the exhaust gases without affecting the performance of the locomotive engine’s turbocharger. To this end, the flow distribution was simulated along with the temperature and pressure build-up of the exhaust gas stream in the EMD engineEGMs.

Figure 11 shows the HiPHEX configured to be non-invasively retrofitted within the EGMs (HiPHEX tube bundles are visible on the right side). In this representation, the exhaust gases inlet the manifolds past the engine’s exhaust ports from the bottom of the EGMs (red arrows) and outlet at a lower temperature from the flange coupling to the turbocharger (orange arrow). The mass-flow-rate per exhaust gas port was assumed constant and at steady-state (no time variation). This allowed for a direct comparison to the test results presented under Task 81-3. As shown in Figure 11, the working fluid inlets and outlets from the left of the computational domain by a single header (opposite to the turbo-charger flange). In this HiPHEX configuration, the tubes are bent in a manner that the working fluid flow is inverted and the flow distribution is symmetric about the plane (i.e., x-y) crossing the manifold’s axis.

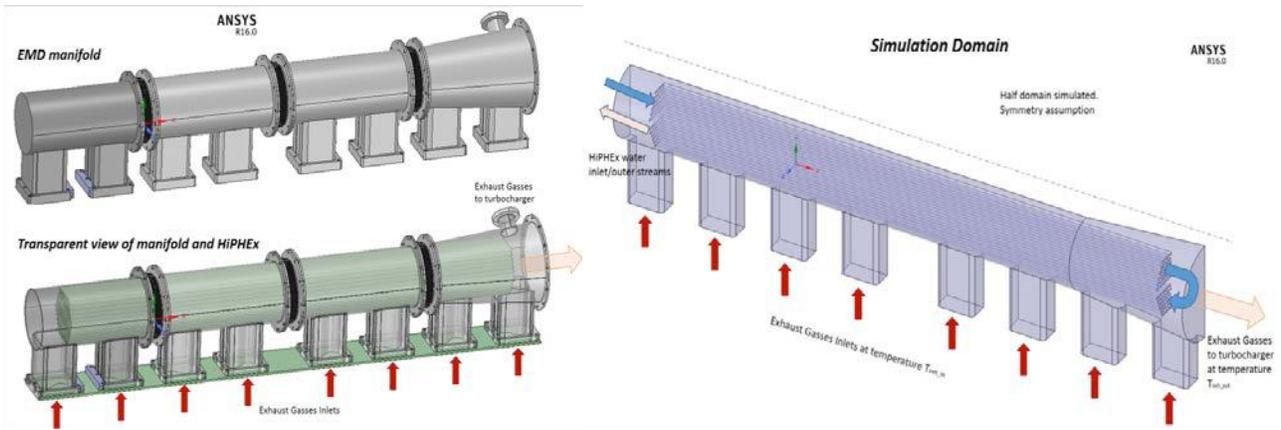


Figure 11: CADs of EMD manifolds inclusive of HiPHEX tubes.

Figure 12 shows the streamlines of the fluid in the simulation domain depicted in Figure 11. The colors represent the magnitude of the velocity vector (dark blue being the minimum, bright red the maximum). As in the EGMs configuration described in Figure 11, the exhaust gases inlet the manifolds from the bottom through the engine's exhaust gas ports (engine head). As the exhaust gases expand within the manifolds the bulk of the gases flow is forced to turn direction (rightwards) while accelerating. Note that the streamlines become denser and the velocity increases downstream as the exhaust gases inletting the manifolds from each exhaust gas port accumulate (the EMD EGMs are represented by one manifold every four cylinders). The mass-flow-rate of the exhaust gases therefore increases as they approach the turbocharger flange (right of diagrams). The recirculation region seen on the left of the left manifold (opposite to the turbocharger) suggests that the fluid mass-flow-rate in this region is low. Therefore, the amount of heat that can be extracted at this location is proportionally decreased.

For this reason, it was concluded that the far left of the manifold opposite to the turbocharger represents the optimal location for the positioning of the HiPHEX header. Additionally, the analysis highlighted that flow buffers at a certain angle are required so as to divert the exhaust gases toward the bottom portions of the manifolds, hence making the flow more uniform while increasing the effectiveness of the HiPHEX.

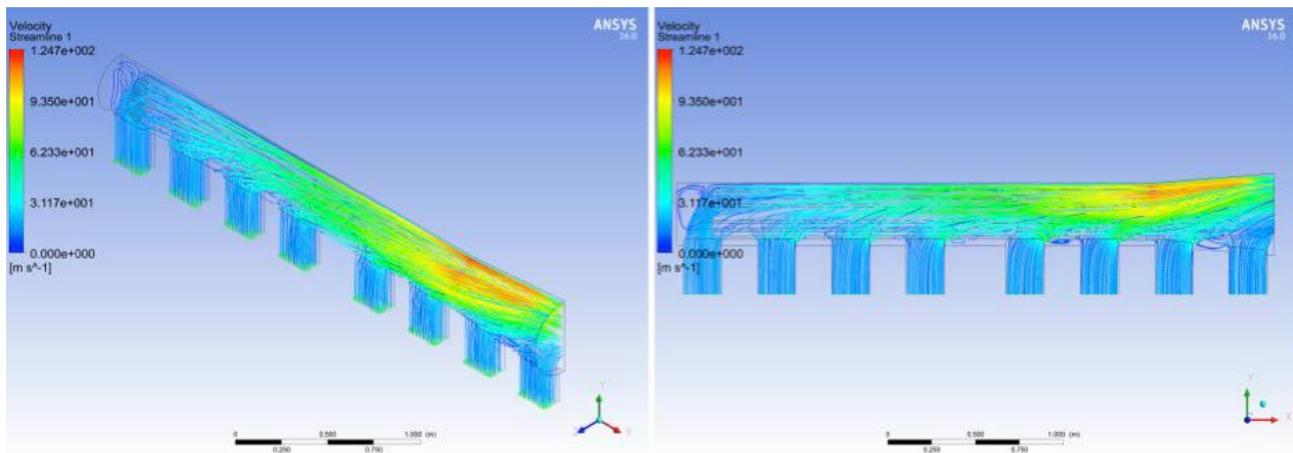


Figure 12: Exhaust gases velocity streamlines through optimized HiPHEX.

Figure 13 shows the pressure distribution in the EMD manifold (red depicts high-pressure regions and blue low-pressure regions). As expected, by inserting the HiPHEX inside the EGMs a pressure build-up develops. However, under the optimized HiPHEX tube sizing and positioning, in absolute values, the backpressure developed does not exceed 60 millibars (0.87 psi) and therefore it may be considered negligible.

This is an important conclusion as it indicates that the HiPHEX can be compliant with the “non-invasive retrofitting” and “no impact on engine operations” requirements. Note that the backpressure results were determined under the worst-case scenario corresponding to the locomotive engine operated at the highest notch setting (maximum engine power). As the

velocity of the exhaust gases is reduced (due to lower mass-flow-rates) at lower notch settings, the corresponding backpressure is also reduced.

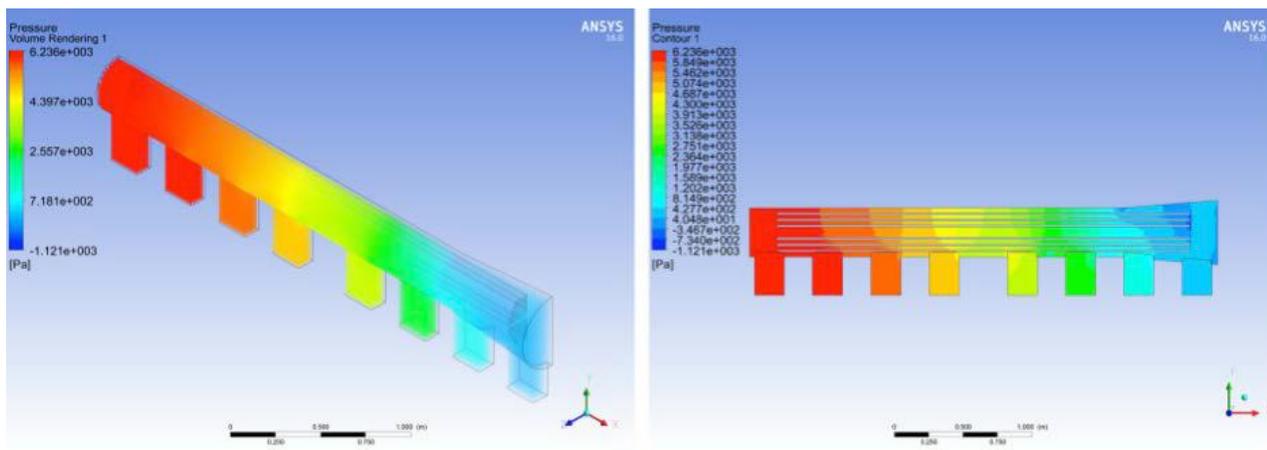


Figure 13: Pressure distribution contour plot of HiPHEX in EMD manifold.

Figure 14 shows a contour plot of the exhaust gas temperature distribution in the EMD manifolds. The high-temperature gases are cooled as a result of heat transfer with the working fluid circulating within the HiPHEX (wherein the color yellow represents the highest temperature). The exhaust gases inletting the manifolds from the exhaust gas ports closer to the turbocharger flange (right end of Figure 14 planar view) are not cooled as much as the ones generated upstream (i.e., exhaust gas ports farther away from the turbocharger). This occurs as the gases produced by the engine ports closer to the turbocharger flange are only exposed to the end portions of the HiPHEX. This also indicates that the HiPHEX could be configured to extract additional energy at these locations.

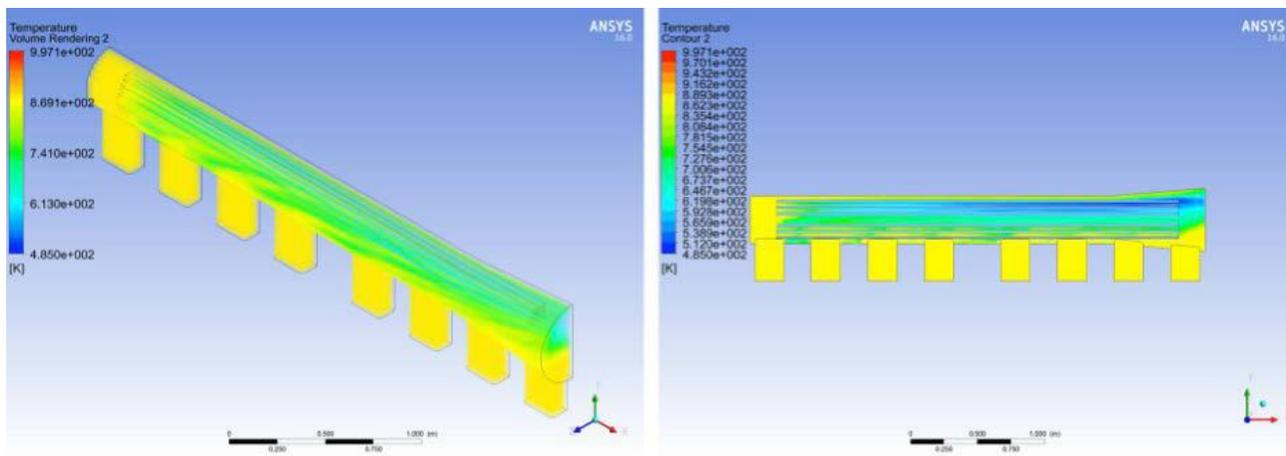


Figure 14: Temperature distribution and contour plot of EMD EGMs retrofitted with HiPHEX.

Under the conditions outlined, the optimized HiPHEX configured for a non-invasive retrofitting of the EMD manifolds can extract approximately 26% of the thermal energy in the exhaust gases. Overall, the full simulation of the HiPHEX configured for EMD engine applications in conjunction with test results outlined under Task T81-3 resulted in sets of data that supported optimization and validation of the EES-based computer code addressed in more details in Task T81-5.

Task T81-5: Optimization of EES-based computer code

Based on the completion of Tasks T81-3 and T81-4, the resulting data were used to increase the accuracy of the EES-based computer codes developed in Stage I of the T67 investigation. Task T81-5 includes the generation of non-dimensional HiPHEX design parameters and the development of heat transfer correlations. More generally, in

order to discuss the computer code optimization, the basic components forming the Rankine power cycle as part of a Waste Heat Recovery System (WHRS) illustrated in Figure 1, are briefly summarized as follows:

- High-pressure pump—pressurizing the working fluid from the condenser pressure to the working pressure.
- Hi-Pressure Heat Exchanger (HiPHEX)—transferring thermal energy from the exhaust gases to the working fluid, thereby increasing the thermal energy of the working fluid to obtain a superheated vapor.
- Expander (turbine)—matched to extract work from the working fluid equivalent to the allowed enthalpy differential (proportional to the expander pressure differential).
- Condenser—matched to condense the superheated vapor at the outlet of the turbine to a sub-cooled liquid (condensate) entering the high-pressure pump.

The thermodynamic system described is complex as it involves several interlinked variables with non-linear dependencies impacting the WHRS overall power conversion. To execute Task T81-5 the main variables that were analyzed included:

- Superheated temperature difference (DT_{sh})—defined as the working fluid superheating by the HiPHEX above the saturated vapor line.
- Expander pressure ratio ($beta$)—defined as the ratio between the pressure of the working fluid at the inlet and outlet of the turbine.
- Bottom pressure (P_{bottom})—defined as the pressure of the working fluid in the condenser.
- Mass-flow-rate of the working fluid (m_w).

For this optimization analysis the turbine efficiency η_T has been kept constant at 80%, even though turbine efficiency is dependent on the aforementioned parameters¹. The EES code developed in agreement with Task T81-5 automatically varies DT_{sh} , $beta$, P_{bottom} , and m_w and calculates a series of non-linear simultaneous equations to determine the turbine power output.

Figure 15 represents the results obtained from the EES code and shows the variation in turbine power output given different DT_{sh} , $beta$, and cycle bottom pressure P_{bottom} . From the observation of Figure 15, increasing the turbine pressure ratio $beta$ from 20 to 40 results in a turbine power output increase of 100 kW. This is an expected larger pressure expansion performed by the working fluid in the turbine directly resulting in a larger enthalpy². However, too high values of $beta$ (would theoretically increase the turbine output, but in practice the value of $beta$ is limited by the manufacturability of the turbine and by the fact that the efficiency of a single-stage turbine is negatively impacted (therefore reducing substantially the total power output).

¹ For instance η_T tends to decrease with increasing $beta$ and decreasing mass-flow-rate. Nonetheless, the relationship between η_T , $beta$ and m_w is very complex, and requires turbo-machinery analysis and data outside the scope of this work.

² $W_T = \eta_T \times \dot{m}_w \times (h_{in} - h_{out})_T$, a larger enthalpy “jump” $(h_{in} - h_{out})_T$ directly results in a higher turbine power output.

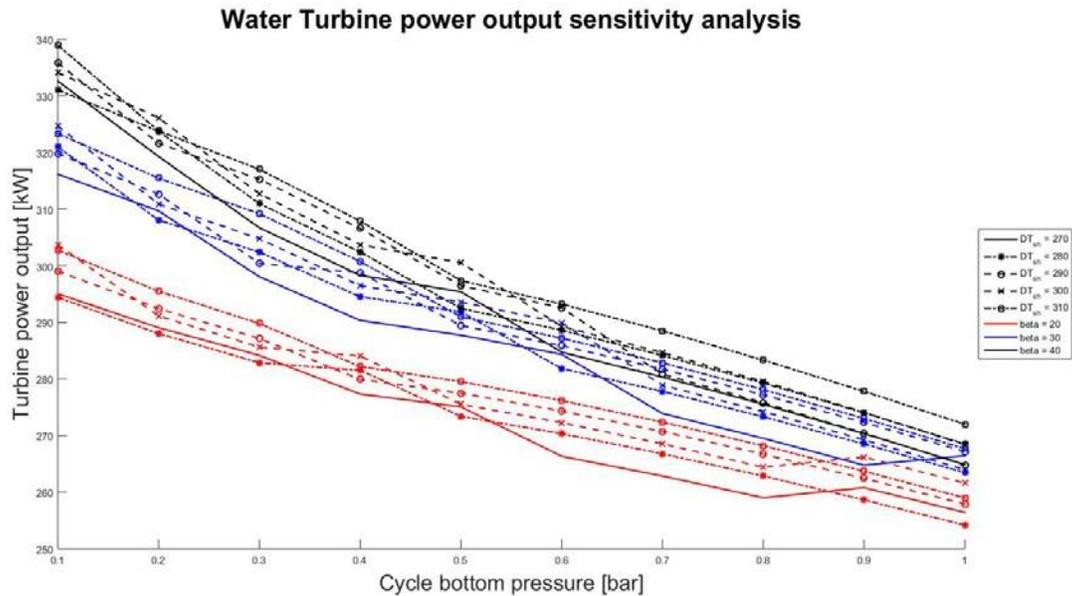


Figure 15: Turbine power for varying pressure ratio superheating T and condenser P .

A thorough analysis was performed using the EES code optimized under T81-5 to determine the equivalent cycle thermodynamic conditions to obtain the desired turbine power output of $W_T = 300$ kW. The analysis is explained in more detail in Appendix A.T81-5, and the final results are tabulated in Table 5.

m_w [kg/s]	DT_{sh} [K]	beta	Condenser P [bar]	W_T [kW]
0.42	270	40	0.5	300

Table 5: Thermodynamic cycle operating conditions to obtain $W_T = 300$ kW

These results provide the necessary boundary conditions for the retrofitting of a HiPHEX capable of recovering the necessary heat from the locomotive exhaust gases and transfer energy to the working fluid to obtain a turbine power output $W_T = 300$ kW. Similarly, the EES code can be used to perform analyses for different exhaust gas ratings.

Task T81-6: Optimization of MATLAB-based computer codes for detailed HiPHEX simulation

The EES-based code was utilized to assess the overall performance of the TDR thermodynamic Rankine cycle, but had limitations on the resolution or details of the physical thermal-hydraulic mechanisms occurring within the HiPHEX. Task T81-6 is dedicated to the optimization of a MATLAB-based code to model the thermodynamic and fluid mechanic mechanisms occurring within the HiPHEX in greater detail. The MATLAB code considered the effects of turbulence and thermal radiation and produced estimates on the heat transfer mechanisms occurring within the HiPHEX, thus providing indications on further optimizations that may be implemented. The MATLAB code was interfaced with the EES code, thereby enabling more accurate predictions of the overall TDR's waste heat recovery thermodynamic cycle performance. Specifically, the MATLAB code was employed to simulate the behavior of the HiPHEX investigated in Task T81-3. Generally, the MATLAB code attempts to numerically solve the heat transfer and fluid mechanics behavior of the exhaust gases and working fluid interactions as they travel through the HiPHEX. The basic mathematical and thermodynamic principles of the code are outlined in Appendix A.T81-6. To validate the MATLAB code, test measurements performed on the first generation HiPHEX (see Task 81-3) were compared with the code predictions.

Figure 16 compares the outlet exhaust gas temperature $T_{g,out}$ measured from analogue test and predicted by the code. The different stages shown in the x-axis of Figure 16 correspond to the test stages described in Task T81-3 (see Table 4 for details). Overall, the MATLAB code predicts the exhaust gas temperatures at the outlet of the HiPHEX with reasonable accuracy, under the assumptions, when compared with test results obtained at different steps.

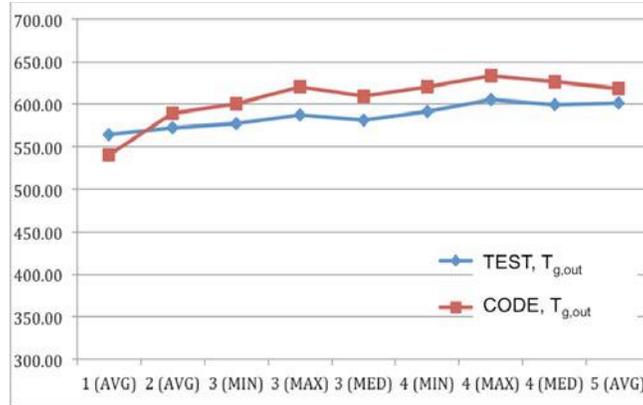


Figure 16: Code versus test data of exhaust gas temperature at HiPHEX outlet.

Table 6 compares the HiPHEX length predicted by the code to increase the water temperature from $T_{w,in}$ to $T_{w,out}$, to the actual length of the HiPHEX used in the tests (fixed length = 0.6 m). The different steps shown in Table 6 correspond to the test steps described in Task T81-3 (see Table 4 for details).

Start - Step	L Test [m]	L Code [m]	Error [%]
Start - Step 2	0.60	0.4-1.4	N/A
Step 2 - Step 3	0.60	0.6	0.00
Step 3 - Step 4	0.60	0.452	24.67
Step 4 - Step 5	0.60	0.442	26.33
Step 5 - Step 6	0.60	0.872	31.19

Table 6: MATLAB code and test results comparisons

The overall findings can be summarized as follows:

- The MATLAB code performed with an overall discrepancy of about ~ 30%.
- In the test step denominated as Start – Step 1, no comparison was possible as the water outlets the HiPHEX as wet steam³. At the conditions indicated, the 0.4 m–1.4 m range shows the length necessary for the working fluid to reach a saturated liquid state ($L = 0.4$ m) and to achieve a saturated vapor state ($L = 1.4$ m).
- The results for Steps 3–4 and Steps 4–5 are less accurate as point measurements were used instead of average values (this was because of pump instability at the mass-flow-rates utilized for this test).

³During evaporation the temperature of the working fluid remains constant and comparison with experiments is not possible.

Overall, the code performed satisfactorily and its accuracy can be further increased by executing additional testing and increasing the quality (and cost) of the supporting test equipment utilized (i.e., pump typology, controller, pressure regulator, flow meter). The next task is dedicated to utilizing the MATLAB code together with commercially available software, to develop the second-generation HiPHEX to be non-invasively retrofitted with a line-haul locomotive EGMs.

Task T81-7: Second Generation HiPHEX optimization

The findings in Stage II of the T67 investigation showed that the first generation HiPHEX has an effectiveness of approximately 50% as it was applied to a relatively small-scale system (i.e., 175 kW diesel engine). As the MATLAB-based code is validated, it can be used to analyze which characteristics of the “first generation HiPHEX” induce the greatest losses and which features can be added to improve the overall HiPHEX performance. More effective HiPHEX configurations can be optimized via iterations and testing so that the results can be applied to optimize retrofitting of EGMs equipping different locomotives.

In the design of a heat exchanger, the main aim is to maximize the heat transfer between the working fluid 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 suggest an increase in the pressure drop (backpressure) of the heat transfer channel design. Consequently, the design selection is subject to the amount of pressurization and pumping system used to drive the working fluid within the heat transfer channels of the heat exchanger. The combination of the optimized EES and MATLAB codes optimized under tasks T81-5 and T81-6 formed the grounds for the investigation and optimization of a second generation of HiPHEX.

As opposed to a set of the single hollow tubes developed by TDR with internal grooves and tested under T67, HiPHEX design optimizations included the retrofitting of multiple annular tubes positioned along the length of the exhaust manifolds. The reason for this choice stems from the geometrical limitations associated with the non-invasive retrofitting requirements applied to the HiPHEX with respect to EGMs equipping the locomotive engines referenced. For example, the EGMs equipping the GE Dash-9 locomotive are modular and develop longitudinally; thus, the least invasive HiPHEX configuration is represented by tube bundles running along the length of the manifold.

Figure 17 shows a particular HiPHEX configuration comprising multiple annular tubes (in this case four) non-invasively retrofitted inside a GE Dash-9 set of EGMs. A preliminary evaluation of the effect of surface area and residence time on heat transfer was carried out using the MATLAB code and Solidworks Fluid Flow Simulation software. As a preliminary investigation the effectiveness of a single tube configuration (as the one in the first generation of HiPHEX) was evaluated.

Tests were carried out to investigate different inner/outer diameter configurations at the conditions of the GE Dash-9 EGM and a detailed analysis was performed for varying HiPHEX tube characteristics.

Overall, the analysis investigated the effects of residence time, turbulence, and surface for varying HiPHEX tube characteristics. Details of this analysis can be found in Appendix A.T81-7.

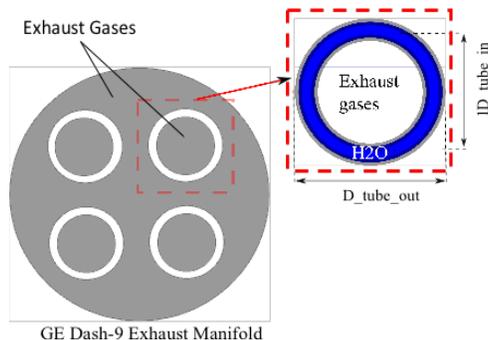


Figure 17: 4 HiPHEX - GE Dash 9 locomotive EGM non-invasive retrofit.

Figure 18 shows the normalized values of extracted energy Q for varying tube diameters, when the maximum number of HiPHEX tubes is fitted inside the GE Dash-9 EGM. From this analysis the HiPHEX effectiveness can be maximized when this particular manifold is fitted with tubes that have to simultaneously satisfy thermal-hydraulic and EGM dimensional requirements.

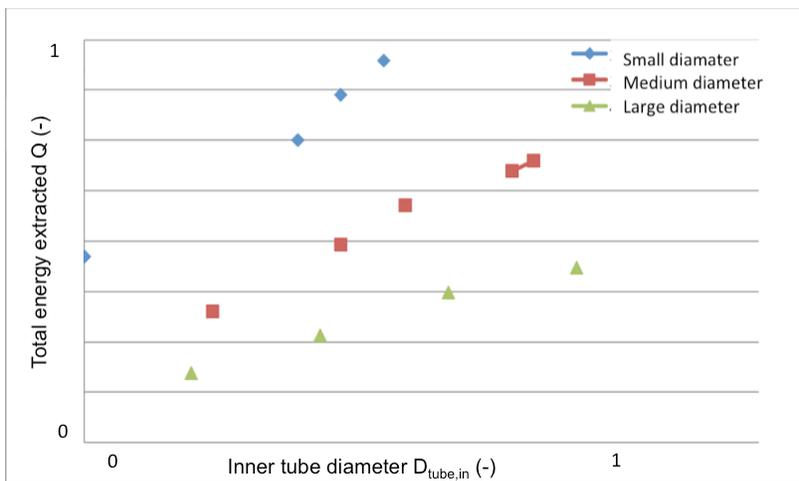


Figure 18: Q vs. $D_{tube,in}$ for different HiPHEX $D_{tube,out}$ (normalized).

Task T81-8: Testing of second generation HiPHEX design

The analysis performed in Task T81-7 showed that the preferred HiPHEX design involves multiple concentric tubes fitted longitudinally inside the GE Dash-9 exhaust manifold. To validate the analysis performed in Task T81-7, test results were performed on a single concentric tube retrofitted in the GE Dash-9 exhaust manifold. To further validate the analysis, thermodynamic similarity was assumed. The testing of the aforementioned tubing and the validation of the numerical analysis can therefore be straightforwardly extrapolated to the final design of the second generation HiPHEX for different locomotive engine EGMs.

Figure 19 shows the test HiPHEX formed by a concentric tube retrofitted with the GE Dash-9 EGMs. Similarly to Task T81-3, test measurements were recorded by exposing the concentric HiPHEX to the exhaust gases produced in the scaled ECC. For this test, the working fluid was pressurized through the concentric tube in a counterflow configuration with respect to the exhaust gas flow direction, and its pressure and mass-flow-rate were varied to obtain superheated steam at its outlet.



Figure 19: HiPHEX concentric tube.

Throughout the test the exhaust gas inlet and outlet temperatures ($T_{gas,in}$ and $T_{gas,out}$), water inlet and outlet temperature ($T_{w,in}$ and $T_{w,out}$), and water pressure and mass-flow-rate (P_w and m_w) were recorded. The main test results are summarized in Table 7.

Time Duration		$T_{gas,in}$ [°C]	$T_{w,in}$ [°C]	$T_{w,out}$ [°C]	P_w [bar]	m_w [kg/min]
Region 1	Min.	644.45	36.81	430.86	6.58	0.1423
18:37:54	Max.	648.88	36.99	440.03	6.73	0.1737
to	Avg.	646.72	36.88	437.46	6.65	0.1594
18:38:14	s.d	1.71	0.06	2.70	0.05	0.0109
Region 2	Min.	664.60	37.42	235.54	2.57	0.1648
18:47:16	Max.	676.16	37.82	347.06	2.68	0.2037
to	Avg.	669.86	37.58	302.59	2.62	0.1909
18:49:52	s.d	2.40	0.10	30.46	0.02	0.0072

Table 7: Optimized HiPHEX tube test results

The tests referenced in Table 7 were executed for an extended time; however, the results were stable only during short intervals as a result of pump instability at the mass-flow-rates of interest (regions 1 & 2 in Table 7), where the standard deviation (s.d.) was consistently <1% (i.e., the measurements were not fluctuating). To further validate the MATLAB code, test results were compared with the code predictions. Similar to Task 81-7, the code uses as input the mass-flow-rate, water pressure, and the exhaust gases inlet temperature to predict the required HiPHEX tube length. The results are shown in Table 8.

Region	HiPHEX Test [m]	HiPHEX Code [m]	Error [%]	$T_{gas,out}$ Test [°C]	$T_{gas,out}$ Code [°C]	Error [%]
1	1.395	1.404	0.68	468.31	438	-6.4725
2	1.395	1.244	-10.79	458.50	441.3	-3.75235

Table 8: Code prediction and test results comparison

The comparison between the code and the experimental results shows that the MATLAB code, under the boundary conditions described, predicts the performance of the HiPHEX with reasonable accuracy against the results from HiPHEX tests.

It can therefore be concluded that the analysis performed in Task T81-7 for the design of the second generation HiPHEX based on the MATLAB code and Solidworks software is sufficiently accurate. Future activities will involve adopting different types of pumps, controller, pressure dampening, and ancillary equipment to increase stability of the mass-flow-rate during testing under variable pressure conditions.

Task T81-9: General accounting and Stage I reporting

In accordance with the TRB IDEA Program Transit-81 agreement, the Stage I report was subjected to the reviews and comments of the expert review panel. Comments from the reviewers were integrated and submitted to the IDEA Program Project Manager and provided together in the Final Report. Overall, Stage I Tasks T81-1 to T81-9 were completed as planned, and the results were satisfactory and in compliance with the Statement of Work. Completing Stage I tasks enabled the execution of the technical tasks contemplated in Stage II. Figure 20 illustrates a summary table of Stage I technical tasks executed.

Stage I - Combustion Chamber and Exhaust Manifold Simulator			Projected Completion	% of completion
T81- 1	Executed	Performed preliminary feasibility studies, manufactured and tested a scaled combustion chamber to determine the total air flow-rate and pressure requirements to mimic locomotive engine intake air parameters.	4/25/15	100%
	Action Items	T81-1 to T-81-7 Tasks activities were shown to the Reviewers to obtain technical feedback. All tasks activities have been performed according to the Statement of Work (SOW)		
<i>Task Description: Design and manufacturing of combustion chamber system</i>				
T81- 2	Executed	Identified extractor power fans to be merged with Simulator exhaust piping system. Fans ordered. Obtained Permit to install duct system on warehouse roof. Completed procurement and assembly of simulator components.	5/30/15	100%
	Notes	Delays were accrued to obtain permits to execute permanent modifications to warehouse roof.		
<i>Task Description: Electric air fan and fuel burners installation</i>				
T81- 3	Executed	Locomotive manifolds procured. Components for Exhaust Gas Simulator (EGS) manufactured and assembled.	5/30/15	100%
	Notes	Safety and additional Exhaust Gas Simulator (EGS) optimization aspects were integrated with the execution of this task.		
<i>Task Description: First generation HiPHEX optimization and testing on GE Dash-9 exhaust manifolds</i>				
T81- 4	Executed	Design completed. Locomotive manifolds installed. Components for EGS assembled.	5/30/15	100%
	Notes	High-pressure heat exchangers optimum configuration was obtained by Computer Fluid Dynamic (CFD) analysis		
<i>Task Description: First generation HiPHEX optimization and testing on EMD 16-645 exhaust manifolds</i>				
T81- 5	Executed	Modeling Completed	6/30/15	100%
	Notes	Modeling results transferred Stage I report		
<i>Task Description: Optimization of EES-Based computer code</i>				
T81- 6	Executed	Modeling Completed	7/30/15	100%
	Notes	Modeling results transferred to Stage I report		
<i>Task Description: Development of MatLab-Based computer codes for detailed simulation</i>				
T81- 7	Executed	Scaled testing successfully completed	8/12/15	100%
	Notes	Results Transferred to Stage I report		
<i>Task Description: Second Generation HiPHEX Optimization</i>				
T81- 8	Executed	Scaled testing successfully completed	8/12/15	100%
	Notes	Results Transferred to Stage I report		
<i>Task Description: Testing of second generation HiPHEX Design</i>				
T81- 9	Executed	Invoice NAS-81-01 Issued	9/12/15	100%
	Notes	Stage I Report ready for delivery on September 12, 2015		
<i>Task Description: General Accounting and Stage I Reporting</i>				

Figure 20: Stage I tasks completion and summary notes.

Tasks Performed in Stage II

T81 Stage II main objectives support the design, manufacturing, assembly, and testing of a full-scale locomotive simulator to closely mimic the behavior of the locomotive exhaust gas system interacting with the High Pressure Heat Exchangers (HiPHEX) to be retrofitted with the locomotive exhaust stack and to enable full-scale testing of waste heat recovery components.

Stage II Exhaust Stack Simulator

Stage II groups a total of five tasks addressing the activities required to support the operations of a full-scale locomotive simulator and validate computer codes optimized to project the performance of various HiPHEX configurations and their performance when subjected to different streams of exhaust gases produced by locomotive engines. Stage II tasks are summarized as follows:

- T81-10: Installation and testing of exhaust stack and turbocharger housing to simulator
- T81-11: Optimization of HiPHEX to be retrofitted on exhaust stack
- T81-12: Testing of exhaust stacks retrofitted with HiPHEX
- T81-13: Full-scale experimentation and testing
- T81-14: General accounting and Stage II reporting

Task T81-10: Installation and testing of exhaust stack and turbocharger housing to simulator

Testing performed with the scaled ECC enabled fine-tuning of the numerical MATLAB- and EES-based computer codes for the optimization of the HiPHEX configured for locomotive applications. Specifically, the scaled ECC enabled the optimization of the HiPHEX configuration, which would both minimize pressure losses in the working fluid and exhaust gas stream, and maximize the heat transfer from the exhaust gas stream to the working fluid.

Table 9 compares the properties of the locomotive exhaust gases with the exhaust gases generated by the scaled ECC. Although the exhaust gases produced by the scaled ECC and the locomotive engine have similar properties (temperature and chemical compositions), the thermal energy content represented by the locomotive exhaust gases is more than an order of magnitude greater than the thermal energy produced by the scaled ECC. Full-scale or “locomotive-scale” testing and validation of the HiPHEX via simulator requires the ECC to replicate both chemical and energy content of the exhaust gases as if these were produced by actual locomotive engines. The activities conducted in Tasks T81-1 and T81-2 enabled scaling of the ECC shown in Figure 3 to a combustion system able to provide the large exhaust gases mass-flow-rates with energy content in the megawatt range represented by line-haul and passenger locomotives. To scale up the ECC, TDR modified a multi-stage compressor coupled to combustors as those utilized for gas turbines. The resulting locomotive-scale ECC can produce exhaust gases representing up to 5 MW of thermal energy content at mass-flow-rates equivalent to those generated at various notch settings of line-haul and passenger locomotives.

Notch setting	T_{exh} °C	$m_{exh,loc}$ kg/s	$m_{exh,scaled\ ECC}$ kg/s
8	608	6.85	0.61
7	537	5.49	0.43
6	511	4.78	0.29
5	510	3.84	0.29
4	512	2.51	0.29
3	508	1.72	0.29
2	360	0.83	0.27
1	260	0.59	0.24

Table 9: GE Dash-9 and scaled-ECC Exhaust gas properties

Figure 21 is a schematic of the full-scale locomotive simulator with the locomotive exhaust gas stack and turbocharger housing thermal-hydraulically coupled to the locomotive-scale ECC.

As shown in Figure 21 air flows at the inlet of the locomotive simulator (left side), undergoes compression through the ECC multi-stage compressor, and is mixed with fuel to produce exhaust gases with mass-flow-rates and energy content equivalent to those produced by locomotive engines at all notch settings. To increase safety and given the large amount of energy processed by the full-scale locomotive simulator during operations, the mega-watt-scale or locomotive-scale ECC was placed inside an ISO transport container essentially sealing the ECC and shielding operators during testing. As shown in this figure, the hot exhaust gases produced by the locomotive-scale ECC flow into the accumulator for distribution to the locomotive EGMs coupled to the turbocharger housing. As the exhaust gases flow through the locomotive stack they also go through the HiPHEX non-invasively retrofitted inside the stack. Overall, the accumulator is connected via 16 ports (16-cylinder locomotive engines) to two sets of exhaust gas manifolds. In this configuration, the EGMs and the exhaust stack utilized are those equipping GE Dash-9 locomotives. However, by changing the accumulator configuration, various types of EGMs and exhaust stacks equipping different locomotive models can be utilized.

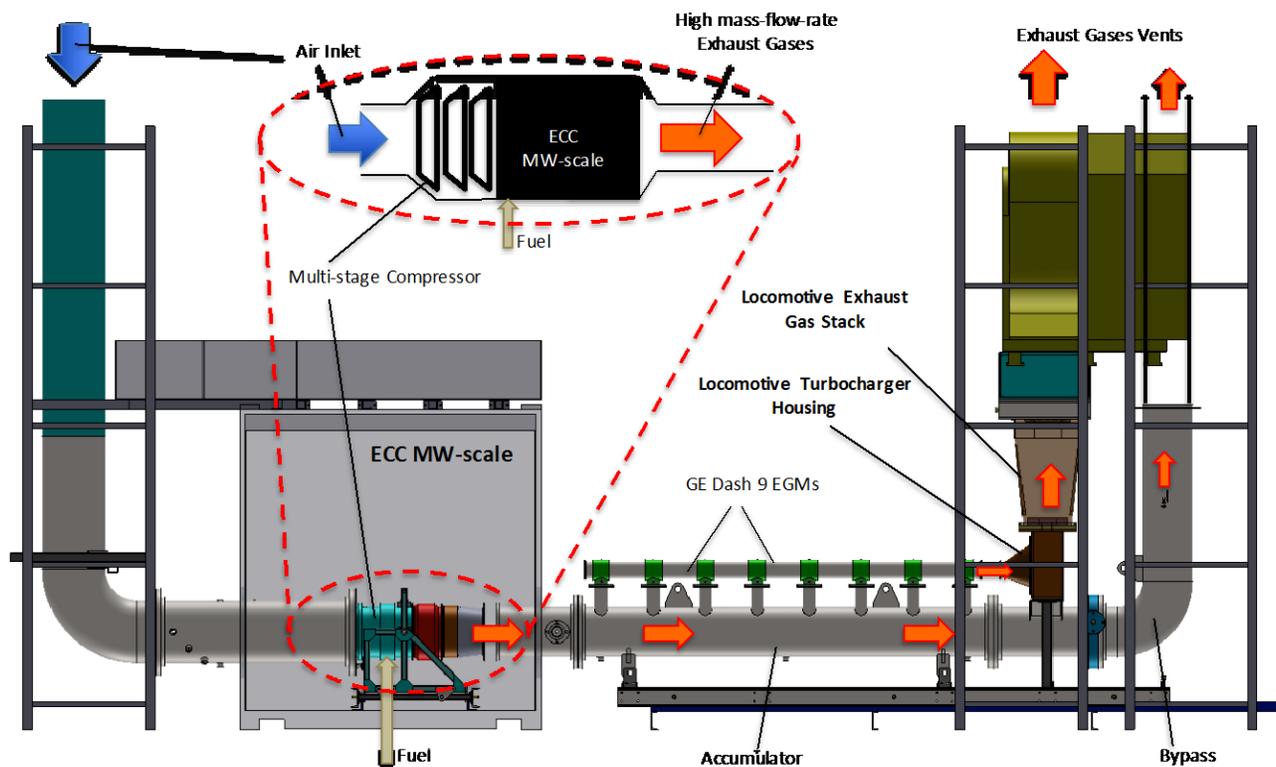


Figure 21: Schematic of MW-scale locomotive-simulator.

Depending on the locomotive engine being simulated (i.e., line-haul versus passenger or switch locomotives), the locomotive-simulator shown in Figure 21 can produce exhaust gases with mass-flow-rates in excess of those represented by a given locomotive at maximum power (i.e., Notch 8). For example, the locomotive model GE Dash-9 utilized as a reference in this project produces 6.85 kg/s of exhaust gases at Notch 8 (see Table 9). To ensure that only the necessary mass of exhaust gases flows through the EGMs and the exhaust stack, the simulator was equipped with a bypass valve so as to bleed the excess mass of exhaust gases through the bypass tubing venting to atmosphere. Task 81-10 consisted of matching actual EGMs and the exhaust stack of a commercially operated locomotive to the simulator thermal-hydraulic loop. To ensure the simulator could be utilized for different locomotive models, a preliminary CFD simulation was performed for varying bypass valve-opening angles. Figure 22 provides an example of the CFD analysis performed for varying bypass valve opening angles and utilized to optimize the simulator coupling to the locomotive exhaust gas stack and turbocharger housing. Accordingly (see Figure 22), the exhaust gases inlet the accumulator from the right at a given pressure, mass-flow-rate, and temperature (proportional to locomotive notch settings). The superimposed black lines represent streamlines of the exhaust gases as they flow through the accumulator, the exhaust gas manifolds, the exhaust stack, and the bypass. As the accumulator becomes pressurized the exhaust gases flow into each exhaust gas manifold and collect at the turbocharger housing prior to entering the exhaust gas stack. To simplify the CFD simulation, the backpressure induced by the bypass valve and that caused by the exhaust stack heat exchanger were simulated as “porous media”⁴. The remaining flow sections were directly modeled.

Although CFD analysis is extremely useful, it cannot guarantee accuracy in absolute values as, in this case, the specific angle indicating the position of the bypass valve may be inaccurate and, for safety reasons, the bypass valve does not entirely seal the accumulator (to allow a minimum flow of exhaust gases out of the ECC). However, the CFD analysis allowed for the investigation of the quality/type of correlations between the valve opening and the mass-flow-rate of the exhaust gases.

⁴ A porous medium is common in CFD analysis and can be used to simulate components that cause a blockage/back-pressure to the flow. In the context of this study, the porous medium represents uniform back-pressure applied onto the exhaust gases due to the bypass valve.

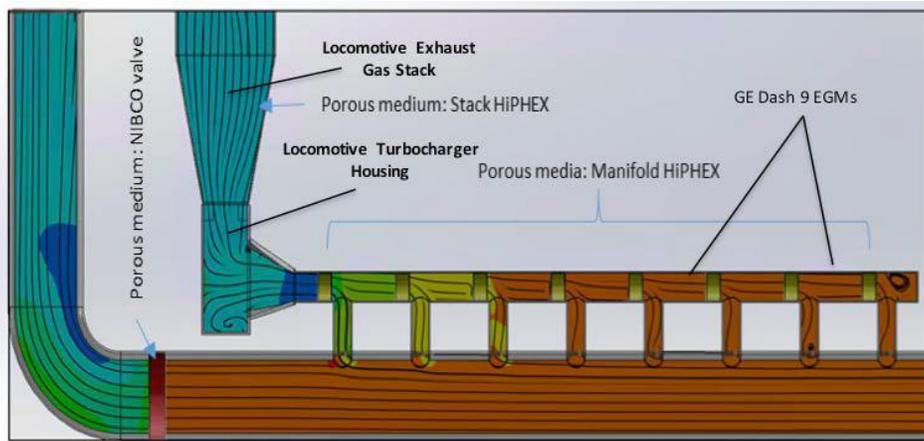


Figure 22: CFD of exhaust gases through locomotive-simulator accumulator.

Figure 23 shows the locomotive-simulator CAD and the final locomotive-simulator components installed at TDR testing facility.

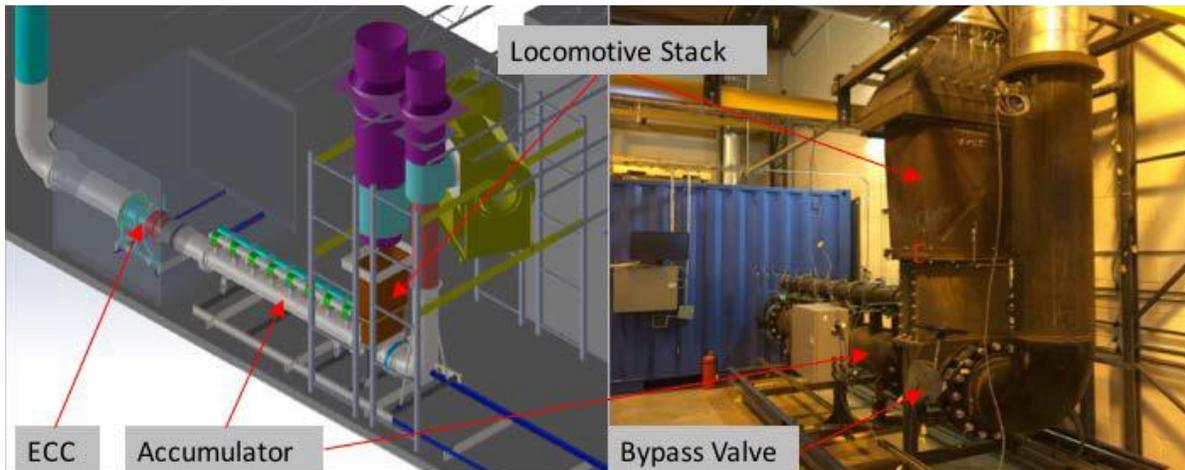


Figure 23: Locomotive-simulator CAD and actual assembly.

Task T81-11: Optimized HiPHEX retrofitted with exhaust stack

Figure 24 (left) shows the exhaust gas stack of a locomotive equipped with a GE diesel engine. Figure 24 (right) shows the exhaust gas stack of a locomotive equipped with a diesel engine manufactured by EMD. Although these exhaust stacks execute the same functions, they manifest substantially different dimensions and geometries.

The HiPHEX are designed to non-invasively universally retrofit these different systems. For example, the geometry of the exhaust gas stacks shown in Figure 24 (rectangular cross section) promotes the use of a cross-flow configuration for the HiPHEX, as opposed to the U-tube counterflow configuration used for cylindrical EGMs (see Task T81-7 for details).

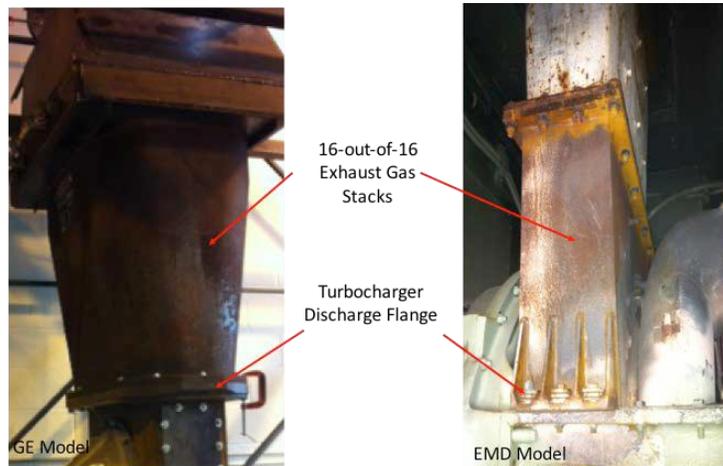


Figure 24: GE (left) and EMD (right) exhaust stacks and turbocharger discharge flanges.

Figure 25 shows simplified schematics consisting of multiple tubes arranged in a cross-flow configuration with the exhaust gas stream flowing across them.

The MATLAB code was further optimized to predict the heat transfer characteristics between the working fluid and the exhaust gases, and pressure losses for varying heat exchanger parameters. Specifically the code assisted in the identification of the optimal values for the:

- Longitudinal and transverse tube distances: S_L and S_T , as shown in Figure 25.
- Number of tubes along the length and width of the stack in the longitudinal N_L and transverse N_T direction.
- Diameter of the tubes.
- Angle between tube rows: 90° for aligned (squared) arrangement, and 30° for staggered (triangular) arrangement. Figure 25 (left) shows a staggered arrangement.

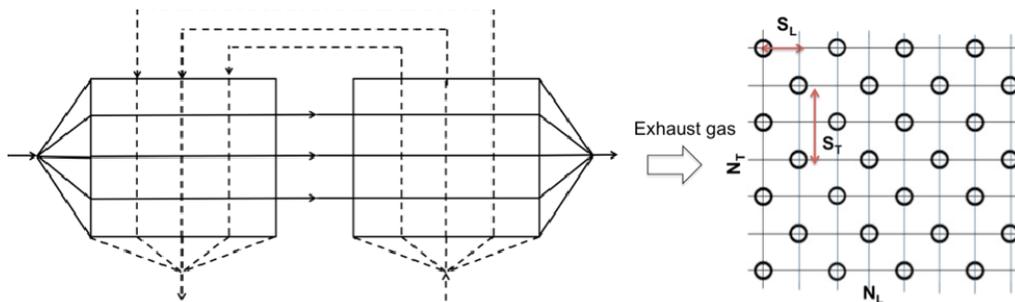


Figure 25: Mixed cross-flow, counterflow configuration.

A number of simulations were performed with the MATLAB code for varying HiPHEX configurations and geometries. An optimized configuration was then selected to minimize the exhaust gas pressure losses, while enabling the desired heat transfer in compliance with the non-invasiveness requirement when retrofitting the exhaust stack.

To ensure HiPHEX adaptability while maintaining low manufacturing cost, TDR optimized a HiPHEX stack configuration that can be easily adapted for various locomotive stack geometries.

Although analytical tools employed in the MATLAB code are very useful for providing an estimate of the expected pressure losses and heat transfer rate of a stack HiPHEX, their accuracy is limited to the “0-dimensional” nature of their correlations. In reality, the flow within the exhaust gas manifolds and stack is highly turbulent, chaotic, and 3-D in nature. As CFD analysis addresses the conservative equations that govern a fluid flow, TDR utilized the software Solidworks Fluidflow and ANSYS Fluent to perform CFD simulations of the exhaust gases flowing through varying cross-flow tubing configurations. Figure 26 shows the CFD simulation results of the exhaust gases flowing through a section of the

HiPHEX fitted inside the GE Dash-9 engine stack. As shown, the temperature of the exhaust gases flowing in the regions occupied by the HiPHEX clearly decreases as the gases flow upward along the y-axis (to the stack venting region).

Generally, along most of the z-axis and y-axis cross sections (see Figure 26 coordinate reference), the exhaust gases transfer energy to the working fluid flowing through the HiPHEX relatively uniformly. The regions of lower exhaust gas temperatures seen downstream and upstream of the engine stack on the left side of the representation are caused by the headers of the HiPHEX (rectangular shapes inside the computational domain). At the sides of the engine stack the exhaust gases remain at high temperature (red colored regions), as gases bypass the HiPHEX in these regions.

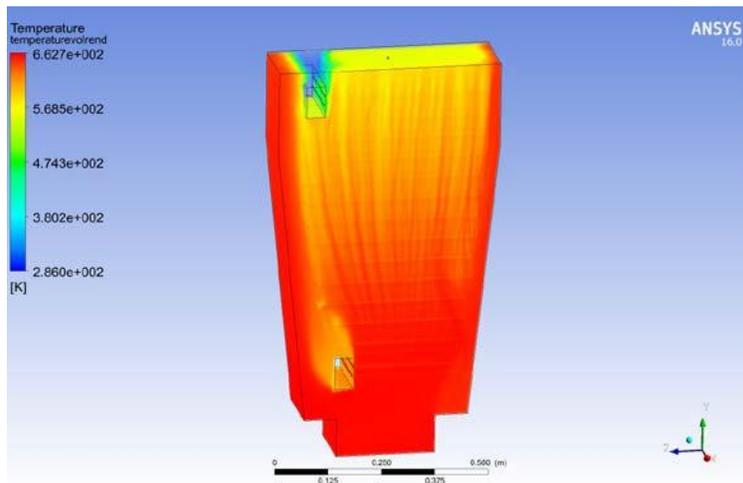


Figure 26: HiPHEX retrofitted stack cross-section exhaust gas temperature distribution.

Figure 27 shows the normalized mass-flow-rate (m/m_{max}) and velocity streamlines (u/u_{max}) of the exhaust gases flowing through the exhaust stack retrofitted with the HiPHEX. As shown, the mass-flow-rate of the exhaust gases is clearly highest (red regions) at the sides of the stack, indicating that a significant portion of the exhaust gases bypasses the HiPHEX. Similarly, the velocity streamlines at the side of the HiPHEX are more densely packed, thus confirming that the exhaust gases are flowing essentially undisturbed in the regions not occupied by the HiPHEX.

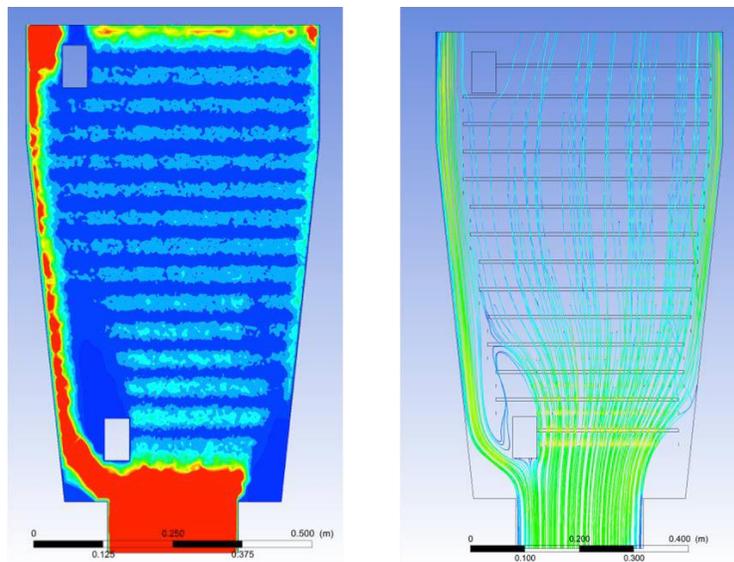


Figure 27: (left) Exhaust mass-flow-rate and (right) velocity stream lines (normalized).

Spacing between the sides of the HiPHEX and exhaust stack walls has been conservatively included to minimize exhaust gas backpressure. Figure 28 shows the exhaust gas pressure contour plots along the length of the HiPHEX stack. The overall exhaust gas backpressure at the inlet of the stack measures only 30 mbar (0.435 psi). This value is negligible and

confirmed that it would not have an adverse effect on the performance of the locomotive engine.

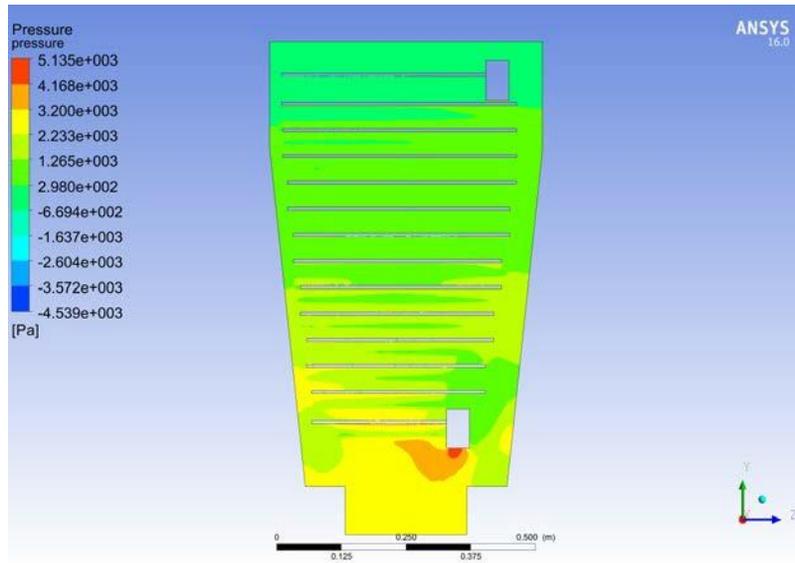


Figure 28: Exhaust gas pressure contour plots along the stack length.

Tasks T81-12 and 13: Testing of exhaust HiPHEX retrofitted stack and turbocharger performance

The locomotive simulator has been instrumented with several measuring devices to record data addressing the components of TDR waste heat recovery and conversion technology. Figure 29 shows the relative location of various pressure transducers (PTs), thermocouples (TCs), and flow meters. PTs and TCs are also positioned to closely monitor the exhaust gases parameters as they travel through the accumulator, the exhaust stack (retrofitted with the HiPHEX), and the bypass open loop.

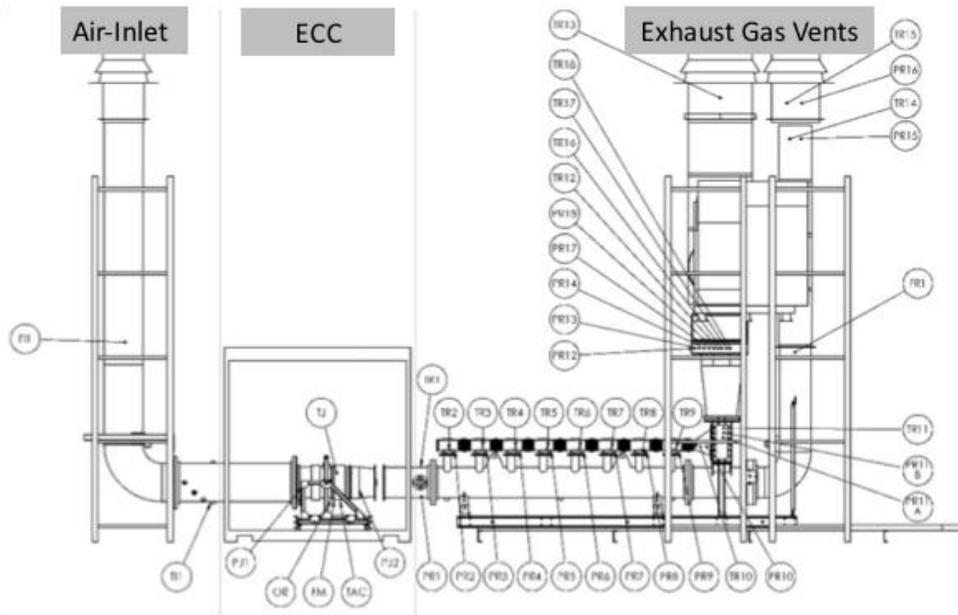


Figure 29: Locomotive simulator instrumentation.

Figure 30 shows two cross sections of the HiPHEX non-invasively retrofitted exhaust stack indicating the TC and PT locations. For example, pressure transducers and thermocouple ($T_{exh,in}$) monitor the exhaust gases inlet conditions at the exhaust gas stack inlet. Additional thermocouples ($T_{exh,mid,1}$ and $T_{exh,mid,2}$) were positioned along the length of the HiPHEX to measure the exhaust gases change in temperature as they flow through the HiPHEX TCs ($T_{exh,out,1}$, $T_{exh,out,2}$,

$T_{ex,out,3}, T_{ex,out,4}$) were positioned diagonally along the outlet of the HiPHEX to monitor exhaust gases temperature distribution (Figure 30 left). Finally, flow meters were positioned at the inlet of the locomotive simulator and in the bypass open loop to measure the velocity of the exhaust gases.

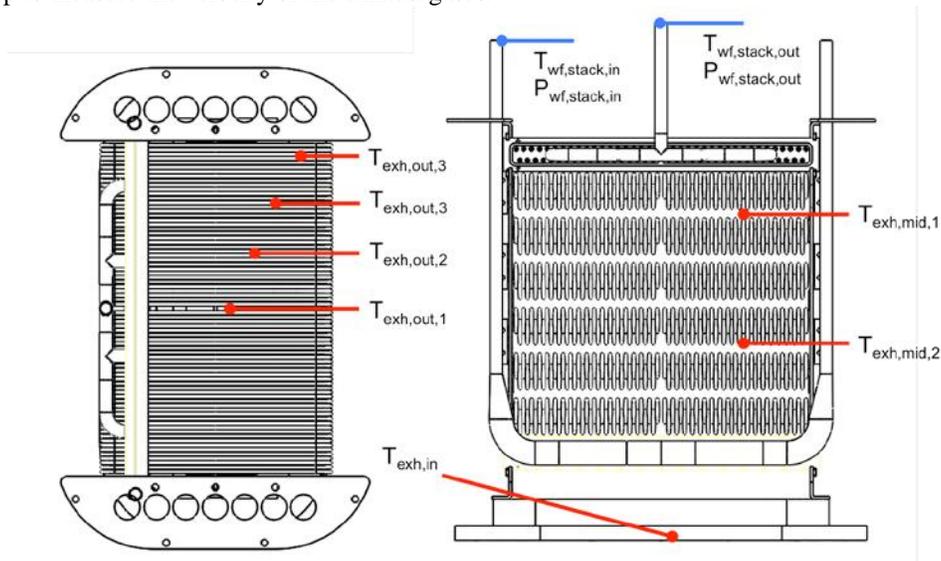


Figure 30: TC and PT positions at outlet of HiPHEX (left) and through HiPHEX (right).

The thermodynamic state of the working fluid as it flows through the various components of the waste heat recovery and conversion system was closely monitored to assess the effectiveness of the HiPHEX. TCs and PCs were also positioned at the inlet and outlet of the positive displacement pump and at the inlet and outlet of the condenser (see Figure 1 and Figure 31). Finally, TCs and PCs were placed at the inlet and outlet streams of a controlled amount of cooling fluid utilized to condense the working fluid in the condenser. All sensors were connected to a Programmable Logic Controller (PLC) for data collection during testing. Sensible data were also outputted in real time onto a control screen during testing. Figure 31 depicts the control screen with real-time data for the monitoring and control of the locomotive-scale simulator and waste heat recovery system.

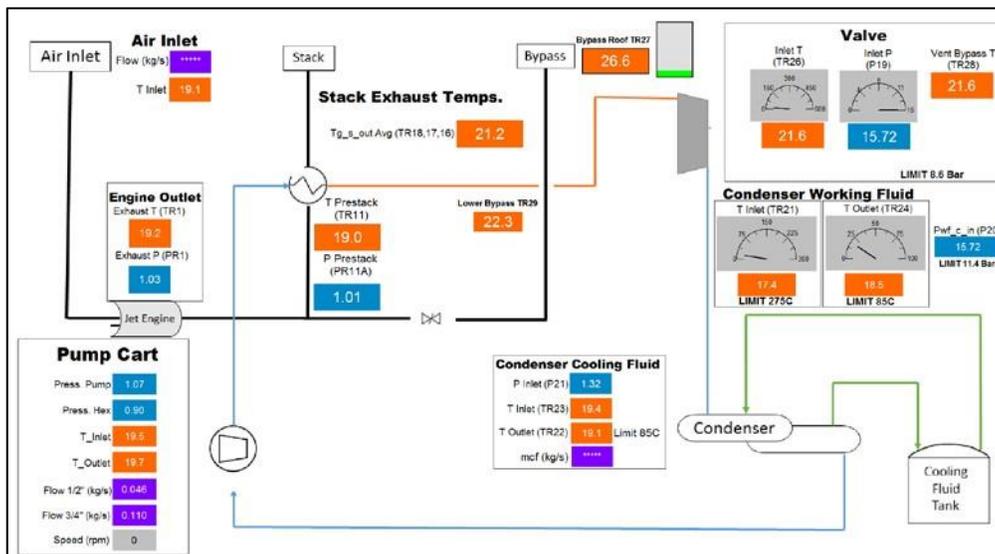


Figure 31: Locomotive-scale ECC-driven TDR waste heat recovery and conversion system.

To further support Task T81-10, a “dry test” was also performed. This test consisted of measuring the exhaust gas temperature and mass-flow-rates at the inlet of the exhaust stack, while operating the exhaust gas bypass valve, without circulating the working fluid through the HiPHEX. Figure 32 shows the exhaust gas mass-flow-rate (left) and temperature (right) through the stack during testing for different bypass valve opening angles. As expected as the bypass valve is progressively closed, a larger amount of exhaust gases flow through the stack HiPHEX. The observed exhaust

gas mass-flow-rate fluctuations are the result of highly turbulent flow conditions in these hydraulic sections of the simulator.

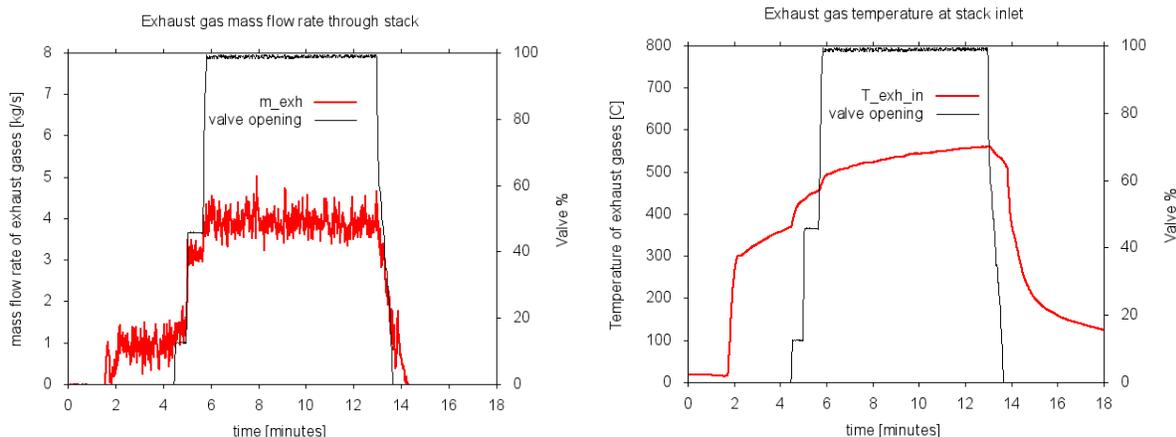


Figure 32: Stack exhaust gases mass-flow-rates and temperature.

Table 10 compares the exhaust gas mass-flow-rate, temperature and energy in the locomotive stack at Notch 8 setting and through the stack retrofitted to the locomotive-scale ECC. The overall energy content (Q_{stack}), when comparing locomotive engine data against locomotive-simulator data, shows a difference of approximately 15%. A more accurate exhaust gas temperature and mass-flow-rate can be obtained by finely varying the amount of fuel injected in the locomotive-scale ECC. Beyond T81 tasks, TDR will continue to support activities dedicated to further fine-tune the locomotive simulator power rating. Overall, representative full-scale locomotive tests of the waste heat recovery components can be performed via locomotive simulator by fine-tuning the locomotive-scale ECC exhaust gas production rates and temperature, and by operating the bypass valve to closely mimic the exhaust gases produced by various locomotive engines.

Locomotive-Engine Exhaust Stack			Locomotive-Simulator Exhaust Stack		
T_{exh} [°C]	m_{exh} [kg/s]	\dot{Q}_{stack} [kW]	T_{exh} [°C]	m_{exh} [kg/s]	\dot{Q}_{stack} [kW]
409	6.85	2,260	488	4.53	1,950

Table 10: Stack exhaust gases locomotive-engine vs. locomotive-simulator

These initial locomotive-simulator test results show that full-scale (megawatt-scale) tests can be executed within controlled laboratory environments, thus minimizing costs prior to locomotive field tests. This allows optimization iterations by full-scale testing of various WHRS components prior to executing tests involving generally more expensive and often not readily available locomotives.

Testing of the thermal-hydraulic closed-loop characterizing the WHRS involved pressurizing the liquid working fluid through the stack HiPHEX as the exhaust gases generated by the locomotive-scale ECC flow through it. The aim is for the hot exhaust gases to transfer thermal energy to the working fluid and produce superheated steam at the HiPHEX outlet. The superheated steam is then condensed by means of a condenser hydraulically coupled to the HiPHEX so as to reset the Rankine thermodynamic cycle. Figure 33, shows the working fluid temperature and pressure versus mass-flow-rate during testing. In this example, the working fluid mass-flow-rate was kept constant at $m_{wf} = 0.2$ kg/s. As shown, the temperature of the working fluid at the stack HiPHEX outlet ($T_{wf,stack,out}$) increases rapidly after approximately 6 minutes from test start and reaches a superheated state with temperatures of approximately 350°C (662°F). In this test, the thermodynamic superheated state is maintained for several minutes to collect stable data before shutting down the megawatt-scale ECC.

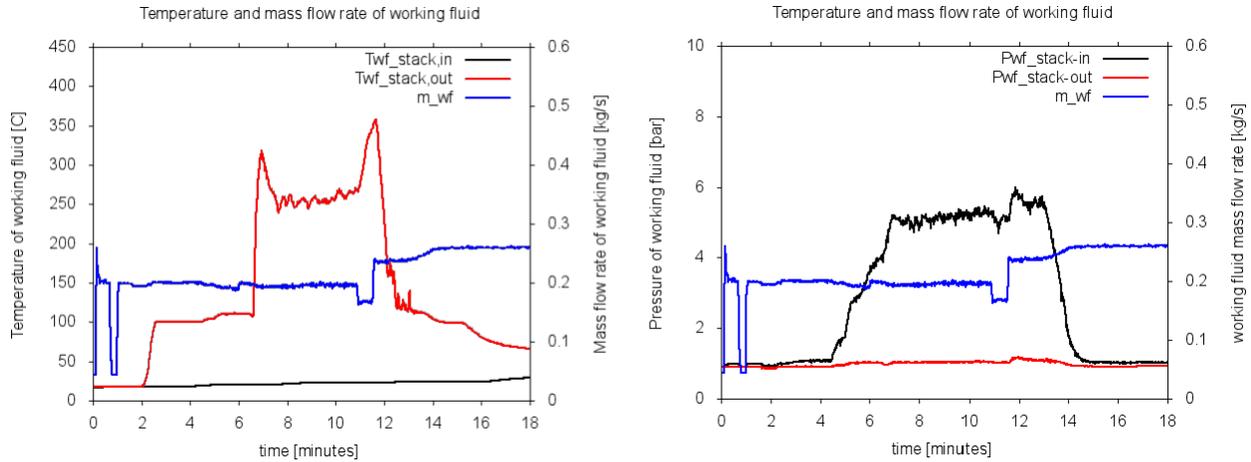


Figure 33: HiPHEX outlet temperature (left) and pressure (right) versus mass-flow-rate.

Similarly, during the same time interval, the working fluid pressure drop through the stack (defined as: $P_{wf,stack,in} - P_{wf,stack,out}$) increases rapidly to approximately 5 bar (72 psi), see Figure 33 right. As the working fluid is superheated, it expands and its density is reduced by a factor in excess of 1,000 compared with its liquid state. This induces a sudden rise in specific volume resulting in increased working fluid’s velocity and consequently increased pressure drop due to frictional losses.

Figure 34 shows the exhaust gas temperature data sampled at various locations of the exhaust stack non-invasively retrofitted with the HiPHEX. As expected, throughout the stack and HiPHEX, the exhaust gas temperatures increase when the bypass valve is closed, as a larger mass-flow-rate of exhaust gases flows through the stack. Figure 34 (left) shows the exhaust gas temperature measured at the inlet of the stack ($T_{exh,out,in}$), and at positions *mid1* and *mid2* (see Figure 30 right). As expected the exhaust gases temperatures are highest at the stack inlet and progressively decrease as the gases flows through the stack. Accordingly, $T_{exh,in} > T_{exh,mid,1} > T_{exh,mid,2}$ and the exhaust gases transfer thermal energy to the working fluid circulating in the HiPHEX. Figure 34 right shows the exhaust gases temperatures at the HiPHEX stack outlet. The TC positioned at the center of the outlet of the HiPHEX ($T_{exh,out,1}$ in Figure 30) measures the lowest exhaust gas temperature. This indicates that the exhaust gases flowing through the center of the HiPHEX more effectively transfer thermal energy to the working fluid. Note that the temperature of the exhaust gases at the outlet of the HiPHEX increases progressively with proximity to the wall: $T_{exh,out,1} < T_{exh,out,2} < T_{exh,out,3} < T_{exh,out,4}$. These results agree with the CFD analyses performed in the context of Figure 26. It is evident that the gases flowing through the center of the stack transfer more energy to the working fluid, whereas the exhaust gases at the sides of the stack remain mostly unaffected.

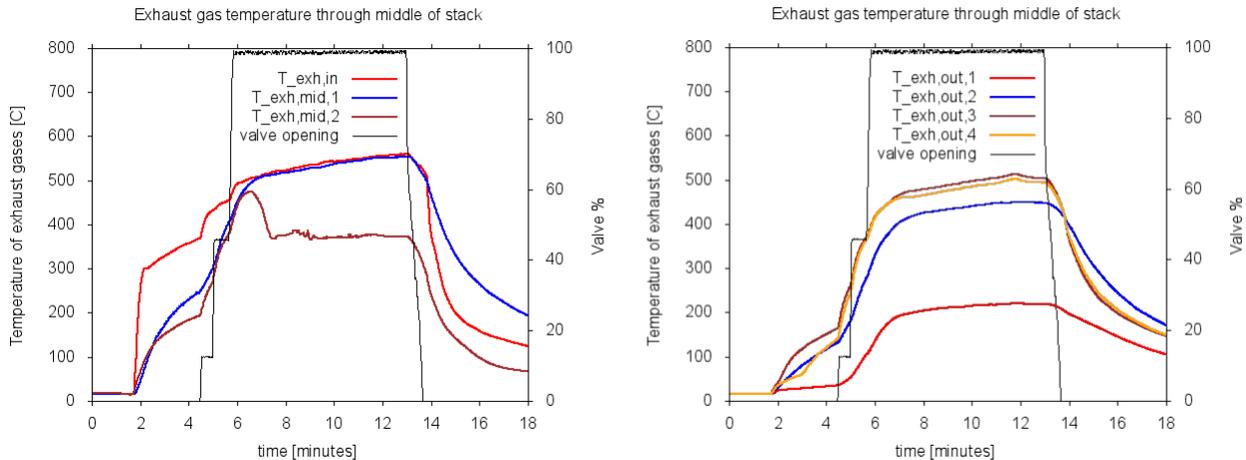


Figure 34: Temperature of exhaust gases at outlet and through middle of the HiPHEX.

The stack HiPHEX performance and the recoverable thermal energy from the otherwise wasted locomotive exhaust gases thermal energy was assessed. The HiPHEX heat transfer parameters can be calculated by knowledge of the thermodynamic state of the working fluid at the heat exchanger inlet and outlet. For the test considered, the averaged mass-flow-rate, temperature, and pressure data were sampled in the time interval between the 6th and 12th minute of test duration, when the working fluid was in a superheated state (see Figure 33) and as displayed in Table 11.

\dot{m}_{wf} [kg/s]	$T_{wf,stack,in}$ [°C]	$P_{wf,stack,in}$ [bar]	$T_{wf,stack,out}$ [°C]	$P_{wf,stack,out}$ [bar]
0.195	22	5.3	345	1.0

Table 11: HiPHEX inlet and outlet working fluid properties

The heat transfer to the working fluid is then calculated from test results as $\dot{Q}_{HiPHEX} = \dot{m}_{wf} \times (h_{wf,out} - h_{wf,in})$, where $h_{wf,out}$ and $h_{wf,in}$ are the enthalpy of water at the HiPHEX inlet and outlet conditions. Accordingly, and based on test results, the energy recovered by the HiPHEX is $\dot{Q}_{HiPHEX} = 590$ kW. The effectiveness of the HiPHEX can then be determined as the ratio between the thermal energy recovered by the HiPHEX and the available energy in the stack exhaust gases as $\dot{Q}_{HiPHEX}/\dot{Q}_{stack} = 30.2\%$. This result shows that the first generation of HiPHEX configured for locomotive applications already operates with reasonably good performance. Table 12 reports the energy recovered obtained from test results and the total energy contained in the exhaust gases prior to venting to atmosphere.

\dot{Q}_{HiPHEX} [kW]	\dot{Q}_{stack} [kW]	η_{HiPHEX} [%]
590	1,956	30.2

Table 12: HiPHEX stack performance

Figure 35 shows the exhaust gas pressure drop (backpressure) through the exhaust stack retrofitted with the HiPHEX tested. As the exhaust gases flow through the HiPHEX, the pressure difference between the inlet and outlet of the HiPHEX is approximately 20 millibar (0.29 psi). This pressure difference is negligible. In fact, the recorded pressure losses from tests are even lower than the ones predicted by the CFD simulation in the context of Figure 28. Consequently, it can be concluded that the HiPHEX, as configured in these tests, does not affect the performance of the locomotive turbocharger. This also demonstrates that the HiPHEX satisfies the “zero-invasiveness” requirement and complies with more general requirements addressing locomotive equipment retrofittability. In other words, the results show that the WHRS utilizing properly configured HiPHEX does not impact normal locomotive operations. Another important conclusion of this test is that failure of the components forming the WHRS does not impair normal locomotive operations.

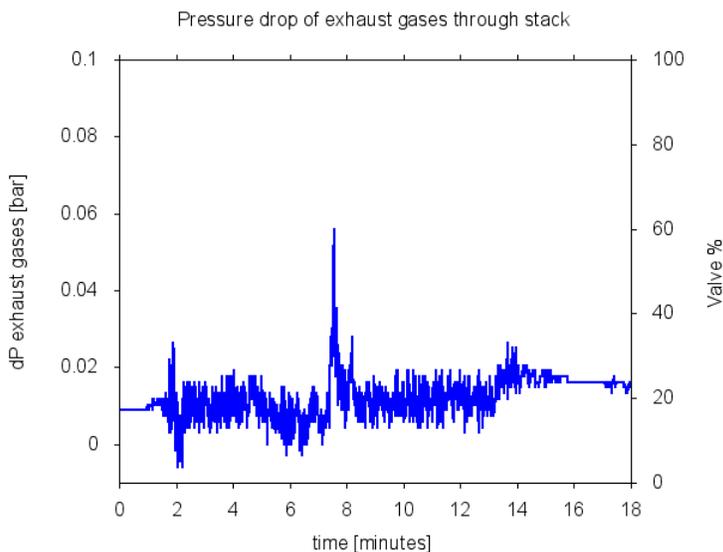


Figure 35: Exhaust gas pressure drop through stack HiPHEX.

Conclusions

The IDEA Program Transit-81 Stage I accomplishments included the successful implementation of a scaled Extended Combustion Chamber (ECC) improving on the findings obtained in the IDEA Program Transit-67. The ECC enabled testing of various High-Pressure Heat Exchangers (HiPHEX) configured to non-invasively retrofit locomotive equipment. Data collected from the ECC coupled to different HiPHEX were used to increase the accuracy of computer codes to estimate the HiPHEX effectiveness when operating under various dimensional, operational, and thermodynamic constraints characterizing locomotive operations. Comparative tests indicated that the computer codes predicted the HiPHEX and the exhaust gases thermodynamic characteristics with satisfactory accuracy, thus enabling scaling the ECC to an extended combustion system capable of simulating locomotive exhaust gases at locomotive-scale (i.e., Notch 8 conditions). Stage I completion enabled the execution of the technical tasks comprised in Stage II.

Stage II accomplishments included testing activities to validate computer codes to demonstrate full-scale locomotive simulator operations with testing of HiPHEX under various configurations. The results confirmed that the locomotive stack can be non-invasively retrofitted with HiPHEX with configurations that induce negligible backpressure with respect to the exhaust gases flowing through the locomotive exhaust stack. Tests enabled by the locomotive-scale simulator enable fine-tuning of the HiPHEX and other WHRS components to ensure the performance of the locomotive engine is unaffected under all operational conditions. These results validated the predictions obtained through CFD simulations, which showed that large portions of the exhaust gases bypass the HiPHEX as they were equipped with safety exhaust gas venting features, thereby reducing the effectiveness of the heat exchanger. The HiPHEX tested performed relatively well by recovering 590 kW from the exhaust gases produced by the locomotive simulator with setting to replicate locomotive engine conditions at Notch 8. CFD simulations and test results further confirmed that exhaust gas pressure losses caused by the HiPHEX reach approximately 20 millibar (0.29 psi) when the locomotive engine is operated at maximum power. This indicated that the spacing between the exhaust gas stack inner walls and the HiPHEX can be further decreased to recover additional exhaust gases waste thermal energy. Preliminary simulations show that substantial recovery of the thermal energy represented by the locomotive exhaust gases can be obtained by increasing the HiPHEX effectiveness from approximately 30% to 66%. Therefore, the HiPHEX can increase the total recovered energy from 590 kW, obtained during Stage II preliminary testing, to 1,200 kW (1.2 MW).

The HiPHEX configured for non-invasive locomotive exhaust stack retrofitting showed the capability of extracting at minimum 590 kW of thermal energy from the exhaust gases prior to venting to atmosphere without impacting locomotive performance at all operating conditions. As CFD simulations and test results indicated that the exhaust gas pressure loss induced by retrofitting HiPHEX is negligible at maximum locomotive power, the HiPHEX effectiveness can be increased to 66%, corresponding to a total of 1.2 MW of recovered energy. TDR will seek funds to continue optimization of WHRS components to extract the maximum allowable, otherwise wasted, thermal energy represented by the locomotive exhaust gases and cooling system, thus decreasing locomotive operational cost and pollutant emissions.

Overall, by employing the locomotive-scale simulator, more effective HiPHEX configurations can be investigated at a much lower cost when compared with similar tests executed with actual locomotives. The locomotive simulator performed as projected with a capacity to provide exhaust gases with thermal energy in excess of 5 MW and allowed full-scale testing of various WHRS components and configurations. TDR plans to continue the optimization of the locomotive-scale simulator to execute long-term reliability testing of WHRS components to include features targeting more aggressive pollutant emissions reduction.

Investigator Profile

Dr. Claudio Filippone, the project investigator, cooperated with TTCI technical staff, railroad consultants, and locomotive owners to access locomotive data required for the purposes of Transit-81. Dr. Filippone is the inventor of several granted patents and patent applications covering waste heat recovery systems, solar-driven displacement of water without electricity or moving parts, spent nuclear fuel passive cooling systems, bio-electric fermenters to support bio-fuel production, high-power lasers, water recovery from exhaust gases, small-scale hybrid engines, and truly transportable compact nuclear generators powered by gas-cooled melt-resistant cores. Dr. Filippone's experience with combustion engines and waste heat recovery systems goes back to the 1980s. In 1986, as an electrical engineer, he patented and became involved with the development and testing of hot plasma, high-voltage, high-frequency ignition systems dedicated to advanced lean-burn stratified engines. The results were published by the Energy Department of the Polytechnic of Turin, Italy, and were also tested by Ferrari Race Team in preparation of the 1986 Grand Prix of Brazil. His work demonstrated that the air-fuel ratio can be significantly extended toward ultra-lean condition without inducing misfiring. He also demonstrated that a plasma flame properly controlled within the combustion chamber reduces unburned hydrocarbon emissions by 60%, while operating with very low NO_x and CO emissions. From 1999 to 2006, Dr. Filippone was a faculty member at the Department of Aerospace Engineering at the University of Maryland where he obtained Master and Ph.D. degrees in nuclear engineering. In 2000, he received an EB1 Extraordinary Ability green card and later became a naturalized U.S. citizen. Dr. Filippone is the developer of CAESAR (Clean And Environmentally Safe Advanced Reactor), a nuclear reactor system with innovative heat transfer mechanisms able to significantly increase nuclear fuel burn up. Since 2010, Dr. Filippone has managed the ThermaDynamics Rail LLC engineering team formed by Mechanical, Combustion, Electrical, Turbo-machinist, Manufacturing, and Aerospace engineers and coordinates an engineering consulting firm in London, U.K., dedicated to design, manufacturing, and testing of complex thermal-hydraulic and high-speed electrical systems. Over several years as a researcher on thermal-hydraulic systems he developed expertise in conventional and advanced energy producing systems whose power source is represented by renewable energy, fossil fuels, generation III+ nuclear power systems, small modular reactors (SMRs), and micro modular reactors (MMRs). Currently, Dr. Filippone's main activities are fully dedicated to furthering waste heat recovery technologies through specialized components customized for non-invasive retrofitting of transport and stationary platforms to reduce their operating cost and pollutant emissions.