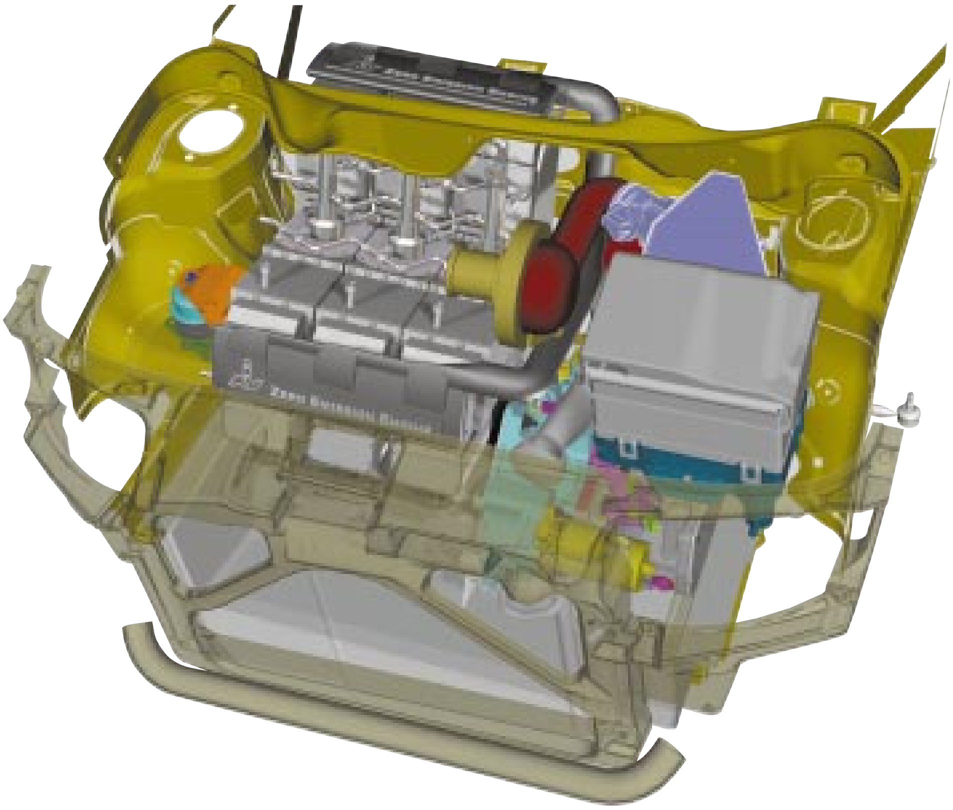

Zero Emission Engine – The Steam Engine with Isothermal Expansion

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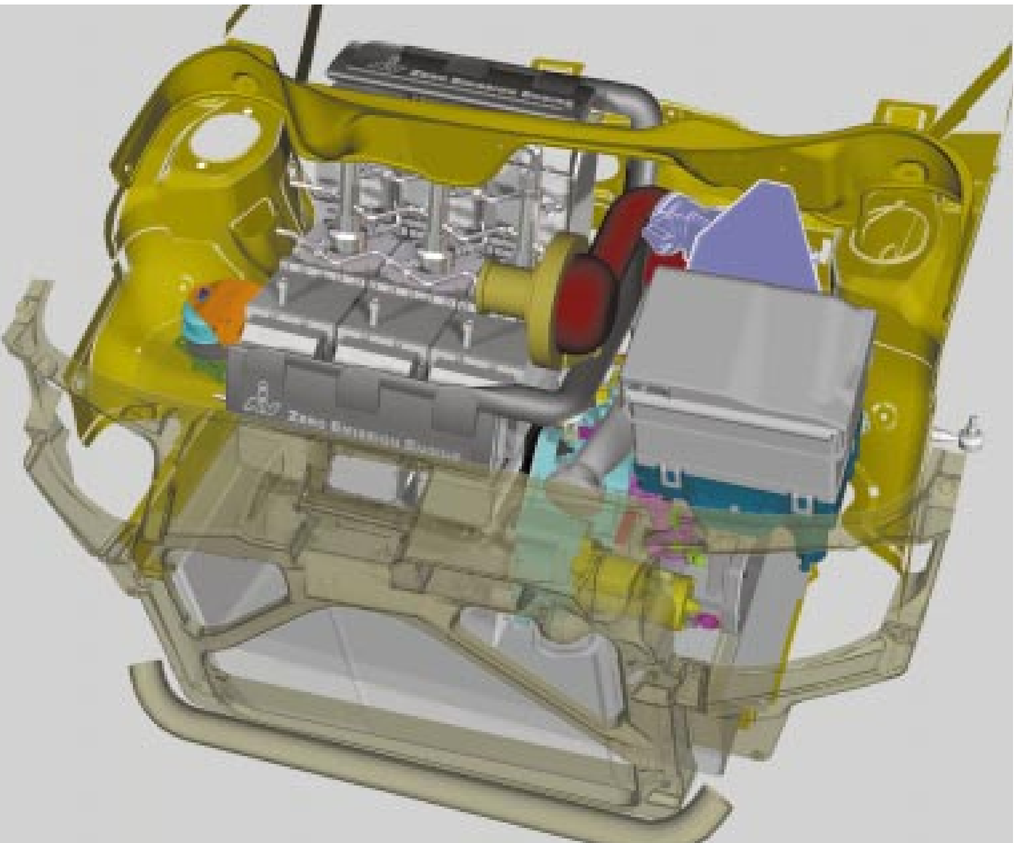

ZEE installation study

Since the middle of the 1990s, IAV GmbH, Ingenieurgesellschaft Auto und Verkehr, in Berlin has been working on an innovative concept for a SULEV power unit. This development involves an advanced steam engine with a high-performance burner which features extremely low pollutant emission. This report presents the entire project and the current status of work. The forecast section describes the ongoing progress and the planned orientation of the project.

1 Introduction

In the early 1990s, the first publications appeared with information on extremely compact and low-emission atmospheric burners. Indications of nitrogen-oxide concentrations of less than 10 ppm, and HC and CO emissions at the very limit of detection, gave rise to the idea at IAV to engineer a vehicle powertrain using this type of burner, and to examine whether such engines would conform to the SULEV standard.

An innovative powertrain must offer a good compromise of a great variety of requirements, demonstrate the potential of operation equivalent in all the essential characteristics of current internal combustion engines and promise superiority to such conventional engines in the future. **Figure 1** describes these requirements. Such an innovative powertrain must also offer an overall concept amenable to series production; individual outstanding characteristics would by no means be able to compensate for serious shortcomings.

At IAV, various powertrain concepts were discussed for the combination with the new high-performance burners. The steam engine proved to be the most promising compromise for the stated objective. The conception of the theoretical steam engine chosen was modified such that it promised to be suitable for applications in stationary operation, especially for small unit-type district-heating power stations – as well as for highly dynamic vehicle operation. The concept was declared to represent a zero-emission engine (ZEE).

In the IAV development team, which was initially small, the realisation grew that the ZEE could not successfully be treated with euphoric pioneering spirit – but rather neutrally, with solid engineering work. In this sense, the present article is intended as a contribution to discussion on a highly interesting object of development, and as a report on the results of development until now.

2 Point of Departure for the Development of an Advanced Steam Engine

In retrospect, the development activities of the early 1970s were significant, in view of upcoming emission legislation in California, as a move towards the objective of developing steam engines as vehicle power units. ([2]-[5])

The benefits were interesting even then: low exhaust emissions without exhaust-gas after-treatment, modest requirements with respect to fuel type and quality, and a highly favourable torque curve. Consequently, it was seen that a conventional transmission system was not necessary.

There were, however, serious shortcomings, such as only moderate efficiency, high weight and lack of regulation possibility. The low efficiency was due to the restricted selection of materials possible at that time, and the resulting low steam temperatures. Microelectronics, controllers and actuators at the present level were unknown.

It was therefore deemed imperative for the present project to concentrate attention on especially these areas for the new development of the desired steam engine: a ZEE. But how can one begin with such development when there was almost no previous experience in this area? The following will elaborate on the prerequisites which form the basis for future project work on the ZEE.

2.1 The ZEE Concept

As early as the first calculated estimates it became clear that SULEV would represent no conceptional problem for the application of an advanced, low-emission burner. The real challenge, however, lies in the conversion of thermal to mechanical energy, while retaining all the familiar characteristics of modern motor vehicles.

A fundamental study of the operational cycle proved to be essential, since the efficiency and the fuel consumption would represent a decisive characteristic for acceptance of the concept.

Upon investigation of the process control employed in highly developed steam power plants, it becomes highly apparent that such systems always employ multiple expansion and intermediate superheating steps to enhance their efficiency. From the thermodynamic standpoint, this amounts to an approximation of an isothermal expansion cycle. In steam turbines, it is not possible to directly admit the required flow of heat during the expansion phase.

The situation is more favourable with a reciprocating internal combustion engine. Compared to turbines, such engines possess a much higher surface-to-volume ratio, with appreciably more wall surface available for heat transfer. The great advantage of an isothermal cycle is the greater efficiency in comparison to the classic Rankine cycle.

Figure 2 shows the concept of the ZEE in an initial test set-up. The surfaces of the expansion chamber, shown greatly enlarged, are heated by a burner. The still-hot exhaust gas then heats the feed water of the closed steam cycle to a supercritical temperature in a compact steam generator. Waste heat which must be dissipated is transferred via two heat exchangers and the burner cooling systems into the feed water. This configuration optimally exploits the efficiency potential of the isothermal steam engine.

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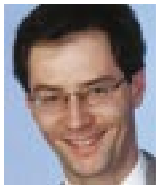

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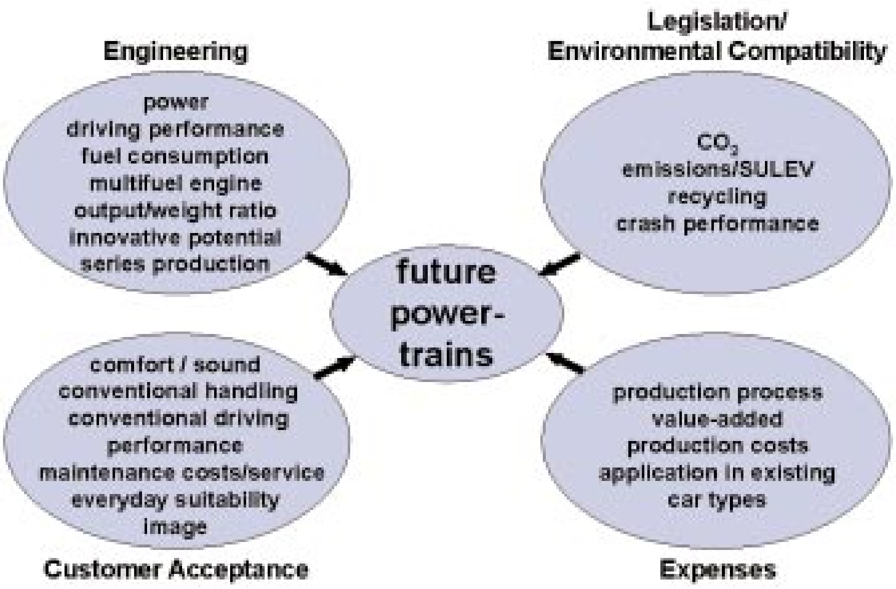

Figure 1: Marketability and customer acceptance demands for future powertrains

For the operational state of the steam, the following compromise was achieved between feasibility and the actual goal of the ZEE:

– Steam pressure p_S = 100 bar
– Steam temperature downstream of the evaporator T_S = 800 °C.

2.2 The Supported Project

Preliminary studies established that the idea of the ZEE was feasible. The next step in a development project was to define the goal. The following was chosen as an objective for the preliminary work: to determine whether the ZEE is suited to serve as a serious alternative to conventional motor-vehicle power units, and whether the ZEE, after successfully achieving the engineered characteristic values, would represent a concept which could be pursued up to the start of actual vehicle production.

In order to be able to answer this question, IAV decided to initiate a development pro-

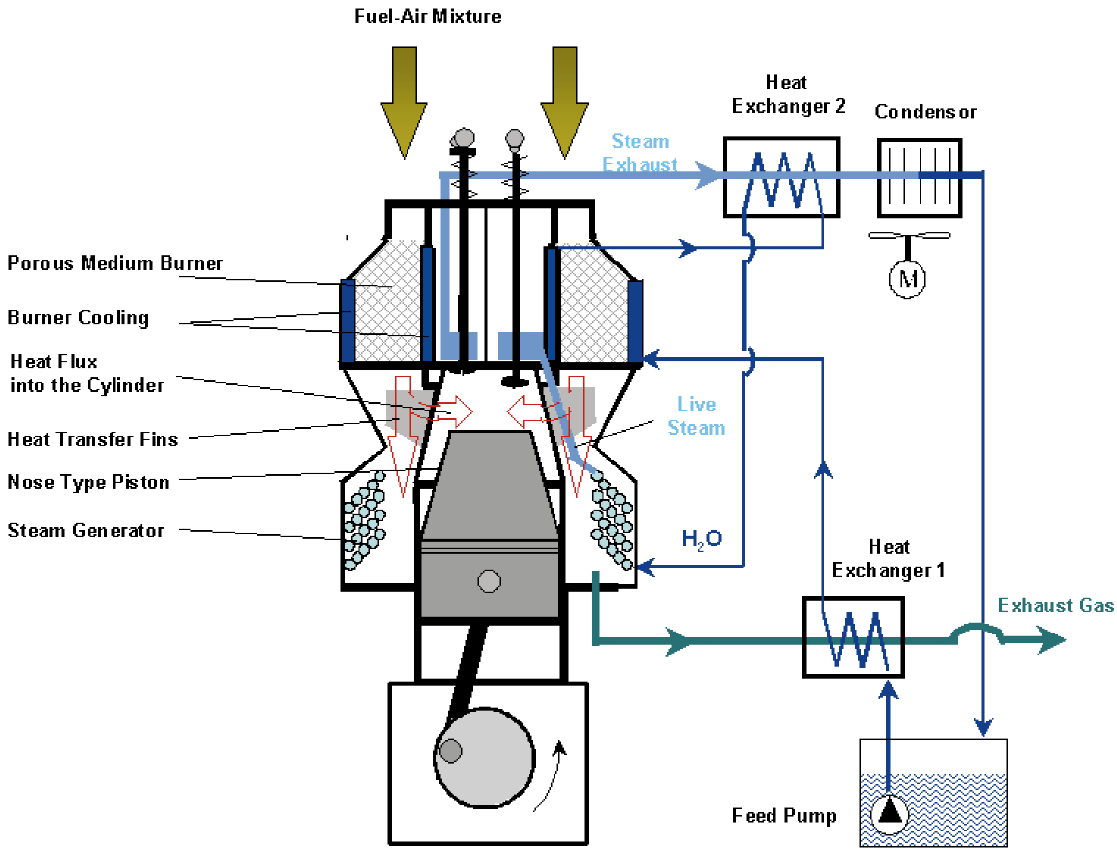

Figure 2: Thermodynamic process of the ZEE with addition of heat (isothermal) during expansion

ject for the ZEE. In this initial phase, a feasibility study, IAV found its project partners and organized a team consisting of engineers, project managers and financing experts.

With the aid of public support and financing shares contributed by the project partners, it was possible to secure the required financing volume of almost 30 million Deutsche marks. The following public sources contributed to the project: the Senate of Berlin, with Senate Administrations for Environment and Technology, Economics, and Business Operations; the Senate Administration for Construction, Housing, and Transport; and the technological foundation Innovationszentrum Berlin. Without the support of these institutions, this project would not have been possible. The goal of the ZEE project is the development, construction and testing of ZEE prototypes for stationary operation in application for unit-type district-heating power stations, as well as for dynamic vehicle operation. Another objective is to draw definite conclusions on whether the ZEE is capable of being developed up to the point of series production.

As of now, 70 staff at IAV GmbH are assigned to the development of the ZEE. Forty additional experts are assigned to the project in the partner companies: Berlin Ober-

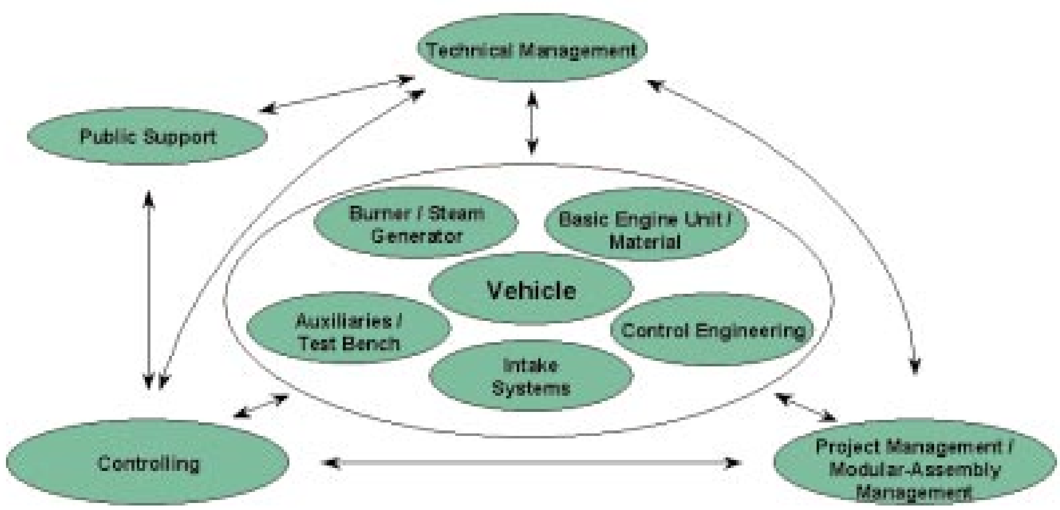

Figure 3: Project organisation

spree Sondermaschinenbau GmbH, Motoren GmbH Greiner, Sachsenring Entwicklungsgesellschaft mbH, Britze Elektronik Gerätebau GmbH, the Institute of Fluid Mechanics at the University of Erlangen and the Institute of Mineralogy at the Free University of Berlin.

2.3 Project Organization

Figure 3 schematically shows the organisational structure of this research project. One objective was to enable interdisciplinary work in a team. Motivation, information exchange and creativity enjoyed top priority. This team was supported by technical leadership and by a tightly organized finance and project-control staff – in order to minimise organisational demands on the development staff and to concentrate all activities on the common goal. As Figure 3 shows, the breakdown of responsibility basically follows vehicle powertrain functions, so-called modular assemblies. One modular-assembly manager is responsible, with his staff, for each particular area of work.

One fact is essential, however. The functions described here do not involve isolated departments: rather, the entire staff is one development team which is also responsible in its entirety for the results of the project.

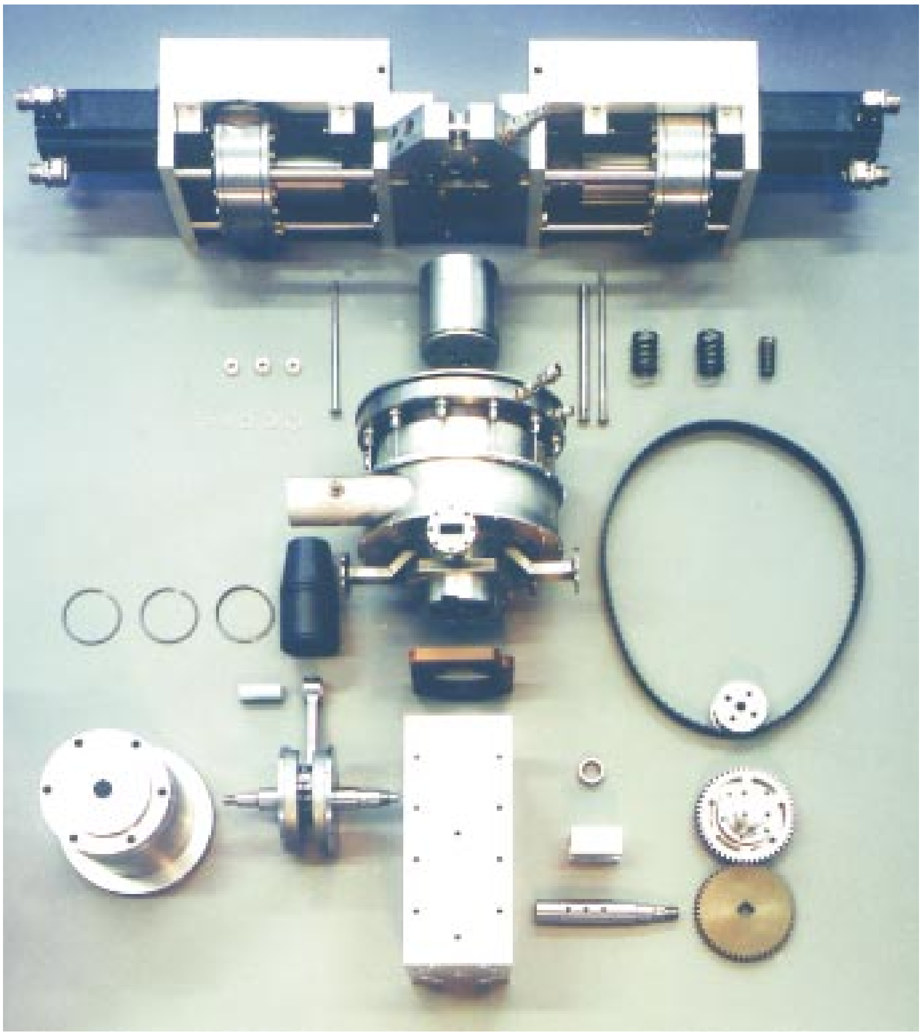

Figure 4: ZEE02 research engine

3 Focal Points of the Development Work

The ZEE01 engine built for study purposes in the context of the feasibility study was further developed after approx. one year of basic work.

The ZEE02 engine followed, and was primarily intended to clarify fundamental questions; it was designed and built as a single-cylinder research engine, **Figure 4**. In addition, the construction of completely new set-ups was required to provide suitable testing systems for the engines and the modular assemblies. As a result, component test benches and test systems are now available for all modular assemblies of the engine.

A series of software tools furthermore supports the conceptional planning, the design and the analysis of the ZEE functions. New development of this software was also necessary.

The following questions were investigated:

- Is approximation to isothermal process control possible, and what efficiency potential results from this?
- Is it potentially feasible to lie significantly within the levels of the SULEV standard?
- What tribological systems (material combinations) are suitable?
- Is pure hydro-lubrication of the basic engine feasible?
- What materials can withstand the great thermal demands?
- Which jointing and sealing technologies can be applied here?
- What requirements must a newly developed controller satisfy?
- How will the machine react to sudden load variations?

The ZEE02 is shown in **Table 1**.

3.1 Operational Cycle

Figure 5 depicts the equivalent thermodynamic cycle of a steam engine of conventional design (the Rankine cycle). It features isentropic expansion ($3 \rightarrow 4$) and a process with isothermal expansion ($3 \rightarrow 4'$) on the

Table 1: Main measures ZEE02

Cylinder bore:	74 mm
Stroke:	75 mm
Displacement:	322 cm^3
Mode of operation:	2-stroke
Cylinder output rating:	8.5 kW
At a speed of:	2000 rpm
Maximum speed:	2500 rpm
Maximum torque:	137 Nm
At a speed of:	200 rpm
Burner output rating:	2 ... 40 kW (infinitely variable)

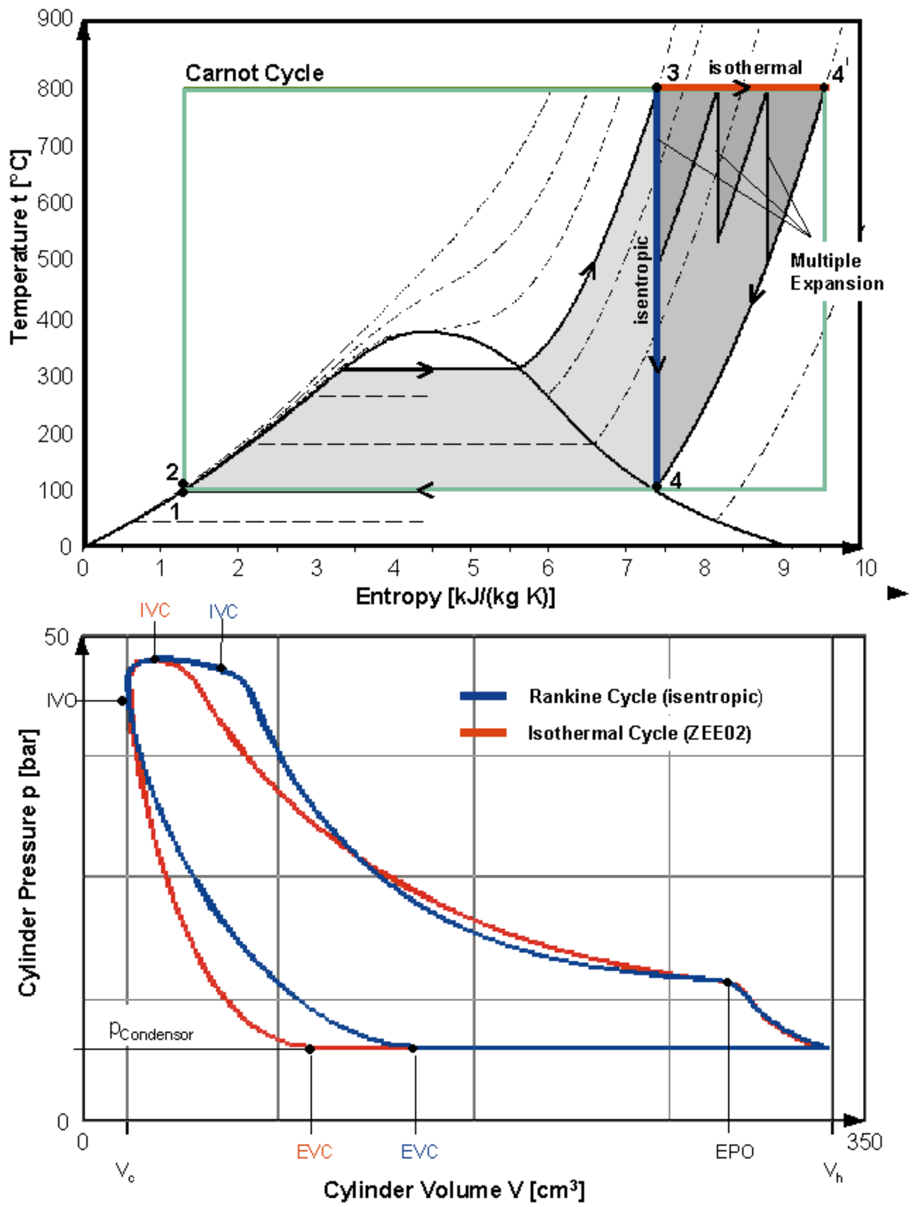

Figure 5: Comparison of the steam cycles: rankine cycle and isothermal ZEE cycle

T-s and p-V diagram. It is apparent that the work capability of the isothermal cycle mode is greater for equal maximum temperatures (evident from the larger enclosed area on the diagram). This follows as a matter of course, since heat continues to be introduced during the expansion step. A comparison of the two cycle courses on the T-s diagram discloses the following difference in thermal efficiency.

For the project-design steam pressure of p_S = 100 bar and a steam temperature of T_S = 800 °C, an ideal Rankine cycle will result in an efficiency of 36.8 %. Isothermal process control will enable an efficiency of 50.3 % – which, to be sure, lies near the optimal Carnot efficiency:

$$\eta_{Carnot} = (1 - T_{min}/T_{max}) \cdot 100\% = 65.2\%$$

With the exception of the curve of the process involving expansion, and apart from the required exhaust-steam heat exchanger in the case of isothermal operation, the remainder of the steam cycle is designed identically as for the Rankine cycle. With its primary components of condenser, feed pump and steam generator, it also consists of the same components as for a Rankine cycle. Owing to the insufficient heat resistance of a number of subcontracted components (especially the control fittings for the steam cycle), and due to the lack of alternatives in this performance class, it was not possible during testing to achieve the project-design operational conditions which had been targeted. It was therefore necessary to reduce the pressure and temperature to moderate values: T = 500 °C and p = 50 bar.

The p-V diagram in Figure 5 presents a schematic representation of the effects of the various process-control types in the powertrain. The following aspects must be taken into sufficient account for the design of the engine operation cycle:

- The useful speed range of a steam engine is restricted owing to the conditions of flow within the steam generator and inside the intake components. High performance requires large flow cross-sections, but the ability to precisely meter out the flowing medium dictates small cross-sections. This imposes a maximum engine speed limit of 2,500 rpm.
- This maximum speed is high for steam engines (the usual speed is within the range of 800 ... 1,200 rpm), and it prevents the use of a slide valve for control. For this reason, poppet valves are used.
- The long-term concept developed by IAV for a compact powertrain capable of effective implementation for motor vehicles features a two-stroke principle with outlet ports, without a crosshead and without double-acting pistons.
- The optimisation of efficiency during the concept phase demands a power control system which ideally functions without a throttle – and which is implemented by variable intake-valve closing and by control of the initiation of compression by variable outlet-valve closing.

For the case represented by equal indexed work at the piston ($W_{KA} = \oint p\, dV$), the intake-valve closing is appreciably earlier, owing to isothermal process control. Less steam consumption consequently results.

An additional significant question for the design of the engine operational cycle concerns the medium of operation. IAV studies disclosed that the classical medium for steam engines – pure water – also represents the best compromise for the ZEE as well. The thermodynamic and calorific data of this medium played a role in this decision, in addition to the following factors: aspects of temperature stability, the position of melting and boiling points, the necessity for hermetically sealed plant technology, and – finally – the environmental compatibility of the medium. Disadvantages of water as a steam-engine medium include its great heat of evaporation and the danger of freezing.

3.2 Materials and Tribology

Conventional steam engines operate with oil lubrication. Great care must be taken to prevent oil from entering the steam cycle – and to prevent excessive water concentrations in the oil.

Lubrication oils are limited in their capabilities to withstand high temperatures. As a result, the respective components must be cooled or the temperature of the live steam must be limited. At the same time, however, a cursory study of the thermal efficiency of the ideal Carnot cycle reveals that the difference of the temperature extremes realised in the cycle must be designed to be as great as possible. Since there is a lower limit to the cycle temperature – as dictated by the transfer of heat to the environment and by the crystallisation of water – the maximum temperature must be as high as possible in order to achieve appreciable efficiency. The use of oil therefore generally opposes the raising of the temperature level and, in turn, of the efficiency. This effect becomes especially important upon consideration of an isothermal process. For this reason, logic compels the use of water or steam for lubrication of the ZEE. **Figure 6** depicts the various aspects which are related to the topic of material selection:

Since water exerts a highly corrosive action at high temperatures and in the presence of oxygen, the material selected for use must be highly resistant to oxidation. Most ceramic substances for such uses satisfy this condition – as well as nickel alloys and steel resistant to high temperatures.

The decision not to use a crosshead structure eliminates the sealing of the process compartment by means of rod sealing. Since it will not be possible to eliminate blow-by even with the use of piston rings, water will build up in the crankcase. This requires a tribological system which is water-tolerant or which is capable of operating dry. It has proven effective to use carbon-ceramic components for sliding contact against lapped and hardened steel surfaces or against ceramic surfaces. From the current standpoint, therefore, the preferred solution here would involve a carbon piston and carbon ring in conjunction with a nitrided or special-finish cylinder liner. Carbon materials evidently offer a great potential for application with current technologies.

In the area of the crankshaft bearing system, a roller bearing is currently being employed which ensures perfectly satisfactory function with water as a coolant and lubricant. Further work is being conducted on a sliding-bearing system for the crankshaft and the connecting rods. Tests are also taking place on using additives in the water, in order to enhance abrasion protection, increase viscosity and provide frost protection.

These developments are a long way from completion. They involve genuine fundamental work in which even experts in these fields have astonishingly great difficulty in making reliable predictions. The dependence of reproducibility on the exact maintenance of initial conditions calls chaotic systems to mind. Through close collaboration with project partners, specialised companies and materials-science institutes, we have in the meantime succeeded in establishing a basic stock of material combinations which have proved effective in tests on the ZEE. They have already undergone initial successful applications in the series-production development of conventional engines.

Figure 6: High-performance materials of the ZEE02

3.3 Burner

The burner must satisfy a great number and variety of requirements. It must feature extremely low-emission operation, compact dimensions and as high a level of power-output modulation as possible. The so-called porous medium burner, **Figure 7**, fulfils all these stated requirements. A further advantage of this type of burner is its freedom of shape, with the result that its design form can be adapted to the prevailing installation conditions. These porous medium burners do not operate with an open flame. Rather, they represent a thermal reactor whose temperature is controlled via a burner cooling system (see Figure 2), in order to prevent thermal NO. The chemical reactions take place in hollow compartments (the pores) inside the burner. These compartments are large enough so that their surface-area/volume ratio (expressed by the Péclet number) allows a reaction, but prevents the proliferation of an individual flame front. In addition, the porous medium structure conducts the resultant heat and ensures a compensated and controllable temperature balance throughout the entire burner.

The so-called ring burner produced for the ZEE02 has a thermal output rating of 40 kW with an air ratio of 1.5. This porous medium burner was operated for natural gas and gasoline with practically identical resultant

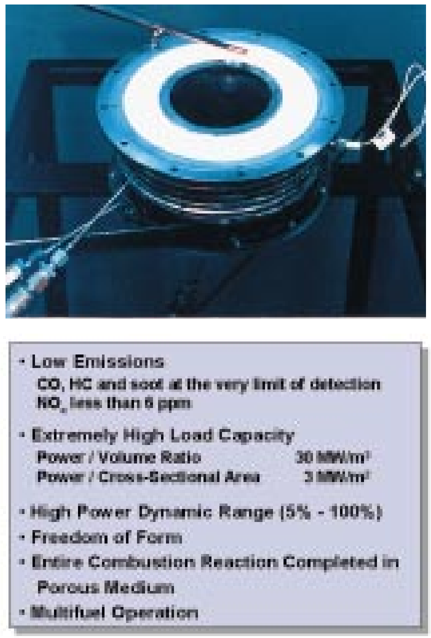

Figure 7: Porous medium burner of the ZEE02

pollutant concentrations. Operation with diesel oil will likewise be possible after the introduction of low-sulphur fuel. There is no objection to operating the burner with any other combustible substance: the only condition is that this substance is available in a gaseous form – or that it allows itself to be atomised sufficiently to produce a sufficiently homogeneous mixture. In this sense, the burner is truly a multi-fuel system, and it is only the admixing circumstances or the vaporiser unit which must be adapted to the respective fuels.

3.4 Steam Generator

The conversion of thermal energy into the medium of operation takes place in the steam generator (see **Figure 8**). The power rating is approx. 40 kW, and the configuration is ring-formed around the cylinder. This steam generator was designed by IAV and manufactured by its project partners.
This generator design features twelve individual tubes made of austenitic steel. They are coiled similar to a spring washer and are stacked on top of each other, each with an offset of 30°.
The result is a compact configuration which, together with the burner, allows the passing of the exhaust gas axially past the cylinder. This produces the introduction of heat into the engine process of approximately 15% of the indicated output rating.

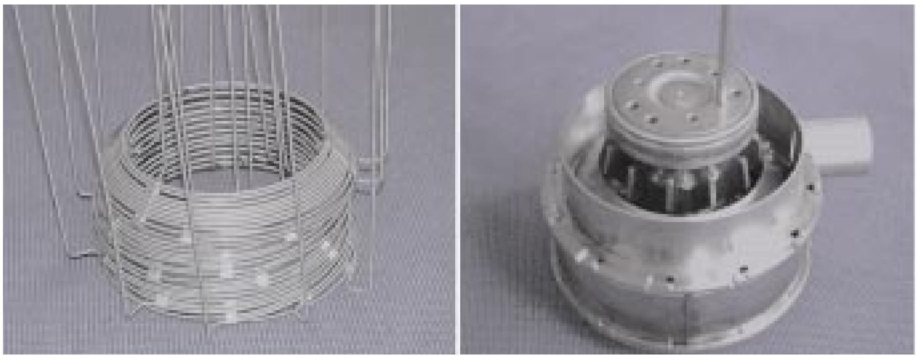

Figure 8: Steam generator of the ZEE02

3.5 Closed-loop Control

The operational cycle of the ZEE also places novel demands on the control system employed. After all, such a vehicle engine may not differ essentially in its operational behaviour – especially in its dynamics – from that of a conventional powertrain. The control requirements and systems, on the other hand, are basically different from those of internal combustion engines. It is necessary to distinguish between two different systems:

1. The pure open-loop control of quantity flow with the aid of the intake units
2. The closed-loop-controlled maintenance of steam quality with the aid of the burner / steam-generation system.

The first system basically corresponds to a conventional injection system (with mechanical or hydraulic control). The second system must compensate for the influence of the steam states which is brought about by the change in the load or by a change in speed. Without closed-loop control, however, this is not possible on a stable basis for stationary operation. This is because each manipulated variable exerts a lesser or greater influence on all controlled variables. In addition, each link in the closed-loop chain has a different response time. For this reason, it is necessary to provide closed-loop control to ensure the required values for the three variables pressure, temperature and steam flow, with the manipulated variables pump speed, burner output and delay angle (cut-off).

In addition, the various response times must be taken into due consideration. The burner, for example, will react within milliseconds. The steam generator, on the other hand, operates within a range of seconds. This leads to a modification in steam quality in processes subjected purely to open-loop control. The purpose of the closed-loop ZEE control system is to prevent fluctuating steam quality from becoming noticeable and to avoid the impairment of the dynamic vehicle behaviour. At present, the test-bench results obtained for the ZEE02 are being used as a basis for developing a controller for its vehicle-suitable successor, the ZEE03. In view of this objective, it is necessary, in addition to the hardware, to provide software tools which simulate the entire steam cycle – including the engine-operation process and the burner/steam-generator system – and to test them with respect to closed-loop control strategies.

4 Results

The ZEE02 described in the previous section has been operated both as a conventional steam engine with an external burner and an unheated expansion chamber (i.e., Rankine cycle), as well as with isothermal process control. This enabled a direct comparison. The trials took 18 months to perform and were accompanied by numerous component tests.

Engine-map ranges in the US FTP-75 cycle relevant to fuel consumption were measured for a medium-range passenger car. To allow comparison, the ZEE results were extrapolated by computer for application to the performance class of a 1.9-litre 4-cylinder diesel TDI engine, and to its mechanical friction losses. Owing to the different performance characteristics, the gear and rear-axle transmission was adapted to the ZEE, so that in this hypothetical vehicle the driving conditions were comparable to those of series vehicles. The trials with the ZEE02 took place with natural gas; owing to the comparability of the consumption data, however, it was possible to convert them to diesel-energy equivalents.

4.1 Engine-map Comparison between ZEE and TDI Diesel

Figure 9 compares the fuel-consumption map of a diesel engine to that of the ZEE02. Since the ZEE can operate directly, without a gear system, results were recorded with respect to vehicle speed in order to allow valid comparison (this corresponds to the diesel engine in 5th gear).

It is obvious that the ZEE does not achieve the peak efficiency of the diesel engine, represented at its best point with a specific consumption of 207 g/kWh. The best point for ZEE is 355 g/kWh; however, this is in a map range which corresponds to normal urban vehicle operation.

4.2 Comparison of Characteristics of the ZEE with other Engines

If the comparison described in Section 4.1 above is carried further, and if the test-bench results are applied to a driving cycle, then conclusions may be drawn with respect to cycle fuel consumption and emissions. **Figure 10** shows consumption and emission comparisons for a US FTP-75 cycle. This figure compares the results of the ZEE02 with those of the 1.9-litre TDI diesel, a 1.6-litre spark-ignition engine and the Mitsubishi Carisma as a GDI.

According to these data, a steam engine in accordance with the conventional principle achieves a consumption figure of almost 15 litres / 100 km, a totally unacceptable value even at this early stage of development. With 8.3 litres / 100 km, the ZEE02 achieves the level of the spark-ignition engine with

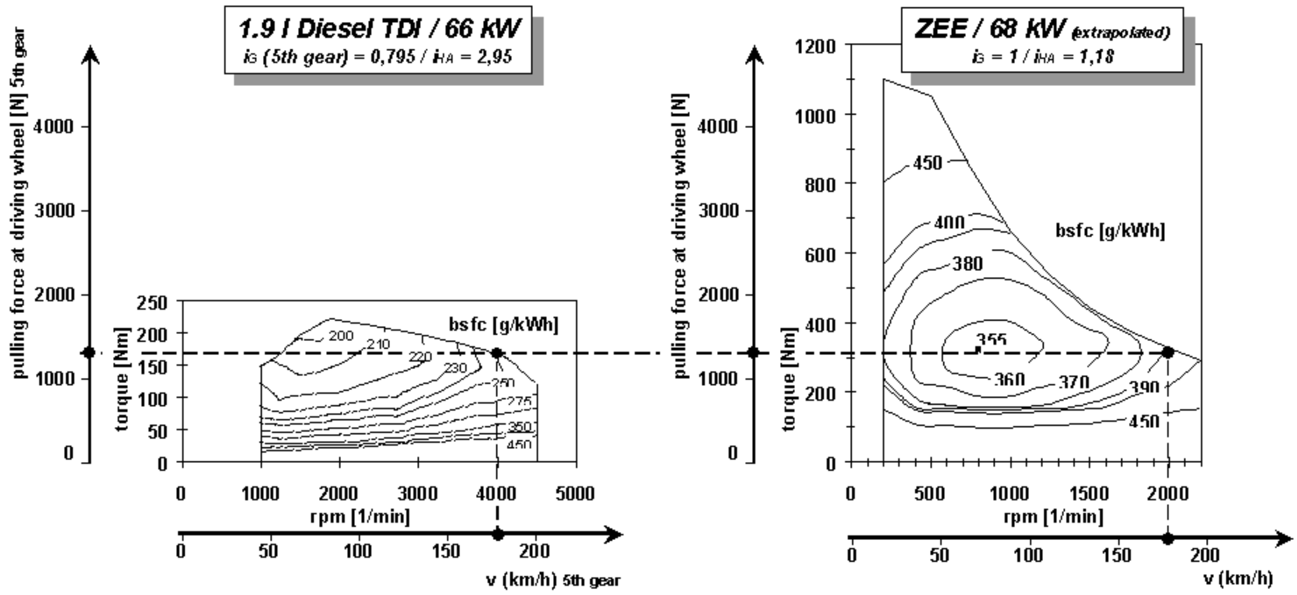

Figure 9: The ZEE in comparison with specific fuel consumption and torque characteristics of modern combustion engines

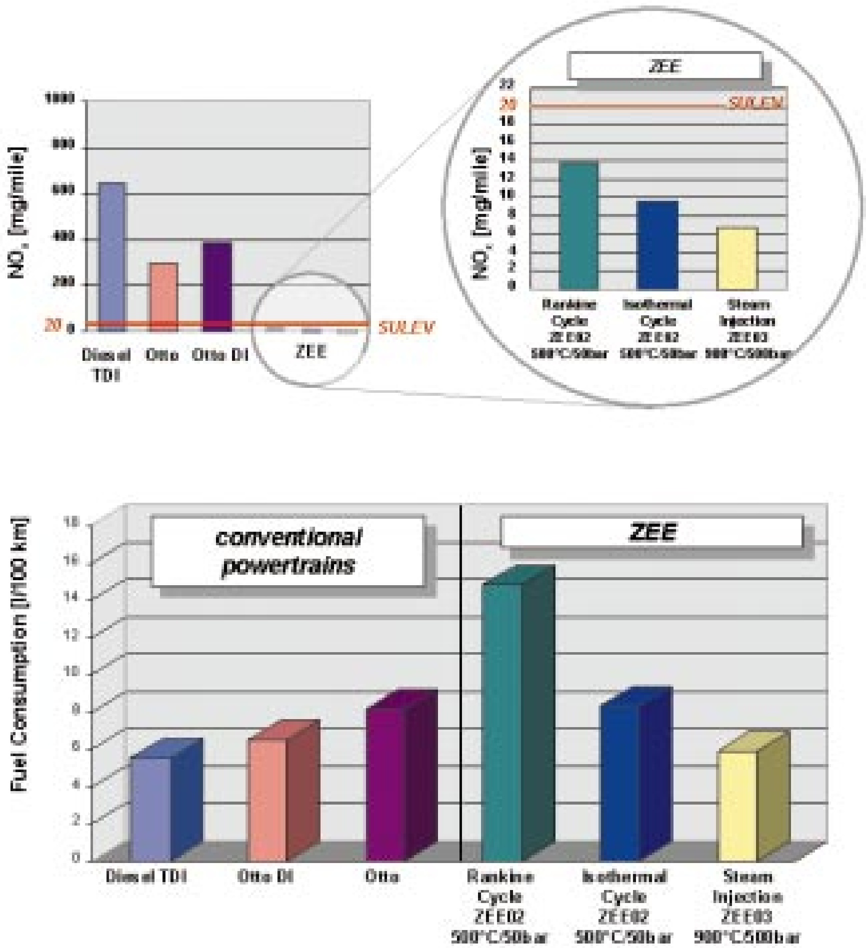

Figure 10: The ZEE in comparison with modern combustion engines. Pollutant emissions and fuel consumption of a mid-size category car in the US FTP-75 cycle

intake-manifold fuel injection, and still offers even further significant potential with the parameters selected here for pressure and temperature of the working medium. The steam temperature of 900°C represents a preview of the ZEE03 (Section 5). The comparisons clearly show that an advanced steam engine has the potential for achieving the level of a DI diesel engine in fuel consumption. The results show the expected emissions behaviour. The non-combusted constituents of the exhaust gas are at the very threshold of detection, and will therefore not be further discussed here. NO_x emissions are significantly below the SULEV limit value and show further potential, depending on fuel consumption.

5 Outlook

The results documented here describe the status of technical development as of mid-1999. The ZEE02 unit was designed as a stationary engine and served to demonstrate the potential of the concept. Owing to sluggish adaptation systems, this model is not suitable for actual dynamic requirements. In addition, the coaxial configuration of cylinder and burner/steam generator has proved to be unsuitable for multi-cylinder models. Since the middle of 1998, therefore, IAV has worked on a concept for a successor model, the ZEE03.

5.1 ZEE03

The design of the ZEE03 is based on knowledge obtained from stationary-engine tests. The following aspects served as primary criteria in the conceptional design of this engine:

– Compact type of construction
– Capability of being installed in a compact car
– Ongoing enhancement of efficiency.

As a result, considerable constructional differences are apparent in **Figure 11**, which shows a 3-cylinder in-line engine variation. The burner and steam generator are each configured to the side of the powertrain, and exhaust gas flows laterally through the cylinder head. The so-called superheater unit is located in the cylinder head, and allows the cylinder to be kept cooler than for the ZEE02. In order to achieve a surface area as large as possible for the superheater, live steam is passed via an intake unit and through a tubular bank around which exhaust gas flows.
A special feature here is the intake units, which are similar to injectors. The feasibility of this system is based on the elevation of the system pressure to 500 bar, and the maintenance of the steam temperature at 500°C, which amounts to supercritical steam conditions. The density here is 257 kg/m³, approx. one quarter that of liquid water. It can be fed in through relatively small cross-sections. The injected working medium is heated to the final cycle temperature in the superheater tubular bank, with the result that the injector and the steam generator are subjected to the relatively moderate temperature of 500°C. The following benefits result:

– no moving parts in extremely hot areas (i.e., T > 600°C)
– additional increase in steam temperature, up to 900°C, depending on load and engine speed, resulting in further advantages:
– Smaller installation size of the powertrain, as a result of smaller steam mass-flow quantities
– Employment of more economical materials and jointing techniques in the steam generator.

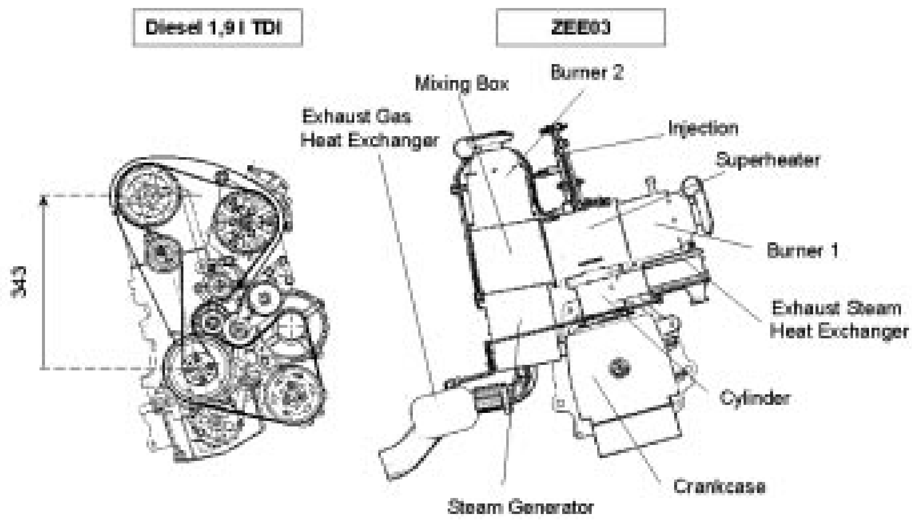

Figure 11: The ZEE in comparison with a modern combustion engine: ZEE03 components and size comparison

Table 2: Main data ZEE03

Number of cylinders:	3
Displacement:	992 cm³
Cylinder bore:	90 mm
Stroke:	52 mm
Max. burner performance:	
– Burner 1: 3 x 36 kW =	108 kW
– Burner 2: 3 x 36 kW =	108 kW
Output rating:	50 kW
Rated engine speed:	2000 rpm
Maximum engine speed:	2500 rpm
Rated torque:	300 Nm
Maximum torque	
(overload operation):	500 Nm
Speed range of rated torque:	200 ... 1500 rpm

The characteristic data of the ZEE03 are listed in **Table 2**.

5.2 Installation Study and Further Development Tendencies

No insurmountable obstacles have occurred in the course of development until now. Nevertheless, the great number of detail problems must not be underestimated. One essential criterion for the capability for series production of innovative power units such as the ZEE is, for example, their overall installed size. The integration of new concepts into existing vehicle packages is critical for assuring acceptance. The CAD installation study (see front illustration) shows that it is possible to integrate an advanced steam engine with its auxiliaries into the engine compartment of a compact car.

There are also additional thematic areas with problems which have not yet been solved and which will require greater attention in the future. Many of these questions, for example those involving comfort and starting behaviour, can be answered only with an operational vehicle.

An additional problem area is frost protection for the feed-water cycle. This problem can be solved; the question is only which of the possible alternatives will be selected. Heating up the feed water from time to time is one possibility. This particular method has already been chosen by Saab. [5] Using additives in the feed water is also feasible, and investigations are currently being conducted on this area.

Solutions to the still-open questions until the year 2001 (the end of the supported project) will reveal the extent to which the ZEE is a concept capable of development to series production. At present, we assume that development of the ZEE to readiness for series production will require a period of an additional 5 to 7 years.

6 Summary

A number of problems must be solved before the ZEE is ready for series production and before it has reached a state of suitability for daily use. The following, however, may be stated in summary from the present standpoint:

– Steam engines are feasible as vehicle power units, and can satisfy currently applicable requirements for powertrain operation.

- The ZEE is able to resolve the conflict in objectives between low exhaust emissions and good efficiency. It shows the potential for achieving the fuel consumption of a diesel-powered vehicle with observance of the SULEV norm and without employing exhaust-gas aftertreatment.
- The weight-to-power ratio and the overall installed size will achieve the level of present vehicle powertrains.
- Owing to the fuel versatility of the ZEE, it is not dependent on a particular type or quality of fuels. Utilisation of existing infrastructure facilities opens up the possibility of the transition from fossil to regenerative power operation while using the same power unit.

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