Laser photoacoustic spectrometer making real-time measurements of the mass of particles in diesel engine exhaust. David M. Roessler is shown operating the instrument, which contains a carbon dioxide laser. The spectroscope has a response time of 0.5 second. (GM Research Laboratory photograph.) Figure 1

Physicists and their work in the automotive industry

Fundamental and applied research on a broad range of topics, including combustion, friction, materials and catalysis is aimed at improving both vehicle performance and manufacturing.

Frank E. Jamerson and Nils L. Muench

"Among the many fields of present-day physics which promise significant contributions to the automotive industry in the near future, is the physics of the 'solid-state'." These words, spoken in a March 1938 address[1] by Cornell University physicist Floyd K. Richtmyer, proved to be prophetic. Today, virtually every vehicle on the road has some solid-state component in its electrical system. In fact, the newest American automobiles embody integrated circuit technology in the form of durable microcomputers, which are an essential part of electronic engine-control systems. Such systems are just one example of the important role that physics has played in the progress of the US automotive industry.

Since Richtmyer's 1938 address—to the first symposium on physics in the automotive industry—the role and character of physicists in the industry has also changed. In the past, physicists contributed to problem-solving and application of physics measurement techniques to automotive materials and combustion.[2] Today, physicists pursue research at the frontiers of areas that show promise for improving materials or manufacturing processes. Research ranges from fundamental calculations of the surface density of states of metals[3] to the development and demonstration of an optical processor that can identify parts and, when coupled to a computer-controlled robot, locate and pick them up from a conveyor belt.[4]

In the course of our discussion of physics research that is being done in the automotive industry we hope the reader will gain some idea of the nature of physicists' careers in this industry. We will look at the way physics research is organized, and then we will examine the research activities themselves, focusing on three major areas of investigation. Naturally, because we know more about the work at General Motors Research Laboratories than elsewhere, that will be the source of most of our examples.

At this point some readers may be wondering: "How much basic research is done in the auto industry?" Unfortunately, the term "basic research" carries with it the National Science Foundation definition, "no relation to a business objective." By this definition the answer is "as little as possible." However, much of the research, especially in the larger laboratories, is fundamental in nature and aimed at a very far time-horizon. This research generates new knowledge, much of which is published in journals such as *Physical Review Letters* or *Applied Optics*.

It is probably most useful to classify applied research by the time-scale of its objectives. The bulk of the physics research in the large automotive corporations is long-range applied research (with objectives more than five years away) and fundamental research (with more broadly defined objectives), with short-range applied research and assistance to divisions representing the remainder.

Management in the automobile industry recognizes the motivations of individual researchers. Professional standing in the scientific community is important to the individual and valuable to the individual's employer. Therefore, management encourages publication of scientific and technical findings. In addition, most automotive research groups employ a "bottom up" philosophy for generating research projects. Ideas for new projects come from many directions, but it is important that the major share come from the individual researchers themselves. This ensures that scientists work on projects they want to work on. Later in the article we will return to the subject of project selection with a specific illustration.

Research projects in the automobile industry are highly interdisciplinary in nature. This is particularly true for applied research, which may involve, for example, physical chemists, mathematicians and mechanical engineers investigating engine combustion or control of exhaust particulates. This interplay of people of differing technical backgrounds is not only effective, but it invigorates and stimulates all members of the team.

Human resources

A continuing and ongoing interaction with the academic community is important to automotive research. University professors serve as consultants in their areas of specialty on a year-to-year basis. The physics department of the General Motors Research Laboratories currently has 12 consultants who contribute to specific projects. Consultant expertise, in topics such as statistical mechanics and neutron scattering, complements the knowledge of the research staff.

Some experts are invited for brief visits to lecture and exchange professional information. During a year, perhaps 100 visitors from university and government laboratories lecture at GM Research Laboratories, with 15 of these at the invitation of the laboratory's physics department. A similar number of seminars are delivered annually at universities by the professional staff of the department. In addition to the broad corporate-level support of universities, automobile companies provide specific grants or contracts that support university activities closely related to research being conducted in the industry. Both the university and the industry benefit from such interaction.

Two US automotive manufacturers have physics departments in their research organizations—Ford and General Motors. Of a total professional staff of 550 at Ford Engineering and Research Staff, 13% are physicists involved in fundamental and applied research as well as product development.[5] Physicists are employed at Chrysler, American Motors, Bendix and TRW, as well as other automotive-related corporations, and have assignments in engineering development groups that are concerned, for example, with electronic engine-control systems.

General Motors Research Laborato-

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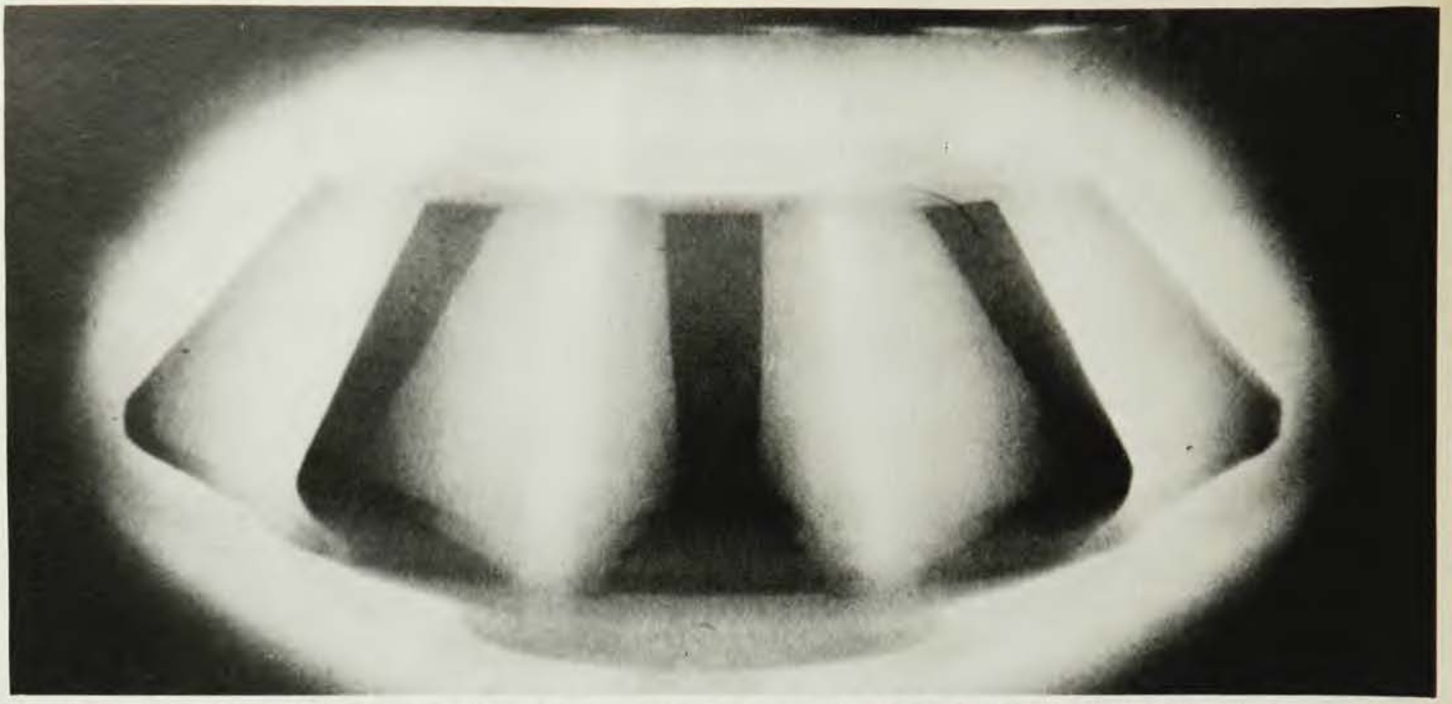


Pinion gear in methane plasma. Plasma carburizing, where carbon generated in the plasma diffuses into the surface of the metal, is a method of case hardening automobile parts. Plasma carburizing for 10 minutes at 1050 °C and 20 Torr produces a case depth of 0.5 mm. The process is still under development. Figure 2

ries is located at the GM Technical Center in Warren, Michigan, a complex that also houses other GM organizations, such as design, engineering, manufacturing and environmental activities. GM Research Laboratories has a total personnel of 1500, including 550 research and development professionals; of these, 330 hold PhDs and 58% have degrees in chemistry and chemical, mechanical or electrical engineering. Physicists comprise 7%, and degree-holders in other engineering fields, mathematics, computer science, metallurgy, social sciences and biological sciences make up the balance. Thus, physicists are able to communicate with experts in many technical areas. For example, physicists conducting fundamental research in laser spectroscopy of flames interact with research engineers who model and conduct experiments on internal combustion engines. Such interaction is stimulating and helpful to both the physicists and the engineers. It can promote new directions for fundamental research on problems that cannot be answered by conventional engineering approaches. Moreover, physicists enjoy contributing to the corporation's products.

The physics department at General Motors Research Laboratories is organized into seven groups with a total staff of 65, of whom 50 have college degrees. There are 35 PhDs, with 21 in physics and others in metallurgy, materials science, chemistry and electrical engineering. The support staff includes many with BS degrees in physics.

Research needs and activity

Major issues face the automobile industry. At the moment, quality, reliability, and cost are areas for primary attention. Other major issues that persist are air quality, safety, and future energy supplies. Each of these problems depends heavily on new technology for its solution. Engines must run on whatever fuel will be available in the future, whether it be petroleum-derived gasoline and diesel fuel, coal-derived methanol, shale-oil derived hydrocarbons, or electricity from nuclear plants. Ultimately, hydrogen may be a real possibility, but problems of production, distribution and on-vehicle storage are far from having an economical solution. However, solid-state physics research may help solve the hydrogen storage problem. Vehicle safety and air quality are each high-technology issues that have occupied approximately half of the resources of automotive research organizations over the past decade. We have made major progress, but there are continuing efforts to better understand phenomena such as rate-dependent metal deformation, catalysis and atmospheric behavior. The goals include improved performance with less use of critical materials.

To surpass overseas competition now requires (in addition to many other actions!) significant advances in the use of technology in product design and engineering as well as in manufacturing. We will give examples of research by physicists in these areas later in this article.

The range of activities in the physics department of General Motors Research Laboratories includes fundamental research and long-range applied research in those areas important to General Motors' business. In addition, we make use of the unique capabilities in this department by doing shorter-range applied research that contributes to current products. The following brief outline of group activities illustrates the range of research topics.

▶ Molecular physics—photoacoustic spectroscopy of particulates, theory of particulate formation in diesel engines, graphite fiber growth and properties.
▶ Chemical and optical physics—laser spectroscopy of flames, optical tomography of flames, combustion reaction theory, global atmospheric modeling.
▶ Interface physics—liquid–solid, oxide–metal and polymer–metal interfaces, optical properties of interfaces.
▶ Solid-state physics—magnetic alloys, rare earth materials, amorphous solids, surface theory.
▶ Electro-optical physics—semiconductor laser diodes, molecular-beam epitaxy, laser diode spectroscopy of gases and solids.
▶ Metal physics—strengthening and stiffening mechanisms in metals, fatigue detection, plasma hardening.
▶ Deformation—metal plasticity relationships, sheet metal formability, friction and lubrication.

The process by which projects are selected is illustrated by the present activity at General Motors Research Laboratories in photoacoustic spectroscopy. As management planned to introduce diesel engines into GM passenger cars, it was generally recognized that more knowledge was needed about all aspects of diesel exhaust particulates. It occurred to researcher Fred Faxvog that he could untilize his laser-optics background to devise a method for sizing and counting diesel particles.[6] By the mid-1970s it was surmised that future particle emission regulations would be based on total particle mass. This led Faxvog to propose in 1976 that the photoacoustic technique described at a conference he had recently attended, could be used to measure particle mass in real time. In the photoacoustic technique, light is absorbed by the particles, heating them and producing an increase in the pressure of the ambient gas. When the light beam is chopped at audio frequencies, the pressure fluctuations are sound waves that can be detected with a microphone. At infrared wavelengths the absorption, and hence the sound amplitude, is directly proportional to the particle mass. Faxvog and David Roessler (figure 1) explored[7] this approach and developed instrumentation that has been used successfully to measure particle emissions at a level well below that required by government legislation.

The results of physics research in the automotive industry are generally published in the scientific literature. These results usually appear first in internal company reports, which are disseminated to interested groups in engineering and manufacturing units in other staffs and at production divisions. Results that the researcher might not think of as directly applicable to a product might, upon review by a production engineer, have direct impact on a material or process in production. Conversely, from a detailed knowledge of relevant product and plant operations, the researcher may develop ideas for new applications or new directions for research. Technology transfers best when there is continuous direct communication between the generators of new ideas—the researchers—and the users of new ideas—the engineering or manufacturing people responsible for new or improved products. Thus physicists visit plants and discuss product development with engineers and manufacturing personnel. Reciprocally, production division personnel visit research laboratories to review specific project areas that might affect their product.

Some projects lead to the dissemination of research results to outside firms that manufacture equipment. For example, research on plasma carburizing by William Grube[8] has led to a process for case hardening of automotive parts such as gears. His method provides exceptional uniformity and up to a 10-to-1 reduction in processing time and up to a 100-to-1 reduction in natural-gas use compared with conventional gas carburizing. With plasma carburizing (figure 2), electrical heating of the part to a temperature higher than in conventional carburizing promotes faster diffusion of carbon (generated in a methane plasma) into the surface. The details of this process have been communicated to manufacturers of heat treatment equipment.

Current automotive industry research activities were reviewed at a Topical Conference on Physics in the Automotive Industry held 15–16 May 1980 in Detroit.[9] The conference was sponsored by the American Physical Society and the American Association of Physics Teachers with the purpose of enhancing the interaction between academic and automotive industry physicists. Research papers presented included: "Non-linear spectroscopy in combustion research," "Infrared diode lasers," "Vehicle emissions measurements with infrared diode lasers," "Electric-vehicle systems," "The role of exoelectrons and oxide films in fatigue detection," "Laser spectroscopy in combustion," "Exhaust-gas-oxygen sensors," "Transition-metal surface electronic structure" and "Thin-film light emitting display devices."

Some of these topics are included in the following examples of research on materials, laser spectroscopy and surfaces. Most of the research that we discuss is being done at General Motors; we have included examples of research by Ford as presented at the topical conference[9] and in these instances have identified the affiliation.

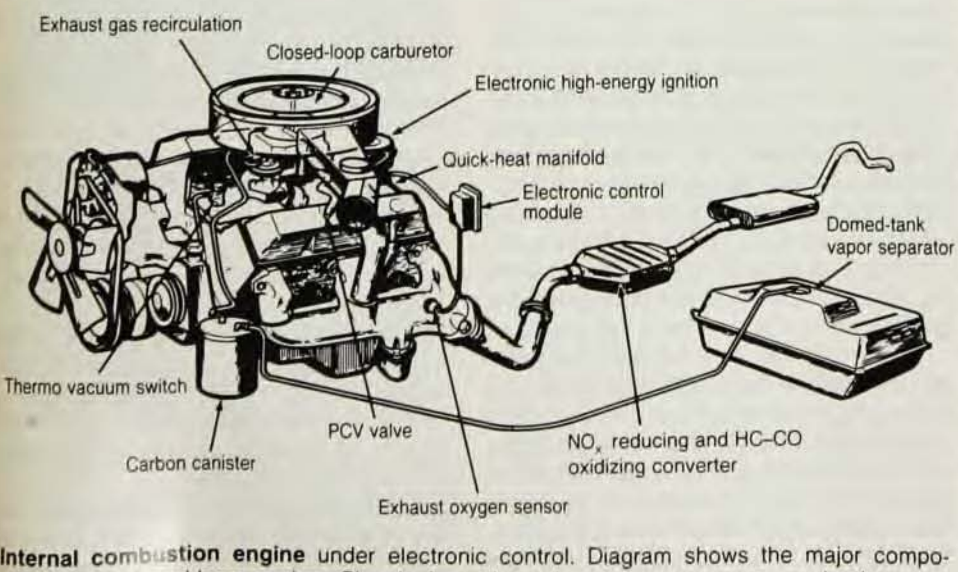
Materials

The automobile industry is a major user of materials such as steel, aluminum and copper. As a percentage of total US consumption in 1978, automotive usage was 22% for steel, 17% for aluminum, and 12% for copper.[10] The automobile industry conducts research on metals because many of the material properties desired are unique to this industry. Materials research can yield important results, which are shared with metals producers. This technology transfer works and leads to improvement and innovation in metal properties and performance in the automobile.

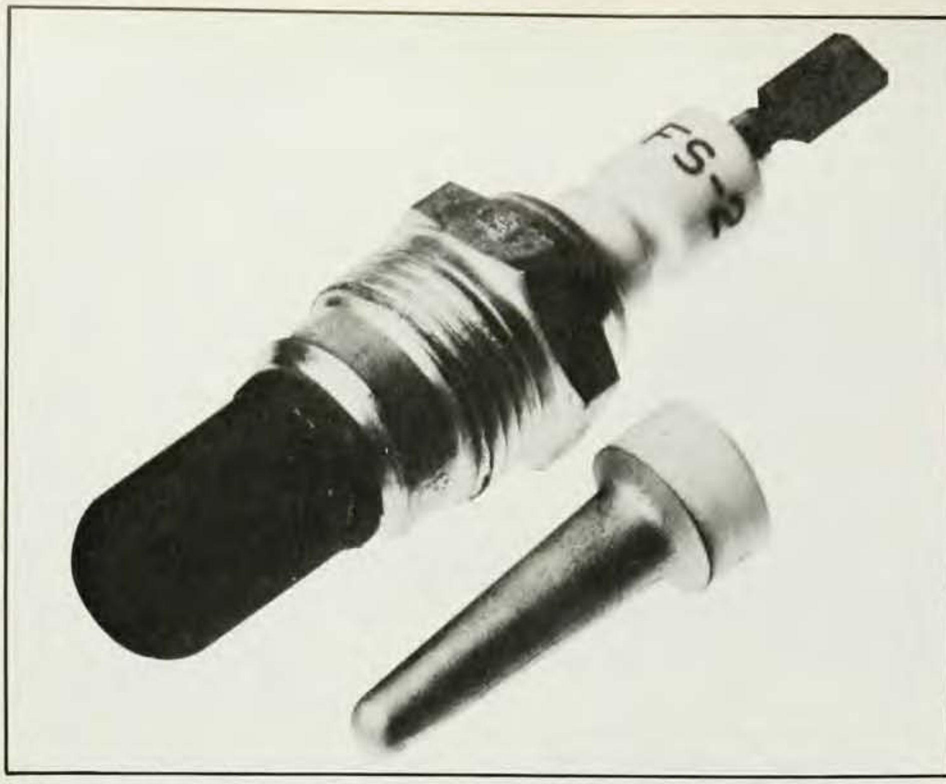
Physics research on metals has included fundamental studies of strengthening mechanisms, and this has led to the development of a high-strength steel that results from thermomechanical treatment of a low-carbon steel.[11] This is one of a new class of dual-phase steels that are soon to be made available to automobile manufacturers by the US steel industry. Because these steels are more formable than conventional high-strength, low-alloy steels, they promise to contribute significantly to the weight reduction of new vehicles.

Research on metal fatigue has given us new information on the early stages of fatigue damage. William Baxter[12] has explored the use of exoelectron emission, the enhanced photoelectron emission from a metal after it has been plastically deformed, to detect microcracks that occur in the natural surface oxide at sites of local plastic strain. A photoelectron microscope has been developed that reveals this emission, and thus the fatigue damage. Baxter has shown that the intensity of the exoelectron emission provides a quantitative measurement of the surface fatigue damage. Such fundamental knowledge may provide a new approach to evaluating the fatigue characteristics of components through a greatly shortened test. While this method is unlikely to eliminate the actual testing of final components to failure, it may substantially shorten the development and testing of new designs.

To meet fuel-economy and emissions goals while maintaining good driveabi-



Internal combustion engine under electronic control. Diagram shows the major components of a closed-loop engine. Signals from the exhaust oxygen sensor and other sensors are processed by the control-module computer to adjust the ratio of air to fuel for the best fuel economy while meeting emissions standards. Figure 3



Oxygen sensor used in the electronic control of a closed-loop engine. The sensor has a slotted cover that shields the zirconia ionic conductor, shown here next to the sensor. The zirconia is reentrant with platinum electrodes on both faces. Figure 4

lity, new closed-loop electronic control systems for gasoline engines were recently introduced (figure 3). A key component is the sensor that measures the partial pressure of oxygen in the exhaust. At an air-to-fuel ratio on the fuel-rich side of stoichiometric balance, the exhaust oxygen concentration is very low. However, at lean conditions the oxygen pressure increases rapidly. In response to this increase, the oxygen sensor produces a large change in signal as the air-to-fuel ratio passes through the stoichiometric balance point of about 14.5. Fortunately, for the best conversion of hydrocarbons, carbon monoxide and oxides of nitrogen in a catalytic converter, it is desirable to operate at stoichiometric balance. Thus, the electronic control system responds to the sensor signal and continually adjusts the air-to-fuel ratio to maintain it at the balance point. The ratio is adjusted by controlling the flow of fuel with a pulse-width-controlled metering system, typically operating at a frequency of ten hertz.

The oxygen sensor (figure 4) consists of zirconia doped with yttrium-oxide (which is an excellent oxygen-ion conductor) with platinum electrodes. Opposing faces of the sensor are exposed to the exhaust gas and to ambient air. The difference in the partial pressure of oxygen between the faces drives oxygen ions through the zirconia, generating a galvanic potential. To improve the response of the oxygen sensor in the lean region, Robert Hetrick[13] and other researchers at Ford Motor Company have devised an oxygen sensor based on zirconia cells with an oxygen pumping scheme. The output of this sensor is directly proportional to the oxygen concentration in the exhaust. Considerable research has been aimed at understanding the basic physical and chemical processes that control its operation[13] as well as meeting the sensor's durability and performance requirements.

Permanent magnets, typically hard ferrites, are found in several places in the automobile, among them dc accessory motors, ignition distributors and radio speakers. In fact, the auto industry uses about 40% of all hard ferrite magnets produced in the US. Research on magnetic materials is aimed at higher strength magnetic alloys that could reduce the size, weight and cost of these components. A misch-metal–samarium–cobalt alloy showed promise,[14] but the high price of cobalt (resulting from the conflict in Zaire, the primary producer of cobalt) has stalled economic development of new products from this alloy.

Research has now turned to studies of rare-earth–iron systems that are formed by ultrarapid quenching (melt spinning). One surprising finding has been the discovery by John Croat[15] of significant room temperature intrinsic coercivity (7.45 kOe) for a $Nd_{0.4}Fe_{0.6}$ melt-spun alloy. During the quench a metastable phase is formed that persists up to 625 K. Additional research is needed before such alloy systems will become practical magnets.

Since rare-earth systems afford an extraordinarily rich variety of physical properties, their potential technological significance extends beyond permanent magnets to areas as diverse as hydrogen storage and superconductivity. Valuable information regarding electronic structure continues to be furnished by x-ray photoemission and other spectroscopic techniques. Part of the challenge on the theoretical side is calculation of the relevant excitation energies. Jan Herbst has been involved in such an effort[16] for the rare-earth metals. Some of the results have also proved useful in interpreting experiments on fluctuating-valence materials, including $CePd_3$ and SmB_6.

Occasionally research leads to totally unanticipated technology. This occurred during the study of another magnetic alloy, MnAlC, which is transformed to a hard metastable magnetic state by heating followed by very rapid quench. This transformation, normally done by conventional oven annealing, was achieved by Herbst, Andrew Chraplyvy and John Croat with a focused one-watt argon-laser beam that locally heats the alloy to 700 K. Thermal conduction to the surrounding mass provides the rapid quench to produce the hard magnetic phase. Magnetic dots and stripes about 0.1 mm wide, as shown in figure 5, are easily produced in an otherwise non-magnetic host. Thus laser-selective magnetization offers the potential for magnetically coded devices and for unique field shaping of motor magnet pole pieces.

Laser spectroscopy

The spark-ignition internal-combustion engine is going through a renaissance because of new demands to improve fuel economy while simultaneously reducing exhaust emissions. Many factors affecting the utilization of fuel in engines are now highly controlled:

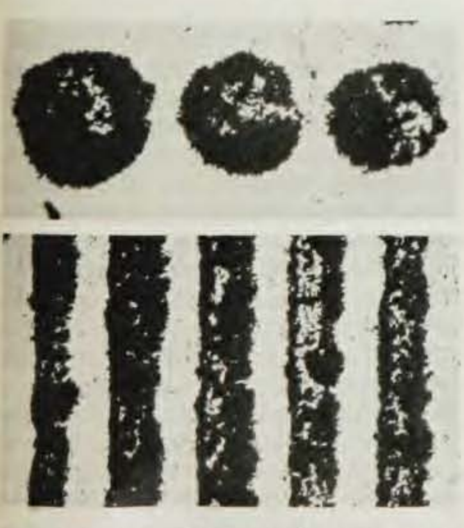
▶ Fuel and air metering. "Pulse width modulated" carburetors and "throttle body injection" fuel metering systems are driven by microcomputer signals that reflect driver inputs.

▶ Combustion chamber design. "Fast burn" and "stratified charge" chambers are in production and under development respectively.

▶ Ignition. Electronic ignition timed by signals from a microcomputer provides the right amount of spark advance for best engine efficiency, consistent with acceptable emissions, under all driving conditions.

Engineers are beginning to model, by finite element methods, fluid flow and heat transfer (with one-step chemistry) in internal combustion engines. What has yet to be fully understood is the combustion event itself: the chemistry and kinetics of the ignition and burning of a nearly homogeneous fuel–air mixture. Physicists in the automotive industry have risen to this challenge by taking advantage of one of the physicist's most powerful measurement tools, the laser.

Laser spectroscopy techniques are being applied to measure nonintrusively the concentration and temperature of combustion products in steady-state flames. New pulse laser techniques offer promise for accurate time-resolved measurements of combustion in engines. Kenneth Marko and Lajos Rimai at Ford Motor Company have reviewed[18] the application of nonlinear laser spectroscopy to combustion. One of the nonlinear methods is coherent anti-Stokes Raman spectroscopy, or CARS. For this spectroscopy the signal is emitted as a collimated beam of coherent radiation. The signal may be thought of as produced when three time-coincident laser pulses interact to produce a new laser frequency. If two of the incident pulses have frequency f_1 (green in cover photograph) and the third has a lower frequency f_2 (red), then the CARS signal is generated at $2f_1 - f_2$. This signal exhibits a resonance when $f_1 - f_2$ is the frequency of an allowed Raman transition. At room temperature most of the CARS transitions originate from the lowest vibrational energy levels of the molecular constituents. However, at flame temperatures, transitions from vibrationally excited states are also observed. The temperature of an individual species may, therefore, be measured by fitting the observed spectral shape to a theoretical calculation of the CARS spectrum with temperature as an adjustable parameter. For hydrocarbon–air flames the temperatures are usually obtained from the CARS spectra of molecular nitrogen. Measurements of a steady flame show that CARS can measure flame temperatures to within 25 K with several laser pulses, and to slightly poorer accuracy with a single pulse measurement. Distribution of carbon monoxide in a flame has also been measured by this technique.

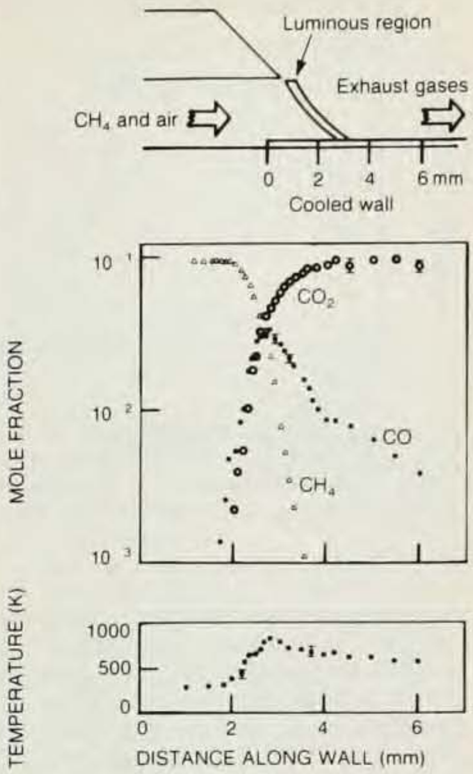


Tiny magnetic dots and stripes, (formed from $Mn_{0.532}Al_{0.445}Ni_{0.006}C_{0.017}$ by laser annealing) have a diameter or width of 0.1 mm. The magnetized regions are made visible here by their attraction of 1-micron-diameter iron oxide particles from a colloidal solution. Figure 5

The high spatial resolution of focused laser beams has allowed James Bechtel and Richard Blint[19] to measure temperature and species concentrations at the laminar flame–wall interface by spontaneous Raman spectroscopy. Concentration profiles of methane, carbon monoxide and carbon dioxide measured parallel to the wall at distances of 1.5 mm (which is in the free flame) and 0.15 mm (near the wall) are similar, even though the free flame temperature is 2000 K while the maximum temperature near the wall is only 870 K (see figure 6). This is a surprising result, in that we would not expect fuel oxidation to occur at such a low temperature. Other experiments show large concentrations of hydroxyl radicals, as measured by laser fluorescence, near the wall in the postcombustion region. This suggests diffusion into and out of the near-wall region.

Laser fluorescence techniques allow the detection of radicals such as OH^- in concentrations at the parts-per-million level. These measurements[19] are effected by scanning a frequency-doubled, tunable dye-laser across the absorption transitions from the various rotation-vibrational states of the electronic ground state to the rotational-vibrational states of electronic excited states. For OH^- these transitions are in the 300 nm region of the spectrum. The intensity of the observed fluorescence is proportional to the population in the absorbing state, but is complicated by the collisional quenching of the excited state. In separate experiments this collisional quenching rate has been shown to be nearly constant throughout the flame. These results, together with the Raman measurements, compare favorably with predictions of theoretical models that include fluid flow, heat transfer and detailed chemistry of the principal reacting species (up to 28 reactions). As our fundamental knowledge about the combustion process evolves, we anticipate that new ideas will emerge and be applied to engine design.

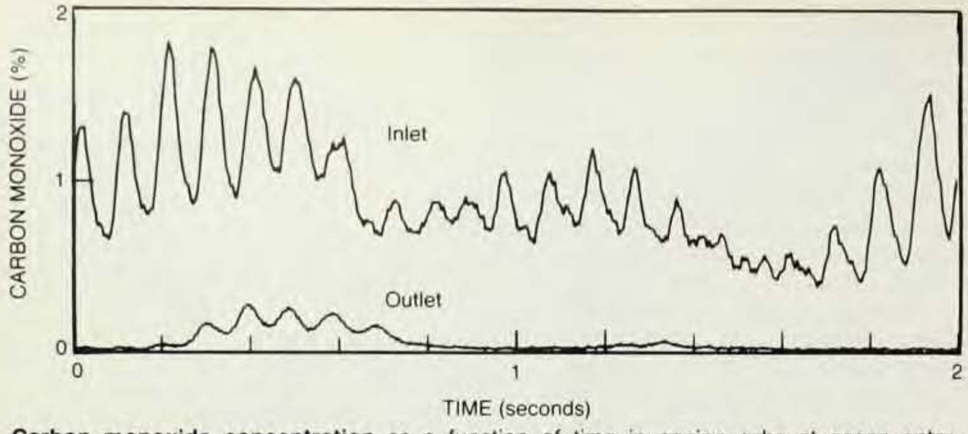
Infrared absorption spectroscopy has been used for many years in the automotive industry for materials analysis, and is also the Federal Test Procedure technique for measurement of carbon monoxide in exhaust. The Procedure calls for hydrocarbons to be measured by a flame-ionization technique and oxides of nitrogen by chemiluminescence.



Temperature and species concentration in a methane–air flame as a function of position. The data, obtained by laser Raman spectroscopy, show how these parameters vary as the point of interest moves from the region of the air and methane mixture, through the luminous region, and into the exhaust gases, always maintaining a 0.15-mm distance from a water-cooled copper wall. Air and fuel, mixed to stoichiometric balance, enter the luminous region from a 3-mm-wide channel. In spite of a maximum gas temperature of only 870 K, methane is consumed and decreases rapidly along the wall. Previously it was assumed that fuel would not be consumed in such "quench-layers." Theory that suggests diffusion of radicals into this region due to large concentration gradients, and diffusion of fuel out of this region, could explain the result. Figure 6

With an infrared diode laser we can measure all species of interest in exhaust emissions with one technique and with a response time of 25 msec, which is one order of magnitude faster than tests with present instruments.

Advances in lead-salt crystal growth and fabrication techniques by Wayne Lo have led to PbSnTe and PbSSe infrared diode lasers that operate at temperatures up to 140 K, with a wide tuning range (450 cm^{-1}), high reliability and long life.[20] The fast time response of diode lasers has led to the first dynamic measurements of the carbon monoxide concentration from a computer-controlled engine.[21] Carbon monoxide is measured both before and after the catalyst and exhibits periodic variations, shown in figure 7, that correspond to the modulation frequency of the carburetor's fuel metering rod. In addition, uneven fuel distribution results in a slightly different ratio of air



Carbon monoxide concentration as a function of time in engine exhaust gases entering and leaving a catalytic converter. The fast time-response of diode lasers makes possible these measurements on a computer-controlled closed-loop engine. Modulation corresponds to the 10 Hz frequency of the carburator metering rod. Figure 7

to fuel in each cylinder. One can detect the corresponding variation in carbon monoxide from the firing of each individual cylinder. These dynamic studies provide important new data for engine control engineers. Diode lasers also have been useful in detection of other exhaust species, such as sulfuric acid, heretofore not measurable in real time.

Laser diodes are beginning to find use in high-resolution solid-state spectroscopy experiments where spectral hole burning in a solid has been observed. Using a carbon dioxide laser to saturate a ground-state–excited-state transition in a solid produces a "hole" 20 Mhz wide in the absorption profile. This "hole" is resolved by scanning it with a tunable diode laser.[22]

Surface physics

Techniques of surface physics are being applied in research on materials of technological importance to the automotive industry. Metallized plastics are used in decorative applications but until recently no research had been done on the fundamental nature of the metal–polymer bond. James Burkstand[23] has used x-ray photoemission spectroscopy techniques to investigate the electronic structure of copper, nickel and chromium overlayers on polystyrene and polyvinyl alcohol. The peak position and width of metallic core levels vary significantly between substrates. In polyvinyl alcohol these parameters are strongly affected by the interaction of the metal atoms with substrate oxygen to form a metal–oxygen–polymer complex. The existence of the complex was independently verified by changes in photoemission line shapes of the substrate carbon and oxygen atoms.

Exhaust catalysts oxidize hydrocarbons and carbon monoxide and simultaneously reduce oxides of nitrogen to decrease exhaust emissions. The first step in both processes is chemisorption, which is accessible to study by methods in surface physics. The surface electronic structures of palladium (100), ruthenium (100) and other transition metals have been computed self-consistently and from first principles by John Smith, Jack Gay and Frank Arlinghaus.[3] Their calculations show that it is a common feature of transition metals that their surface states are relatively heavily populated with electrons. They are now working to understand the role of these localized states in the chemisorption bond.

At Ford, Ron Baird, Bob Ku and Paul Wynblatt[24] used photoelectron spectroscopy, low-energy electron diffraction, and desorption techniques to study the room temperature chemisorption of carbon monoxide and nitric oxide on the (110) surface of ruthenium. The measurements show that although carbon monoxide chemisorbs and desorbs molecularly at all coverages (that is, at any fraction of a complete monolayer), nitric oxide (NO) chemisorbs dissociatively at low coverage but chemisorbs molecularly at high coverage. Nitric oxide decomposes to oxygen and molecular nitrogen when flash desorbed (desorbed by the quick application of heat), a reaction that can be enhanced by coadsorption of additional oxygen. Automotive catalysts perform their designed function extremely well, but a total understanding of the physical and chemical process involved is still elusive.

Surface analytical tools in the conventional arsenal usually involve electrons (incident or emitted) and thus require high-vacuum environments. There is now strong motivation for developing optical methods for studies of atomic and molecular interactions at surfaces, since practical situations such as catalytic gas flows and electrochemical cells do not normally operate in a vacuum. Application of the numerous laser spectroscopies to surface studies has been impeded largely by their insufficient sensitivity to the small number of molecules (about 10^8) of an interacting species that is illuminated by a small laser spot. Advances in laser technology, coupled with a better understanding of optical interactions at surfaces, can improve this situation. One important direction being pursued by Gary Eesley[25] is the development of surface Raman ellipsometry as a probe of surface vibrations. In addition to identifying absorbed species and determining bond strengths, the relatively high frequency-resolution of Raman spectra (about 1 cm^{-1} or 0.12 meV) will allow observations of subtle changes in bonding sites. The application of this and other laser spectroscopies to surfaces should give the surface physicist a powerful complement of tools.

Other careers for physicists

Physicists serve in important roles in the automotive firms. At Ford Motor Company, for example, a corporate officer is a physicist. At General Motors two corporate officers and two members of the board of directors are physicists. Also, physicists are involved in various areas of research, such as societal analysis, robotics and vibration analysis. To illustrate the diversity of roles physicists play in the automotive industry, let us look at the background and work of three particular physicists.

▶ The Societal Analysis Department at General Motors Research Laboratories is currently headed by a PhD solid-state physicist, Walter Albers. Prior to joining General Motors in the early 1960s, Albers was a member of the technical staff at Bell Telephone Laboratories and then the Bendix Corporation Research Laboratories. In his early years with General Motors, he was responsible for a solid-state group in the physics department, where he specialized in semiconductor surface physics and electro-optics. In the early 1970s, Albers was asked to participate in a group to identify how the company might develop a capability for quantitative research in the social sciences. Later, he was given the responsibility for developing a societal analysis activity, eventually assuming the department head position he now holds. He has worked on cost–benefit and cost–effectiveness analyses, risk assessment, the social impact of community noise, energy supply and consumption, and technology assessment. Albers believes his training as a physicist provided the quantitative tools and systematic problem-solving approaches that were particularly useful in making the transition to an effective societal analyst.

▶ Another PhD physicist, Walton Perkins, worked for 14 years at Lawrence Livermore Laboratory and Lawrence Berkeley Laboratory on plasma instability phenomena, and then became interested in computer vision and knowledge representation. To make the career change, he first moved to the Stanford University Artificial Intelligence Laboratory, and then joined the pioneering machine perception group at General Motors Research Laboratories. Here he conceived new approaches to computer vision and translated these into operating systems. One of the systems he helped create, KEYSIGHT, is now operating on a number of General Motors engine assembly lines, continuously inspecting for proper installation of key components with great speed and almost infallible precision.

▶ Yet another example of a physicist working outside of basic research is Joe Wolf. In spite of his original goal of a career in nuclear engineering, he was drawn into mechanical engineering by his assignments in vibrations and dynamics at the aerospace company where he worked while pursuing a master's degree in applied physics. He subsequently earned a doctorate at MIT in applied mechanics and taught mechanics and structures courses at UCLA before joining General Motors Research Laboratories in the engineering mechanics department. At GM he has worked on applications of the finite element method to automotive structural analysis. Most recently he has worked on problems involving passenger comfort—specifically, analysis of the structural–acoustic systems that help determine the amplitude and spectral distribution of noise inside vehicles.

We hope that the examples we have presented in this article make it clear that physics research in the automotive industry embraces a wide range of topics. Physicists in this industry have the dual responsibility of responding to the issues of the day and conducting research for the future. Occasionally that future research becomes a need of the present. Success will come from choosing a promising area, conducting fruitful research, and communicating the results to the internal corporate community and to the scientific community. Accomplishments of the past and present suggest that physics research, and physicists, will continue to flourish in the automotive industry. They will contribute to the science as well as the technology that is needed to meet the challenges of this industry.

Physicists in industry and the educators who train them need to be keenly aware that the target is always moving: What is today's physics research is tomorrow's engineering. The outstanding track record of physics research and physicists in the automotive industry, together with the industry's increasing awareness of the importance of new science and technology, suggests a fruitful and rewarding future.

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