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WHILE RECENT DECADES MAY HAVE PRODUCED INCREMENTAL ADVANCES IN INTERNAL COMBUSTION ENGINE TECHNOLOGIES, THEY ARE ADDING UP TO CREATE SOME DISRUPTIVE OPPORTUNITIES.

BY ROBERT M. WAGNER

O ver the past several years, road transportation has seen some significant advances in what are considered alternative technologies. Energy storage, electric drive systems, and fuel cell technology all seem to be poised to find a significant place in the automotive marketplace.

But it would be a mistake to believe that such technologies will completely sweep aside what has come before. Instead, the internal combustion engine will continue to be integral to the transportation of people and goods for the foreseeable future.

INES *of the* FUTURE

That is not to say that things will stay as they are now. The engine is undergoing a significant evolution of its own, as new fuel economy and emissions standards in the light-duty and heavy-duty sectors push the development of new technologies on an unprecedented scale toward the theoretical limits of engine operation. Coupled with continuing research into fundamental engine processes, the introduction of affordable high-performance computing, and the adoption of advanced manufacturing techniques throughout industry, those new technologies are leading to potentially disruptive opportunities for the introduction of engines with extraordinarily high efficiencies. How these new engines perform and how they will be integrated into new vehicle architectures will be the story of personal mobility for this half of the 21st century.

From my position at Oak Ridge National Laboratory, I have been able to see the intersection of knowledge discovery, advanced engine and vehicle technology development, and the use of one-of-a-kind computing resources. Although the public tends to think of automobile and engine research as a purely private-sector concern, my colleagues and I at ORNL are helping to realize the full efficiency potential of internal combustion engines.

EMISSIONS RESEARCH
Vitaly Prikhodko of ORNL's Fuels, Engines, and Emissions Research Center (above) studying advanced catalysts which are used to reduce vehicle pollution.
Photo: ORNL

The internal combustion engine

has seen a remarkable evolution over the past century. Before 1970 the evolution of engine design was driven by a quest for performance and an increase in octane in the fuel supply. Since then, however, the imperative was the need to meet new emissions and fuel economy regulations.

Internal combustion engine efficiency has historically been limited more by the state of technology than innovation. As an example, the potential of technologies such as gasoline direct injection were known and attempted in production more than 50 years ago, but direct injection has only become widely available in production within the last decade and now makes up approximately 38 percent of new light-duty vehicle sales. Another example is low-temperature combustion modes such as homogeneous charge compression ignition combustion—in which fuel and air are injected during the intake stroke and then compressed until the entire mixture reacts spontaneously—which were demonstrated in a laboratory more than 30 years ago but are still many years away from market introduction.

Game-changing advances in recent years are improvements in engine technologies, sensors, and onboard computing power. This combination of technologies will enable un-

FUEL-IN-OIL

Fast, real-time, on-engine measurement of oil contamination by fuel can enable improved engine calibration and better efficiency. (This technology has been licensed to Da Vinci Emissions Services.)
Photo: ORNL

CATALYTIC CONVERTERS

Glass capillaries with diameters on the order of a human hair allow sampling of exhaust pollutants inside the flow channels of catalytic converters (left) yielding critical understanding of the chemical process for the whole device (below).
Photos: ORNL

"ADVANCES ARE ENABLING NEW CONCEPTS THAT OF BOTH SPARK-IGNITION

precedented control of the combustion process, which in turn will enable real-world implementations of low-temperature combustion and other advanced strategies as well as improved robustness and fuel flexibility. In fact, technological advances are blurring our historical distinction between spark-ignition and compression-ignition engines; we will see new engine concepts that blend the best characteristics of both engine types to push the boundaries of efficiency while meeting stringent emissions regulations worldwide.

The push toward higher-efficiency engines will alter exhaust temperatures and chemistry and may create challenges for emission control technologies.

For example, new higher-efficiency engines will have lower exhaust temperatures, due to more efficient work extraction at the piston. Lower exhaust temperatures will, in turn, require the development of new emission control technologies, which must not only be effective at low temperatures but also must survive high exhaust temperatures encountered under high load conditions.

Even the most efficient and robust engine technologies will never make it to market without the vehicle system meeting emissions regulations. But this is not the first instance where significant emissions control advances were needed to transition a combustion technology to market. Advances in catalyst technologies more than 40 years ago were critical to meeting emerging emissions regulations; the effectiveness of catalysts for conventional spark-ignition engines has since improved by a factor of 100 while achieving a substantial reduction in expensive platinum group metals. Meeting the new challenges is a very active area of research at ORNL and other U.S. Department of Energy national laboratories, as well as in industry.

Low-temperature combustion

processes are of significant interest due to very high thermal efficiencies with significant reductions in many criteria pollutants. As mentioned above, LTC has been a challenge due to the state of technology: unlike conventional spark-ignition and compression-ignition combustion modes, most LTC modes are kinetically controlled and hence much more sensitive to environmental conditions and ever-changing speed/load demands. Recent advances in enabling technologies such as fuel injection systems, turbomachinery, valve actuation, sensors, and onboard computers have led to new real-time control opportunities which are enabling the potential of LTC engines with production-viable hardware.

Gasoline compression ignition combustion is an advanced combustion mode that has received considerable attention in recent years. While GCI combustion is not

NEUTRON IMAGING OF FUEL INJECTOR
Using neutrons to penetrate the internal structure of the engine part, researchers are studying cavitation, the physical event that leads to bubble formation inside the body of a gasoline fuel injector.
Photo: ORNL

COMBUSTION MODES
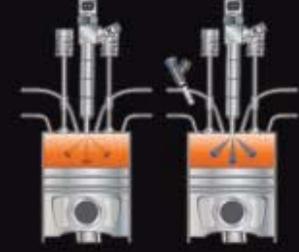Low temperature combustion modes have the potential for very high efficiency with very low emissions.
Image: Scott Curran, ORNL

SPARK IGNITION GASOLINE	LOW TEMPERATURE COMBUSTION	COMPRESSION IGNITION DIESEL
Low Reactivity Fuel	Range of Fuel Properties TBD (Depends on combustion mode)	High Reactivity Fuel

BLEND THE BEST CHARACTERISTICS AND COMPRESSION-IGNITION ENGINES

a new concept, it has evolved over the past several decades as technologies improve. Earlier GCI research was focused primarily on homogeneous charge compression ignition combustion, but in recent years, we have seen increasing interest in a continuous range of GCI combustion modes spanning fully homogeneous HCCI to partial fuel stratification modes to full stratification modes which are diesel-like in execution. These technologies have also led to a strong interest in reactivity controlled compression ignition combustion (RCCI), which makes use of the differences in reactivity of two fuels to manage the combustion process for maximum efficiency with lowest possible emissions.

Understanding the potential of these combustion modes—as well as understanding emissions and emissions control challenges and fuel technologies opportunities—forms the foundation of much of the fuels, engines, and emissions research at ORNL and builds upon more than two decades of experience in these areas. This research also includes a detailed comparison of the landscape of GCI and RCCI combustion modes to better understand the challenges and opportunities from efficiency, emissions, noise, and controllability perspectives. Simultaneously, other national

laboratories are performing complementary and synergistic research providing new insight into areas such as combustion fundamentals, advanced engine technologies, spray atomization, and simulation.

Stability and control have been major roadblocks to the implementation of many advanced combustion modes. Many low-temperature combustion modes such as GCI and RCCI operate on the edge of stability—in other words, at conditions under which very small variations in engine boundary conditions (such as intake temperature) may result in unintended excursions that result in undesirable emissions, reduced efficiency, and the potential to destroy the engine or emissions control system. One can imagine the challenge of these types of combustion modes under ever-changing conditions of a real-world drive cycle where a single unintended excursion could be catastrophic. Meeting that challenge requires a control system which is predictive for avoidance rather than reactive after the occurrence of a potentially damaging event.

ORNL has a long history in improving the understanding and control of these combustion instabilities to push the operating window and benefits of advanced combustion modes. That research and approach has a foundation in deterministic chaos theory and has evolved over the years from high-dilution spark-ignited combustion to include GCI and RCCI combustion in more recent years.

ORNL research has shown that for those combustion modes, the cyclic dispersion is made up of stochastic, or random, processes driven by in-cylinder fuel-air mixing and deterministic, or non-random, processes driven by the previous combustion event through residual gases. The resulting high level of instability is further amplified by cylinder-to-cylinder variations. While the high level of instability is a challenge, the existence of deterministic structure—non-random behavior—enables the potential for short-term prediction and control and ultimately to force stabilization of inherently unstable combustion modes.

That sort of prediction and control would have been inconceivable with production-viable technologies even 10 years ago. With the recent significant advances in low-cost sensors, fast actuators, and onboard computers, however, that level of control will be possible on production vehicles in the very near future.

WHILE SIGNIFICANT ADVANCES in engine control technologies, sensors, and onboard computers are leading to unprecedented opportunity, that work is also leading to an ever-expanding and unmanageable parameter space in modern engines. Current trends are showing an exponential increase in the parameter space which is expected to continue to grow for the foreseeable future. The inability to efficiently and effectively optimize this parameter space is leading to sub-optimal engines in the market and pushing the need for

ENGINES of the FUTURE

new approaches to engine design and optimization. Model-based and self-learning controls will be important for more robust and optimal calibration as well as for accelerating the calibration process. Current approaches to engine calibration depend primarily on reference tables, experimentally derived algorithms for parameter interactions, and manual optimization of calibration vehicles. Model-based controls will reduce the amount of experiments while better representing the complex interactions of engine hardware. Self-learning controls will take this one step further to enable autonomous intelligent systems which will have the ability to learn, adapt, and manipulate engine controls to maximize efficiency and

minimize emissions under ever-changing vehicle demands.

Self-learning controls will also be a critical component to the development of connected and autonomous vehicles that make use of vehicle-to-vehicle and vehicle-to-infrastructure information for the further optimization of engine and vehicle fuel efficiency.

Faster and more predictive simulation will be important to the design and optimization of the next generation of internal combustion engines. This will be important to critical knowledge discovery, managing the ever-expanding parameter space, and the development of reduced order models amenable to real-time control implementations. The continuing increase in computational speed and affordability of high-performance computing is leading to a new frontier in engine and vehicle development, including the ability to solve problems that were once deemed unsolvable.

Trends in the cost of high-performance computing indicate that "petascale" computers (and beyond) will be affordable to industry within a decade. For reference, a petaflop is one quadrillion floating point operations per second. The ORNL Titan supercomputer has a theoretical peak performance exceeding 27 petaflops. (To put this in perspective, 28 petaflops is equivalent to all 7 billion people in the world simultaneously performing 4 million calculations per second.) The affordability and availability of these types of resources to industry will be revolutionary to the design and calibration of engines as well as vehicles.
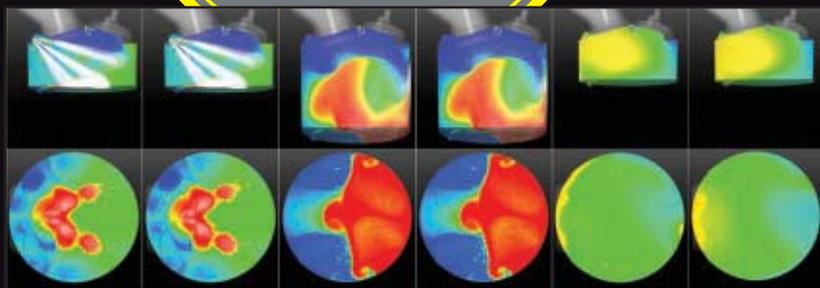
The supercomputers at the national laboratories are currently being used in support of DOE and in collaboration with industry for improved simulation of sprays, advanced combustion, and engine design. ORNL has ongoing projects which make use of these resources for furthering the understanding of combustion instabilities, accelerating injector design optimization, and even bridging high-

SIMULATED TRUCKING
One way to cut engine emissions is to reduce the workload on the vehicle. Supercomputer simulations conducted at Oak Ridge modeled a system that could reduce drag—and increase freight efficiency—in long-haul trucks.
Image: Michael Matheson, ORNL

COMBUSTION SIMULATION
CFD modeling provides insight into in-cylinder processes during RCCI combustion. This simulation shows the fuel air distribution across a sector mesh during the midpoint of combustion.
Image: Adam Dempsey, Scott Curran, ORNL

Equivalence Ratio [-]

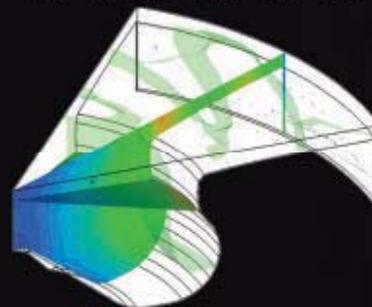0.37 0.42 0.46 0.51 0.55 0.60

FLUID DYNAMICS
Visualizing fuel concentration during charge preparation at the beginning (left) and end (middle) of injections, and at spark (right) helps improve the understanding of how small, random changes in fuel distribution impact cycle-to-cycle variability in combustion performance.
Image: K. Dean Edwards, Charles Finney, ORNL

Titan (top) is operated as a national user facility by the Oak Ridge Leadership Computing Facility at ORNL, which is supported by the Office of Science of the U.S. DOE.

PRINTED VEHICLES
The entire concept of the vehicle is being rethought for the 21st century. But even if 3-D printed trucks like this one become practical, advanced engines still will be vital to mobility.
Photo: ORNL

INTEGRATING VEHICLE SYSTEMS
The Vehicle Systems Integration laboratory at ORNL supports research and analysis related to hybrid powertrains, advanced combustion engines, and fuels and emissions research.
Photo: ORNL

> ## THE NEXT 10 YEARS WILL BRING ADVANCES WHICH WERE BEYOND THE REALM OF IMAGINATION JUST A FEW YEARS AGO.

fidelity combustion and structural codes for material property prediction.

ORNL recently led an industry stakeholder meeting with several other national laboratories to explore next steps in leveraging the massive power of high-performance computing for vehicle design. More specifically, the meeting focused on the potential of high-performance computing and industry interest in the development of an integrated software environment for bridging multiple technologies for multi-physics full 3-D high-fidelity vehicle simulation to make use of the power of the next generation of advanced computing architectures.

The new simulation environment would be developed specifically for vehicles, based on recent experience developing similar environments for nuclear reactors and batteries. As an example, consider the integration of 3-D high-fidelity models for the integrated design of thermal management, aerodynamics, and structure: this approach not only has the potential to greatly accelerate the design process, but also to reveal synergistic opportunities beyond what could be identified with more conventional approaches.

MOST OF THE DISCUSSION

up to now has focused on knowledge discovery and the development of better engine technologies—all areas within the control of automobile and engine manufac-

turers. There is now an ambitious program at the DOE and the national laboratories which is addressing the co-optimization of fuel and engine technologies for maximum performance with minimum greenhouse gas emissions, in other words removing the constraint that current fuels impose on engine design.

The "Optima" program bridges the broad expertise and resources of the Vehicle Technologies Office and the Bioenergy Technologies Office at the DOE. The overall plan includes a near-term phase which builds upon current engine technologies with a goal of new fuel and vehicle technologies in the marketplace by 2025, together with a longer-term—and arguably more ambitious—phase focused on kinetically controlled combustion processes and fuel technologies with impact expected in the 2030 timeframe. The Optima team is working closely with a broad range of stakeholders representing vehicle and engine manufacturers, energy companies, biofuel producers, fuel distributors and retailers as well as identifying and addressing potential deployment issues to ensure maximum success.

The combination of new regulations, consumer expectations, and the changing role of internal combustion engines with advanced vehicle architectures is increasing the demands on the next generation of engines and driving technology development at a rapid pace. An automotive executive recently said that the engine has changed more in the past 10 years than in

the previous 100 years. I completely agree and believe the next 10 years will bring even more rapid change with advances which were well beyond the realm of imagination just a few years ago.

I encourage members of ASME to explore the extensive research supported by DOE and under way at many of the national laboratories. The national laboratories are in a unique position to bridge large one-of-a-kind science resources with application and drive solutions to the energy challenges of the future. **ME**

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