# TPL – a new turbocharger series for advanced diesel engine generations

**ABB Turbo Systems has developed a new turbocharger series, designated TPL, for use on present-day as well as new-generation low-, medium- and high-speed engines rated from 1,000 kW up to the highest powers. Performance improvements include a higher pressure ratio, increased efficiency and higher flow capacity; user priorities addressed by the new, compact turbocharger are high reliability, long service life, increased time between overhauls and easy maintenance. Engine experience with the TPL turbocharger, 300 of which have already been installed, confirms the results of thermodynamic performance measurements carried out in the laboratory.**

The modular design of the new TPL turbocharger 1 provides the flexibility necessary to meet the turbocharging requirements of new types of four-stroke and two-stroke diesel engines ranging from 1000 to 25,000 kW per turbocharger. Main design features of the TPL are inboard sleeve bearings which can be lubricated directly by the engine lube oil, uncooled casings, an integrated speed sensor and integrated washing nozzles. A wide range of turbine inlet casings, including optional waste gate connections, cover all known turbocharging systems.

A new axial turbine family, developed especially for the TPL, increases the flow capacity. The new, unique bearing assembly includes a free-floating thrust disc. Two new centrifugal compressor stages of different designs ensure a high pressure ratio and high flow capacity, plus a wide operating range and high efficiency levels.

TPL turbochargers are designed to satisfy the following market requirements:

- High compressor pressure ratio, for increased power output
- High turbocharger efficiency levels, for reduced fuel consumption and lower exhaust-gas temperatures
- High specific flow capacity, resulting in a compact design and low weight
- High reliability, long lifetime, longer times between overhauls
- Easy maintenance, even for machines run under adverse conditions (eg, low-quality heavy oil as engine fuel)

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The modular design concept adopted for the TPL turbocharger series, although completely new, is based on experience gained with the highly reliable VTR..4/VTC..4 series.

Seven TPL turbocharger sizes are required to meet the current and future needs of the targeted market. Two centrifugal compressor stages cope with different pressure ratios and volume flow rates, allowing optimum coverage of the market requirements. The seven TPL turbocharger sizes are shown with their corresponding volume flow rates and pressure ratios in 2.

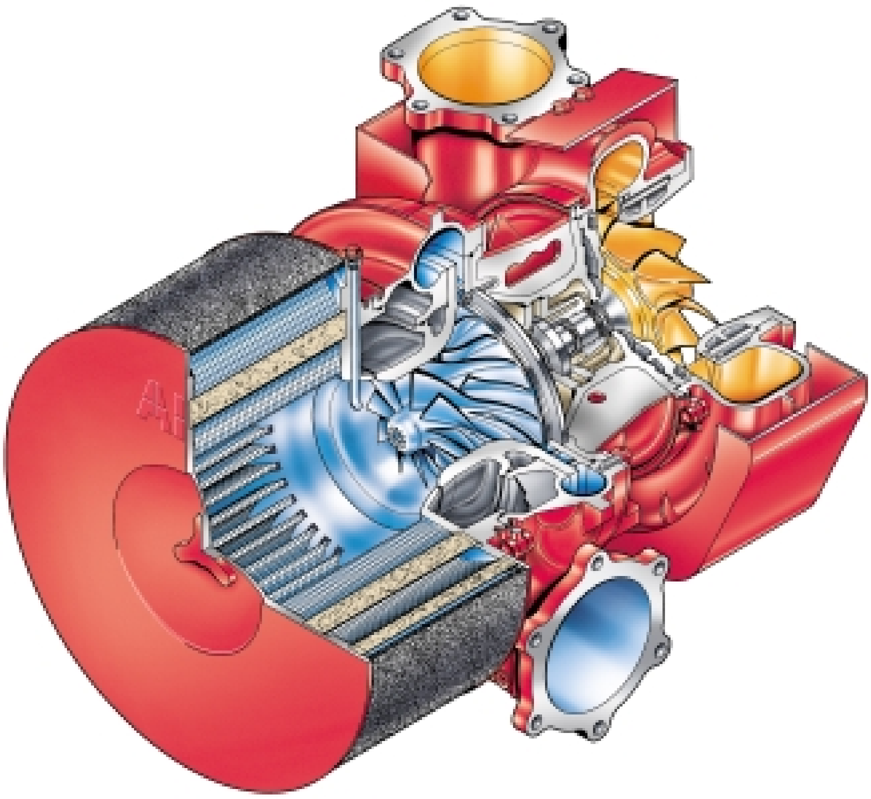
### Turbocharger design

The main design goal set for the TPL was a robust, simple and compact construction with a considerably smaller number of parts than in the popular VTR turbocharger. The modular design 3 offers maximum application flexibility. TPL turbochargers operate without water-cooling. All parts are easily accessible for servicing.

The turbocharger can be completely dismantled from the cold side, leaving the exhaust pipes and insulation in place. The round DIN-standard gas exit flanges provide a convenient connection to the exhaust pipe. Speed measurement, plus pressure and temperature connections in all the casings and washing devices on the turbine and compressor sides are standard features (although optional with the smallest size, the TPL61).

The two smaller sizes, ie TPL61 and TPL65, are built with an integrally cast turbine, a boreless compressor and a single-piece compressor outlet volute. The bigger sizes have single turbine blades, a split compressor volute and a center bore through the compressor.

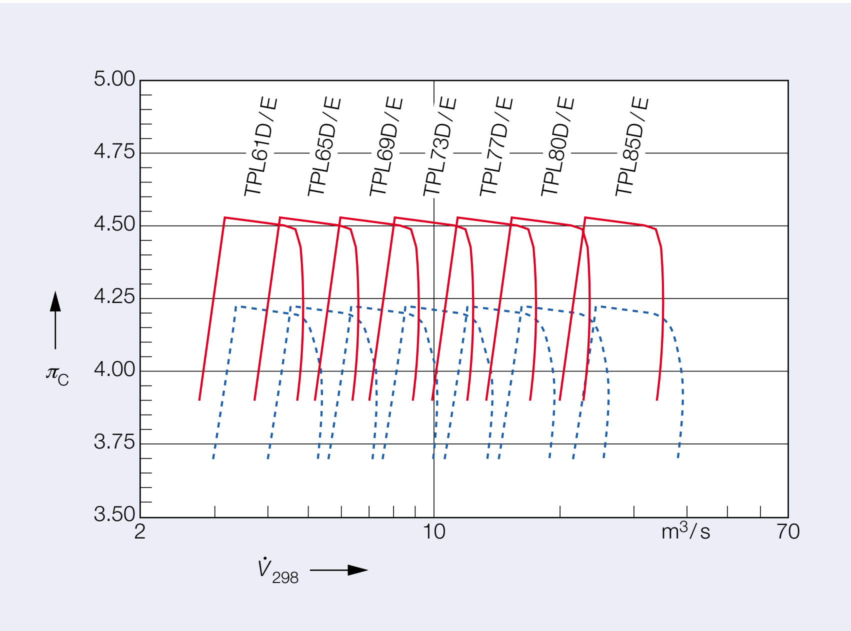
Two completely different compres-



*TPL turbocharger, designed for new types of four-stroke and two-stroke diesel engines rated from 1,000 to 25,000 kW per turbocharger* **1**

*Volume flow range of the TPL turbocharger series* **2**

$\pi_C$ *Compressor pressure ratio* Blue *D-version*
$\dot{V}_{298}$ *Air volume flow* Red *E-version*




sor designs provide the full range of pressure ratios required by modern turbocharged engines. The D-version is designed for a high flow rate, high efficiency and a pressure ratio of 4.2 : 1 at nominal engine load; the E-version allows a pressure ratio of 4.5 : 1 with an aluminium wheel for 50,000 h lifetime. These figures are based on ISO conditions and a load profile which is common to most applications. Higher pressure ratios at the moment require the use of titanium compressor wheels.

For pulse-charging systems there are gas inlet casings with one to four inlets in the axial and radial directions. The waste gate connection flanges in all the single entry gas inlet casings and in the gas outlet casing are precast and can be machined to order. Thus, the TPL is well prepared to handle all existing charging systems.

The design of the bearing casing is based on a cartridge concept. With the TPL69 and larger sizes there is also the possibility of dismantling single parts when the complete cartridge is too big or cannot be lifted on board the ship. All bearings are integrated in the bearing bush. The turbine side is separated from the bearing casing, thereby reducing the thermal load in the bearing region and keeping the temperature at an acceptably low level even after a hot shutdown.

## Component development

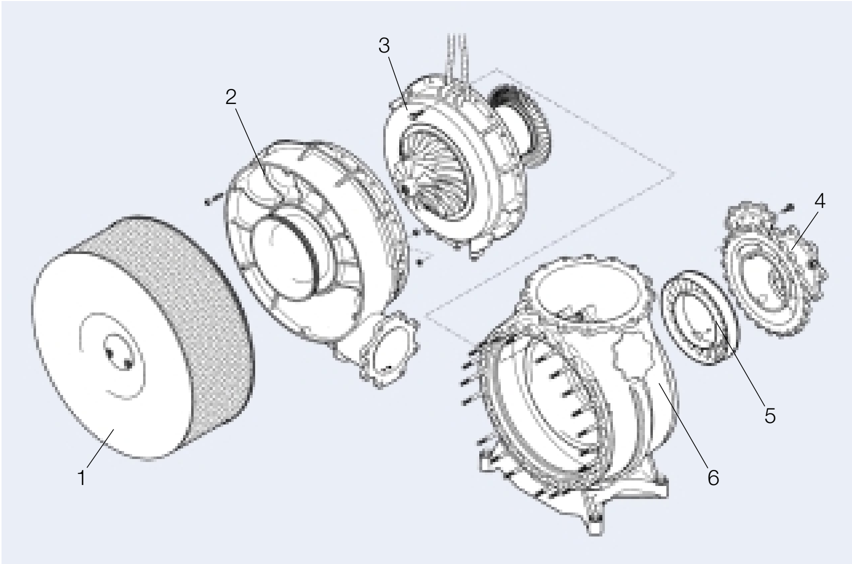
### Compressor

A market analysis has indicated that two centrifugal compressor stages with different flow capacities and pressure ratios are required for the various applications and allow optimum matching.

The development goals set for the TPL were:

- Full-load pressure ratios of 4.2 : 1 and 4.7 : 1 for the TPL..D and TPL..E, respectively
- Aluminium alloy impellers up to the pressure ratio of 4.5:1 (higher pressure ratios with titanium impellers)
- A high specific flow rate and state-of-the-art efficiencies
- A wide operating range for safe running on typical propeller and constant-speed operating lines

After the main dimension of the impellers had been determined by means of a one-dimensional analysis and design programme, comprehensive quasi-three-dimensional and three-dimensional viscous flow field calculations were performed to assist the aerodynamic design. The use of splitter bladed impellers allows high

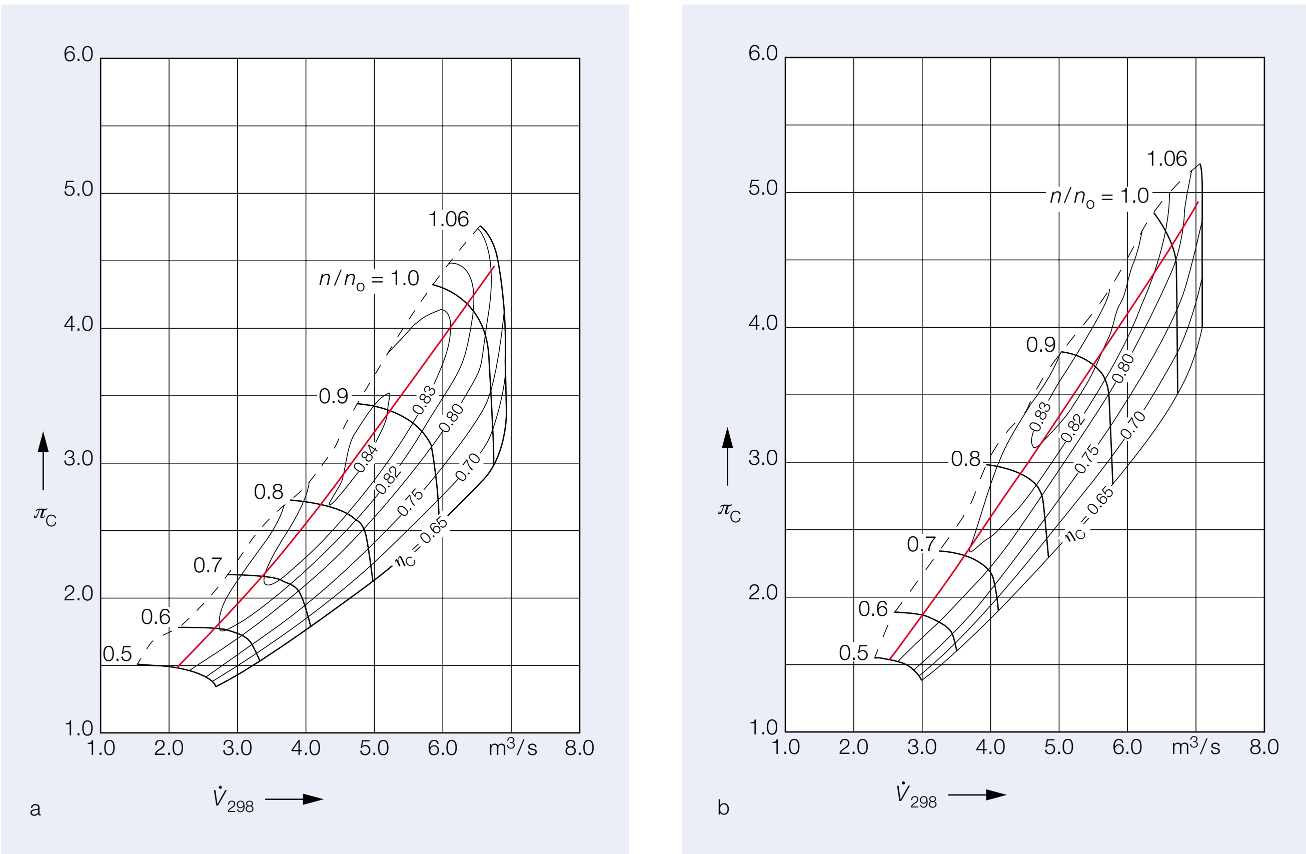


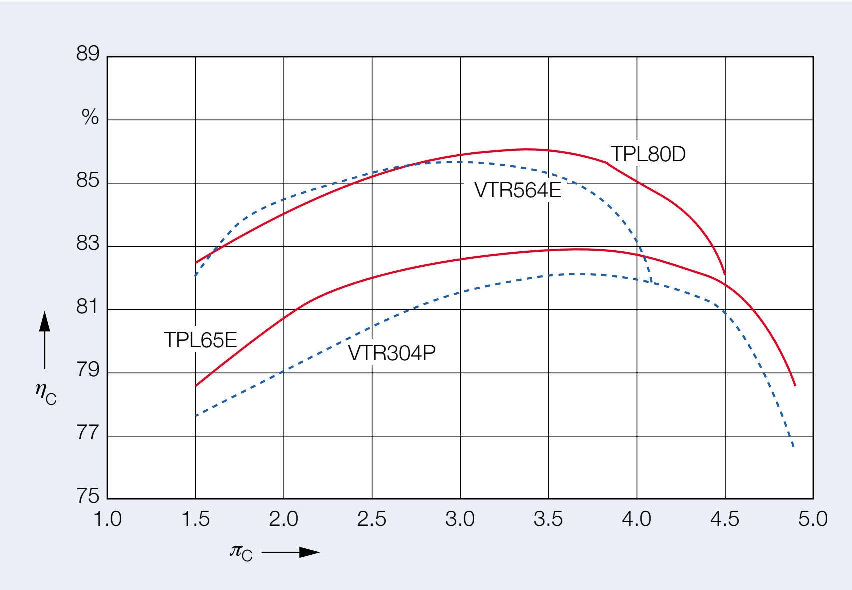

***Modular design concept*** **3**

1 *Filter-silencer*
2 *Air volute*
3 *Rotor block*
4 *Gas inlet casing*
5 *Nozzle ring*
6 *Gas outlet casing*

***Compressor performance maps of the TPL65D (a) and TPL65E (b) turbochargers*** **4**

$\pi_C$ *Compressor pressure ratio*
$\dot{V}_{298}$ *Air volume flow*
$n$ *Compressor speed*
$n_o$ *Design speed*
$\eta_C$ *Compressor efficiency*
— *Standard operating line*






***Compressor efficiency on a constant-speed engine operating line versus the pressure ratio. TPL..D/E compared with the VTR..4P and VTR..4E turbochargers*** **5**

$\eta_C$ *Compressor efficiency* $\pi_C$ *Compressor pressure ratio*

specific flow rates, while backswept blades at the impeller exit result in a broad compressor map **4**. Simultaneous two- and three-dimensional finite element calculations provided stress levels throughout the entire impeller as well as blade eigenfrequencies. This iterative design procedure ended in two thermodynamically and mechanically optimized compressor stages, which were then tested and further optimized on a compressor test rig and on the turbocharger itself. The resulting impellers, with backwards curved blades and cutback leading edges, were manufactured on modern five-axis milling machines.

The progress in achievable pressure ratio and compressor efficiency on a constant-speed engine operating line is shown clearly in **5**. In the one case, the performance of a TPL80D is compared with that of a VTR564E; in the other the efficiency of the TPL65E is compared with that of the VTR304P.

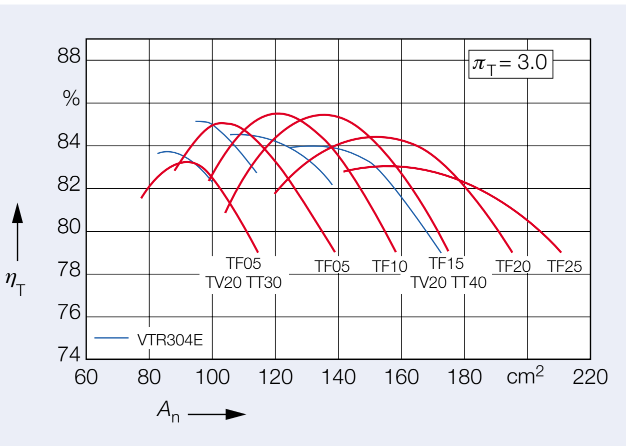
### Turbine

New demands are made on the turbine as the result of the increased compressor pressure ratios, the high turbocharger efficiency and the wide range of volume flow, which has to cover turbine inlet temperatures up to 750 °C. The need for pulse-charging and high pressure ratios

***TPL turbine efficiency versus nozzle area, compared with the VTR..4E*** **6**

$\eta_T$ *Turbine efficiency*
$A_n$ *Effective nozzle area*
$\pi_T$ *Turbine pressure ratio (constant at 3.0)*

TV *Blade version*
TT *Blade length*
TF *Stagger angle of blade*

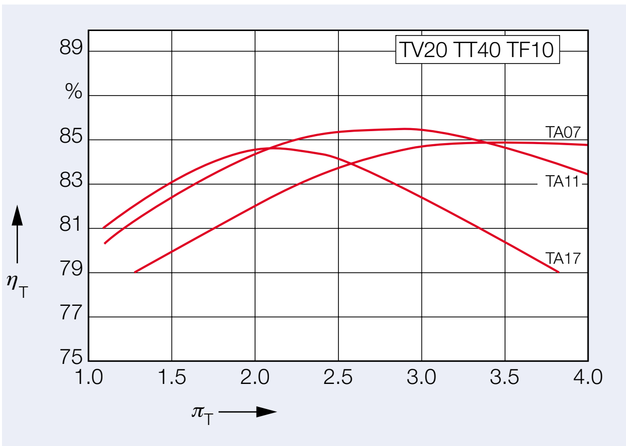



***TPL turbine efficiency versus turbine pressure ratio*** **7**

$\eta_T$ *Turbine efficiency*
$\pi_T$ *Turbine pressure ratio*

TA07, 11, 17 *Blade stagger angles in nozzle ring*

TV *Blade version*
TT *Blade length*
TF *Stagger angle of blade*



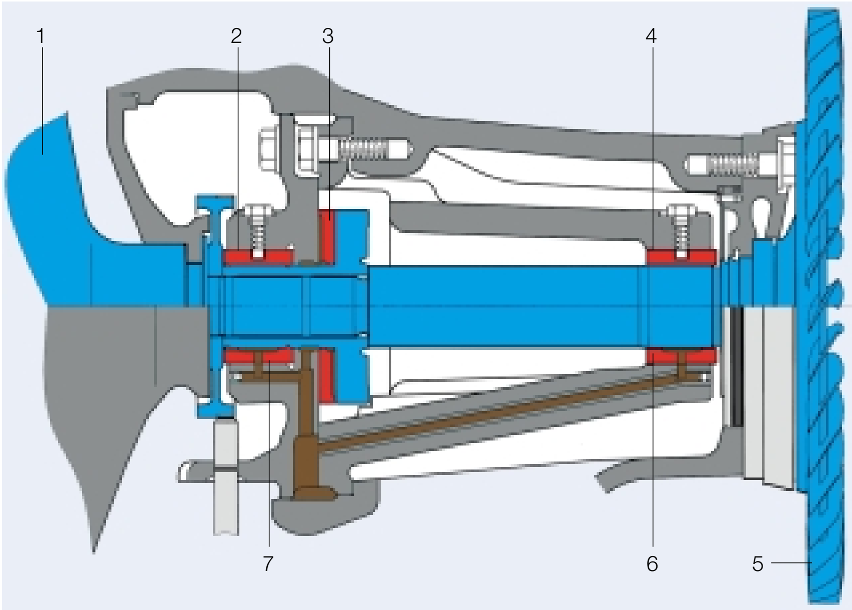
calls for maximum high cycle fatigue strength resistance.

To achieve the ambitious goals it was decided to use a proven 1-D code, including loss correlation, for the main dimension. The blade profiles were calculated using an inverse method that aimed at well-distributed Mach numbers at the lowest possible level. The overall design of the blade region and of the exhaust casing was checked by means of a fully three-dimensional computer code.

The aerodynamic design included strength calculations, in which finite elements were used to determine the stress and eigenfrequencies.

Six turbine families with different blade lengths and stagger angles cover the complete volume flow range. **6** shows the efficiency level versus the effective nozzle area for a constant pressure ratio of 3.0 : 1. The values are compared with the VTR..4E, calculated for the unit size 304.

The turbine efficiency versus the pressure ratio for three different specifications (ie, full load, intermediate and part-load optimization) is shown in **7**.




***Bearing assembly used in the TPL turbocharger*** **8**

| | | | |
|---|---|---|---|
| 1 | *Compressor* | 5 | *Turbine* |
| 2, 4 | *Squeeze oil damper* | 6, 7 | *Radial bearing* |
| 3 | *Free-floating thrust disc* | | |

## Bearings

Plain bearings were chosen as they ensure a long lifetime and stable operation over the full speed range. Of the total of 150,000 ABB (BBC) turbochargers so far delivered, more than 30,000 units have been built with plain bearings. All TPL bearings are designed for 50 µm mesh size filters and can be lubricated directly with the engine oil. The bearing assembly is shown in **8**.

The radial bearing bushes are fixed with three screws and centered in a squeeze oil film damper. The main thrust bearing consists of a free-floating thrust disc, including the profiled parts on both sides. The rotational speed of the thrust disc is about half the turbocharger speed. Due to this construction the speed gradient between the rotating parts and the casings is reduced by a factor of 2, resulting in reduced bearing wear when the oil is contaminated with particles. The thrust disc is coated with ADLC, an amorphous, diamond-like carbon layer and one of the hardest surface coatings known. As a result of this design the TPL bearings will give at least 35,000 hours of reliable service.

## Turbocharger performance

Performance measurements were carried out on ABB test rigs for all the turbocharger sizes and for different specifications. Typical results of these measurements are given in **9**. The high level of performance, especially at high pressure ratios, underlines the progress that has been made with state-of-the-art turbochargers.

## Mechanical test programme

Prior to market release, the TPL turbocharger was put through an extensive mechanical qualification programme that included:

- Dynamic strain measurements on the compressor blades
- High cycle fatigue tests performed on the turbine blades
- Shaft motion measurements
- Testing of the load carrying capacity and the limits of the thrust bearing
- Compressor and turbine end-seal oil leaking tests
- Gas leaking test
- Thermal cycling tests, carried out on the turbine casing
- Hot shutdown test
- Containment test for the compressor and turbine casings
- Low cycle fatigue test performed on the turbine components

Since the TPL65 and TPL69 are constructed differently, a containment test was performed with both of these sizes. It involved the compressor wheel being weakened so that the burst speed would equal approximately 120 % overspeed – the calculated maximum possible speed in the case of a fire in the exhaust receiver. The turbocharger was heated to its normal operating temperature and then accelerated to the burst speed of the compressor wheel. The wheel consequently broke into several large pieces and the turbine continued to accelerate up to its natural burst speed. The requirements of the containment test were met by both sizes. All parts remained inside the casings and the kinetic energy was completely absorbed through internal destruction. No signs of damage were visible on the outer surface of the casings **10**.

### Experience with TPL turbochargers on engines

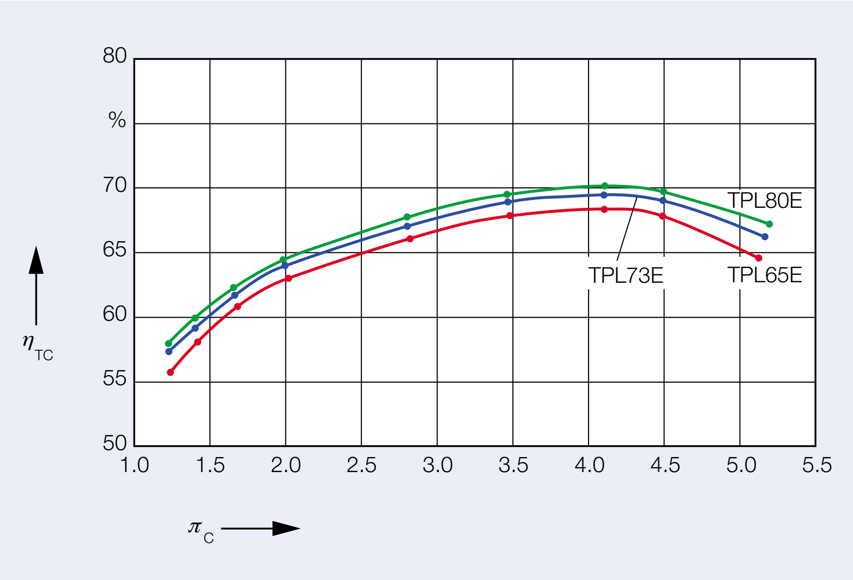
Even the best qualification programme in a laboratory cannot replace the experience gained through real engine operation. A small number of prototype TPLs in each frame size were therefore produced at an early stage in the project and supplied to some ABB clients for intensive testing on their diesel engines.

The feedback from these prototype tests enabled ABB to identify critical mechanical areas at an early stage in the design. Where weaknesses did occur, solutions could be found and introduced before start-up of production of the 0-series.

In addition, the engine builders were able to simultaneously design and test new engines, utilizing the benefits of the TPL from the very beginning. It is worth noting that TPL prototypes have been used to turbocharge no fewer than seven prototype engines, two of which are now in commercial operation: the Wärtsilä 12V38 (turbocharged with two TPL69E units) and the MaK 16M32 (two TPL65D units **11**). The thermodynamic performance of the TPL measured in the ABB laboratory could generally be confirmed.

***Turbocharger compressor ratio, for different TPL turbocharger sizes*** **9**

$\eta_{TC}$ *Turbocharger efficiency*
$\pi_C$ *Compressor pressure ratio*




The TPL turbochargers have also proved their capabilities on well-established engines. For example, the Wärtsilä 6L46, originally designed for high bmep, was turbocharged with a prototype TPL73E for an experimental 1,000 hours endurance test at very high mean effective pressure and operated on a special high-ash, heavy fuel oil. During this test, the turbocharger pressure ratio was 4.8 : 1, the load being increased in the last 50 hours until the pressure ratio was close to 5.0 : 1. This achievement was only made possible by the superior turbocharger efficiency at this high pressure ratio. In every other case (except for 2-stage turbocharging) the heat load of the engine would have been intolerably high.

Still more highlights were experienced during the test phase of the TPL: the world's most powerful 4-stroke medium-speed engine, the Wärtsilä 6L64 **12**, was turbocharged with the first TPL80E to be produced. As this engine was also the first ever of its kind, the schedule for the prototype TPL80E was accelerated in order to meet the required delivery date.

In addition to the engine tests carried out in various laboratories, a field test turbocharger on board the ferry *M/S Polonia* has been running since November 1996. The TPL69E was fitted instead of the original VTR354 on the Wärtsilä 6L38 and has since accumulated more than 5,000 running hours. The purpose of the field test is to gain long-term experience of bearing wear, gas erosion, turbine cleaning, etc.

A further test turbocharger was installed on board the same vessel in October 1998. This field test serves as a platform for more futuristic mechanical solutions inside the turbocharger, but will also provide a better statistical base for component lifetime predictions, etc.

Two TPL73E units have also been in field test operation since December 1997 in a 4-stroke marine application, while a number of 2-stroke marine applications with the larger TPL frame sizes additionally got under way in 1998. In all, some 300 TPL units have been installed in marine applications to date.

### Mechanical behaviour

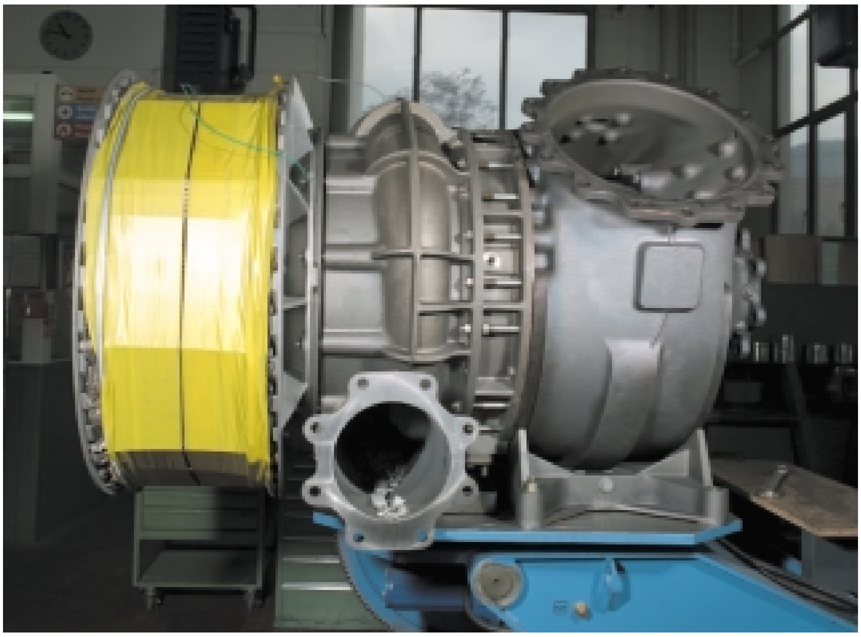
The various engine tests confirmed the mechanical reliability of the new turbocharger. Problems that did occur in the first prototypes were eliminated by introducing new solutions, the reliability of which has since been proved by further tests, eg involving the heat shield and auxiliary bearing.

The ABB bearing concept has proved to be successful. No signs of wear have been found on the main thrust bearing parts during the longest running field test on board the ferry *M/S Polonia*. Typical running-in marks are found on the radial bearing bushes. Some wear on the auxiliary bearing occurred during start-up of the engine with cold oil and high oil pressure, but this could be cured by a new auxiliary bearing design and by increasing the supply of lube oil. The improvements have been confirmed in the laboratory and by engine tests.

*Black start*

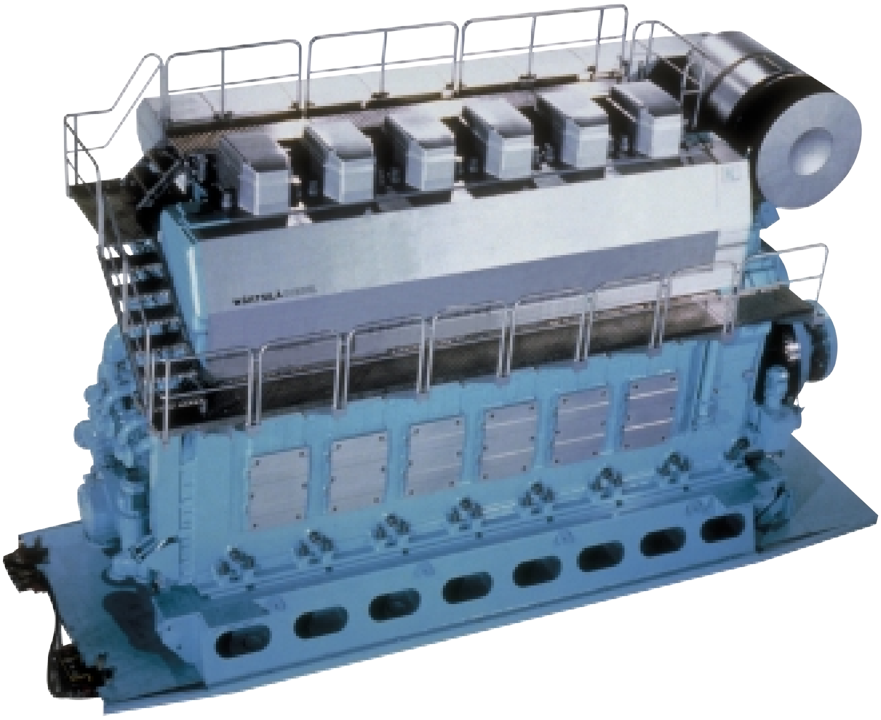
Although pre-lubrication is generally prescribed, a customer wished to see the consequences for the bearing of an engine start-up without pre-lubrication. This requirement could apply, for example, in cases where a ship is started after a black-out (ie, a total loss of electrical power).

Several tests were conducted, with encouraging results: after a standstill of 30 minutes the engine in question was started and the turbocharger went to 8,000 rev/min in less than 4 s. However, it took the engine-driven lube oil pump 10 s to build up the oil pressure in the turbocharger. For the few seconds in between, the turbocharger was in principle running without oil. In spite of this, no signs of wear could be detected during the



***TPL69 after the containment test*** **10**

***TPL65D turbocharger on an MaK 16M32 engine*** **11**




***TPL80E turbocharger on a W6L64 engine from Wärtsilä*** **12**

following inspection. This is taken as a good sign that the bearings are also safe during certain off-design operating conditions. ABB does, however, still insist on pre-lubrication of the turbocharger before operation. During another test with a repeated number of black starts and slower build-up of lube oil pressure, wear was visible on the axial free-floating bearing disc.

**Outlook**

Further demands are sure to be made on the pressure ratio in the future. To be prepared for this, ABB Turbo Systems has taken first steps towards developing the F-Version, including new compressor and turbine stages. The goal for the pressure ratio is 5.2:1. This pressure ratio is only possible with a titanium compressor wheel, however at a very much higher cost. Another interesting question that is still unanswered is the pressure ratio that can be achieved with an aluminium alloy impeller.

One of the main difficulties in developing the new turbocharger generation involved the high cycle fatigue resistance of the turbine blade when strong pulse-charging systems are used. Efforts in this domain continue to produce stronger profiles without punishing the turbine efficiency too much.

ABB Turbo Systems has many years of experience with roller bearings in the VTR. The better part-load and acceleration behaviour due to the low mechanical losses in the roller bearings is well known and indicates that it could be worthwhile considering such a solution for the TPL. Roller bearings demand very clean oil, which probably rules out using the engine lubrication oil for the turbocharger. An independent oil supply system will therefore probably be needed.

With higher pressure ratios, part-load behaviour becomes more and more of a problem. A variable turbine geometry can help to reduce this problem. The modular design of the TPL allows such an option to be considered if and when it is needed.

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