

# LERF Accountability Report

## Summary

This report details the investments for and the outcome of the CCEM research project “Large Engine Research Facility – LERF”, which was recently completed at the Paul Scherrer Institute. Entailing the construction of a completely new building to house the generator-set and the needed peripheral systems, it took a mere 7 months from first groundbreaking in March 2008 to first engine start in October 2008. Commissioning and comprehensive baseline testing of the standard engine had been achieved until August 2009. The different instrumentation systems - including cylinder pressure indication, multi-component exhaust gas analysis and complete energy balance – was validated and LERF has been fully operational.

The investments taken were two-fold being related to the construction of the new building with infrastructure on the one hand and for the test bed itself with measurement equipment on the other.

Funding came from own contributions and from CCEM-CH. Additionally, third party funding was committed by ABB and Wärtsilä for joint research projects.

## Budget and Financing

The two investment packages are detailed in the following section. The first package labeled infrastructure comprises everything related to the building and necessary interfaces to the utilities. The second package labeled research entails everything related to the engine and its operation. A brief overview of all major components is given in the following table.

Infrastructure: 1.99 MCHF (PSI)	Research: 2.0 MCHF (CCEM-CH)
Three story test cell with engine foundation, operating room, utility power room, grid power distribution room, primary cooling water line, 16 kV 3-Ph power line to grid, 3.2 ton crane, test-cell climate control and ventilation, lighting and cabling.	W6L20_CR 1080 kW engine, variable speed generator, F/V-Converter, SCR-system, fuel storage, heat exchanger, air supply silencers, engine peripherals, exhaust gas analyzer, operation system for real time engine control, data acquisition system for mean and dynamic variables, general measurement equipment

# Investments

## **Building and Infrastructure (1.99 MCHF - PSI)**

The new building for the LERF had to comply with restrictions limiting the noise emission and also the coupling of vibrations into the ground. The former was achieved by having a closed concrete construction with heavy fitted and sealed doors and noise silencers for the air supply cross section and the air vent.

The direct coupling of vibrations into the ground had to be limited since the LERF is located in vicinity to a laboratory for nano-positioning. The problem was solved by casting a massive concrete block, which was independently founded in the ground, to say it is decoupled from the building ground floor. The engine frame rests on eight spring damper elements which elastically support the generator set on the concrete block. Both restrictions were met as the noise and vibrations measurements from different sources showed.

Similar noise restriction requirements were set for the operator room which is adjacent to the engine test bed. Here also heavy duty sealed doors and insulation window were used to reduce the noise to acceptable levels.

In addition the new construction also provided for the power transmission room and a service room for utility power distribution and communication equipment.

The 16 kV 3-phase power line to feed the generated electric power to the medium voltage grid and the 3.2 ton crane were considered infrastructure expenses.

The LERF incorporates a part of an already existing building to which the new construction was added. This older part was fitted to contain the fuel storage tanks, the heat exchanger for engine cooling and control systems for the engine room air coolers. The primary water supply from the Aare River to the heat exchanger was placed into an already existing supply tunnel coming from the nearby pumping station.

## **Test bed and Instrumentation (2.0 MCHF – CCEM-CH)**

Everything related to the motor, its safe operation and the installed measurements were considered research expenses.

The installed engine is a Wärtsilä W6L20-CR mounted on a common base frame to an ABB AMA 450L6L squirrel cage induction engine. This primary output feeds to a frequency/voltage converter which synchronizes to 400VAC/50 Hz and from which it is transformed to 16kVAC/50 Hz and delivered to the electrical grid. This brake system allows running the engine at variable speed but still feeding the generated power synchronously to the power grid.

The engine cooling is implemented using a shell and tube heat exchanger that transfers the waste heat to water from the Aare River. The control system allows setting the supply temperature of the secondary circuit by varying the flow rate of the primary flow. Here we are free to choose as long as the water temperature returned to the Aare River is lower than 30°C.

The fuel storage was designed to hold 40'000 L in four separate compartments, two of which had provisions to install a tank heating for the option of using heavy fuel oil. A day tank of 1000 L capacity is placed in the test cell ground floor. Large efforts are made to ensure ultra clean fuel to the engine, since the common rail fuel injection system is very sensitive to impurities. The fuel supply pump ensures enough pressure at the intake of the common rail pump and allows fuel circulation when the engine is stopped.

Other engine peripheral systems include the start air pressure vessel, lube oil system,

generator cooling and the exhaust line with after treatment system and chimney.

To comply with the Swiss regulations for the conservation of air quality, a Urea based SCR catalyst was installed to minimize the NO<sub>x</sub> emissions of the exhaust gases. The catalytic converter system has an independent controller using an engine load signal for feed forward control and fine tuning the Urea injection rate using as feedback the actual NO concentration downstream of the catalyst. To ensure good operating conditions, the exhaust pipe was designed having a long mixing section for Urea vaporization.

The real time operating system for the test bed control (AVL Puma Open) was installed in the operating room and the test cell. It provides the general interface to all installed components and safety systems enabling engine start /stop, load and speed variation, safety monitoring and measurements synchronization. It also handles hardwired emergency stop signals either from emergency buttons or initiated from failed components. There are two main operation modes available in which the engine controls the speed and the electric motor controls the load (default case) or vice versa. For the default case the engine can either be operated in the generator mode at nominal speed or in the propeller mode at variable speed.

Whereas the previous section detailed the bare bone engine operational hardware we want to sketch the installed instrumentation that was required for a successful and complete analysis of the engine behavior.

The installed measurements and sensors can be grouped into three categories. In the first group we gather all system variables that allow estimating the engine efficiency for the fixed load cases. These variables are acquired via the PUMA analogue interface and are averaged over a period of two minutes. To measure the shaft power a 15 kNm torque flange (Kistler 0325DF) is installed between flywheel and coupling. The torque flange signal is used as feedback sensor for the load controller. The engine speed is measured on the engine itself and is also available at from the F/V converter. Both speeds are used by the operating system to control the speed and monitor a possible shaft break.

The fuel consumption is measured using two screw displacement flow meters (Kral OMC) in the supply and return line, respectively. The air consumption is calculated measuring the pressure difference over a Venturi nozzle mounted upstream of the compressor inlet. In addition, the heat fluxes entering and leaving the system boundaries carried by cooling water and exhaust gas are measured. All temperature differences are measured using PT100 thermo-elements or k-type thermocouples. The cooling water flow rates are metered using two MHD flow meters mounted in the LT and HT return pipes. The exhaust gas flow rate is estimated from the mass balance and the exhaust gas composition is used to apply the correct heat capacities for the estimation of the exhaust gas enthalpy.

The second group of measurements addresses the transient cylinder and gas exchange pressures during the working and gas exchange cycles. The exact timing signal is supplied by a crank angle encoder mounted at the free end and being aligned with the TDC measured from two piston head positions of cylinder #6, which was chosen for the measurements. A timing belt with 2:1 drive ratio connected to a 180° disk with inductive pickup allows identifying the combustion stroke TDC position. The pressure sensors used for the cylinder indication are supplied by Kistler Instrumente AG. A piezoelectric (p/e) pressure sensor mounted with a water cooled adapter measures the transient cylinder pressure. The induced charge signal is fed to a charge amplifier providing a linearly scaled voltage signal to be acquired by the transient recorder. For the cylinder reference pressure a piezoresistive (p/r) pressure transducer is used mounted with a water cooled adapter that has a pneumatic switch valve, opening only when the cylinder pressure is below the applied control pressure. This signal is used as the absolute pressure reference for the p/e sensor. Additionally to the in-cylinder pressures, the transient pressures upstream of the intake and downstream of the exhaust valves are measured using two p/r sensors mounted on the cylinder head through water cooled switching adapters opening when the

control pressure is applied. The p/r transducer signals are fed to the data acquisition system via a preamplifier also giving linearly scaled voltage signals.

The third group of measurements encompasses the detailed exhaust gas analysis using independent measurement systems. The most powerful analyzer used is a Fourier-Transform Infrared Spectrometer (FTIR) which can simultaneously quantify a large variety of emission species. In our case the instrument provides measurements of NO, NO<sub>2</sub>, NO<sub>x</sub>, N<sub>2</sub>O, CO, CO<sub>2</sub>, H<sub>2</sub>O, NH<sub>3</sub>, SO<sub>2</sub>, COS, AHC, C<sub>2</sub>H<sub>2</sub>, C<sub>2</sub>H<sub>4</sub>, C<sub>2</sub>H<sub>6</sub>, C<sub>3</sub>H<sub>6</sub>, C<sub>4</sub>H<sub>6</sub>, NC<sub>8</sub>, HCHO, and HCD with an acquisition rate of 1 Hz. In addition to the FTIR we operate an Opacimeter (AVL 439) to determine the exhaust gas opacity for different load and speed cases. Using a Blow-By Meter (AVL 422) we also measure the combined gas leakage passing the piston rings und turbocharger seals.



Fig. 1: Large Engine Research Facility outside and inside view.



Fig. 2: Day tank and Aare water heat exchanger



Fig. 3: Exhaust gas after treatment: Long mixing length for Urea vaporization (left) and outside placement of large catalytic converter before treated gas leaves through the chimney in the background (right).

In the following section we want to present some results obtained during baseline testing where we also varied rail pressure and start of injection at a nominal load point. This allows influencing the heat release rate and peak combustion pressure and as a consequence also fuel consumption and exhaust gas composition. Typically there exists a tradeoff between low  $\text{NO}_x$  and high efficiency or low soot production, respectively. Early injection timing yields high peak pressure and temperature and therefore favors production of thermal  $\text{NO}$ . On the other hand, the efficiency is higher because of the raised peak process temperature. Figure 4 shows a typical tradeoff between BSFC and  $\text{NO}_x$  concentration in the exhaust.

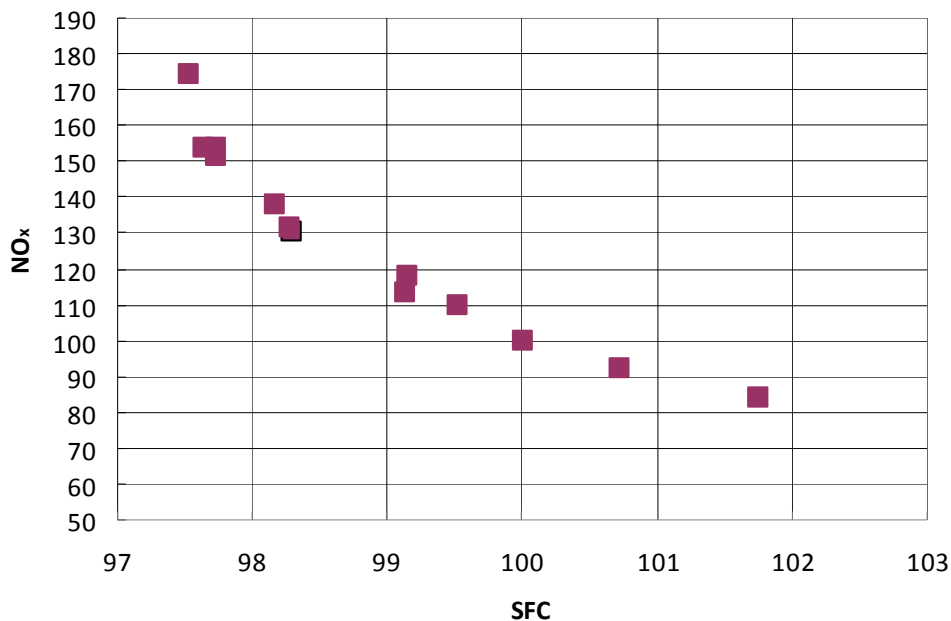


Fig. 4: Typical tradeoff between specific fuel consumption and  $\text{NO}_x$  concentration. Data is scaled with respect to the specific load point at 100 %.

One further result is the overall efficiency of the engine at different load points at nominal speed as it requires all data previously mentioned. The exhaust gas heat loss was

determined by summing all individual enthalpies for the major gas species present in the exhaust ( $N_2$ ,  $O_2$ ,  $CO_2$ ,  $H_2O$  and  $NO_x$ )

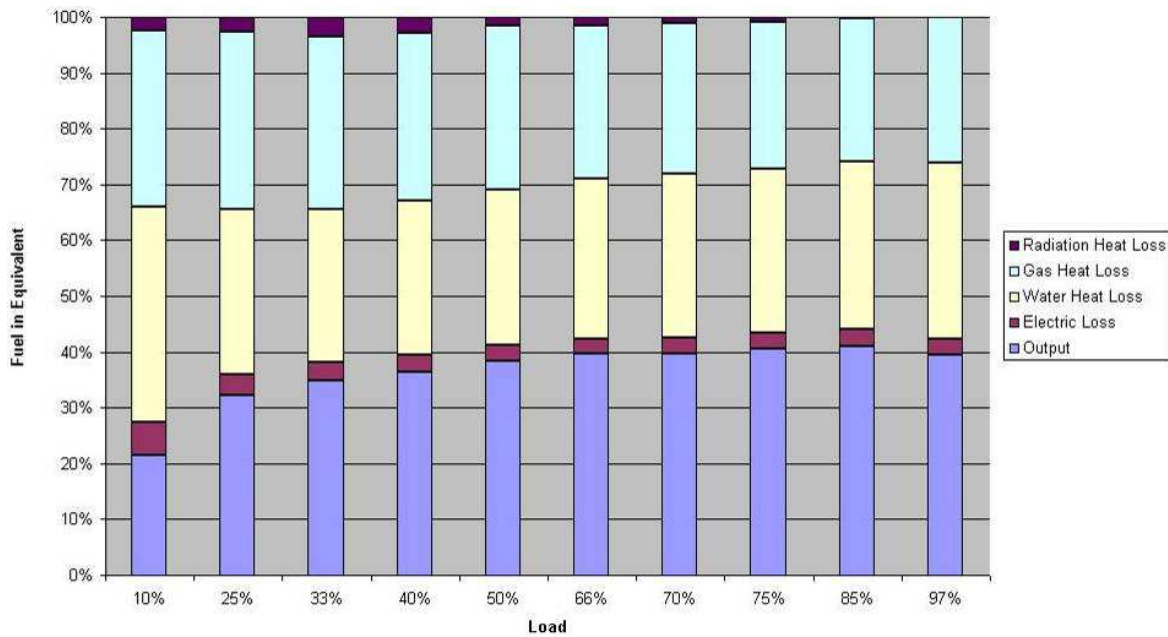


Fig. 5: Energy flow diagram for our generator set at different load points at nominal speed. Data is scaled with the lower heating value of the equivalent fuel energy input at each load point. The maximum efficiency at 85% load is related to the injection parameters as mentioned previously.

Another important functional engine test is the transient response to a steep change in load demand, e.g. a 33% to 66% load step change within 0.5 s. Here the engine tries to keep the nominal speed constant and dips after applying the load change by only about 2.5% and recovers to nominal speed within 10 s. The transient behavior is mainly governed by the dynamics of the turbocharger speed pickup and the charge air volume. The speed pickup therefore is limited by available air mass and the corresponding

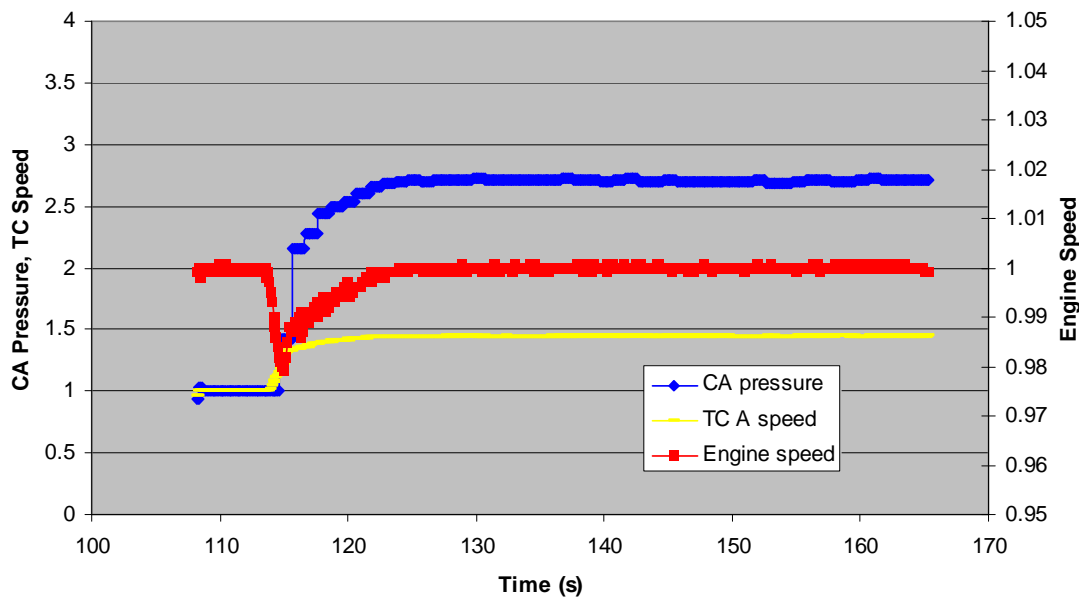


Fig. 6: Load acceptance test for a step change in applied load.

stoichiometric limit for fuel demand. The data displayed in figure 6 is scaled with the value

before the load change and shows the development of turbocharger speed, charge air pressure and engine speed.

## **Benefits**

### **Local support for Swiss Industry**

ABB Turbo Systems and Wärtsilä Winterthur are contributing project partners within the EU 7<sup>th</sup> framework program Hercules Beta looking for solutions to meet the upcoming stricter IMO Tier 3 limits for emission control areas.

A valuable partner is Kistler Instrumente for providing us with the pressure indication hardware, pressure sensors and amplifiers. A future cooperation with Kistler Instrumente will be focused on a new pyrometric sensor allowing estimation of the soot temperature and soot generation and oxidation.

While performing baseline testing we had a first service measurement cooperation with a Swiss developer of a motor diagnostic tool (Fuchs Technologies).

### **Realize clean and efficient large diesel engines**

During the course of the project we have been in close cooperation with the CELaDE project at ETHZ to enable better predictive capabilities of numerical model simulations for the entire engine and combustion. To name here are predictions of heat release rate, soot formation and NO<sub>x</sub> production. The LERF supplies important calibration data for the modeling.

Future projects involve testing for best ways to further reduce NO<sub>x</sub> generation and increasing overall efficiency to reduce CO<sub>2</sub> emissions accordingly. The most promising are most likely combinations of different measures like increased charge air pressure and cooling in combination with variable valve timing and exhaust gas recirculation.

In addition to these, we will increase our efforts to apply optical diagnostic tools to further our knowledge regarding diffusion flame combustion.

### **Support the development of new catalyst systems**

SCR catalyst systems for the selective reduction of NO<sub>x</sub> have an optimum temperature window in which they operate best and can also be controlled easiest. One challenge emanating from the increased efficiency will be lower exhaust gas temperatures at which operational difficulties like storage and ammonia slip may arise. We can learn about the behavior of the catalytic conversion and come up with reasonable solutions and control strategies. The modular construction of the gas passage allows exchanging parts of the cross section with new developments and testing them in on a prototype scale.

## Summary

The Large Engine Research Facility has become a valuable tool for combustion research and allows us to vary process parameters and directly observe the results with a variety of sensors and analysis tools. The entire operating envelope of the motor is accessible through our variable speed brake and the common rail system allows us to vary injection parameters at varying speed and load. In total, the engine has run 115 hours and the high quality data produced confirms that the money was well invested. We have a reliable workhorse available that will help us in answering the important questions.