The Steam Engine – Status of Development and Market Potential

By Gerhard Buschmann, Herbert Clemens, Michael Hoetger and Bertold Mayr

In 2000 the company IAV GmbH, Ingenieurgesellschaft Auto und Verkehr, reported on initial developments achieved with a steam engine. As of early 2001, IAV has almost completed the Zero Emission Engine (ZEE) project. The present report will describe the research results achieved, using the example of the three-cylinder engine as a SULEV power plant for a medium-sized car. This report will also provide an outlook as to how the results of this project could be further exploited.

1 Point of Departure

In 1994 the company IAV began with development of an advanced steam engine. The objective of this development was to achieve exhaust-gas emission values which were significantly less than given limits, with any of a variety of different fuels, and without the use of a catalytic converter. The initiative for the ideas leading to this development were pioneering breakthroughs in the development of stationary burners that enabled nearly zero-emission combustion.

For the following reasons, IAV selected a reciprocating engine with a closed steam cycle for application of the external combustion process:

- In the 1960s, steam power plants achieved a highly promising status of development in comparison to Wankel, Stirling, and gas-turbine engines [1 – 34].
- Since the 1990s dramatic progress has taken place in the areas of tribology, materials technology, automotive electronics, and burner technology.
- The steam engine may be considered as a power plant not only for motor vehicles, but also for applications in power plants for co-generation of heating and power (CHP), and for auxiliary power units (APU).

The first report of our findings was published in MTZ 5/2000. The following now presents a description of test-bench results obtained with a 3-cylinder car steam engine. The results are highly promising. This steam engine is capable of competing with the fuel cell with respect to fuel consumption, exhaust-gas emissions, driveability, and capability of installation in conventional vehicles. Crucial advantages of the steam engine are its relatively low production costs, and its ability to burn a variety of fuels.

Development of steam engines is not part of the core business of IAV as a production-vehicle engineering company. IAV has nevertheless found a concept which enables the further exploitation of the findings from the basic development achieved in the supported project. The founding of the company enginion AG by the primary developers of the ZEE is the response to this positive development. This company will undertake further development and marketing of auxiliary power units (APUs), based on the Ezee-Technology for steam engines.

With the APU as initial implementation, it will be possible to achieve rapid access to the markets, especially since a number of details for the ZEE which will require further development, will not prove of significance for an APU. Cold starts and control quality for dynamic operations, for example, are not essential for an APU. Applications will prove possible on a relatively rapid basis for the Ezee-APU as a power generator for houses and buildings, for the leisure market, and in motor vehicles and boats.

Whereas the company enginion AG will undertake direct marketing of the ZEE in a number of different products, IAV will exploit the results from steam-engine development. Work by IAV will, for example, feature the application of new tribology systems. This approach will enable positive developments for wear, friction, and exhaust-gas emission of the engine – as well as new developments in lubrication systems.

2 The ZEE03

The ZEE03 is the first multi-cylinder steam engine. It represents a research engine which will enable clarification of the requirements associated with application of a steam engine for automobile use, **Table**.

With the aid of this prototype, it was possible to estimate the potential results with respect to output, dynamic behaviour, fuel consumption, and exhaust-gas emission. Investigation of two concepts took place:

- A so-called low-pressure variation, with rated steam pressure of 50 bar, and with engine control by means of hydraulically activated poppet valves
- A high-pressure variation for operation at 500 bar, with a high-pressure injector system.

Table: The parameters engineered during the project for the ZEE03

Number of cylinders:	3
Displacement:	992 cm^3
Bore:	90 mm
Stroke:	52 mm
Max. burner output – Burner A: 3 x 36 kW: – Burner B: 3 x 36 kW:	 108 kW 108 kW
Rated output:	50 kW
Rated speed:	2 000 rpm
Maximum speed:	2 500 rpm
Rated torque:	300 Nm
Maximum torque (overload operation):	500 Nm
Speed range for the rated torque:	200 …1500 rpm

You will find the figures mentioned in this article in the German issue of MTZ 5/2001 beginning on page xxx.

This second version existed as a component test bench with burner, steam generator, high-pressure feed water pump, and injector – and not as a complete engine. Results obtained from the second version were mathematically combined with power-plant data obtained from the low-pressure concept: this made possible an overall evaluation of the injector system.

2.1 General Design

Figure 1 shows a schematic representation of the design of the ZEE03. This engine features modular design with six identical burners. Each cylinder can operate separately from the others. It is likewise possible to regulate the status of the live steam, as well as the superheater temperature, independently of each other. Each cylinder has one exhaust-steam and one exhaust-gas heat exchanger, which enable exploitation of residual heat.

The following is a brief description of the feed-water cycle: A high-pressure pump raises the system pressure to 50 bar. The water first flows through the exhaust-steam heat exchanger, in which the flashed steam transfers its residual heat. Further heating of the water takes place in the exhaust-gas heat exchanger. The steam generator raises the temperature to the rated steam temperature of approx. 500 °C. The superheated steam finally passes to a variable intake system, from which it moves into the superheater. The steam reaches a temperature of up to 900 °C here, depending on the set superheater temperature, the engine load, and engine speed.

2.2 The Burner

As already implemented in the ZEE02 engine version, the burner consists of thermal reactors in which the combustion process takes places inside a porous matrix [35-39]. With this design, it is possible to achieve flame stabilisation with extremely homogeneous temperature distribution – a feature which enables a whole series of advantages over burners with open flames. Noteworthy in this context are the following benefits: extremely low emissions (5 ... 10 ppm NO_x), great output modulation possibilities (infinitely variable from 1.5 to 36 kW) with extremely compact installation size, greater diversity of possible form, as well as possibility of burning a variety of fuels.

It is possible to design the distribution of pore sizes inside the burner in such a manner that one single burner can employ a great spectrum of fuels: e.g., natural gas, hydrogen, propane, butane, and all conventionally available automobile fuels. With use of liquid fuels, it is necessary only to install a vaporiser unit upstream.

2.3 The Steam Generator

The majority of the heat contained in the hot gases of combustion passes to the working medium inside the steam generator. As for the burners and the heat exchangers, IAV decided on modular design for the steam generator as well. As a result, a separate steam generator feeds into each cylinder unit of the 3-cylinder engine. A compact heat exchanger was developed for the individual cylinder units; this exchanger supplies the required steam qualities – at constantly high efficiency – throughout the entire output range of the engine. The requirements placed by the dynamics of a motor vehicle dictate that a minimum of water or steam volume respectively is highly essential: approx. 250 cm^3 per cylinder unit.

In the steam generators of the ZEE03, the working medium flows through a series of parallel tubes. These tubes, which consist of heat-resistant alloys, feature a convolution design that ensures uniform flow with a maximum of heat-transfer area, and with only moderate pressure losses.

2.4 The Superheater

The superheater unit is located between the expansion chamber and the intake element; the superheater comprises the cylinder head. The most essential element of the superheater is a bundle of tubes, which is heated by the exhaust gas from burner A. This bundle of tubes superheats the intake steam, on its way from the intake element to the cylinder. The exhaust gas produced by the burner has a temperature of approx. 1300 °C; the gas flows around the tubes and causes the temperature of the steam to rise by up to 400 °C.

The superheater consists of a bundle of 44 tubes and is enclosed by a housing. This housing, bolted to the cylinder flange, contains insulating, fibre-ceramic components for purposes of guiding the passage of exhaust gas. This housing is flange-connected on one side to burner A, and on the other side to the mixing chamber.

The superheater tubes represent a limitation for the heat-transfer properties of the superheater. In order that a maximum amount of heat passes into the intake steam, it is necessary to heat the superheater tubes to the maximum possible extent. Although the tubes consist of a nickel-based alloy which has great heat-resistance properties, these tubes reach their strength limit at temperatures over 1000 °C. In addition, the material of which these tubes is made exhibits great thermal-expansion properties and only poor thermal-conduction characteristics. For future versions, it is planned to use high-performance ceramics with constant strength characteristics, great thermal conductivity, and slight thermal expansion: e.g., carbon-fibre-reinforced silicon carbide (C/SiC). The use of such ceramic materials permits raising the temperature level, and enables further enhancement of superheater efficiency.

2.5 Tribology

Work with the properties of the materials used here, and the interactions of contacting surfaces which move in relation to each other, requires fundamental development efforts.

Figure 2 shows the possibilities which result from systematic work on the tribology of such a system. This figure shows the surfaces involved in various tribology samples that were selected and tested in the course of the past years. The illustration also provides data on the coefficient of friction and on wear.

The depicted samples slide across each other in steam atmospheres at high temperatures. Initial results originated from combinations which functioned significantly worse than oil-lubricated pairs. The most recent stages of testing, however, have provided results for wear and friction which are considerably superior to data for conventional solutions. **Figure 3** shows the classical case of application: piston against cylinder liner, with components which were in use for approx. 50 hours. Owing to load pressure, they demonstrate a mirrored surface, but no wear.

2.6 Electronic Control Unit

The electronic control unit (ECU) is an IAV development on the basis of a 16-bit microprocessor platform. Since the conditions and requirements of a steam engine are fundamentally different from those of conventional engines, it was necessary to develop completely new software.

The purpose of the ECU is to implement engine and process management. This system transforms the wishes of the driver with respect to engine torque and engine speed, into the required valve positions in the steam cycle, the intake control times for the cylinders, burner performance, and speed of the feed-water pump. Several closed control loops are required to ensure satisfactory steam quality under conditions of fluctuating torque requests. **Figure 4** gives an overview of process control in engine operation. The control system allows a certain quantity of steam to enter the cylinder, in accordance with torque requests. As a result, pressure and temperature in the steam cycle will change under conditions of dynamic processes. It is necessary to correct these variables in accordance with their required values. The ECU must also perform additional functions: e.g., monitoring and fault diagnosis, initiation of responses to safety scenarios, automatic runup and rundown of the steam processes after activation of the ignition switch, and (not least) communication in the ECU network.

In this project IAV developed a differential-equation model of the ZEE03. The thermodynamic part is presented in [40]. This model was physically parameterised and was calibrated with test-bench data. Together with a longitudinal-dynamics model of a passenger car, it is possible to investigate the dynamic behaviour of the ZEE03 without the presence of an actual test vehicle. The results section will discuss the behaviour for cases of two sudden load variations.

A separate technical paper will present an extensive representation of the engineering requirements presented by the closed-loop control system of a dynamic steam engine.

3 Results

3.1 Fundamentals

The ZEE02 concept with a heated cylinder liner provided the necessary basic verification of thermodynamic functionality. The superheater concept of the ZEE03, however, is better suited for a vehicle power plant. This solution entails greater constructional expense, but combines the following benefits:

- During the intake operation and up until the initial phase of expansion, the superheater feeds considerable amounts of heat into the process steam. This procedure extensively eliminates the need for the isothermal process of continued input of heat, and relieves the cylinder liner from exposure to high temperatures otherwise necessary (up to 800 °C). Throughout the movement range of the piston rings, the temperature of the cylinder liner in the ZEE03 reaches temperatures not exceeding 550 °C. Operations on the test bench have disclosed that it is possible to manage these temperatures with the material pairing solutions developed for this project.
- The process steam need not reach its final temperature in the steam generator, with the result that the steam generator and the intake components will be subjected to moderate temperatures of only 500 °C. This benefit serves to increase the expected component service life. In addition, it is possible to use relatively inexpensive materials for the steam generator and the intake components.

It is difficult by means of measurement-technology to determine exactly what share of the process heat passes in steam through the superheater unit. In this context, computer-aided process design is more effective which, in addition, fulfils two supplementary tasks: thermodynamic design of further concepts, and the calculation of potentials which measuring systems alone cannot (or cannot exactly) deal with.

The measured data obtained, **Figure 5**, enable calibration of this computer-aided process design. This technique offers insights into the variables depicting the status of the engine-cycle process: especially momentary values for the steam state in the cylinder, for mass flow, and for heat flow.

3.2 Torque and Output

Restriction of the superheater temperature to 900 °C (owing to the characteristics of the materials used) signifies restrictions in the maximum output of the ZEE03. Since, therefore, burner A cannot operate with its maximum thermal output, the engine output shown here is lower than predicted. Increasing the superheater temperature, or the output of burner B, enables engine output to reach the target of 50 kW without difficulty – and the plot of the achieved torque would likewise reach the predicted value of 300 Nm within the range of 200 ... 1500 rpm.

The torque characteristics of the steam engine in **Figure 6** are unmistakeable: it calls to mind the plots for an electrical vehicle power plant. The engine achieves a maximum output of 32 kW at 1800 rpm. The maximum torque is 350 Nm at 200 rpm. The control timing of the hydraulic valve-train assembly causes restriction in maximum torque within a range up to 600 rpm, and the burner system restricts the development of torque at speeds above 600 rpm.

3.3 Fuel Consumption and Exhaust-Gas Emission

Figure 7 shows the efficiency map of the ZEE03. This map is based on fuel mass flow as measured, as well as on use of a cylinder-pressure indicator technique. Owing to a number of auxiliaries which have not yet been optimised with respect to tribological aspects – such as the hydraulic pump of the valve-train assembly and the feed-water pump, the friction losses of an advanced 4-cylinder DI diesel engine have been subtracted from the indicated output.

The extreme flatness of the plot of the efficiency map is highly obvious here: as was also the case during basic research carried out on the ZEE02 [39]. Owing to the greater variability of intake control in comparison to the mechanical control system implemented in the ZEE02 – and because of the uniformity of heat input via the superheater – the ZEE03 map demonstrates significantly enhanced efficiency at low engine speeds. Although the ZEE03 exhibits range of best efficiency of barely 24 %, these results nevertheless support prediction of outstanding fuel-consumption characteristics for mixed-cycle operations featuring routine test cycles. Comparison of a medium-sized car (1250 kg) in a US FTP 75 cycle – already used for the ZEE02 – has also been used for this work with the ZEE03 to emphasize the fuel-consumption potentials, **Figure 8**. In this context, the fuel-consumption data for the ZEE versions are results calculated from stationary maps: as is the case with classical diesel and spark-ignition engines. The values for spark-ignition and diesel engines were given a 10 % increment for dynamics, and the calculated values for the ZEEs received an increment of 15 %. This procedure was followed because the effects of the dynamic control system for the ZEE on fuel consumption are not yet exactly known.

Data provided on pollutant emissions are restricted to figures for NO_x emissions, since uncombusted hydrocarbons have not been able to be detected. The same applies to CO emissions. Since a stationary burner of the design used here does not require dynamic enrichment, calculation operations are justified here that are analogous to those applied for determining fuel consumption. **Figure 9** shows the results obtained for the various ZEE versions. In the case of the ZEE03, the SULEV results fell more than 75 % below specified limit value: and this result was achieved without exploiting the potentials offered, for example, by exhaust-gas recirculation systems.

3.4 Assessment of Potentials

Figure 10 shows an energy-flow analysis for the range of best efficiency.

Especially evident here is the large share of surface losses: for the optimal point of the engine as considered here, this admittedly amounts to approx. 15 % of the input burner energy, i.e., just under 4 kW in this case. These results consequently emphasise the importance of effective thermal insulation for the engine.

Exhaust-gas losses (here, approx. 5 %) may likewise be reduced by recirculating part of the air of combustion: i.e., up to one-third of the total exhaust-gas flow volume. This measure represents a highly effective measure for pre-heating the air. It furthermore reduces – as preliminary tests have verified – the share of nitrogen oxides in the exhaust gas to less than 4 ppm.

As mentioned earlier here, the influence of the superheater can be even more significantly enhanced if it is possible to considerably raise the operational temperature of this component. **Figure 11** clearly shows that the superheater temperature plays a dominant role in efficiency as compared to steam temperature before injection. Whereas increased steam temperature is associated at the same time with greater surface losses in the steam-generator system – which signifies no real benefit – a superheater temperature of approx. 1100 °C offers the possibility of raising the optimal point of the engine to 27 %. A concept with a material demonstrating high-temperature resistance would also offer additional benefits, since implementation with such material would render it no longer necessary to divide the thermal energy into two burner units. One single, high-performance burner installed where burner A is not located would make the entire design considerably more simple and compact. It would also eliminate burner B and the mixing chamber.

Further measures for optimisation of details would enable a not-insignificant potential for enhancement of engine efficiency. These measures would include shortening of steam lines, enlargement of flow cross-sections, reduction of friction in the power train, and inclusion of power from the auxiliaries analogous to current developments in design of classical internal-combustion engines.

The limit for steam pressure of 50 bar, as stipulated for purposes of working with this concept, do not in actual fact represent a real upper limit. During the concept phase and during test operations, the setting of this limit represented the most favourable compromise. As Figure 11 shows, increase of the steam pressure with application of hydraulic intake control does not afford major benefits. If one followed other concept approaches and employed the high-pressure injector that has been applied in component tests under actual conditions, then an optimal point between 27 % and 32 % is even possible, depending on superheater temperature. The basis for such enhancement lies first in the thermodynamically more demanding, but more efficient steam-cycle process, **Figure 12**. Secondly, this solution enables benefits offered by the engine cycle process for approximation to the constant-volume cycle, by virtue of the great density of the live steam, and the associated great mass flow during injection.

3.5 Dynamic Tests

Figure 13 shows initial results for the dynamic behaviour of the ZEE03, with consideration taken of the vehicle mass with two consecutive sudden load variations. The plots of torque show the stipulated sudden variations. The figure further shows the actual course of torque at the crankshaft, as well as an engine speed plot. This speed plot results when the process model is combined with the mechanical balance equations for a longitudinal-dynamics model, without a transmission system, on a level roadway. A vehicle of the compact class was assumed for purposes of calculations, with further assumption of engine output of 32 kW (vehicle mass = 1150 kg; overall multiplication factor = $i_G \cdot i_{HA}$ = 1.35). The following curves show the reactions in the steam quality with respect to temperature and pressure. The actual values fall with respect to the fixed specified values during the acceleration phase, but increase during deceleration.

Conclusion: the vehicle accelerates from 80 to 120 km per hour in 22 s, without shifting gears. These initial assessments for future potentials support the conclusion that the controllers for pressure and temperature allow additional leeway for significant improvements. In addition to non-linear and predictive control concepts, work is continuing on the implementation of process maps. These maps allow on the one hand various damp qualities for various output stages, and on the other monitor the driver's torque requests.

4 Summary

The attempt will be made here to summarize the status of work, at this point in time approx. 6 years after beginning of the ZEE project. The following is possible in summary:
- Although the stage of basic research is not complete in the ZEE project, it has proved possible to gain a comprehensive overview of the potentials of a fully new technology in vehicle power-plant engineering.
- During the course of these years it has become increasingly apparent that an advanced steam engine is capable of solving the goal conflicts of future power-plant concepts as they arise between environmental friendliness and cost-effectiveness. The steam engine offers further advantages owing to its capability of burning many different kinds of fuel, as well as to the elimination of strict requirements for fuel quality.
- Systematically consistent further development of ZEEs is capable of implementing vehicle performance and comfort aspects in advanced power plants as they are known to present drivers, with two exceptions: the peak efficiency of an advanced diesel engine cannot be achieved, and it will take at least 10 ... 20 seconds for an engine to start and become ready for operation (depending on ambient conditions).
- It was not possible to treat a number of topics in detail during this project. Concepts or specifications have been prepared for such topics: e.g., for frost protection and treatment of feed water.
- Work has also taken place on a series of interesting basic aspects that would prove of interest as spin-off in other areas of power-plant development. Examples here include the technology of high-temperature-capable, dry-operation tribological pairing with extremely low friction and minimal wear. Also included here are water-based operational fluids for hydraulic applications and for power-plant lubrication.

References

[1] L.C. Hoagland, R.L. Demler, J. Gerstmann; Design Features and Initial Performance Data on an Automotive Steam Engine Part I - Overall Powerplant Description and Performance; Scientific Energy Systems Corp.; SAE 740295

[2] W.D. Syniuta, R.M. Palmer; Design Features and Initial Performance Data on an Automotive Steam Engine Part II – Reciprocating Steam Expander - Design Features and Performance; Scientific Energy Systems Corp., Ricardo & Co. Engineers (1927), Ltd.; SAE 740296

[3] Roger L. Demler; The Application of the Positive Displacement Reciprocating Steam Expander to the Passenger Car; Scientific Energy Systems Corp.; SAE 760342

[4] Ove B. Platell; Progress of Saab Scania's Steam Power Project; Saab Scania AB (Sweden); SAE 760344

[5] Olaf v. Fersen; Saab Dampfmotor; mot 12/75

[6] Harold M. Nelson; Saab's Axial Steam Engine; Automotive Industries; Oct. 15, 1974

[7] A.W. Gardiner; Automotive Steam Power - 1973; Tennessee Technological University; SAE 730617

[8] A.P. Fraas; Application of modern Heat Transfer and Fluid Flow Experience to the Design of Boilers for Automotive Steam Powerplants; Reactor Div., Oak Ridge National Laboratory; SAE 690047

[9] A.P. Fraas; Control of Mobile Steam Powerplants; Union Carbide Corp.; SAE 700118

[10] Stanislav Jakuba, James A. McGeehan; Component Development of automotive Reciprocating Steam Expanders; Scientific Energy Systems Corp.; SAE 750068

[11] W.D. Syniuta, R.M. Palmer; Design Features and Initial Performance Data on an Automotive Steam Engine Part II - Reciprocating Steam Expander - Design Features and Performance; Scientific Energy Systems Corp., Ricardo & Co. Engineers (1927), Ltd.; SAE 740296

[12] P.T. Vickers, C.A. Amann, H.R. Mitchell, W. Cornelius; The Design Features of the GM SE-101 - A Vapor-Cycle Powerplant; General Motors Research Laboratories; SAE 700163

[13] P.T. Vickers, J.R. Mondt, W.H. Haverdink, W.R. Wade; General Motors' Steam Powered Passenger Cars - Emissions, Fuel Economy and Performance; General Motors Research Laboratories; SAE 700670

[14] C. A. Amann, D. C. Sheridan, C. J. Sagi, G. D. Skellenger; The Uniflow Steam Expander - Its Relation To Efficiency of The SE-101 Powerplant; General Motors Research Laboratories; IECEC 729142

[15] R. D. Brooks, S. E. Eckard, R. G. Frank, K. F. Barber; Design Of Reciprocating Single Cylinder Expanders For Rankine Cycle Engines; General Electric Company, Space Division, Environmental Protection Agency, Office of Air Programs; IECEC 729051

[16] R. L. Burton; Recent Advances in Vehicular Steam Engine Efficiency; Steam Power Systems, Inc.; SAE 760340

[17] J. J. Brogan, G. M. Thur; Advanced Automotive Power Systems Development Program; Advanced Automotive Power Systems Development Division, Environmental Protection Agency; IECEC 729125

[18] E.F. Doyle, T. LeFeuvre, R.J. Raymond; Some Developments in Small Reciprocating Rankine-Cycle Engines Using Organic Working Fluids; Thermo Electron Corp.; SAE 700162

[19] D. Morgan, P. Patel, E. Doyle, R. Raymond, R. Sakhuja, K. Barber; Laboratory Tests Results Low Emission Rankine-Cycle Engine with Organic-Based Working Fluid and Reciprocating Expander for Automobiles; Thermo Electron Corp., Research and Development Center, Environmental Protection Agency; SAE 739062

[20] P. Patel, E.F. Doyle, R.J. Raymond, R. Sakhuja; Automotive Organic Rankine-Cycle Powerplant - Design and Performance Data; Thermo Electron Corp.; SAE 740297

[21] T.O. Wagner; Fuels and Lubricants for Steam Propulsion Systems; American Oil Company; SAE 700662

[22] R.E. Engdahl, E.S. Tillman; A Compact supercritical Steam Engine for Automotive Power; Energy Research Corp.; SAE 719110

[23] F.C. Younger; Characteristics of the Brobeck Steam Bus Engine; William M. Brobeck & Associates; SAE 720684

[24] Advanced Powerplant Report; Automotive Steam Power: Where it stands Today; Automotive Engineering; Jahr:73, Bd: 81, Heft: 4

[25] R. A. Renner; Reviewing the California Steam Bus Project; California Steam Bus Project, International Research and Technology Corp; SAE 730218

[26] J. Gerstmann, F. Pompei; Performance of a Homogeneous Combustor for a Rankine Cycle Steam Engine; Scientific Energy Systems Corp.; SAE 730671

[27] P.H. Schneider; Steam Power Systems' California Clean Car Project; Steam Power Systems, Inc.; SAE 750070

[28] D.D. Norton; The Design of a Steam Powered Paratransit Vehicle; Steam Power Systems, Inc.; SAE 750736

[29] R.D. Burtz, T.E. Duffy; Alternate Fuel Capability of Rankine Cycle Engines; Steam Power Systems, Inc., Solar Division of int. Harvest; SAE 769211

[30] J.W. Carter, Jr.; The Carter System - A New Approach for a Steam Powered Automobile; Jay Carter Enterprises, Inc.; SAE 750071

[31] T.J. Smith; Toward a High Efficiency Rankine Cycle Automotive Engine; Dutcher Industries, Inc.; SAE 789526

[32] Th. A.E. Heron, K.J. Bullock; Design Concepts of a New Generation Reciprocating Steam Engine; University of Queensland; SAE 850032

[33] J. Haag, J. Heuer, M. Krämer, S. Pischinger, K. Wunderlich, J. Arndt, M. Stock, W. Coelingh; Global Technology Toward 2000: Reduction of Hydrocarbon Emissions from SI-Engines by Use of Carbon Pistons; SAE Fuels & Lubricants Meeting & Exposition, 10/95 Sheraton Center, Toronto

[34] S.S. Miner; Developments in Automotive Steam Powerplants; The Steam Automobile; SAE 690043

[35] D. Trimis: Verbrennungsvorgänge in porösen inerten Medien, BEV Heft 95.5, ESYTEC Energie- und Systemtechnik GmbH

[36] S. Mößbauer: Entwicklung von Zusatzheizungen auf Basis der Verbrennung in porösen inerten Medien, Diplomarbeit, Lehrstuhl für Strömungsmechanik, Universität Erlangen-Nürnberg (http://www.uni-erlangen.de/ber5a)

[37] D. Trimis, F. Durst: Combustion in a Porous Medium – Advances and Application, Combust. Sci. and Tech., Vol. 121, 1-6, p.153, 1996

[38] F. Durst, A. Kesting, S. Mößbauer, K. Pickenäcker, O. Pickenäcker, D. Trimis; Der Porenbrenner – Konzept Technik und Anwendungsgebiete, Gaswärme International, Band 46 (1997), Heft 6, S. 300 – 307

[39] G. Buschmann, H. Clemens, M. Hoetger, Dr. B. Mayr; Zero Emission Engine – Der Dampfmotor mit isothermer Expansion, Motortechnische Zeitschrift 61 (2000), Heft 5

[40] J. Beilharz; Hardware-in-the-Loop Simulation des dynamischen Verhaltens eines Gegenstromwärmetauschers, VDI Berichte 1534, VDI Verlag, 2000

[41] B. Mayr, G. Buschmann, M. Hoetger, H. Clemens; Zero Emission Engine (ZEE) – Der isotherme Dampfmotor als Fahrzeugantrieb, VDI Berichte 1565, VDI Verlag, 2000

Expression of Appreciation

At this point we would like to express our gratitude to the Senate of Berlin, in which the following Senate Administrative Departments contributed to the project: Environment and Technology; Economy and Business Operations; and Construction, Housing, and Traffic. We were also supported by the innovation foundation Technologiestiftung Innovationszentrum Berlin. Without this support from the above-mentioned institutions, this project would not have been possible.

The project on which this report / publication was based is supported by funds from the innovation foundation Technologiestiftung Innovationszentrum Berlin, as well as the European Fund for Regional Development (EFRE). The author of this publication is responsible for its contents.

The authors

Dipl.-Ing. Gerhard Buschmann
Director of Business Area Engines/Drives, IAV GmbH

Dipl.-Ing. Herbert Clemens
Assistant Technical Manager ZEE and Vice President, enginion AG

Dipl.-Ing. Michael Hoetger
Technical Manager ZEE and CEO, enginion AG

Dr.-Ing. Bertold Mayr
Managing Director, IAV GmbH

IAV's corporate profile

Who is IAV ?

IAV is the world's largest independent automotive R&D service provider in the design, prototyping and development of vehicles and powertrains. Founded in 1983 as "the missing link" between universities and the automotive industry, IAV instantly developed a reputation as an effective problem solver and began to establish itself as a successful provider of production ready solutions. The result was a rapid expansion and later an alignment into three major business areas. Today IAV is the automotive industry's leading engineering firm. Our quality of work is proven in several million vehicles around the globe.

OUR COMMITMENT

IAV's goal is an unmatched technological and qualitative superiority in its business areas. We employ a highly qualified workforce and provide them with extensive facilities in which to complete their work. By performing projects in-house we are able to combine all of our resources to develop an optimal, cost effective solution for our clients. This approach allows IAV to ensure that our levels of quality are maintained through a unique training and mentorship program. As a result IAV has the industry's lowest employee turn-over. We earned our client's trust by delivering our services on time while meeting their specified objectives and keeping strict confidentiality. At project completion we submit a comprehensive documentation of all performed work including results.

SERVICE PROFILES OF IAV'S BUSINESS AREAS:

VEHICLE DEVELOPMENT

The expertise of our vehicle development division lies in its innovative solutions for detail orientated problems as well as complex modules in the fields of bodywork, equipment, electrical systems and electronics. Whether it is the optimization of a heating system, a new cockpit design or even an entire vehicle, IAV is the right partner for you. After establishing a basic outline proposal, developments are carried out in close cooperation with the client until the product is ready for production. Extensive simulation and testing of all body and interior parts up to physical vehicle crash tests in our own facilities round out our portfolio. The key goal is the highest quality of the vehicle as a whole.

ENGINES/DRIVES

In our business area Engines/Drives we are experienced in all aspects of modern engine and drive development. Our project scopes cover the entire spectrum from clean sheet design up to full-scale, production ready integration into new vehicle concepts and their variations. The optimization of base engine technology, combustion processes and calibrations in accordance with customer demands as well as emissions regulations and exceptionally low fuel consumption are important elements of this work. Digital mock-up is performed using the latest technology; even the crash behavior of the package is simulated and tested in-house. Services related to the engine management are performed in close cooperation with our powertrain control division. With modern equipment and top of the line test dynamometers we develop tomorrow's drive technology.

Excellence in Automotive Research & Development

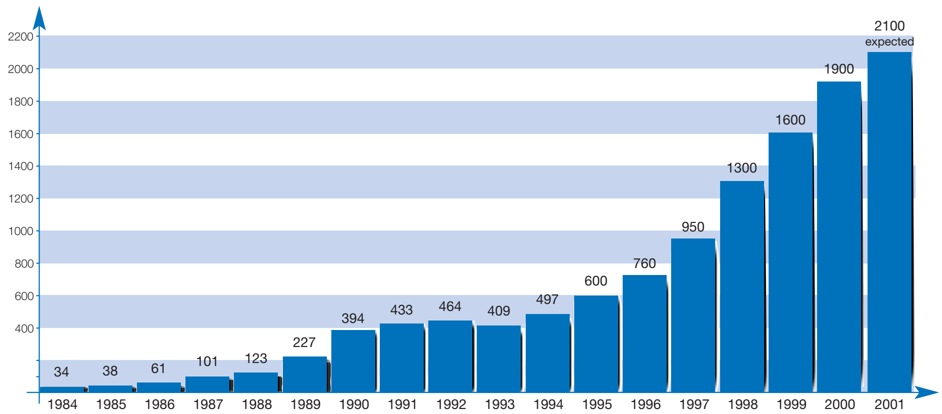
AUTOMOTIVE ELECTRONICS

Powertrain & Body Electronics

IAV develops and adapts both complete powertrain control systems as well as individual algorithms and control structures for pre-production and production applications. We are proud of our more than 10 years of experience in the development and calibration of torque based and electronic throttle controlled systems (ETC). We use the latest modeling, simulation and hardware-in-the-loop technology in our own labs. Calibrations are expertly performed by the world's largest powertrain calibration group. Here we follow written, very rigid guidelines. IAV is the leader in the exploration and application of rapid calibration technology such as DOE and auto-calibration. For the growing demands on diagnostic systems, in particular OBDII and EOBD, we develop new procedures and techniques. We offer hardware and software development support for the entire body and powertrain electrical system as well.

Telematics

Telematics is the basis for the mobility of the future. IAV has been developing powerful solutions for commercial fleets as well as private users and public transportation. We design traffic guidance strategies and products as well as complete intelligent driver assistance systems for a wide variety of customers. This also includes passenger information services and strategies for reducing traffic loads and protecting the environment. Furthermore, we focus on in-vehicle networks, mobile internet and multimedia applications, which will play an increasingly important role in the vehicles of the future. IAV's services range from the development of individual hardware and software components to the planning and realization of complex end products and integrated solutions.



Personnel Strength

IAV RESEARCH

In order to maintain our excellent reputation and strong market position, intensive research is carried out in-house - frequently this is also done in cooperation with our clients, industry partners and international universities. Here we are working on the implementation of new technologies and problem-solving methods into the development of tomorrow's vehicles. One of the latest results of our activities is the development of the world's first Zero Emission Combustion Engine (ZEE) without employing any exhaust after-treatments.

Outsource your Engineering

We will help you shorten your development cycles, cut costs and increase the productivity of your own resources. With our support you can focus on the objectives of your projects. IAV will provide a turn-key solution to nearly all your engineering needs.
We are using unique, ISO-certified methods to perform your projects, which are constantly monitored and improved. They result in an efficiency that can not be matched by any competitor or contract labor firm.

Customers

Proof of our work can be seen on the roads every day. Nearly all automotive manufacturers and their system suppliers are among our worldwide customers. Here are a few examples: **Audi, BMW, Bosch, DAF (Paccar), DaimlerChrysler, Detroit Diesel, Deutz, General Motors, Dynamit Nobel, Fiat, Ford, Freudenberg, GEP/GEPDA, Meritor, Opel, Renault, Rolls-Royce, Seat, Siemens, Skoda, Sommer Allibert, Temic, Volvo, Volkswagen, and many more.**

Europe: contact@iav.de · +49 (30) 3 99 78-0
USA: info@iavinc.com · +1 (7 34) 9 71-10 70

Engines/Drives · Automotive Electronics · Vehicle Development

IAV Inc.
Automotive Engineering

IAV GmbH
Zentrale Berlin
Carnotstraße 1
10587 Berlin
Tel. (0 30) 3 99 78-0
Fax (0 30) 3 99 78-97 90

IAV GmbH
Nordhoffstraße 5
38518 Gifhorn
Tel. (0 53 71) 8 05-0
Fax (0 53 71) 8 05-12 50

IAV GmbH
Kauffahrtei 45
09120 Chemnitz
Tel. (03 71) 23 73-0
Fax (03 71) 23 73-44 94

IAV Kft.
Futó u. 72
H 3508 Miskolc
Ungarn
Tel. +36 (46) 5 60-7 00
Fax +36 (46) 5 60-7 99

IAV Automotive Engineering Inc.
4110 Varsity Drive
Ann Arbor, Michigan 48108
USA
Tel. +1 (7 34) 9 71-10 70
Fax +1 (7 34) 9 71-05 70

www.iav.de · www.iavinc.com