Porsche Engineering
MAGAZINE

CUSTOMERS & MARKETS Records on the circular track at Nardò
PORSCHE UP CLOSE Battery development for the Porsche 919 Hybrid
ENGINEERING INSIGHTS High-voltage testing from the cell to the battery

ISSUE 2/2014

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INTELLIGENT
THERMAL MANAGEMENT
Insight into new solutions

MACAN MODELS: Fuel consumption (combined) 9.2–6.1 l/100 km; CO_2 emissions (combined) 216–159 g/km; Efficiency class: E–B


919
DMG MORI
DMG MORI

Malte Radmann and Dirk Lappe,
Managing Directors of Porsche Engineering

About Porsche Engineering

Creating forward-looking solutions was the standard set by Ferdinand Porsche when he started his design office in 1931. In doing so, he laid the foundation for today's engineering services by Porsche. We renew our commitment to that example with each new project that we carry out for our customers.

The scope of services provided by Porsche Engineering ranges from the design of individual components to the planning and execution of complete vehicle developments, and is also transferred to other sectors beyond the automotive industry.

Dear Readers,

_____ We would like to welcome you to this issue with a friendly "ni hao." Our new location in Shanghai will shortly be opening its doors. For over 20 years, we've been devoting ourselves to the specific requirements of our Chinese customers. Thus, the foundation of this subsidiary is the logical consequence of our two decades of involvement in China—a tradition-infused step into the future.

The focus of this issue—thermal management—has a number of parallels with this: a traditional topic in the field of vehicle development, but one which, with a view to future-oriented mobility and alternative drive technologies, is becoming ever more diverse and complex. More than enough reason for us to take a closer look at this matter, from function development to temperature management for batteries, in the spirit of our commitment to forward-looking and "intelligent thermal management."

One special highlight this year for Porsche was the return to Le Mans. Vehicle development of the 919 Hybrid and ultimately the spectacular race itself have been a major focus of this year. In our "Le Mans" article, we take another look at the event and also report on the special challenges that had to be mastered in the battery development process for the 919 Hybrid.

You've learned about the special features of our testing grounds in Nardò in previous issues of the magazine. Join us this time for a spin on the circular track in "A Perfect Ground for Records—Nardò," as we take a look back at the most fascinating records of recent years.

We hope you enjoy this issue
of the Porsche Engineering Magazine.

Sincerely,
Malte Radmann and Dirk Lappe

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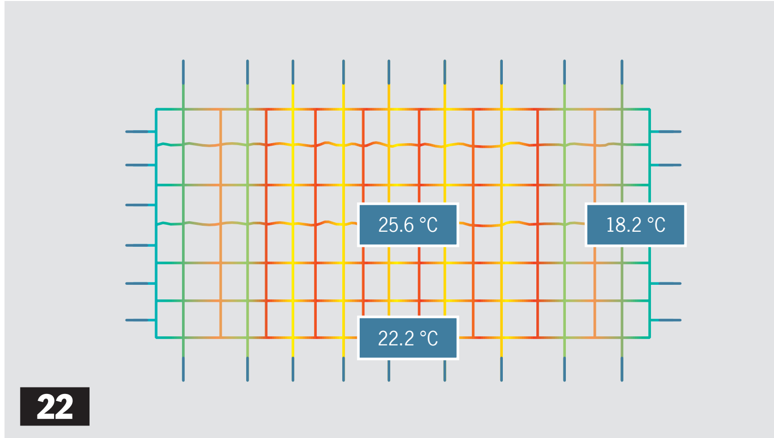
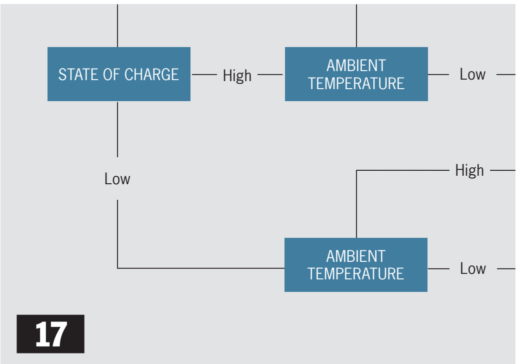
RECORDS IN NARDÒ

History is written in Nardò. Again and again. We take a look at some of the most exciting record drives of recent years.





MACAN MODELS: Fuel consumption (combined) 9.2–6.1 l/100 km; CO_2 emissions (combined) 216–159 g/km; Efficiency class: E–B

保时捷工程技术研发公司在华成立子公司

保时捷工程（Porsche Engineering）通过建立中国子公司进一步拓展亚洲市场：保时捷工程技术研发（上海）有限公司（Porsche Engineering Shanghai Co., Ltd）将于新旧年交替之际正式挂牌成立。

继捷克布拉格和意大利纳尔多之后，上海将成为保时捷工程在德国之外的第三个基地。随着各个子公司与总公司的专业一体化的保证，客户可享受引领未来的汽车领域高端服务。在上海，保时捷工程的工程师们将继续致力于发挥整车研发和系统研发方面的核心实力。

保时捷工程投身于中国市场已有20逾年的历史。为中国客户提供研发是保时捷工程的传统业务。“我们在中国的客户特别重视一体化的项目团队，以实现最优化的合作”，首席执行官雷德民（Malte Radmann）说道，“上海子公司可助我们在未来更全面满足客户这一需求。”

与同济大学合作是保时捷工程在中国的重要战略之一。双方已于今年6月签署合作协议，计划在培训、研究及工程技术领域携手展开广泛的合作。以布拉格分公司与布拉格理工大学成功的合作模式为典范，双方将在科学、研究、教学、试验台架和实践方面密切交流。

News

PORSCHE ENGINEERING FOUNDS SUBSIDIARY IN CHINA

___ With the foundation of a subsidiary, Porsche Engineering is expanding its traditionally strong engagement in Asia: The Porsche Engineering (Shanghai) Co., Ltd. will open in China with the beginning of the new year.

Besides Prague and Nardò, Shanghai will become the third location outside of Germany. As a result of a perfect integration of the locations it is for sure that the customers always receive holistic premium engineering services for future-oriented mobility. In Shanghai, the Porsche engineers will concentrate on proven core competencies of overall vehicle development and system development.

Porsche has a strong tradition of working with Chinese customers—engineering services have been offered in China for over 20 years. “Our customers in China place great importance on integrated project teams for best cooperation,” says CEO Malte Radmann, “and with our new location in Shanghai, we’ll be able to fulfill that demand even better in the future.”

One important component of the engagement in China is the collaboration with Tongji University in Shanghai. A collaboration agreement was signed in June of this year for a wide-ranging cooperation. Based on the example of the successful cooperation between the Prague location and the technical university there, the collaboration in Shanghai will also strive for a fruitful exchange in terms of science, research, teaching, testing facilities and practical experience. ■

DEVELOPMENT CENTER EXPANDED

___ With the putting into operation of the new design studio together with a conception building, the aero-acoustic wind tunnel and the electronics integration center, on July 18, 2014, the completion of an important step in the expansion of the Weissach Development Center was concluded. By 2016, a new powertrain testing building with 18 test benches will be built for the development of new hybrid drives as well as new combustion engines and electric motors. Engineering services for external customers will also profit from these new high-tech facilities. With these investments, Porsche is further expanding its core competencies and creating new resources not only for its own developments; through the symbiotic connection between sports car series development and engineering services, these resources will also be available for external projects. ■

GREENTEC AWARDS PRESENTATION

___ At this year's awards ceremony for the GreenTec Awards—Europe's biggest environmental and business award—Malte Radmann, CEO of the Porsche Engineering Group GmbH delivered the speech in honor of the winner in the automobility category. The victor was the RUBIN project, a collaboration between the tire manufacturer Continental and the Fraunhofer Institute for Molecular Biology and Applied Ecology. The aim of the project is to further develop the yield of natural rubber from Russian dandelion plants and also its cultivation for industrial use. The prizes have been awarded for outstanding environmental engagement and green technology since 2008. This year the award was presented for the first time in cooperation with Messe München as the opening event of the world's largest environmental trade fair—the IFAT. ■

WORK-LIFE BALANCE AT PORSCHE ENGINEERING

___ The success of any company is based on motivated and capable employees, and a good work-life balance is a fundamental factor in promoting that. Porsche Engineering offers flexible, individualized work models to enable employees to successfully balance their family, free-time and working lives. And it's not only employees who benefit—students receive optimal support as well. One current example of this is the professional athlete Jonathan Scholz, handball player for the first-league club SG BBM Bietigheim. The mechanical engineering student has been with Porsche Engineering as an intern in the engine design department since the beginning of September. A flexible working schedule enables him to combine the regular training activities that a professional sports career requires with important practical experience for his studies. ■

News

PRIZES FOR “DRIVING TECHNOLOGIES” IMAGE FILM

___ The new Porsche Engineering corporate film “Driving Technologies” has been honored with two international film prizes: It received a Gold Award at the Communicator Awards in New York and a Silver Victoria from the Internationale Wirtschaftsfilmtage in Vienna. The film shows the company as an innovative engineering services provider for future-oriented mobility. The film focuses in particular on the employees and their engineering expertise. What makes the film special is its trailer-like effect that has been unprecedented in the world of corporate videos. ■

WEBLINKS

www.porsche-engineering.com
www.youtube.com/watch?v=nJL9v8KXmmo

PORSCHE STRENGTHENS ITS PRESENCE IN NARDÒ

___ In a visit to Stuttgart-Zuffenhausen by Nichi Vendola and Angela Barbanente—president and vice president of the southern Italian region of Apulia, Porsche and the Apulian political leaders jointly reaffirmed their partnership for the strategic development of the Nardò Technical Center and the region of Apulia. “The Nardò Technical Center with its rich array of facilities has become an integral part of the holistic Porsche engineering services and the Porsche concern itself,” said Matthias Müller, Chairman of the Executive Board of Dr. Ing. h.c. F. Porsche AG. Porsche plans large-scale investments in the proving ground. Nichi Vendola emphasized that Porsche and the Nardò Technical Center are important partners for the region: “With Porsche we will continue to develop our region in a positive direction in terms of economic strength, jobs and infrastructure.” ■

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INTELLIGENT

Thermal Management

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____ Thermal management ensures that temperatures in the vehicle are maintained within an optimum range. Mastering the challenge involves an extensive range of tasks and applications requiring intelligent solutions. Yet thermal management is about much more than keeping a cool head. One goal, for instance, is to direct heat flows in a way that reduces fuel consumption while improving interior comfort. An essential challenge in creating forward-looking mobility.

Within this broad subject, there are various sub-areas that come into play—thus on the following pages we describe the efficient interplay between component protection, comfort and emissions reduction. Two other vital aspects are also discussed: function development and battery temperature management.

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Efficient Interaction

____ The increasing electrification of the powertrain has given rise to new challenges in many areas of vehicle development. In the last edition, we took a brief look at the significance of thermal management in the area of electric motors and we would now like to explore this interesting topic in more detail.

By Björn Pehnert
Photos by Jörg Eberl

An essential part of the development of every vehicle: testing in a climatic wind tunnel

Simulation of extreme conditions in a climatic wind tunnel

MACAN MODELS: Fuel consumption (combined) 9.2–6.1 l/100 km; CO_2 emissions (combined) 216–159 g/km; Efficiency class: E–B

Thermal management

The field of thermal management originally arose from the need to ***protect components***, in particular the engine, transmission, and all other parts in the engine compartment. Modern thermal management now has three core areas, two of which are relatively new: ***improving comfort*** and ***reducing emissions***. These individual areas will be discussed in detail on the following pages.

Component protection

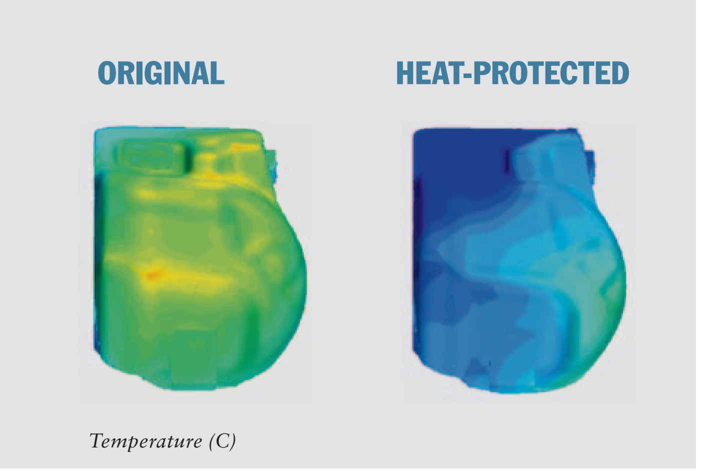
Nearly every component in a vehicle has a threshold temperature range in which it can operate. Keeping within this range is the focus of the component protection aspect of thermal management. An example of this is the engine, which must not be operated in temperature ranges in which cavitation (the formation and disintegration of steam-filled cavities in liquids), knocking, or thermo-mechanical stress can cause damage or result in a breakdown. This means that heat currents of up to 100 kW might have to be discharged. Above a certain waste heat level one coolant radiator is insufficient and further coolers have to be used.

Several thousand liters of air per second are required to discharge these high capacities to the environment via the cooler. A large part of the overall engine heat does not flow into the coolant, but is discharged into the atmosphere by means of convection.

The potential heating of the engine compartment due to this mechanism is a further focus of component protection—heat protection. If the engine compartment is overheated, components such as engine control units, spark coils or plugs can exceed their threshold temperatures. Reflectors, air vents, and active ventilation from the subfloor or hood are used to counteract these high temperatures.

Even if threshold temperatures are not exceeded, lowering the temperature can be sensible, for example to ensure that components can be operated more efficiently. ›

Preparing a cooler on a test bench



Representation of a simulated temperature reduction at a generator with intelligent heat protection measures

The figure above shows the result of heat protection measures for a generator. A two-component heat protection plate has considerably reduced the heat exerted on the generator by the exhaust system. The generator temperature has been considerably decreased, with the result that efficiency could be raised from 70 percent to 90 percent. As the thermally protected generator now had a considerably higher output, it could be replaced by a smaller, lighter, and cheaper component.

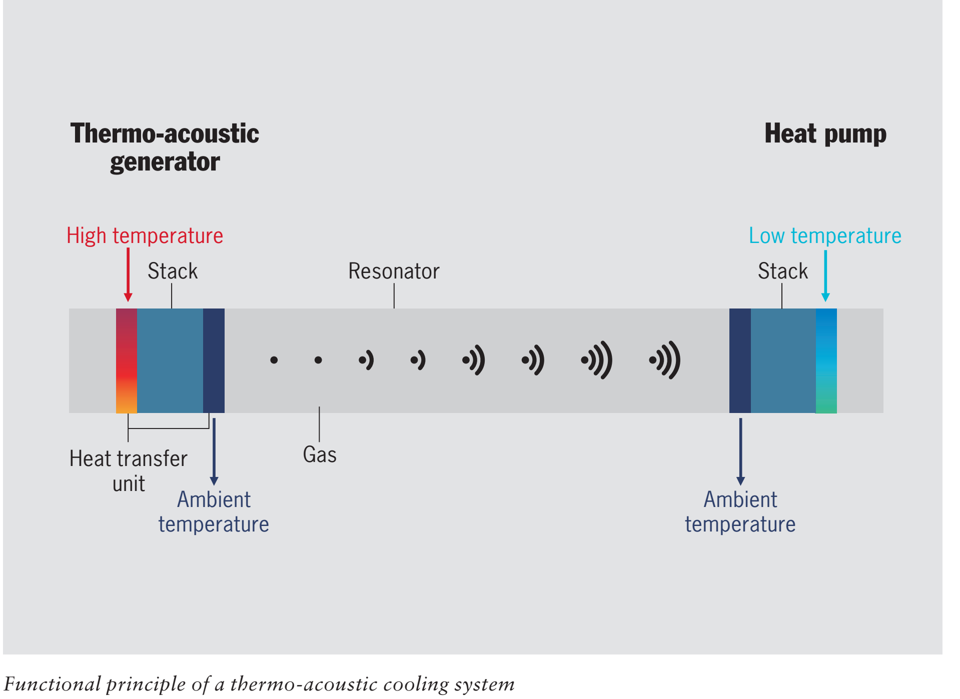
Ensuring component protection has long been an established part of the series development of conventional vehicles. One area where new challenges and special requirements are arising is the thermal management of (hybrid) electric vehicles.

New heat-conducting materials and cooling concepts are being used to ensure component protection in vehicles with alternative drive systems. Graphite, heat pipes, and vapor chambers are approaches currently being developed to make the best use of hybrid components and to protect them against undercooling and overheating. In particular, maintaining the optimum temperature for batteries has proven to be very complex, as the different output requirements and cell types require different approaches. The article “Optimal Battery Temperature Management” (page 22) provides a deeper insight into the design of such systems.

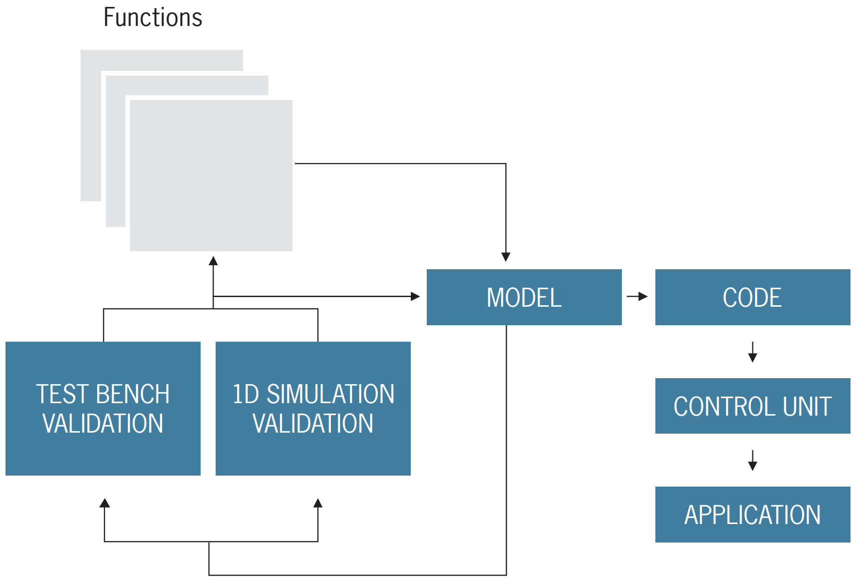
Comfort—warm feet and a cool head

The second core area of thermal management is improving the comfort, illustrated here by the appropriate air conditioning of the vehicle cabin. Modern combustion engines and particularly hybrid and electric vehicles produce so little heat at low loads that sufficient interior heating is no longer possible with conventional methods. Though, in order to provide the necessary levels of comfort in the cabin, additional heating units are used to compensate for the heat deficit.

One technological component in this area that is gaining in importance is the heat pump that applies energy to transfer low temperatures to higher heat levels. When the heat transfer runs from high levels to a low temperature level, the term used is air conditioning. The heat pump or air conditioning system can be driven thermally, thermoelectrically, or by a compressor. As an alternative to using a heat pump as an



Functional principle of a thermo-acoustic cooling system



Functional development process sequence in thermal management

additional heating unit, PTC heaters can be used that provide warmth in a highly dynamic way.

The rising number of technologically different devices makes it increasingly more complex to find the optimum concept for one particular vehicle. To be able to compare various cooling concepts quickly and meaningfully, Porsche Engineering has developed several simulation and calculation tools.

Compressor-driven cooling systems are used in conventional cabin air conditioning. In this case a hermetically sealed circuit compresses a gaseous medium with a compressor. This is liquefied in the downstream condenser and the compressed hot coolant gives off its heat into the atmosphere. The heat can be given off into the air at the front end of the vehicle or alternatively into a cooling circuit integrated in the overall vehicle cooling system. The liquid coolant is fed to a vaporizer via a throttle, turning from liquid to gas and thereby acquiring heat. The warmer cabin air is fed into the vaporizer and cooled, creating a pleasant climate in the vehicle interior at high ambient temperatures. In winter, this process can be reversed so that the air conditioning system can now be used for heating and thereby functions as a heat pump.

The refrigerant R134a is largely used in passenger car air conditioning systems, which in coming years will be replaced by more environmentally friendly alternatives. In addition to R1234yf, natural coolants such as carbon dioxide (CO_2), referred to as R744 by specialists in the field, will be used. The alternative coolant CO_2 requires especially innovative solutions to be capable of creating efficient cooling/heating circuits for passengers and components.

The thermal dynamics experts at Porsche Engineering have even more innovative solutions in their repertoire. An interesting example of this is the thermo-acoustic air conditioning system (see illustration on the left page). Here, thermal energy from the engine is used to start oscillations in a resonator. These oscillations are used to drive a cooling system. For this to function, in addition to the resonator, so-called stacks are required. Stacks are components that can convert thermal energy into oscillations and vice versa. A stack (driver) generates a pressure gradient via an externally created temperature gradient and thereby an acoustic impulse in the resonator. The excitation created is then converted into a temperature gradient by the second stack (generator stack) so that the hot and cold sides that arise here can be used as a heat pump. This alternative has no moving parts and has the advan- ›

tage that it only requires engine heat to operate.

Emissions reduction

In addition to the fields of component protection and comfort, modern thermal management is also playing an increasingly important role in reducing CO_2 emissions for example. The familiar engine thermostat alone is no longer sufficient for the thermal management of modern engines. While heating up, every degree more of engine temperature can contribute to reducing emissions.

To be able to efficiently use the waste heat generated by the engine, standing water, integrated exhaust manifolds, and split cooling are used. So that useful engine heat is not lost into the atmosphere, engine encapsulation and the correct choice of cooling system dimensioning must be given exact consideration. Optimum valve control also plays an important role here as it contributes to minimizing CO_2 emissions and waste heat.

The effective cooling system size can be influenced by valves such as thermostats or proportional valves. To increase the dynamic response of the cooling system for example, its size is scaled down, by disconnecting thermal ballast such as compensating reservoirs, air extraction ducts or non-required plate heat exchangers via the controller.

One basic task of thermal management not yet discussed is the determination of the heat energy transferred to the coolant. In conjunction with the analysis of real engine heat balances on the test bench, simulations are used to design the cooling system in the first development phases. Porsche Engineering uses its own developed software for this. This determines the relationship between heat being transferred to the coolant and effective engine performance while taking the engine geometry, number of cylinders and other parameters into account.

The constant further development of the combustion engine and continuously falling emission and consumption values means the demands on thermal management are increasing. Downsizing sees the use of supercharged engines that have a high specific output, a wide revving range with maximum torque, and good transient response characteristics. However, the exhaust gas turbocharging required for this results in greater levels of residual gas content and higher temperatures and pressures in the combustion chamber that in turn result in an increased tendency towards knocking in the engine. Later ignition is required to prevent knocking. This means a later combustion center of gravity and therefore a lower engine efficiency level.

To counteract this effect, Porsche Engineering is examining the possibilities of reducing intake temperatures. Cooler intake air reduces the likelihood of knocking as well as the exhaust temperature, thereby increasing efficiency and reducing CO_2 output. Measures such as more efficient charge air coolers and using super cooling or refrigerant cooling are being investigated with the aim of reducing intake temperatures.

Emissions cannot only be reduced by components and parts; intelligent functions in the vehicle also have a role to play (see article "Intelligent Functions"). It is important that the many components in a vehicle cooling system are doing the right thing at the right time. This is the only way to achieve good overall levels of efficiency and performance. Here it is also necessary that new functions are developed and applied in vehicle management systems. Only a combination of software and hardware can obtain the maximum performance of a thermal management system integrated in a vehicle.

Complete package thermal management

Today's thermal management with its three major fields of component protection, comfort, and emissions reduction takes on an important superdisciplinary function in the overall vehicle. Conventional cooling concepts are increasingly being stretched to their limits and innovative approaches are gaining in importance. The increasing complexity requires a better understanding and a greater degree of integration of the fields involved. ■

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Intelligente Funktionen

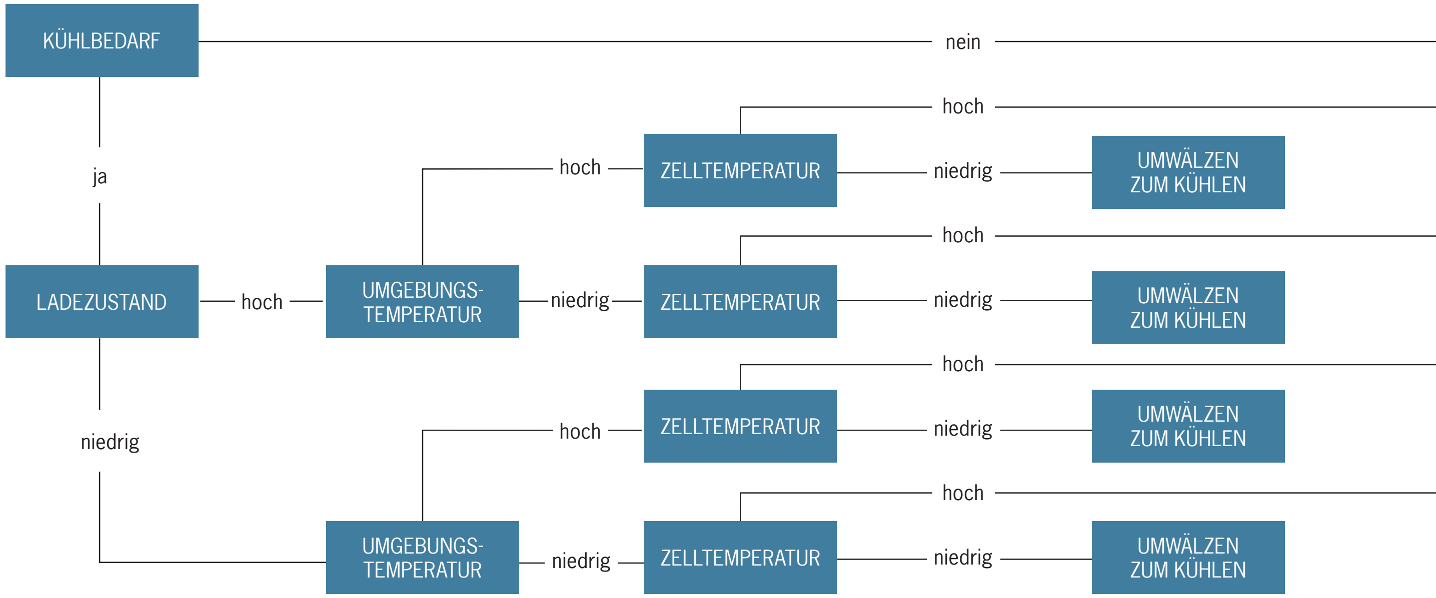
____ Für ein aktives Thermomanagement in Fahrzeugen ist die Funktionsentwicklung für Kühlsysteme eine Grundvoraussetzung. In diesem Artikel erfahren Sie, wie genau diese beiden Themen zusammenhängen und wie Porsche Engineering das optimale Zusammenspiel im Entwicklungsprozess und in der Anwendung sicherstellt.

Text: Thomas Warbeck

Ein leistungsfähiges und effizientes Thermomanagement in Fahrzeugen erfordert nicht nur eine sorgfältige Auslegung von Kühlkreisläufen, sondern auch eine intelligente Steuerung der im Kreislauf verbauten Teile. Hierbei wird stets eine bedarfsgerechte Kühlung angestrebt, was bedeutet, dass jede Komponente wie zum Beispiel Verbrennungsmotor, Batterie oder E-Maschine im optimalen Betriebstemperaturbereich liegt und im Kühlsystem verbaute Lüfter und Pumpen nicht unnötig in Betrieb sind. Dadurch wird eine höhere Reichweite sowohl von brennstoffgetriebenen als auch von Elektrofahrzeugen ermöglicht. So werden beispielsweise Kühlerlüfter an kalten Tagen im Winter erst bei höheren Kühlwassertemperaturen zugeschaltet als im Sommer, wenn selbst nach Abstellen des Fahrzeugs für kurze Zeit oft noch Kühlbedarf besteht, um eine lokale Überhitzung von Kühlmitteln und Bauteilen zu vermeiden. Solche Funktionen müssen im Entwicklungsprozess erarbeitet und schließlich im Motorsteuergerät hinterlegt werden. Besonders bei Prototypensteuergeräten erweist es sich als vorteilhaft, wenn sie schnell an neue Anforderungen und Messdaten angepasst werden können und mit der eigentlichen Entwicklung des Kühlkreislaufs einhergehen.

Von den Anfängen der Wasserkühlung zu schaltbaren Kühlkreisläufen mit Kennfeldthermostat

Die einfachste und älteste Art der Motorwasserkühlung ist die Thermosiphonkühlung. Hier wird Wasser nur aufgrund der Dichteunterschiede von warmem und kaltem Wasser in Motor und Kühler umgewälzt. Nachdem warmes Kühlwasser vom Motor in den Kühler gelangt ist, wird es abgekühlt, sinkt nach unten und wird von dort dem Motor wieder ›



Schematische Darstellung einer Batteriekühllogik als Basis für die Funktionsentwicklung

zugeführt. Durch Hinzufügen eines mechanisch angetriebenen Kühlerlüfters konnte Anfang des 20. Jahrhunderts die Effizienz gesteigert werden, auch wenn eine Regelung zu diesem Zeitpunkt noch nicht möglich war.

Der Einsatz einer Wasserpumpe verbesserte die Umwälzung, was zu höheren Kühlleistungen führte. Um eine schnellere Aufheizung des Motors nach dem Kaltstart zu ermöglichen, wurde in den Kreislauf schließlich ein Thermostatventil eingesetzt, wodurch das Kühlwasser temperaturabhängig über die Kühler oder an ihnen vorbeigeleitet werden konnte. Somit hatte das erste regelnde Element Einzug in den Kühlkreislauf gefunden.

Stellglieder in Kühlkreisläufen

Während sich einfache Thermostate bei Erreichen der Betriebstemperatur öffnen und dem Kühlwasser den Weg zu den Kühlern freigeben, lassen sich moderne Varianten so ansteuern, dass die Öffnungstemperatur des Thermostatventils zum Beispiel in Abhängigkeit von der Motorlast angepasst werden kann. Anfänglich wurde ein Lüfter mechanisch an den Motor gekoppelt und lief somit bei niedrigen Drehzahlen im Stand langsam und im Fahrzustand mit großem Kühlluftmassenstrom entsprechend schnell. Heute ist eine elektrische Ansteuerung möglich, die ein umgekehrtes Verhalten erzeugt.

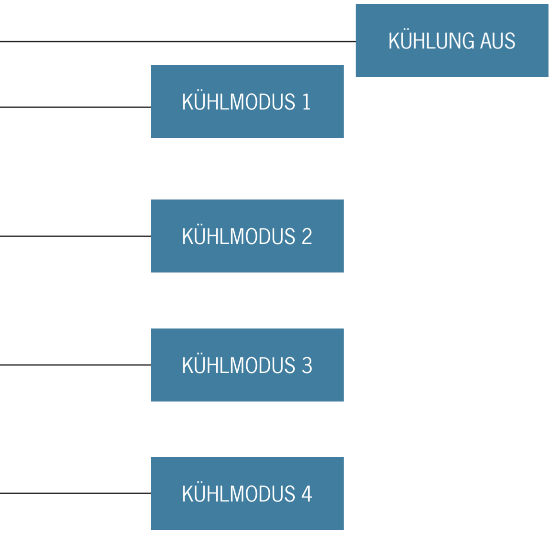
In Fahrzeugen mit Verbrennungsmotor werden mechanisch drehzahlabhängige Wasserpumpen derzeit noch standardmäßig verbaut, jedoch sind elektrische und damit flexibel regelbare Wasserpumpen in Serienanwendungen immer häufiger vorzufinden. Hinzu kommen je nach Anwendung verschiedene Ventile, die zum Beispiel die Innenraumheizung vom Kreislauf zu- oder abschalten können.

Mehr als nur ein Kühlkreislauf

In modernen Fahrzeugen wie zum Beispiel Hybriden ist ein einzelner Kreislauf aufgrund der Vielzahl an unterschiedlich zu temperierenden Komponenten längst nicht mehr ausreichend. Das Kühlwasser im Verbrennungsmotor kann nicht zur Temperierung von Batterien benutzt werden, da deren Betriebstemperatur in der Regel weitaus niedriger ist. Die Abstimmung und der Wärmeaustausch zwischen den Kühlkreisläufen sind ebenfalls wichtige Teile des Thermomanagements, für die Kühlstrategien entwickelt und in Steuergerätefunktionen umgesetzt werden.

Stetig steigende Nachfrage nach angepassten Funktionen

Insbesondere aufgrund der immer strenger werdenden EU-Vorgaben hinsichtlich des CO_2-Ausstoßes und anderen Emissionen wird eine intelligente Steuerung des Kühlsystems immer wichtiger. Für den Kunden sind darüber hinaus im Falle verschiedener hinterlegter Modi ein verminderter Verbrauch, gesteigerter Komfort oder auch herausragende Performance direkt spürbare Vorteile.



Funktionsentwicklung als Prozess, Entwicklung von funktionellen Kühlkreisläufen

Die grundlegenden Funktionen im Kühlsystem werden bereits während der Auslegung des Kühlkreislaufes bestimmt. Verbaute Aktuatoren und Schnittstellen zwischen verschiedenen Kreisläufen geben einen gewissen Spielraum vor. Es stellt sich die Frage, anhand welcher gemessenen Werte von Temperaturen, Drücken oder auch vorgenommenen Einstellungen durch den Endkunden welche Aktuatoren verstellt werden sollen.

Zunächst werden die zu verwendenden Eingangsgrößen festgelegt und somit bestimmt, auf welche Parameter das Kühlsystem reagieren soll. Solche Eingangsgrößen können beispielsweise die Kühlwassertemperatur oder die Umgebungstemperatur sein, aber auch Drehzahl und Last des Verbrennungsmotors. Im Batteriekühlkreislauf ist darüber hinaus auch der Ladezustand zu berücksichtigen, da die von den Zellen abgegebene Verlustleistung und damit der Kühlbedarf hiervon abhängig sind. Auch für eine elektrisch angeschlossene Batterieheizung ist diese Größe interessant.

Die Ausgangssignale sind überwiegend durch die verbauten Aktuatoren vorgegeben, jedoch können auch weitere Signale ausgegeben werden, die an anderen Stellen der Motorsteuergerätsoftware Verwendung finden. Dies kann beispielsweise dann der Fall sein, wenn die Anforderung zum Abschalten der Klimaanlage ans Motorsteuergerät gesendet werden soll.

Nach Definition der Ein- und Ausgangssignale werden die eigentlichen Funktionen beschrieben. In Abhängigkeit vom Betriebsmodus, dem Ladezustand der Batterie (SOC, engl. „state of charge“), der maximalen Zelltemperatur und der Umgebungstemperatur werden für jeweils unterschiedliche Kombinationen andere Setups gewählt. Wichtig ist ebenso die Definition von sinnvollen Parametern, die während der Applikation im Fahrzeug noch einfach geändert werden können. Grenzwerte für den Ladezustand, die Umgebungs- und maximale Zelltemperatur sind Beispiele hierfür.

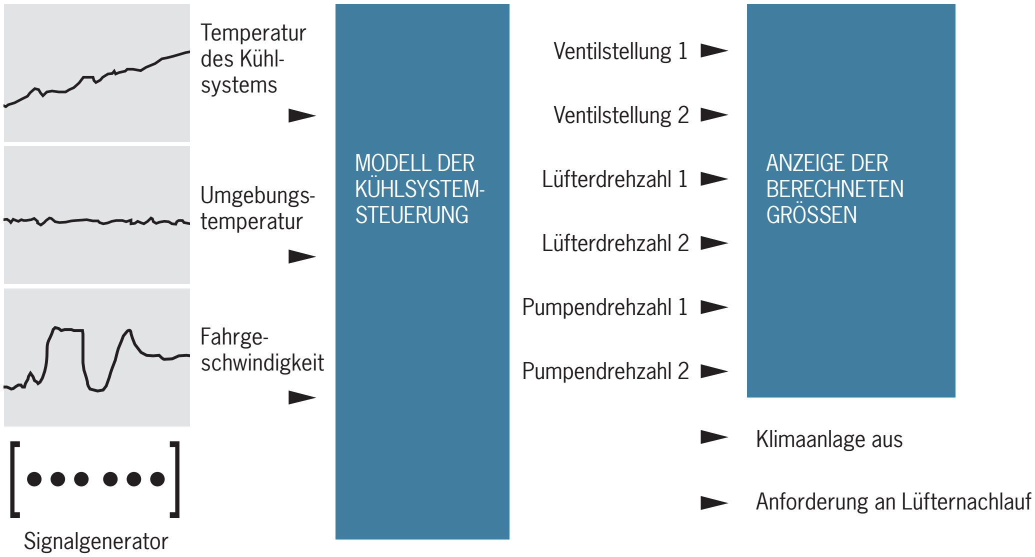
Modellierung in MATLAB/Simulink

Nach dem Entwurf müssen die gewünschten Funktionen mithilfe geeigneter Software modelliert werden. Bei Porsche Engineering geschieht dies mittels MATLAB/Simulink. Die Modell- und Simulationseinstellungen werden so gewählt, dass das Programm schließlich echtzeitfähig ist. Hierfür muss die Rechenzeit so kurz wie möglich gehalten werden, damit sämtliche Rechenprozesse auf dem Steuergerät weniger Zeit in Anspruch nehmen als das Zeitintervall, in dem die entsprechenden Messwerte übermittelt werden. Nur so lässt sich sicherstellen, dass die Ausgangssignale jeweils passend zu den entsprechenden gemessenen Eingangssignalen berechnet werden können.

Das fertige Modell kann nun zunächst in MATLAB/Simulink in einem ersten Schritt getestet werden, indem Eingangsvariablen mit zeitlichem Verlauf gezielt vorgegeben und die Ausgangswerte auf Plausibilität geprüft werden. Hierbei spricht man von „Model in the Loop“-Testing (MIL).

Virtueller Prototyp des Kühlsystems

Ein weitaus näher an der Realität liegender Modelltest kann mithilfe einer gekoppelten Simulation stattfinden. In vielen Projekten von Porsche Engineering werden während der Entwicklung und Optimierung von Kühlkreisläufen mit Prüfstands- und Fahrzeugmessdaten validierte 1D-Modelle erstellt. Diese bilden die Physik des Fluids auf seinem Weg durch Elemente wie Kühler, Leitungen, Pumpen und Ventile sehr genau ab. Hierfür wird die Software GT-Suite verwendet, welche sich mit MATLAB/Simulink koppeln lässt. ›



Modellvalidierung des Kühlsystemfunktionsmodells mittels vordefinierter Testszenarien

Der Einfluss der Kühlsystemsteuerung auf das Verhalten des Fahrzeugs kann somit direkt getestet werden, indem über die modellierte Steuerung in MATLAB/Simulink Parameterwerte wie zum Beispiel Ventilstellungen an GT-Suite übergeben werden. Das physikalische 1D-Modell wiederum übergibt Messwerte wie Temperaturen zurück an MATLAB/Simulink, die den dort modellierten Funktionen als Eingangsgrößen dienen.

Der enorme Vorteil dieses Verfahrens liegt darin, dass schon frühzeitig die Kühlsystemfunktionen an die Physik im Kühlsystem des Fahrzeugs angepasst werden können und bereits ein erster sinnvoller Datenstand festgelegt werden kann, bevor überhaupt mit dem Fahrzeug gefahren wird. Da das Kühlsystemmodell ständig aktualisiert und auf den Fahrzeugstand abgestimmt wird, kann die kostenintensive Testzeit im Fahrzeug deutlich reduziert werden. Das physikalische Modell fungiert gemeinsam mit dem Funktionsmodell als virtueller Prototyp, mit dem schnell und günstig gearbeitet werden kann.

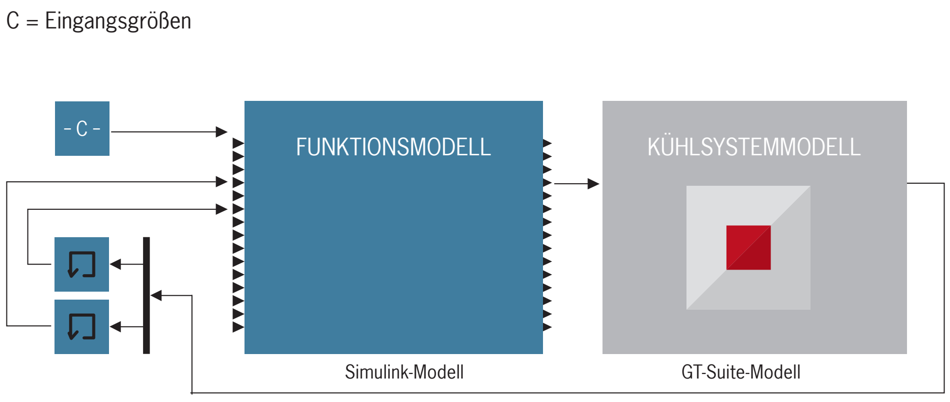
Vom Modell zum Code

Nachdem das Modell in einem ersten Schritt validiert wurde, steht die Umwandlung zur Software an. Somit wird das Modell, das nur in MATLAB/Simulink lesbar ist, zu einem universell lesbaren Programmcode. Geschieht die Umwandlung mittels der dSPACE-Software TargetLink, kann die Software analog zum Modell direkt in der MATLAB/Simulink-Umgebung getestet werden. Hierbei handelt es sich um einen „Software in the Loop"-Test (SIL). Um die Software schließlich aufs Steuergerät, beispielsweise das Batteriemanagementsystem (BMS), übertragen zu können, wird diese in Maschinencode übersetzt und auf den Flash-Speicher des Geräts übertragen.

Mit einem speziellen Testaufbau ist es nun möglich, die Steuerung des Kühlsystems direkt an der später verwendeten Hardware zu testen. Über ein Hardware-Interface kann das Steuergerät mit den entsprechenden Aktuatoren und Sensoren verbunden werden, um dort über eine ETK-Schnittstelle verschiedene Programm- und Datenstände direkt zu erproben. Zum einen kann somit die korrekte Ansteuerung und Bedatung der Aktuatoren und Sensoren überprüft und zum anderen die Logik der Kühlsystemsteuerung validiert werden. Eventuell auftretende Probleme lassen sich so einfacher erkennen und beheben als im aufgebauten Fahrzeug. Es handelt sich hierbei um ein „Hardware in the Loop"-Testing (HIL).

Applikation im Prototyp, Tests in Weissach und Nardò

Den nächsten Schritt in der Kette stellt die Applikation dar. Durch Fahr-Erprobung im Prototyp werden das Systemverhalten untersucht und die Modellparameter angepasst. Idealerweise müssen zu diesem Zeitpunkt nur noch kleinere Anpassungen am Modell gemacht werden, sodass während der Fahrt mithilfe der INCA-Software von ETAS vorrangig Änderungen in Kennlinien, Grenzwerten und Fahrmodi direkt vor-



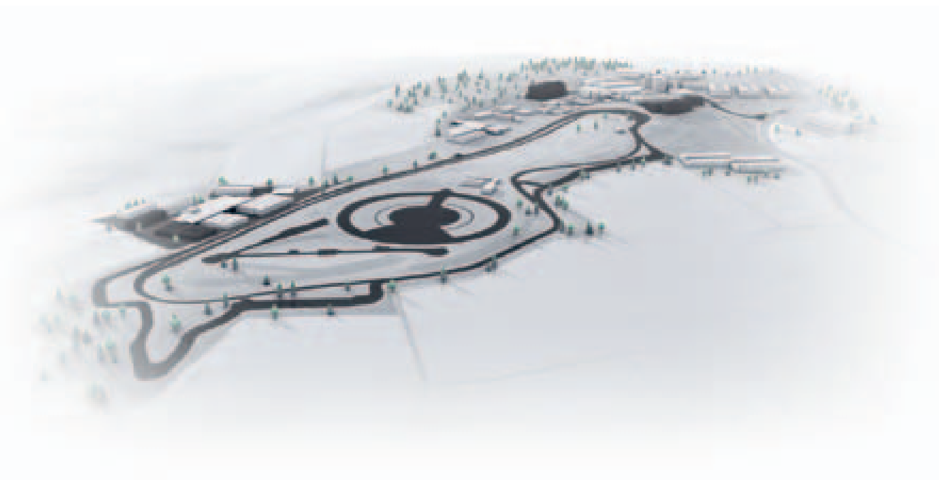
Co-Simulation von Funktionsmodell und validiertem 1D-Kühlsystemmodell

genommen und bewertet werden können. Anstatt Parameter am PC oder Prüfstand vorzugeben, werden zum Bestimmen der Größen, unter anderem Geschwindigkeit und Umgebungstemperatur, mehrere Fahrzyklen gefahren, beispielsweise auf dem Porsche-Prüfgelände im Entwicklungszentrum Weissach oder auch auf den Strecken des Nardò Technical Centers. Zusätzlich können für die optimale Applikation der Thermomanagementfunktionen im Steuergerät Extrembedingungen – warm und kalt – im Klima-Windkanal simuliert werden.

Am Ende der Applikationsphase steht ein finaler Stand von Programm und Parameterdaten, womit das Thermomanagement auch in der Serie fähig ist, erarbeitete Regelstrategien und Funktionen darzustellen.

Der Blick auf das gesamte Fahrzeug

Porsche Engineering hat stets das große Ganze im Blick. Um die Funktionalität im Fahrzeug zu garantieren, geht mit der Entwicklung von Kühlsystemen die dazugehörige Funktionsentwicklung einher. Durch die Vernetzung dieser beiden Aufgabenbereiche und die stetige Betrachtung aus der Gesamtfahrzeugperspektive erhält der Kunde erstklassige Entwicklungsdienstleistungen. ■



Prüfgelände des Porsche-Entwicklungszentrums in Weissach

–30° –20° –10° 0° 10° 20° 30°

Optimal Battery Temperature Management

____ Only an optimum temperature of the battery in electric and hybrid vehicles guarantees the range targets and the desired functionality. We give you an insight into the three phases of the special development of the storage battery.

By Manuel Groß

In spite of the still-limited range of electric vehicles, driving performance requirements particularly for sports cars are very high. Today's lithium-ion cells are capable of delivering the required performance, but they also cause major losses of multiple kilowatts. Dissipating that loss in the form of heat from the battery system requires considerable cooling capacity. The energy required for cooling reduces the already low range compared to conventional vehicles even further. The cooling system must therefore be designed with maximum efficiency in mind. As already discussed in article "Efficient Interaction" (from page 12 onwards), heating the passenger compartment is also a problem: Unlike in a conventional combustion engine vehicle, at cold temperatures there is not enough thermal energy in the form of usable waste heat. The additional energy required for heating reduces the range of the vehicle even more. Customer expectations with regard to the functionality, range and comfort of conventional vehicles must ultimately be met by battery-powered vehicles if they are to succeed on the market. This requires new technical solutions to make this a reality.

The optimum battery temperature

To manage the battery temperature, it is necessary to know the optimal operating temperature of a battery cell. A lithium-ion battery can be operated at temperatures between approx. –20 °C and approx. +50 °C. Outside of these limits, the cell chemistry can be affected in ways that accelerate the aging (degradation) of the battery. Low temperatures, in particular, also lead to a rapid increase in the internal resistance and thus significantly limit the performance of the battery. Lithium-ion batteries are therefore often heated or at least thermally insulated to retard cooling. The respective cell type must be taken into account when determining the optimum battery temperature. Different cell types have different cell chemistries and geometric shapes, which must be taken into account in the integration of the battery in the cooling system from the outset. Depending on whether direct cooling of the cells or an indirect cooling plate solution is implemented, the proper cooling medium must also be chosen. The cooling media available to the engineers at Porsche Engineering include water/glycol, thermal oils, air, and refrigerants.

Real or numeric—hand in hand to a perfect product

For the determination and thermal description of specific factors and system limits of the complex battery heat system, transient heat calculations and different material characteristics are taken into account. Corresponding rough calculations can always be done manually with the aid of simplified thermodynamics formulas.

Since these basic equations are of limited usefulness, in thermal management one makes use of special commercial tools or tools developed by Porsche Engineering that utilize numeric approximation methods to create a sufficiently precise representation of the transient behavior of the battery. The different simulation methods then make it possible to design new battery cooling systems and further optimize existing ones.

The tools used differ significantly in their complexity and are used in a targeted manner depending on the project state and depth. The following section describes exemplarily the processes and tools used in the three phases of battery thermal management development.

Feasibility phase: evaluating ideas

As in any project, the thermal management development process for batteries begins with an idea that must first be assessed in terms of its technical feasibility. In this first phase, a large number of variants is simulated and information processed to estimate the risks and potential of the idea. To quickly generate meaningful information, Porsche Engineering has developed a thermal management tool. It is based on MATLAB/Simulink and can be used for waste heat calculations for the entire vehicle.

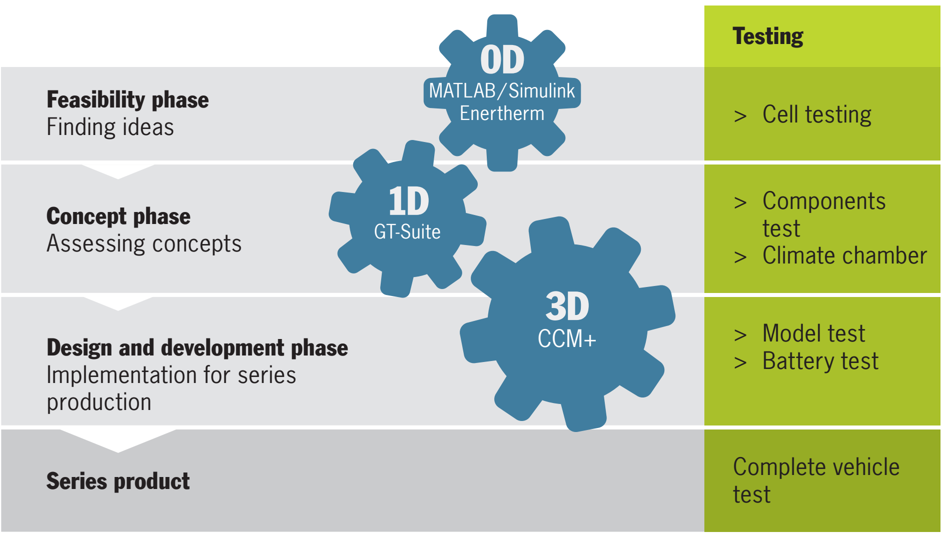
To prevent overheating of the battery, the generated waste heat must be dissipated. Based on the current and by means of complex internal resistance control maps, the waste heat can be determined by a driving cycle. The internal resistance control maps, if not provided by the cell manufacturer, are recorded on the cell level in the Porsche Engineering cell test bench. This makes it possible to determine how much waste heat is produced. Since it is only sensible in rare cases to dissipate the exact amount of heat flow that the battery generates as waste heat, it must be calculated how much actually has to be discharged via the cooling system.

Concept phase: finding resilient solutions

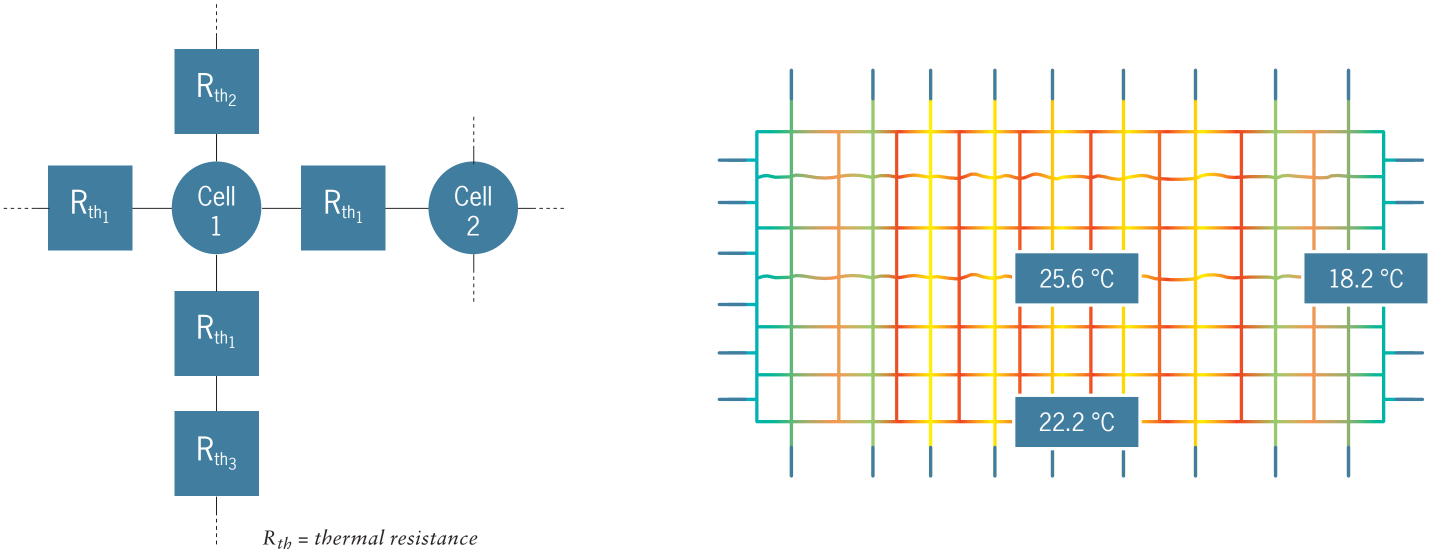
Once the project has successfully passed the feasibility phase, the next step is to find concrete technical solutions and compare them. Detailed questions with regard to the right cooling medium, a suitable cooling concept, and the thermal connection in the existing package are now analyzed.

For every concept, a cooling performance analysis is carried out which can be conducted in quasi 3D or 3D-CFD (Computional Fluid Dynamics). This analysis shows the potential of every concept and must be able to convert package restrictions, for example, into viable thermal results. In some cases, each individual cell has to be looked at here. A suitable simulation model would then have to represent a highly complex thermal network of more than 500 cells.

To determine and evaluate the temperature homogeneity concerning the cell, module, and battery levels, a tool such as the GT-Suite is used. Depending on the concept, a CFD calculation may also be required in order to evaluate the homogeneity caused by the fluids. The STAR-CCM+ tool is used for this. How good or realistic a simulation is depends on the input. Cell, module, and cooling trials are conducted in parallel with the simulation process and close the gap between the virtual and ›



Example of the process of thermodynamic battery development



Model (left) of the thermal network of an individual cell as the basis of a 1D overall battery simulation (right)

real worlds. At the end of the concept phase, an optimal concept has been determined which can now be handed over to the detailed design and development phase.

Design and development phase: the result is the product

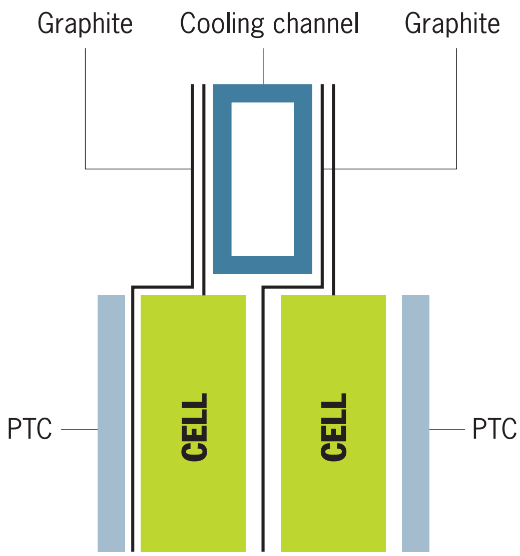
Prototype batteries only become available relatively late in the project process. The application as well as the driving and operating strategy, however, have to be developed earlier. For this, Porsche Engineering uses self-developed thermoelectric battery models that can map current-flow inhomogeneities as well as voltage and temperature drifts on the individual cell level. The special feature of these models is that they run in real time and can therefore emulate the battery behavior for control units and other hybrid components on the hybrid test bench. MATLAB/Simulink and in-house model libraries are used as tools. 3D simulations can also be conducted during the whole development process in order to determine critical heat transmission coefficients, for example, and transfer them to other models.

In 3D simulation, the focus can be on temperature behavior as well as hydraulic features. CFD and solid models are coupled to determine the transfer of heat from the cell to the fluid. Validation measurements on the in-house test bench ultimately enable correct implementation of key parameters in control units and simulation models.

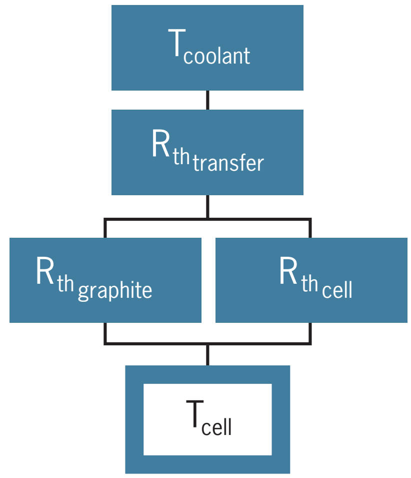
For transient calculations, 1D calculation with the GT-Suite is also suitable —particularly for mapping the limit temperatures and heating-up and cool-down times in dynamic driving cycles. Parameter variations are especially easy to conduct using this method. Material thicknesses, tolerances, and material characteristics can be varied and their impact evaluated over a driving cycle. One positive side-effect is the option of coupling the battery model with the cooling circuit model. In the context of function development, these models are of major importance for the development and virtual testing of software based on a realistic scenario.

The key to success—thermal resistance

To precisely describe the behavior of the battery under electrical loads and simultaneous cooling, knowledge of the thermal network of the overall battery system is indispensable. This network can usually be summarized in terms of a thermal resistance. As a rule, thermal resistance is composed of multiple thermal paths. These are comparable to a



PTC = positive temperature coefficient



T = temperature
R_{th} transfer = thermal transfer resistance
R_{th} graphite = thermal resistance graphite
R_{th} cell = thermal resistance cell

Conversion of real structure into a thermal network model

parallel and serial resistance like in electrical applications. The graphic above depicts a simplified thermal path using the example of a battery with pouch cells and integrated PTC heating.

The heat is directed from the pouch cell towards the conductor—the electric cell contact in this case—in a parallel path via the graphite foils. The heat is then conducted into the coolant via an optimized cooling plate. To efficiently move the waste heat from the cells to the cooling plate, in the battery technology area Porsche Engineering uses new materials such as graphite, phase transition materials and heat-pipes. These can be used to achieve thermal conductivity coefficients of over 1000 W/mK.

Unfortunately, good heat conductors also conduct electricity well. Therefore good electrical insulation is essential in high-voltage batteries for vehicles. Resolving this conflict requires an ideal compromise between thermal conductivity and high-voltage safety, which makes the material selection process considerably more difficult.

Testing processes from the cell to the battery: cross-sectional-function

Characterizing the thermal network in a complex simulation model requires detailed thermal analysis on the test bench. When the actually measured data is compared with results from the thermal network model, the differences that emerge can be used to configure the model parameters with great precision. This enables the successive development of a coordinated and validated simulation model of the battery.

This coordinated model now enables the process of adapting limit and threshold values of control unit functions to factors such as the ambient temperature. This capability of pre-applying the control units before real prototypes are available significantly accelerates the later final application in the complete vehicle.

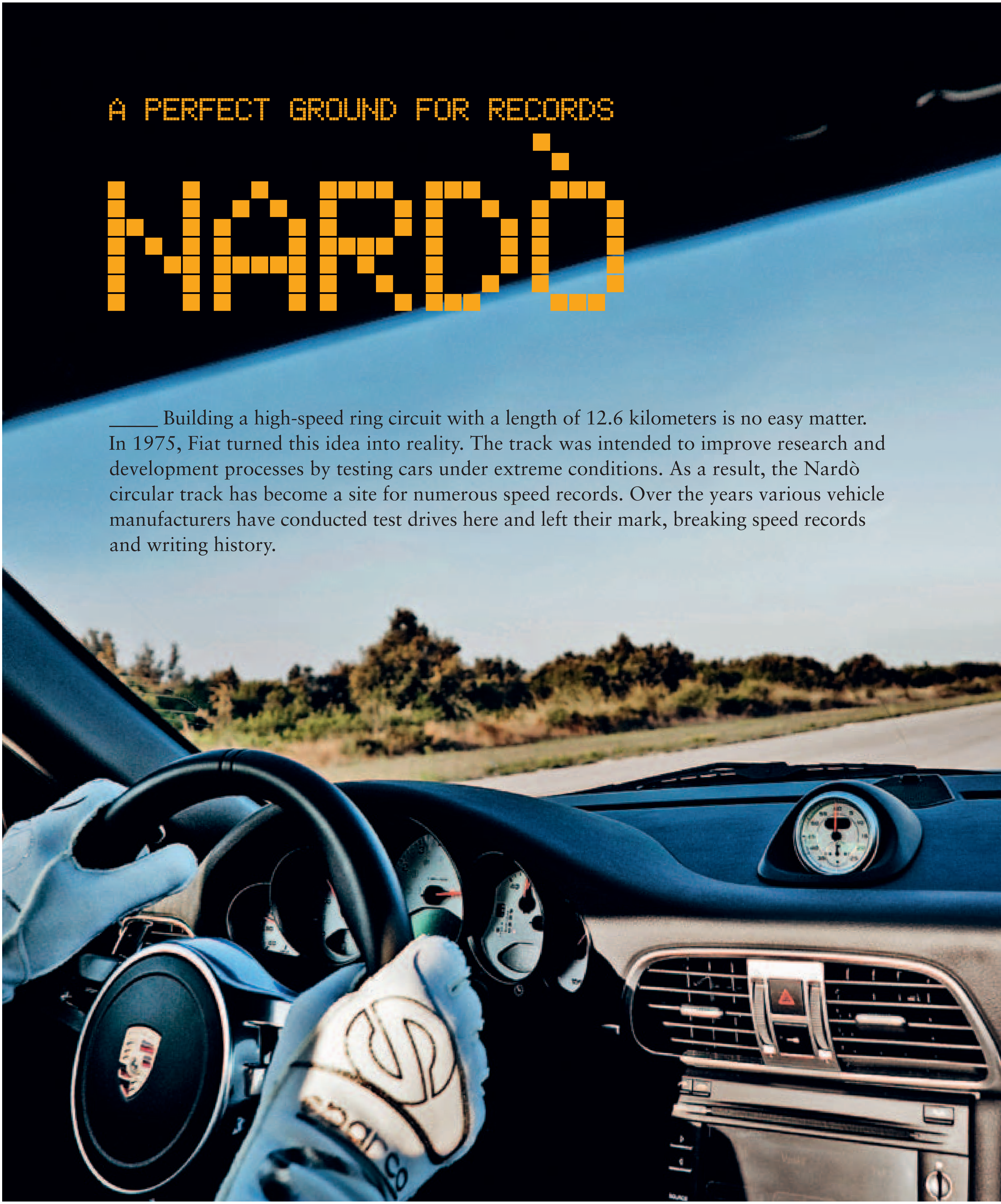
Outlook

The future of thermal management for batteries depends on developments in cell chemistry. Lab research is currently focusing intensively on lithium-air and lithium-sulfur technology. Whichever direction the developments may take, thermal management will have to react accordingly. This could lead to solutions that go beyond the automotive technology used heretofore. ■

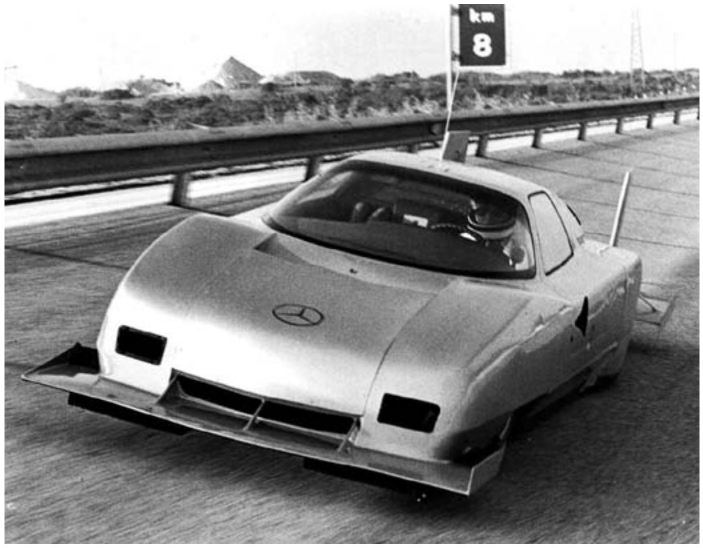
A PERFECT GROUND FOR RECORDS

NARDÒ

Building a high-speed ring circuit with a length of 12.6 kilometers is no easy matter. In 1975, Fiat turned this idea into reality. The track was intended to improve research and development processes by testing cars under extreme conditions. As a result, the Nardò circular track has become a site for numerous speed records. Over the years various vehicle manufacturers have conducted test drives here and left their mark, breaking speed records and writing history.



911 MODELS: Fuel consumption (combined) 12.4–8.2 l/100 km; CO_2 emissions (combined) 289–191 g/km; Efficiency class: G–F



1979 1979: THE MERCEDES-BENZ C 111-IV HITS 403 KM/H

A long list of records

At the entrance of the Nardò Technical Center, which has been managed by Porsche Engineering since 2012, a large board lists the most significant records set on the track. It honors special achievements and acts as a summary of 40 years of record-breaking history. All these achievements have always been conducted in private, far from spectators and prying eyes.

1979: The Mercedes-Benz C 111-IV hits 403 km/h

The Italian record for the highest speed was attained in Nardò by the Mercedes-Benz C 111-IV. On May 5, 1979 it reached precisely 403.978 km/h thereby breaking the 400 km/h mark. Behind the wheel was Hans Liebold, who was not a race driver, but the chief project engineer, who completed the flying lap of the circular Nardò track in 1 minute 57 seconds. His car was built specifically with a twin turbo 4.82 liter biturbo V8 engine producing 373 kW (500 hp) at 6,200 rpm. The huge central fin and long tail of the vehicle were in stark contrast with the otherwise rather narrow body. The appearance of this vehicle on the track was the culmination of a project launched in the late 1960s by the brand with the three-pointed star. ›

1982 THE PORSCHE REVOLUTION WITH THE 928 S

1983 A MERCEDES-BENZ 190 E 2.3-16 FLAT OUT FOR 201 HOURS

1982: The Porsche revolution with the 928 S

Both performance and endurance are aspects that the Nardò ring track was specifically created for, while the focus was always on reaching the highest speeds. Could the 928 S be as successful as the legendary Porsche 911? This was a challenge that Porsche set itself, as it veered away from the original DNA of the brand itself, with a front engine/rear transaxle layout. As innovative as the car appeared, however, the German engineers had simply changed the formula, and the result was just as successful. On November 7, 1982, Porsche broke the 24-hour record with the 224 kW (300 hp) 4.7-liter V8, covering a distance of 6,033 kilometers at an average speed of 251.4 kilometers per hour.

1983: A Mercedes-Benz 190 E 2.3-16 flat out for 201 hours

After the Porsche record in 1982, Mercedes responded accordingly and from August 11 to 21, 1983 undertook a series of record attempts with the 190 E 2.3-16: a race car, that later dominated the DTM series and which had yet to be homologated for public roads. Over eleven days, the car set non-class records as well as the 25,000 and 50,000 kilometer records. Everyone involved was enthralled for 201 hours, 39 minutes, and 43 seconds. The special version of the sedan reached a top speed of 250 kilometers per hour, made possible with a modified fuel injection system and by eliminating the power steering.

1994: Max Biaggi on the Violent Violet

While Nardò has always been a test track and has never hosted a real race, there is nevertheless a feeling of unspoken competition in the air, as every company strives for the best performance. Max Biaggi broke the "flying kilometer" record on June 4, 1994, in the saddle of the Violent Violet—a motorcycle built by Fabio Fazi: "It was an incredible experience," recalls the Roman rider. "All I could hear was the rushing wind and the sound of the electric rotor; I felt like I was going to blast off at any moment. Lead acid batteries were installed instead of an engine. It had incredible torque and there were no gears. You just pressed a button on the handlebars and the bike shot off with a massive surge of power. At that time such performance from electric engines was completely unexpected." Max Biaggi's ride entered the Fédération Internationale de Motocyclisme (FIM) world records list with a performance of 164.198 kilometers per hour.

1994 BERTONE Z.E.R. (ZERO EMISSIONS RECORD)

2000 PIRELLI BEATS THE FLYING KILOMETER RECORD WITH SUZUKI

1994: Bertone Z.E.R. (Zero Emissions Record)

The Bertone Z.E.R. (Zero Emissions Record) was a cigar-shaped electric vehicle created to challenge the Americans on the Bonneville Salt Flats in Utah. The idea was the brainchild of Oscar De Vita, an engineering student at Milan Polytechnic. “The vehicle was shaped like a rocket and was only as wide as my shoulders,” recalls De Vita. “I submitted this project—the thesis for my degree—to Mr. Bertone. He then decided to support and to push my project. The required wind tunnel studies were done in eight months, while I worked on the electric motor.” The project was also sponsored by the battery producer Fiamm, which wanted to promote lead acid batteries. “Instead of going to America for the tests, we decided to take the car to Nardò in order to try to beat the one-hour distance record there. The goal was to reach 200 kilometers per hour with an electric motor. Our result of 199.882 kilometers per hour was very close. There was a slight drop in battery voltage towards the end of the run so we didn’t quite manage to reach 200 km/h. If we had had nickel cadmium batteries, we would have crossed the 200 km/h speed barrier.” This was just a first taste, however: “We developed the project even further in 1995 for an attempt on the flying kilometer record at the Nardò track. Bertone presented the new project at the Geneva Motor Show.” Former rally champion Sandro Munari turned the drive down, as he feared the risk of overturning under the centrifugal forces of the circular Nardò circuit. So Oscar de Vita decided to drive himself. “I drove the car flat out in the fourth lane, the one with the steepest bank, but at first we could not get above 295 kilometers per hour.” However success was not far away. At the end of the test, de Vita reported via his helmet microphone: “I’m past 300 km/h!” The timekeepers then officially confirmed the new record of 303.977 km/h.

2000: Pirelli beats the flying kilometer record with Suzuki

Salvo Pennisi, Pirelli motorcycle product development manager and motorcyclist himself, has achieved 23 speed records in Nardò. “Nardò,” says Pennisi, “is the ideal facility for developing high-performance motorcycle tires, but it is also a place of unforgettable memories. I shared my records with four-time world champion Fabio Villa. And it means a lot to me that the SBK tires for the Superbike World Championship at the Phillip Island circuit were developed at the circuit in Apulia.” He speaks with pride, because the ring was decisive in convincing a number of Japanese managers to choose ›

2002 THE W12—A CAR THAT STILL HOLDS SEVEN RECORDS TODAY

2004 ELIICA, A 370 KM/H SEDAN FROM JAPAN

Pirelli tires as original equipment for their motorcycles. "In 2000, we made a bid for the flying kilometer record with the Suzuki GSX 1300 R," explains Villa. We set it with a speed of 306.598 km/h, but this was only the average of the two runs in opposite directions. During the second run, I had actually hit 320 km/h."

2002: The W12—a car that still holds seven records today

In addition to a tire, a car has also been named after the world-famous Nardò proving ground: The Volkswagen "W12 Nardò," a concept car designed by Charlie Adair, was presented at the Tokyo Motor Show in 2001. The vehicle set ten records on April 14, 2001 with the drivers Dieter Depping, Jean-François Hemroulle, Marc Duez, Mauro Baldi, Emanuele Naspetti, and Giorgio Sanna. However, it was the later W12-record version that on February 24, 2002 even exceeded the former performance by setting a 24-hour distance and speed record by covering 7,740.576 kilometers at an average of 322.891 km/h. The Wolfsburg-based car manufacturer had created a 441 kW (600 hp) vehicle with 621 Nm of torque weighing just 1,200 kilograms. Today, twelve years later, this vehicle still holds seven world records.

2004: Eliica, a 370 km/h sedan from Japan

Nine years after the Bertone record, another electric sedan set down a clear mark. The Eliica ("Electric Lithium-Ion battery Car") was an outlandish project developed by 40 students from Keio University in Japan, under the guidance of Prof. Hiroshi Shimizu. The electric sedan was an eight-wheel drive car with eight electric motors of 60 kW (80 hp) each and a combined total of 480 kW (640 hp) powered by a bank of 80 batteries mounted in four rows. Charging the car to a full 100 volts took about ten hours. In 2004, the 2,100-kilogram car rocketed at 370 kilometers per hour on the ring circuit in Apulia.

2005: New record with the Koenigsegg CCR

On February 28, 2008, Loris Bicocchi set a speed record of 388 km/h with the Koenigsegg CCR on the circular track. The Swedish sports car powered by a 4.7-liter V8 produced 601 kW (806 hp) and 920 Nm of torque. It is relatively simple to drive on the Nardò circuit at up to 240 km/h, as at this speed the driver doesn't need to steer in the outermost lane. At this relatively moderate speed, the car behaves as though

2005 NEW RECORD WITH THE KOENIGSEGG CCR

2012 PANAMERA DIESEL, 24 HOURS CHALLENGE, ECONOMY RUN

it were driving in a straight line. However, at faster speeds the driver has to keep correcting the driving line with the steering wheel. Even though Bicocchi tried to steer as little as possible during the attempt in order to minimize tire wear, he still reached a steering angle of 30°.

2012: Panamera Diesel, 24 Hours Challenge, Economy Run

In recent years, the focus of vehicle testing has shifted from pure performance to efficiency. In 2012, Porsche Italia organized the "Panamera Diesel, 24 Hours Challenge, Economy Run." The purpose behind this electrifying 24 Hours was highlighting the road-racing features offered by the comfort and reduced fuel consumption of the Porsche Panamera Diesel, one year after it came onto the market. The winning strategy was focusing on the efficiency of the Panamera Diesel: the drivers who simply attempted to save fuel, with an absolute peak of 18.9 km/l, were beaten by the drivers who combined this with the highest speed. Basically, it was unnecessary to go slowly and, on the contrary, the maximum saving could actually be made with the car travelling at the speed limit according to the Highway Code. The three Panamera cars covered a total distance of 7,967 km at an average speed of approximately 120 km/h, with consumption of 6.1 l/100 km, in line with the values declared by the manufacturer.

Who knows what surprises the next record attempt in Nardò holds in store? Technology evolves constantly, and humanity continues to love pushing back the boundaries of progress. ■

PANAMERA DIESEL: Fuel consumption (combined) 6,4 l/100km; CO_2 emissions (combined) 169 g/km; Efficiency class: B

LE MANS

The Return

____ Compact and light, yet powerful, highly efficient, and innovative—this is how Porsche returned to the top class LMP1 of endurance racing. With the development of the 919 Hybrid, the engineers once again pushed their core expertise to the limit and thereby enabled an impressive comeback.

The engineers of the participating carmakers accepted the challenge of reducing the energy consumption of the vehicles. The result: Race cars sent out to the track with very different solutions under their bodies.

Andreas Seidl, Porsche team boss, Wolfgang Hatz, board member for Research and Development of Porsche AG, and Fritz Enzinger, LMP1 head (from left to right) follow the performance of the Porsche vehicles from the pit.

The 24 Hours of Le Mans is the most famous endurance race in the world. Back in 1951—production of the first sports car in Stuttgart-Zuffenhausen has only been under way since March of the preceding year—a small contingent from Porsche KG braves the high-speed course 200 kilometers west of Paris. The class victory of the light-alloy 356 SL Coupé in its very first start marks the beginning of one of the great legends of motor racing: Porsche and Le Mans. Only Porsche has been at the start for 63 years running, and the reward for this remarkable staying power is a series of records, including 16 triumphant overall victories and 102 class victories. The sporting competition and the success at the top level of motor racing at one of the most famous venues belong to Porsche just as much as the number combination 911.

The return in 2014

Since 1998, Porsche had not started in the top class Le-Mans-Prototype-1 (LMP1) of endurance racing. The Stuttgart-based sports car manufacturer returned to the fray this year and answered the new FIA efficiency rules, which limit energy consumption per lap, with the innovative 919 Hybrid. Wolfgang Hatz, board member for Research and Development at Porsche AG, announced the return to the top class of the sports car World Endurance Championship (WEC) as follows: "We remain ideally positioned in the GT area, but it was simply time for the brand to return to the top echelon of motor racing. As far as I can remember, there has never been a set of rules that granted engineers so much freedom and demanded so much innovative ingenuity. (…) The hybridization requirement and the efficiency formula are revolutionary challenges, and in the end Porsche customers will profit from that."

New rules

Not only Porsche's return to Le Mans, but also the technically demanding rules, were practically revolutionary this year: With a reduced fuel consumption requirement in place, the Fédération Internationale de l'Automobile (FIA) and the Automobile Club de l'Ouest (ACO) are making the fastest race cars in the world fit for the future. To stoke innovation, the engineers were given unprecedented freedom—the FIA and ACO declined to prescribe a uniform hybrid system. And there were no limits on either displacement or the number of cylinders. Diesel or gasoline, turbo or not—the decision was up to the engineers. Whether one or two recuperation systems, battery storage, ultracapacitor or flywheel, nothing was off-limits. So the engineers at the participating carmakers tinkered to beat the band, weighing the benefits and disadvantages of every parameter. Viewed from the outside, the companies came to similar conclusions, but a closer look revealed that under the bodies, the developments could scarcely have been more different.

919 Hybrid: the technology

In its design of the combustion engine, Porsche opted for an approach that matches the brand DNA: A gasoline engine fires the new Porsche 919 Hybrid. It's an extremely compact and highly charged 2-liter V4 with direct fuel injection and an output of 370 kW (500 hp)—highly efficient combustion in a downsized engine.

Porsche employed two systems for energy recuperation. On the front axle, the 919 Hybrid recuperates the kinetic energy released by braking. Fundamentally new is the second system: recuperation from exhaust energy. The generator is driven by a turbine that generates energy like a bicycle dynamo. This energy is stored in a liquid-cooled lithium-ion battery. When the driver calls it up from there, a several hundred hp-strong electric motor uses it to drive the front axle. When boosted, the 919 Hybrid transforms into a quiet all-wheeler with exceptional traction. With the development of both recuperation systems and the storage technology, Porsche AG and its in-house engineering services provider Porsche Engineering have advanced their core competences once again.

Race outcome and conclusion

It was a tense and exciting 24 hours, the most fiercely contested race in years. With start positions two and four coming out of qualifying, the two hybrids showed that that they were competitive from the get-go. After an exciting start in temperamental weather, numerous dropouts, and a comparatively quiet night, Timo Bernhard took the lead in his Porsche 919 Hybrid after 20 of the 24 hours. At 12:36 he handed over his car with start number 20, still in the lead, to Mark Webber. But just 20 minutes later, the Australian slowed and rolled back to the box on electric power alone. The cause was a damaged powertrain—irreparable for the mechanics. The second prototype, driven by the trio Romain Dumas, Neel Jani and Marc Lieb, had a similar outing, beginning strong and holding its own for most of the race before falling back due to transmission trouble and finally being rolled into the pit at 12:54 while in fourth place. The car—start number 14—did return to the track shortly before the end of the race and crossed the finish line under its own power, but also failed to place.

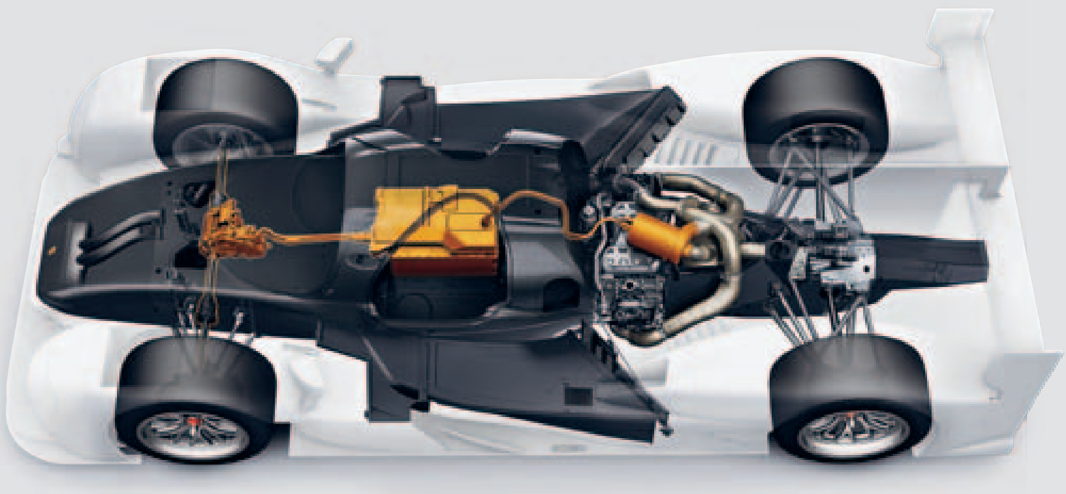
In spite of the initial disappointment—especially among team members, of course, but also the fans—in retrospect the excitement and feeling of success predominate. “In our return to Le Mans we put on an outstanding team performance. The dream of ending our first start in this legendary endurance race in the Porsche 919 Hybrid on the podium very nearly came true. For quite some time we even held the lead. We’re now looking ahead and will be back in 2015 stronger than ever,” concluded Matthias Müller, Chairman of the Executive Board of Porsche AG. In spite of missing the LMP1 victory, one winner of Porsche’s return to the top class was decided even before the race got under way: the customer. The insights and sharpened development expertise will have a direct impact on the series models of the future. ■

In the pit, every second counts: Whether the 919 Hybrid can win the day with its innovative recuperation systems does not depend solely on the development expertise of the engineers. The performance of the team on the track has to be right too.

Battery Development for the 919 Hybrid

____ In the course of development activities for the return to Le Mans, Porsche opted to conduct battery development internally. Porsche Engineering has carried out a number of successful battery projects in recent years and took over the battery development for the new LMP1 race car—from the mechanical structure to the entire system control and testing.

By Michael Fürstner



Two recuperation systems make the 919 Hybrid a true Porsche. The exhaust energy recuperation enables charging of the liquid-cooled lithium-ion battery not only when braking, but also when accelerating.

The development of energy storage for the 919 Hybrid presented the engineers with various challenges:

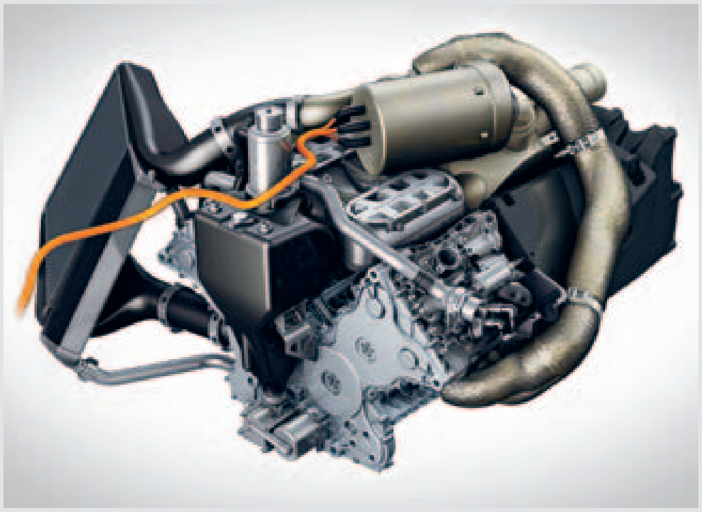
Weight problems and lack of space

Low system weight is always an important requirement and is therefore at the top of the priority list in motor racing as well. The very limited space within the vehicle also posed great challenges for the engineers. For safety reasons, the entire system is located next to the driver in the monocoque—in the crash-protected area with just millimeters separating it from neighboring components. It was therefore necessary to develop a highly compact, extremely small and lightweight battery without compromising electrical system performance. After all, the drive motor on the front axle of the LMP1 lays down 220 kW (300 hp) and naturally requires a sufficient and reliable power supply to perform its function.

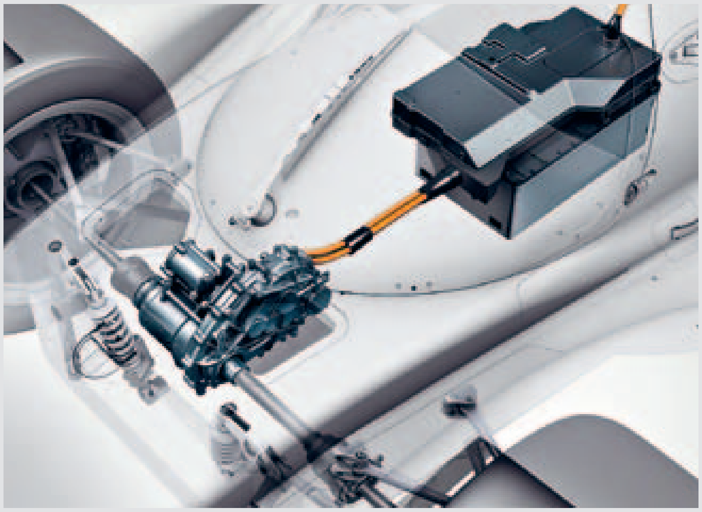
High voltage

The electrical energy is stored in lithium-ion cells from A123 Systems which were specially developed for this motor racing application and combined into compact modules using a special welding procedure. Each individual module has less than 60 volts. This modular construction is important not least for safety reasons when assembling the overall system since, in DC applications, the hazardous high-voltage range begins at 60 volts.

The overall system voltage of the 919 Hybrid is significantly above the 300–400 volts normally found in conventional electric vehicle applications. Higher voltages allow the load current-bearing components to have smaller diameters, which in turn results in lower weights. However, the components required for the development of the battery control were not immediately available from suppliers—the system voltages in this range are found in locomotives, for example, which for reasons of traction are designed with a high unit weight in mind. So all of the required components had to be individually developed and manufactured.



Performance and efficiency: a V4 with direct gasoline injection, turbocharging and exhaust recuperation system for the Porsche 919 Hybrid.



The single electric motor distributes its power as needed via a differential on both front wheels; the state-of-the-art battery energy control center is positioned in the center of the vehicle.

Durability

The cooling system is of major importance for the durability of the battery. In the 919 Hybrid, the Computational Fluid Dynamics (CFD) based fluid cooling system dissipates the waste heat so effectively that even at full throttle only very small temperature differences are detectable across the entire battery. The thermal and electrical loads on the individual cells in the system are evenly balanced, which has a positive effect on the durability of the battery as a whole.

Testing to the limit

The mechanical loads on every component in a race car are enormous. Due to the extreme total system drive forces of the current LMP1 hybrid cars and the all-wheel drive used in the 919 Hybrid, the vehicle accelerations before, during, and after every corner are at nearly Formula One levels due to the extreme grip. In terms of top speeds, the LMP1s are even a bit above that level, with top speeds of over 330 km/h achieved at this year's Le Mans.

While in operation, all components must withstand the vibrations passed on by the extremely rigid monocoque, including the vibrations from the drive motor and those caused by unevenness of the road surface. The curbs present in many corners have centimeters-high transverse grooves that rattle any car driving over them to the core. For this reason, the mount of the battery had to be designed to provide maximum damping for precisely these stresses while still taking up as little space as possible and weighing next-to-nothing.

To ensure functionality, the newly developed system was ultimately put on the test bench. There it had to withstand hours on the hydraulic shaker with maximum vibrations. In addition, in the course of the homologation process, the placement and fastening of the battery was checked and assured.

System control and monitoring

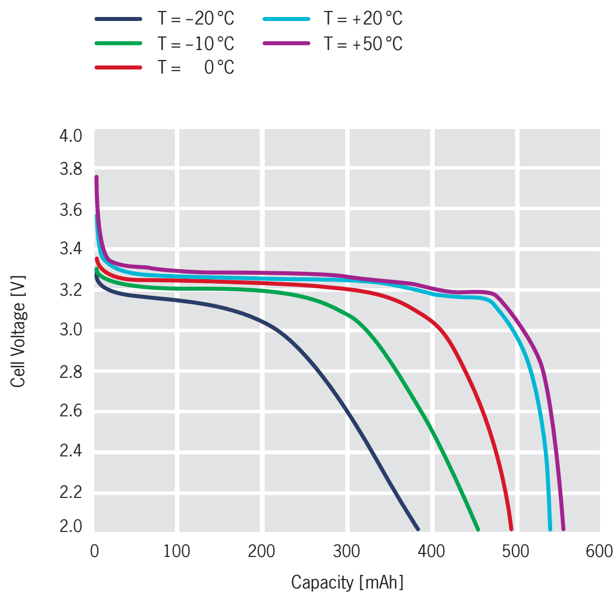
A significant component of the system is the integrated control unit. This includes various components, e.g. crash and current sensors, relay for switching off the system and individual components, resistors and interfaces for the power electronics, back-up and battery management system (BMS). The BMS monitors the entire battery system from the temperature and voltage values of the individual logical cells to the calculation of the charge level by means of special algorithms to evaluation of the crash sensor signals. ■

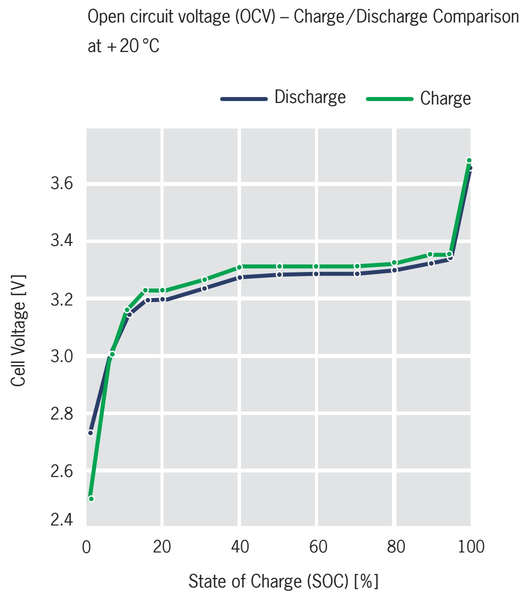
Keeping Current

Testing from the cell to the battery

____ Electromobility is of ever-greater significance in the automotive industry and requires comprehensive expertise in the areas of battery development and management. Exploiting the manifold potential applications of individual cells and the complex combination of them to form modules and batteries requires extensive testing. This is the only way to ensure safe and efficient functioning of the cell, module, battery component and complete battery under different conditions and thus ultimately provide the desired driving performance.

By Emmanuel Dhollande, Michael Geier, Manuel Groß, Florian Richter, Dr. Harald Schöffler





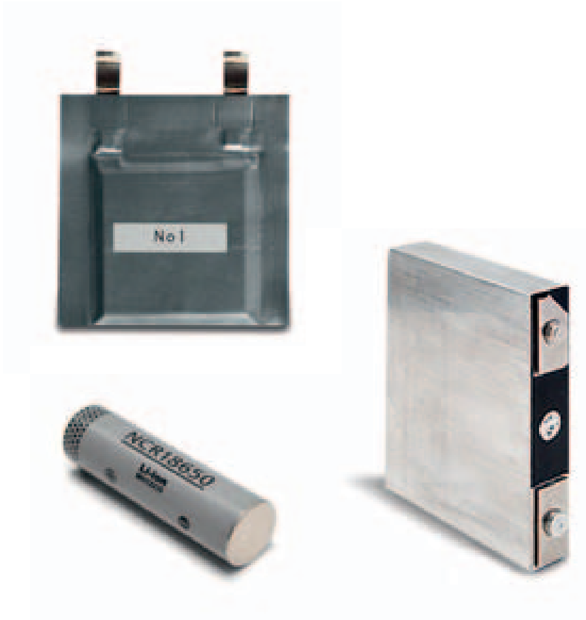
Standard measurements of capacity (left), open-circuit voltage (center) and internal resistance (right)

Qualification of individual cells

Lithium-ion cells are the smallest storage units in a battery. These are connected serially or in parallel to create modules, which in turn are serially connected to form the battery.

The cells come in different shapes and with varying capacities. This allows an optimal selection with regard to the field of application and, based on that, the voltage, capacity and structure. Due to the great number of different possible applications and the lack of standardization, adequate comparison of cells based on manufacturer specifications is not possible.

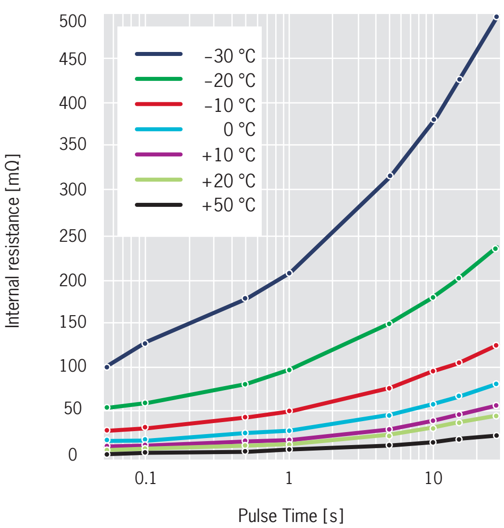
For this reason, at Porsche Engineering a baseline measurement is carried out for all relevant cells on the cell test bench to enable the creation of an identical and thus comparable data record of the characteristics of different cells for storage in a database. Using this cell data, the electrical parameters of a battery (e.g. voltage, current, and power loss) can be defined, or the specifications verified. If a commissioning party only specifies the performance and package conditions, the data in the cell database can be used to determine the most suitable cell for the respective application.



Various cell constructions

The standard measurements are conducted over the entire temperature range in the vehicle from –30 °C to +50 °C. First the temperature-dependent capacity of the cell is determined. Then the open-circuit voltage (OCV) and time-dependent internal resistance of the cell are determined for each temperature step at different charge levels. This data enables a sufficiently precise calculation of the static and dynamic properties of the cell to determine its suitability for the planned battery.

Internal Resistance discharge
at 0.5 A (1.0C) – 70% SOC



In the case of special applications, the data from the standard measurements is often insufficient to create a complete characterization. In that case, additional, more specific measurements are carried out on the test bench. Special cases such as the performance of the cells outside of their specifications (for extreme cold starts), changes to the standard parameters with age, or behavior in case of failure of an individual cell can be tested in this manner. This makes it possible to expand and confirm the range of the battery's potential application. Moreover, specific measurements can enable extrapolations to complete batteries which in turn allow performance comparisons with existing batteries based on other technologies, such as lead-acid batteries. ›

The cell test bench at Porsche Engineering

The cell test bench used by Porsche Engineering for such tests integrates four measurement modules that can be operated individually or in parallel. To increase the maximum current, the modules can each be connected in pairs so that either two modules can be operated at twice the current or one module operated at four times the usual current. In parallel with the measurement channels, up to 16 temperature sensors can be read and their measurement values stored alongside the voltage and current values.

The cells are set to the specified measurement temperature in a climate chamber. The configurable temperature range here is from –30 °C to +120 °C. The climate cabinet is controlled from the test bench. In the case of temperature changes, the program pauses until the target temperature is reached.

The test bench is completely programmable in its own scripting language so that test plans can be created in advance or modified from existing ones. An individual test plan runs on all activated channels completely independently so that, for example, the end-of-charge termination condition is carried out for each cell individually. With higher-order measures (for example change of cell temperature), the channels are synchronized.

Once started, the test bench can run fully independently for hours, days or weeks, while the current status can be monitored on the test computer at any time. There are various safety steps so that safe operation without supervision can be assured. Each channel has an overarching monitoring function for the minimum and maximum cell voltage as well as an optional temperature upper limit. If one of these limits is exceeded, the test bench switches itself off. Additionally, individual limits can be set for each test step. If these limits are exceeded, the current process step is terminated, but the test plan is continued.

CELL TEST BENCH

Voltage range	0 … 5 V
Current range 1	4 x ±30 A
Current range 2	2 x ±60 A
Current range 3	1 x ±120 A
Current increase	<100 µs
Sampling rate	5 ms
Temperature sensors	16
Control	Ethernet
Connection to thermal cabinet	Ethernet

Technical data for the cell test bench of Porsche Engineering

Cell modules on the battery test bench

Depending on the requirements of the battery design and calculation, multiple individual lithium-ion cells are combined to form cell modules, sometimes connected serially and sometimes in parallel. For safety reasons, the module voltage is kept below 60 volts to avoid any danger from the current to people touching the cell and module connections. The cell modules feature mechanical contact protection so that once construction is complete, the cell modules can be safely handled at any time.

After construction, the cell module is tested on the test bench. This involves connecting the high-current connections and the signal lines to the in-house-developed battery management system (BMS) with the module.

The first time the unit is put into operation, first the statistical distribution of the cell voltages is checked and, if necessary, brought to the same voltage level through targeted discharge of individual cells. Now a complete charge/discharge cycle is carried out at a low current to determine the total capacity and the voltage curve of the module. If no apparent problems occur here, further tests are carried out with steadily increasing currents until ultimately the maximum currents are tested.

With prototypes in particular, unexpected events regularly occur. For instance, local heat generation can indicate a poor connection between two cells caused by production errors. Especially, the determined internal resistance of the module at different charge states (SOC) and high currents provides a particularly good indication of the quality of the module. The insights thus gained aid in the continuous improvement of the module design and ultimately also electric and thermal optimization.

Battery baseline tests and battery startup tests

After the completion and final check of the battery with the previously individually tested modules, the baseline startup of the battery is conducted in the high-voltage test lab. Here we see, among other things, whether plausible voltage and temperature values are reported by the BMS and the contactors can be switched.

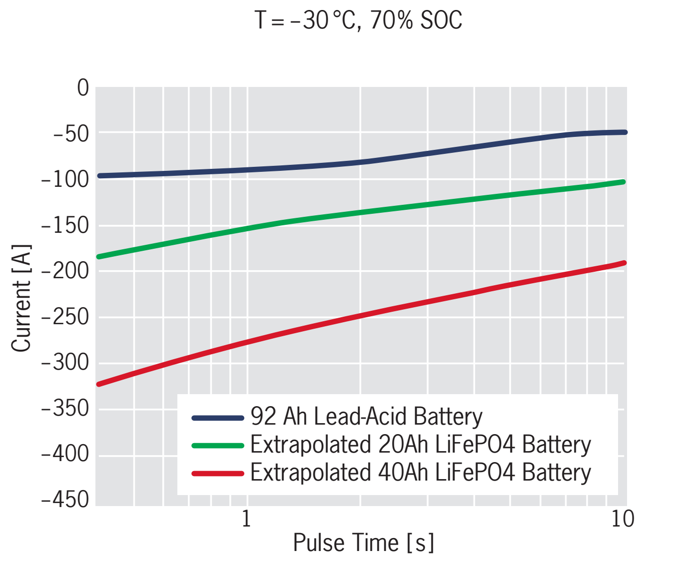
The insulation monitor performs an important safety function for the battery by continuously monitoring the insulation resistance between the battery and the chassis. If this insulation resistance sinks below a critical value, the potential for an electric shock exists. For the test of the insulation monitor, a test resistor is connected between the housing of the battery (chassis ground) and a battery terminal. Since the connection, for safety reasons (contact protection) has to take place behind the battery contactors, for this test the main contactors must be closed. The insulation monitor must identify and report the error within a certain time. A subsequent test checks whether the insulation monitor reliably recognizes and reports a cable break in its chassis connection. For all tests, all data is recorded on the test bench computer to ensure that all measurements can be evaluated and documented later.

Another test concerns the interlock (pilot line), which is run parallel to the HV lines through the vehicle and identifies open connectors. For this test, the contactors are switched and subsequently the interlock line is disconnected on the test bench. As a result, all of the battery's contactors must open immediately.

It is equally important for later use in the vehicle that the intermediate circuit is correctly precharged. Premature activation of the main contactor would damage or jam it. For this test, any test capacity can be connected to the battery output in accordance with the converter specifications.

When all performance data (end-of-charge/end-of-discharge voltage) and threshold values (maximum currents and coolant temperature) for the battery is ok, further tests in which the battery is actively charged and discharged begin.

To determine the capacity of the battery, it is charged up to the end-of-charge voltage. This also indicates whether the current sensor returns the correct values and whether the individual cell voltages are homogeneously distributed. At the end-of-charge limit the cells must be brought to the same voltage (balancing). After completion of the balancing procedure, the capacity of the battery is determined by discharging it up to the end-of-discharge voltage.



Comparison of the maximum current of a lead-acid battery with lithium-ion batteries projected from cell data with 11V discharge

Electrical characterization

If no noticeable problems occur in the baseline tests, further tests to characterize the battery are started. An important performance parameter here is the internal resistance of the entire battery. For this test the battery is charged with a current pulse after a sufficiently long rest period. The internal resistance determined in this measurement defines the maximum performance and the power loss of the battery. It also reflects significant aging effects.

Specified driving cycles are then simulated on the test bench. This makes it possible to test and qualify the battery with a real driving profile. The complete contact protection and the fireproof testing cell ensure maximum safety in the process for laboratory personnel.

Component tests

The high flexibility on the test bench makes it possible to test individual components and thus also individual fuses or connecting lines to obtain data for creating electrical and thermal models and measure the heating of the components for a certain current profile. ›

Software tests

The focus of the tests on the source-drain test bench is on the electrical components such as cells, high-voltage connections or contactors and is primarily used for verification of the high-voltage battery. But the quality of BMS algorithms can also be assessed. Validation of the BMS using “Software in the Loop” (SIL) and “Hardware in the Loop” (HIL) tests is a prerequisite for software tests on the test bench.

The test cases are executed either as EXAM or CANoe scripts and allow a high degree of automation. The baseline tests include monitoring the time parameters of the voltage and temperature measurement by the BMS. For thermal and electrical profiles, the distribution of this data is analyzed using MATLAB. Defective contacts can be localized this way. Increased connector impedance leads to thermal hot-spots and accelerated cell aging.

The charge state of the battery is an important factor that can be determined through charge meters and voltage-based indicators. Characteristic diagrams are usually obtained from the cell data sheets, validated on the test bench and are temperature-independent. The charge meter is calculated by the current sensor integrated in the battery. This generally represents a compromise between space, weight, accuracy and costs. The battery’s SOC is defined by the weakest link, i.e. the cell with the lowest charge.

To check the SOC algorithms, a charge counter is determined based on a reference current sensor and compared with the BMS data. Additionally, specific cells can be specifically discharged and later checked to see whether the BMS adapts the SOC. With a battery based on lithium iron phosphate cell technology, the SOC cannot always be determined from a voltage indicator. In this case more complex algorithms are applied which generally require special test cases.

One important task of the BMS is calculating the performance of the battery, which has a major impact on driving performance. For testing, the currents released by the BMS are applied to the battery in both quadrants (charge and discharge). The changes in the current limits are monitored and compared to the requirements.

Tests on the test bench represent an important element in the characterization process. They also deliver important measurement data to generate new SIL vectors for the BMS development. These have the advantage of always being reproducible.

Thermal tests

The thermal test bench is directly connected to the battery test bench, which enables highly flexible testing options. Depending on the internal resistance and current, the waste heat from a battery with a 300 kW traction output is around 6 kW due to the high electrical efficiency. This waste heat is dissipated into the environment through a coolant medium.

For the thermal characterization of batteries at Porsche Engineering, various tests are conducted. Different measurement parameters are recorded on the cell, module and battery level depending on the cooling system and stage of development. For precise characterization, up to 40 thermal elements can be mounted in one module to determine the thermal paths. Another important figure is the mass flow of the cooling medium, which in conjunction with the inlet and outlet temperatures of the cooling medium can be used to calculate the cooling performance. The waste heat of the battery can be determined through the internal resistance of the lithium-ion-cells.

The thermal start-up tests also include the stress test. Here a current profile is applied to the battery until it has achieved thermal balance. This is the case when the waste heat of the battery is equal to the cooling performance of the cooling system. In this state the thermal resistance is calculated which determines the cooling capacity of the battery.

PORSCHE CAYENNE S E-HYBRID

In a hybrid vehicle like the Porsche Cayenne S E-Hybrid, optimum battery management is of supreme importance.

The Cayenne S E-Hybrid is the first plug-in hybrid in the premium SUV segment. The technological advancement compared to the previous Cayenne S Hybrid is immense: It has a lithium-ion drive battery with a capacity of 10.8 kWh, which enables a purely electric range of 18 to 36 kilometers depending on driving style and terrain. The power of the electric motor has more than doubled from 34 kW (47 hp) to 70 kW (95 hp). Overall fuel consumption (combined) is now 3.4 l/100 km (CO_2 emissions (combined) are 79 g/km and electricity consumption (combined) is 20.8 kWh/100km). The combined power of the 3-liter V6 (245 kW/333 hp) supercharged engine and the electric motor of 306 kW (416 hp) at 5,500 rpm as well as total torque of 590 Nm at 1,250 to 4,000 rpm enable sports car-worthy performance figures: zero to 100 km/h in 5.9 seconds and a top speed of 243 km/h. The electric top speed is 125 km/h. The drive battery can be charged via the electricity grid or while driving.

The battery is also subjected to dynamic driving cycles according to the specified requirements. This involves checking for a balanced temperature distribution both within the individual cell and within the complete battery system as a whole. The tests also determine the permissible operating temperatures at which the system can provide the required performance without safety or durability concerns. Typical driving cycles include the Artemis cycle (CADC 150), highway cycles and various racing profiles.

Because almost all batteries that are tested on the test bench are also completely developed and produced at Porsche Engineering, the engineers have an ideal understanding of precisely how the units are equipped with temperature measurement points.

Conclusion

Using the described procedure and test methodology, all battery components are tested both individually as well as in terms of their interaction to ensure their functionality and especially their safety during the application. ■

CAYENNE S E-HYBRID: Fuel consumption (combined) 3.4 l/100 km; Electricity consumption (combined) 20.8 kWh/100 km; CO_2 emissions (combined) 79 g/km; efficiency class A+

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