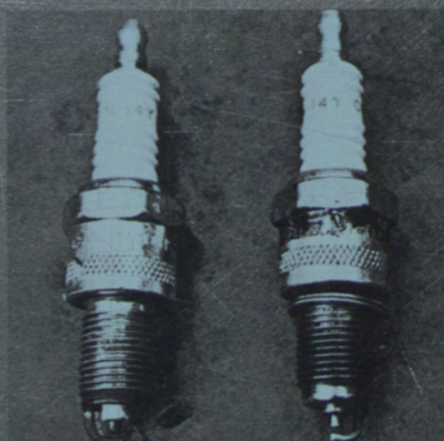
ENGINEERING

CORNELL QUARTERLY



VOLUME 8
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WINTER 1974

OPTIONS FOR ENGINES

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Ingenious and workable ways to reduce pollutants in internal-combustion-engine exhausts have come from the Sibley School of Mechanical and Aerospace Engineering. E. L. Resler, Jr., director of the School, describes how he and a Ph.D. student have developed modifications that would enable the automobile-manufacturing industry to meet emission standards without abandoning current technology.

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Outside front cover: Design elements represent some of the options for automobile engines discussed in this issue. The "Cornell spark plug" provides control of NO_x emissions. The power turbine is part of the gas turbine engine. Battery power is used in the electric car. Hydrogen gas has potential as an automotive fuel (the "Hindenburg Society" button decorating the tank is sported by researchers interested in the hydrogen economy, according to author de Boer).

CORNELL'S LOW POLLUTION INTERNAL COMBUSTION ENGINE

by E. L Resler, Jr.

With a Cornell-developed "flaming muffler" under the hood and a simple modification of the engine, a conventional automobile could surpass the ultimate emission standards. Dramatic reduction of nitrogen oxide pollution —without loss of power, performance, or gas mileage—may be achieved as simply as inserting a new set of Cornell spark plugs.

The modified engine and the Cornell spark plug were designed and built in the laboratories and shop of the Sibley School of Mechanical and Aerospace Engineering, are in the process of being patented, and are now being road tested in a number of vehicles. They are the first practical results of a project to find ways of reducing pollution by internal combustion engines —a project that is part of a wide-ranging program of pollution-control research at the School. As principal investigator for this particular project, I would like to outline the problems and tell the story of why the research was undertaken three years ago, how it has progressed, and what we hope it will contribute to the solution of an urgent national problem.

THE FEDERAL PROGRAM FOR POLLUTION CONTROL

Motor vehicles cause a large fraction of the air pollution in the United States. There are five major air pollutants of concern to the general public—carbon monoxide (CO), unburned hydrocarbons (HC), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and particulates —and the internal combustion engine is largely responsible for three of them: CO, HC, and NO_x.

The federal regulations set by the Congress to limit pollutants emitted by motor vehicles (see Table I) have been and still are the subject of considerable controversy, especially now that the so-called energy crisis has assumed such prominence. After the enactment of the original legislation, some initial large gains in the reduction of pollutants were made, but further attempts to achieve the ultimate goals have made our vehicles more expensive to run and to maintain, and progressively worse in performance.

Even before the energy crisis became so acute, much pressure was exerted by the car manufacturers and oil companies to have the regulations changed or postponed, and now that fuel economy is mandatory, the whole program of emission controls is bound to be reviewed. The Congress can certainly be accused of overenthusiasm in legislating such extensive pollution reduction. On the other hand, it seems that the car manufacturers are capable of more improvement than they are willing to provide. The hope is that a realistic pollution control program will eventually evolve to achieve clean air for all of us.

TECHNICAL DIFFICULTIES IN CONTROL MEASURES

The control of pollutants from a motor vehicle is not easy and involves a degree of understanding and sophistication beyond that required of the automobile industry in the past. To achieve the desired controls, pollutants in the exhaust must be measured in very low concentrations, expressed as parts per million (one ppm is equivalent in magnitude to 31.5 seconds in the time span of a year). One of the difficulties of effective control is in obtaining independent measurements of each of the

"... effectiveness in pollution control, good performance for the driver, apparent absence of maintenance problems, fuel economy, and minimal sacrifice of power."

offending pollutants when they occur in such dilution. Neither the automobile dealers who service the vehicles nor the law enforcement agencies have the instruments or the expertise to monitor the pollutants from vehicles to the degree required by law. Another important problem without a solution is how the maintenance of rigid standards can be enforced once a vehicle is in the hands of its owner. It seems ironical that the government should force the consumer to purchase an ill-performing, gas-guzzling, intricate automobile, which has underneath the hood ill-understood pollution controls; forbid tampering with the controls; and yet not have a reasonable way to guarantee that pollution is indeed being controlled. Such is the problem facing us all.

The pollution regulations are complicated and difficult to interpret and meet. The allowable amounts of pollutants are specified in terms of grams per mile; and the complexities of interpretation are evident when one considers that a given vehicle burns different amounts of gasoline per mile, depending on its speed, the road conditions, how many stops are made, etc. In order to provide more usable criteria, standards have been established which prescribe a certain mode of driving over a particular course (specifically, a "federal test" that takes almost half an hour to complete), and stipulate how the pollutants must be measured and the results are to be interpreted.

TABLE I.
ULTIMATE EMISSION STANDARDS FOR AUTOMOBILES*

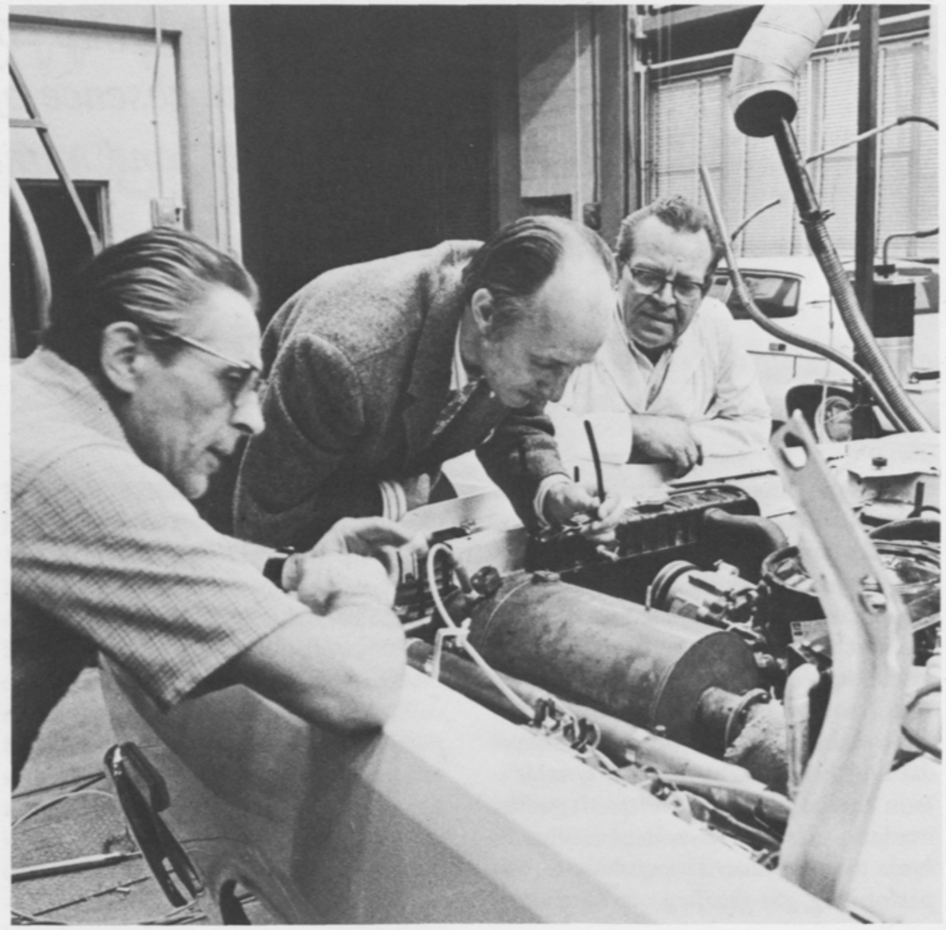
Pollutant	Allowable Emissions		Percent Reduction as Compared with Average Uncontrolled Engines
	(grams/vehicle mile)	(ppm in exhaust)	
CO	3.4	77 × mpg†	96
Hydrocarbons	0.41	9.2 × mpg	97
NO_x	0.4	9 × mpg	93

* According to present legislation. The time table for achievement of these standards is, at the time of this writing, still being negotiated in the Congress.

† Gas mileage in miles per gallon.

HOW MUCH CONTROL IS NEEDED?

In spite of the complexity of the requirements, suppose we attempt a quantitative estimate of the degree of control required in terms easily understood. This can be done fairly simply in terms of the stoichiometric ratio of air to gasoline. This ratio represents the amount of air required to supply the correct amount of oxygen so that all the hydrogen and carbon in a unit quantity of gasoline is converted to water and harmless carbon dioxide. The stoichiometric ratio of air to gasoline is about 15 by weight, and so the total weight of exhaust products is 16



Working on the Cornell internal-external combustion engine are, left to right, M. L. Tompkins, manager of the technical services facility in Upson Hall; Professor Resler; and Ralph A. Cochran, machinist.

times the weight of the gasoline. Since gasoline weighs about 6.1 pounds per gallon and there are 454.6 grams in a pound, the total number of grams of exhaust resulting from the use of one gallon of gasoline is $16 \times 6.1 \times 454.6 = 44 \times 10^3$ grams. The amount of gasoline used per mile may be expressed as the reciprocal of the familiar unit of miles per gallon (mpg). The amount of exhaust expressed as grams per mile is therefore:

$$\text{g of exhaust/mile} = \frac{44 \times 10^3}{\text{mpg}}$$

The ultimate pollution levels called for by legislation are given in grams per mile (see Table I), but they can be converted to parts per million (ppm) calculated on the basis of gas mileage of a particular vehicle, a designation that is perhaps more useful and meaningful to most people. Since ppm equals 10^6 times the ratio of the amount of pollutant per mile to the amount of total exhaust per mile:

$$\text{ppm} = \frac{\text{g/mile} \times \text{mpg}}{44 \times 10^3} \times 10^6$$

where g/mile is the allowed pollutant level as given in Table I. It is apparent from inspection of the Table I data, and a matter of common sense, that the more miles per gallon a car gets, the easier it is to control pollution.

WHERE THE POLLUTANTS COME FROM

In order to control the pollutants, their source must be understood.

Unburned hydrocarbons and carbon monoxide are present because of incomplete combustion in the cylinders. This occurs because although combustion temperatures in an internal combustion engine are between 5,000 and 6,000°R, well above the melting point of steel, the walls of the cylinders must be kept a great deal cooler, and because the walls are relatively cool, there is an adjacent layer of fuel-air mixture that burns incompletely or not at all. Excessive CO production is also promoted if any region is rich in fuel and therefore has insufficient oxygen to effect complete oxidation of the carbon.

Excessive NO_x, chiefly nitric oxide,

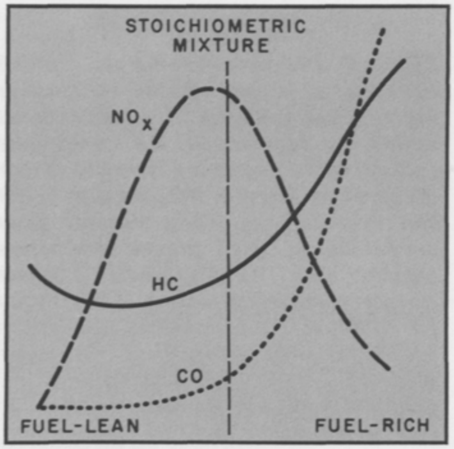


Figure 1. Dependence of pollutant levels in exhausts on the fuel mixture. When the engine is run rich, performance is good and NO_x emissions are low, but CO and hydrocarbons (HC) are high. When the engine is run lean, the levels of all three pollutants are relatively low, but engine performance is poor. The Cornell scheme makes use of a combination of combustion conditions so as to provide both pollution control and good engine performance. (Emissions not to scale.)

NO, occurs for a different reason. It is formed in a chain reaction (known as the Zeldovich mechanism) involving atoms:

$$(O) + N_2 \rightleftharpoons NO + (N);$$
$$(N) + O_2 \rightleftharpoons NO + (O),$$

and conditions that affect the final concentration of NO in the engine exhaust are complex and diverse. The big asset of the internal combustion engine is its small weight for a given power, and this is due to the high temperatures that can be sustained by the gases in the cylinders after combustion. Unfortunately, these high temperatures favor the formation of NO, and we have a dilemma: the higher the temperature, the better the performance of the engine, but also the greater the NO production. In principle, the NO should disappear during the power or expansion stroke of the piston when the gases are cooled. The chemical kinetic processes are such, however, that the conversion of NO back to N_2 and other products does not, in fact, occur in the short time available during the expansion stroke. After the expansion stroke the gases are too cool to effect the desired reduction of the NO before they are exhausted to the atmosphere. A common description is that the NO concentration leaving the engine is that appropriate to the highest temperature in the working cylinders.

Since the NO_x pollutant is a result of nonequilibrium, the description of what actually happens can be accomplished only with a detailed calculation using rate equations for the proper chemical kinetic processes. These processes are well understood, however, and the necessary computations for a typical engine have been performed.

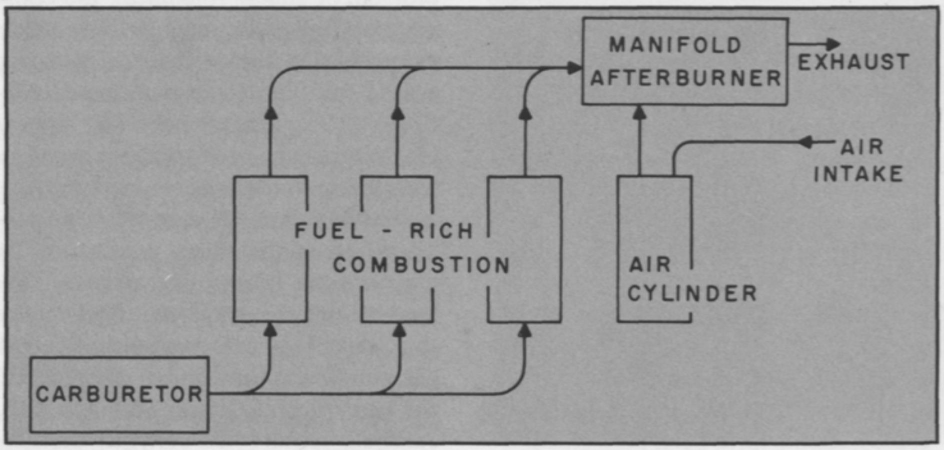
METHODS USED TO REDUCE POLLUTANTS

Since the power of an engine depends on high temperature but the amount of NO_x emitted increases with temperature, initial efforts to control NO_x emission relied on recirculation of exhaust gas. The idea was that dilution of the mixture with inert gases would lower the combustion temperature and therefore reduce NO_x concentrations. Unfortunately, exhaust gas recirculation also reduces engine power and causes rough operation. To relieve the problem of engine roughness, the compression ratios of engines have been reduced; this allows the use of lower octane fuel, but it also decreases efficiency. The penalties of lower power, lower efficiency, and rough operation are all due to attempts to control NO_x.

Another way to control the pollutant emissions is to accelerate the reactions by means of catalysts. Unfortunately, the catalysts effective for the control of NO_x require different gas conditions than those effective for the control of CO and HC: the NO_x catalysts require low oxygen concentrations, whereas excess oxygen is required for the catalysts that promote the oxidation of CO to CO_2 and HC to H_2O and CO_2. Catalysts work very well, but their durability is in doubt, and there is also concern about other pollutants that result from their use, namely sulfuric acid, ammonia, and particulates.

Some control of emission levels can be achieved by adjusting the richness of the fuel-air mixture. The effects on pollution levels are well summarized in Figure 1. The curves show that running lean can never remove all of the

Figure 2. Diagram showing the Cornell modification of the internal combustion engine. Four cylinders of a conventional engine are represented. All except one cylinder in the engine are run rich, so that the spent gas is low in NO_x but high in CO and hydrocarbons. These exhaust gases are fed into an added external combustion chamber (the "flaming muffler") where further combustion occurs. Compressed air to support this external combustion process is provided through the single modified cylinder. The end result is low pollutant emission without sacrifice of good performance and fuel consumption.



CO and HC pollutants; this is because of the cool layer of gas near the cylinder walls. The NO_x level, however, is reduced when the engine is running lean; this is because with a lean mixture the combustion temperature is lower. The NO_x level is also reduced in rich mixtures, a result due not to lowered temperatures, but to a deficiency of oxygen: because of the greater affinity of carbon and hydrogen for the oxygen, there is little left to combine with nitrogen to form NO_x.

A general summation is as follows. An engine run rich has lots of power because the combustion temperatures are high; its emissions are high in HC and CO but low in NO_x. On the other hand, an engine run lean produces little CO and HC and less NO_x than it produces with a stoichiometric mixture, but it has little power and does not run well.

A reasonable compromise is achieved by the so-called stratified charge method. Here one attempts to provide a rich mixture next to the spark plug in the combustion chamber and a lean mixture farther away. The rich mixture ignites and burns well and little NO_x is produced. The hot gases from the combustion of the rich mixture then mix with and ignite the lean mixture, and again little NO_x is produced because the temperature is now low. Also, the excessive oxygen minimizes the CO and HC levels. Unfortunately, the appropriate stratification is difficult to achieve under all operating conditions and success has been moderate. The Honda Company, however, has recently obtained good results by actually dividing the combustion chamber into two sections, each fed with separate mixtures—one rich and one lean—from separate carburetors. The additional intake valve and carburetor are not excessive in comparison with the hardware required by more complicated arrangements that have evolved in other attempts to achieve the same degree of pollutant control.

DESIGN OF THE CORNELL ENGINE

The original scheme attempted at Cornell was similar in concept, but not in execution, to the stratified charge approach. Our initial criteria were:

1. Make use of the present internal combustion engine.
2. Permit retention of present tooling in the industry.
3. Make use of available fuels.
4. Maintain high efficiency so as not to aggravate the energy crisis.

The present internal combustion engine has evolved over many years, it is reliable and convenient, and there is much expertise within the population in its maintenance and care. To abandon it, if not absolutely necessary, seems foolhardy. The investment in tooling for our present engines is large, and to abandon that does not seem prudent. The investment of the oil companies in their refineries and distribution system is also large, and to require major modifications in this industry is also not economically feasible. Finally, our petroleum resources are limited, even without the present crisis, and their prudent use is required.

In all our work, we took the point of view that we should concentrate on reduction of NO_x, since this is the most difficult pollutant to control. Since an engine runs well and NO_x formation is minimized when the fuel mixture is rich, we decided to run some of the cylinders rich and to use the exhaust gases, after mixing with air, to sustain a lean flame in an external combustion chamber. With the lean mixture, the uncombusted HC and CO would be oxidized, but the temperature would be low enough so that again NO_x would not be produced.

Our experimental modifications are diagrammed in Figure 2, which depicts a bank of four cylinders from, say, a V-8 engine. The first three cylinders are run rich, by adjustment of the carburetor already on the car, so that little NO_x but high levels of CO and unburned HC are produced. The fourth cylinder is disconnected from the intake manifold so that only air can enter it. This is easily accomplished by blocking the intake manifold between the carburetor and the cylinder and opening the manifold to the atmosphere just downstream of the blocking plate by means of a port which consists of a hole drilled in the manifold passageway. The valve and cam shaft arrangement are not altered, so that the last cylinder, which is still

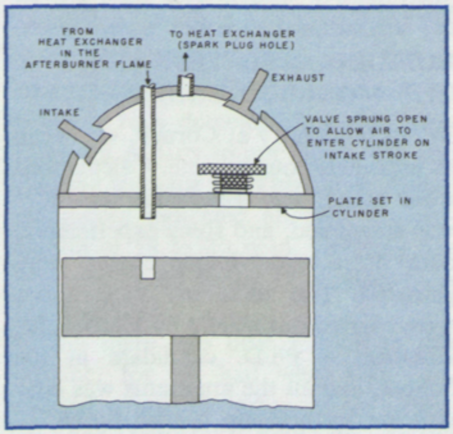


Figure 3. Diagram of the modified cylinder. A plate inserted above the piston divides the cylinder into a working portion, which helps drive the crankshaft, and an upper auxiliary chamber which serves as an air reservoir.

connected to the cam shaft, goes through its usual four-stroke cycle. The system is completed with an afterburner, mounted near the engine, into which the exhaust from the cylinders is fed.

The sequence of events in the fourth cylinder can be followed by reference to Figure 3, a diagram of the actual hardware. The cylinder has been modified by the addition of a plate above the piston, which serves to divide the cylinder into a working portion and an upper auxiliary chamber. The two parts are connected through a spring-biased valve. During the intake stroke, air is admitted to the cylinder through the intake valve and the spring-biased valve. During the compression stroke, the air is forced under pressure into the combustion chamber above the plate; near the end of this stroke the biased valve is forced shut and, as the piston rises, one duct to the heat exchanger (not shown) becomes covered by a recessed hole in the piston face. During the expansion stroke, the compressed gas is forced through the heat exchanger via the port for the spark plug (now removed) and on into the working part of the cylinder again, through the duct which was covered by the piston when this was at top dead center. During this phase of the cycle, work is done on the piston face, and is accordingly delivered to the crankshaft. The exhaust stroke delivers the spent but still hot gases to the flame in the afterburner, by passage through the biased valve and the exhaust port.

This air cylinder acts as a power source, for it converts the flame energy into useful work. (This function is distinct from the pollution-control aspects of the design, for if the heat exchanger were omitted, the pollutant control would be just as effective.) The modified cylinder also acts as a compressor, supplying the air necessary to sustain the flame. The first three cylinders operate at peak power; the last cylinder, because of the lower flame temperature, operates at about half the power of the first three. The efficiency of the combination, however, is very high. Since the last cylinder makes use of the waste heat of the first three, and also delivers its own waste heat to the flame, a degree of regeneration is supplied.

BUILDING AND TESTING THE MODIFIED ENGINE

In our laboratory at Cornell, we began to implement our scheme. Calculations were made, the associated hardware was assembled, and some experimental data on a one-cylinder engine were gathered. The tests and calculations were carried out chiefly by Herbert M. Kosstrin, a Ph.D. candidate in the School, and all the apparatus was constructed in the shop headed by M. L. Tompkins.

It was encouraging to find that all parts of the system functioned as expected, and our confidence in the scheme was strengthened. We soon learned, however, that our findings were not necessarily accepted. In the field of vehicle pollution control, no one is interested unless an actual vehicle is outfitted, so this was our next step. We obtained an old 1963 Pontiac with a 389 cu. in. V-8 engine, and had the engine rebuilt and bored out to 400 cu. in. Since a large engine is more difficult to clean up than smaller ones, we thought that the old Pontiac, if successfully modified, would prove our point. We were aided in this project by the local Pontiac dealer, R. Davis Cutting, a 1948 Cornell graduate, who made his shop, personnel, and facilities available to us. We also hired a consultant, Paul Stimson of Independent Associates in nearby Newfane, New York.

"These levels of pollution are much lower than those required to meet the ultimate standards."

Next we proceeded to modify one bank of the V-8 engine as described. Cylinder number two of the engine was used as the air compressor; it was disconnected from the carburetor so that air rather than a fuel-air mixture was ingested by the cylinder. After some initial difficulties with burner design and pulsations, which were overcome, the system worked satisfactorily. Initially we chose to have two exhausts —a "good" exhaust from the modified bank of cylinders, and a "bad" exhaust from the other bank, which was not equipped with our burner. The "good" exhaust turned out to be very good—more than sufficient to pass ultimate standards, according to our tests. (We did not have an official test run on the car, since we did not have the necessary equipment.) The "bad" exhaust turned out to be so bad that the comparison seemed unfair. Incidentally, the difference could be detected easily by one's nose: an indication not of how good the "good" exhaust was, but of how sensitive the nose is and how bad the "bad" exhaust was.

For more extensive testing, we decided to clean up all the exhaust. This was accomplished by running seven cylinders rich and one as an air compressor to supply the oxygen to burn the pollutants. We mounted the burner

The Cornell "flaming muffler" is actually an external combustion chamber mounted under the hood of the car. The blue flame is visible in this photograph taken during preliminary testing. CO and hydrocarbons remaining after combustion of a rich fuel mixture in the cylinders are fed into the external chamber, where further combustion takes place in a lean flame.

above the engine for easy access and exhausted forward (see photograph). The configuration was given the name "flaming muffler" by the Cornell patent attorney, Ralph Barnard, since the flames were visible (a covering plate may be added) and the whole chamber is about the size of a muffler. Incidentally, it did reduce the exhaust noise sufficiently so that a muffler was not required. The engine ran well on seven cylinders, and the only bad effect of running rich (about 30% rich) was excessive oil dilution by gasoline.

With this engine running at 35 mph, the gas mileage as measured on a dynamometer was 12.5 mpg (good compared with gas mileages of 1973 models), the NO_x concentration was about 50 ppm, and there was so little HC and CO that we could not measure their concentration. These levels of pollution are much lower than those required to meet the ultimate standards, as can be seen by reference to Table I.

These results were greeted at first with extreme skepticism by our friends, especially members of the New York State Department of Environmental Conservation, who have worked with us and been very helpful. William Balgord, then a research scientist for the State of New York, arranged for an independent check of our results by bringing NO_x detectors from his laboratory in Albany to our laboratory and running tests for us. This more refined equipment indicated an NO_x concentration of 18 to 20 ppm, verifying our tests and again giving us confidence in our approach.

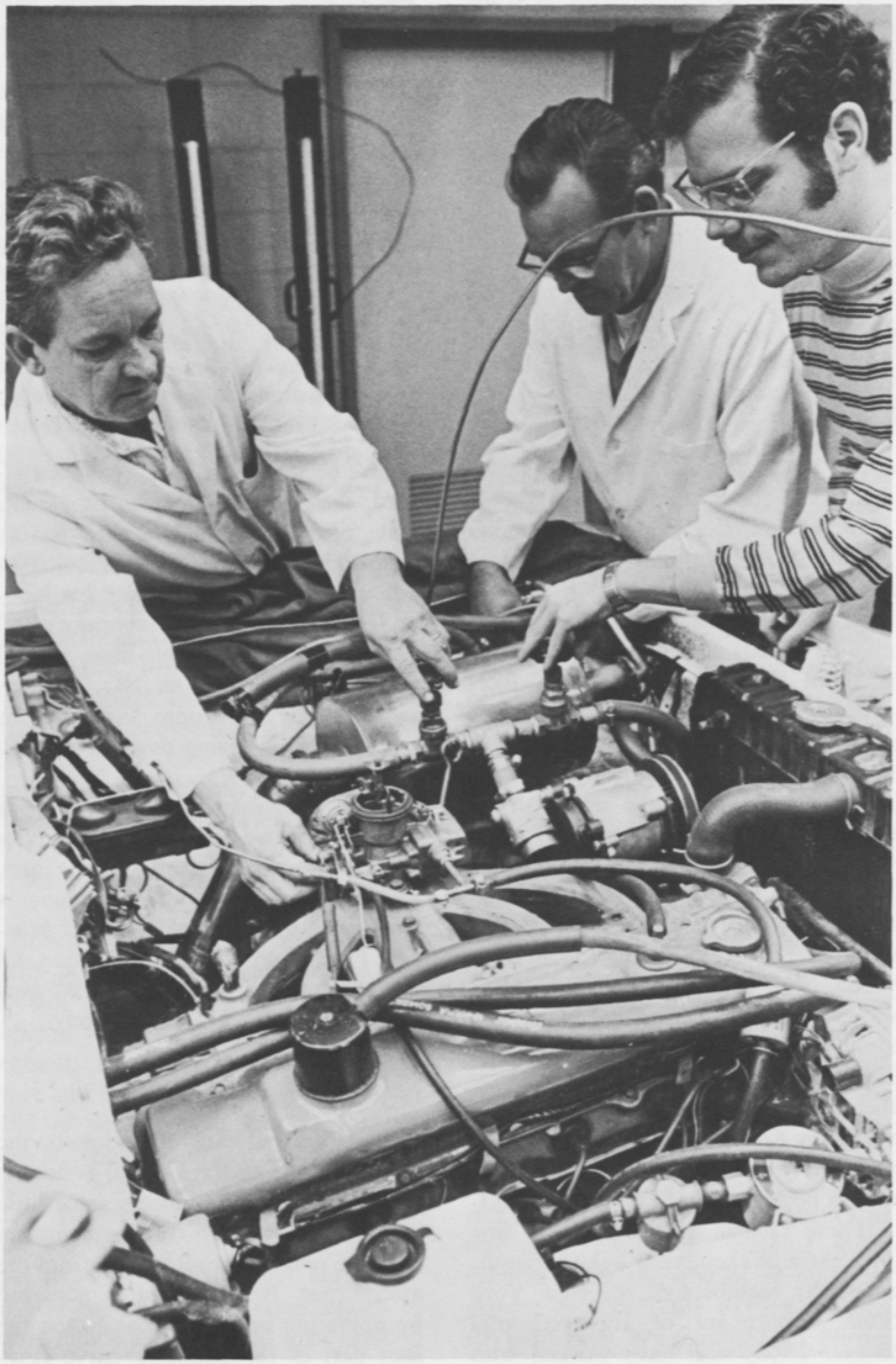
Still there was little interest in our scheme, for we had what was considered a horrible arrangement. First, we had tampered with the engine block, and this is considered bad practice. Furthermore, our modification did not consist of a simple "bolt on" part that could be marketed separately.

WHAT THE CORNELL DESIGN CAN OFFER

From the standpoint of pollution, the big advantage of the Cornell system is that little NO_x is produced, since little is formed in the rich-running cylinders or in the relatively cool lean flame of the afterburner. NO_x control is achieved by operating on the rich and then the lean part of the pollution curve (Figure 1), much as in the stratified charge scheme. However, while lean combustion in a cylinder can be troublesome, a lean flame is easy to control. The advantage of the combination of rich cylinder plus lean flame is that the cylinders run well rich and the lean flame can be controlled conveniently; more control of the combustion processes is possible with this system than with the stratified charge technique.

The arrangement involves minimal modification of an existing engine and is therefore promising in terms of cost, installation, and maintenance. All it requires is modification of one cylinder and its connections, and the attachment of the external combustion chamber with its heat-exchange unit.

Calculations show that the efficiency of the engine is not compromised by the introduction of these alterations. Gas mileage appears to be unaffected. The power is reduced by about 12.5%, but a moment's thought shows that the power could be recovered by operating the last cylinder at a higher manifold pressure, or operating the last cylinder on a two- instead of four-stroke cycle, or both. Overall, the merits of the Cor-



The Cornell engine, now being road tested, is adjusted by, left to right, Donald Van Dermark, research technician; Ralph A. Cochran, machinist; and Herbert M. Kosstrin, Ph.D. student who collaborated with Professor Resler in the development of the engine modifications. During his graduate years, Kosstrin has held a Joseph Newton Pew Jr. graduate fellowship and a Ford Foundation fellowship for research relevant to society.

" . . . the Cornell spark plug already developed may be all that is required to meet NO_X emission standards."

nell scheme, as we see it, are effectiveness in pollution control, good performance for the driver, apparent absence of maintenance problems, fuel economy, and minimal sacrifice of power.

A NEW METHOD FOR NO_X REDUCTION

Our success to this point had been greater than an examination of the efforts and results of others had led us to expect. We tried to discover why.

As a project for a professional Master of Engineering (Aerospace) degree, John Nordmann, with the assistance of Kosstrin and others, performed an experiment to measure how fast NO_x is eliminated. He took a portion of the untreated exhaust from the Pontiac engine operating as designed and having an NO_x level in the exhaust of about 3,000 ppm, and passed it through an oven at 2,600°R, a bright orange heat. At the other end of the oven there was no measurable NO_x. The experiment indicated that the NO_x disappeared after flowing through the hot oven in the flow time of about 10 milliseconds, although the well understood and widely accepted Zeldovich mechanism predicts that under these conditions, with no catalyst, more than 200 seconds would be required for reduction of the NO_x.

Although our results were again greeted with skepticism, we knew that we had either a new mechanism to eliminate NO_x or, as others conjectured, a very effective catalyst in the tube. An interesting aspect of the experiment was that the oven did nothing more than heat the exhaust to approximately the same temperature it had just been subjected to in the cylinder; the question was why the reduction we had measured did not occur in the cylinder.

Kosstrin suggested that this apparent anomaly may be explained on the basis of distribution of gas components. In the cylinder the unburned hydrocarbons are not in the whole gas volume, but are confined to the vicinity of the walls; during the exhaust process, however, the piston ring scrapes them from the walls and injects them into the bulk of the gas. The possibility that this difference should effect NO_x levels was a new concept. Remember that a rich mixture, when burned, produces little NO_x because carbon and hydrogen have a greater affinity for oxygen than nitrogen does. It is not hard to imagine that in the absence of free oxygen, hydrocarbons in the form C_zH_y would reduce NO_x.

Having conducted numerous tests and checks, we now believe we have a new approach to the control of the NO_x pollutant. It is based on the idea that if a small amount (about 0.5%) of hydrocarbon is introduced into an oxygen-starved exhaust containing NO_x, then at a given temperature (say, 2,600°R) the reduction of the NO_x is accelerated to its equilibrium value in a useful time interval (about 10 milliseconds, an interval appropriate to the application at hand). The exhaust must be oxygen-starved or, more precisely, there must be more NO_x than O_2; otherwise, the C_zH_y easily finds the required oxygen to form H_2O, CO, and CO_2 without attacking the NO_x. Note that the C_zH_y is not a catalyst, since it is consumed in the process; it is an agent that provides a mechanism for the rapid return of NO_x to its proper equilibrium concentration.

THE CORNELL SPARK PLUG: A SIMPLE REMEDY

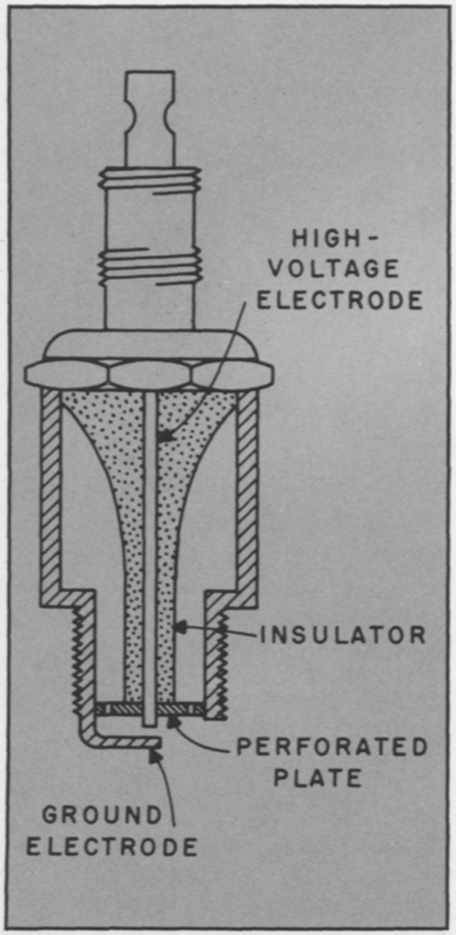
Now that we think we understand this new mechanism of NO_x reduction, it is much easier to design controls for a vehicle. The development of the Cornell spark plug, one of many devices that have evolved as a result of this discovery, illustrates how the mechanism can be utilized for pollution control.

Most of the NO_x produced in the engine is formed in the area immediately adjacent to the spark plug; this is because the gas in this vicinity is ignited first and is heated further by adiabatic compression when the rest of the charge in the cylinder burns. If we are to attack the NO_x in the cylinder, the most advantageous position is at the spark plug.

Our method was to enclose the cavity at the end of an ordinary spark plug with a stainless steel plate containing a number of holes (see Figure 4). When the plug is inserted in the cylinder, this plate separates the combustion chamber of the cylinder from the cavity in the plug. Now let us

Right: Figure 4. Diagram of the Cornell spark plug. An ordinary plug has been modified by enclosing the cavity with a steel plate containing a number of small holes. When the plug is inserted into the cylinder, this plate serves to control the movement of gases so as to promote reduction of NO_x by unburned hydrocarbons during the expansion stroke of the piston.

Below: The perforated plate identifies the Cornell spark plug, the first to be developed in a continuing project. Road tests have shown that use of this spark plug reduces NO_x emissions to a currently acceptable level.

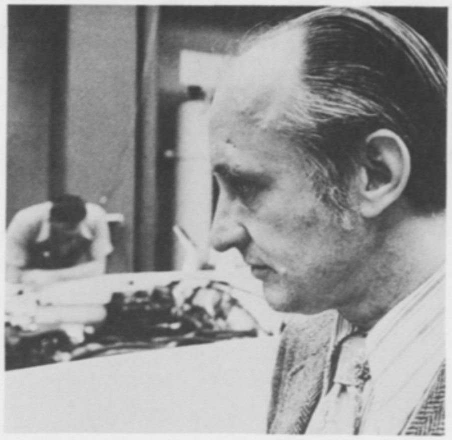


consider the sequence of events in the cylinder. The intake stroke is as before. The compression stroke compresses the mixture in the combustion chamber and cavity. When the spark plug fires, only the mixture in the combustion chamber burns, as the fire cannot penetrate the holes and the large surface-to-volume ratio in the cavity keeps the mixture below its ignition temperature. As a result of the combustion, the pressure rises in the combustion chamber and the combustion products enter the cavity through the holes; these products mix with the unburned mixture in the cavity and render it noncombustible. During the expansion stroke, the pressure in the cylinder decreases, permitting the unburned hydrocarbons to leave the cavity, and they mix with the NO_x near the plug and effect its reduction.

POLLUTION CONTROL WITHOUT PENALTIES

We have tested these plugs in one- and six-cylinder engines, and the effected reduction in pollutant has been beyond our original expectations. For example, in a six-cylinder Dodge Dart running at 35 mph, the NO_x level would ordinarily be as much as 3,500 ppm, but with this minor modification, it was reduced to 400 ppm. This modification is easily better than all the exhaust gas recirculation schemes now in existence, and there is no penalty in loss of power, performance, or gas mileage. With new, less severe requirements in the offing, the Cornell spark plug already developed may be all that is required to meet NO_x emission standards.

This brief resume presents the highlights of some of the efforts in the area of automotive pollution that have been made at the Sibley School over the past three years. We believe that pure air can be achieved by the proper application of modern technology. The needed technology is still evolving, and we believe that a university, with its broad resources, its support by public and private agencies and dedicated alumni, and its eager, talented students interested in taking a new look at old problems, is the most appropriate place for that evolution.



E. L. Resler, Jr., the Joseph Newton Pew, Jr., Professor of Engineering, was cited in 1971 for his "important and innovative work in the fields of shock tube technology, high temperature gas dynamics, magnetohydrodynamics, and laser phenomena" on the occasion of his election as a fellow of the American Institute of Aeronautics and Astronautics (AIAA). To this list of activities must be added research on pollution reduction in automobile engines, a recent interest and the subject of his Quarterly *article.*

The correlation of mechanical and aerospace engineering activities at Cornell is evident not only in Resler's research interests, but also in the academic organization of the two disciplines. In 1972 the Sibley School of Mechanical and Aerospace Engineering was formed as a merger of the Sibley School of Mechanical Engineering and the Graduate School of Aerospace Engineering. Resler, who had served as director of the aerospace school since 1963, became director of the combined School.

Resler first came to Cornell in 1948, when he began graduate study after earning the B.S. degree in aeronautical engineering at the University of Notre Dame. He was awarded the Ph.D. in 1951 and remained at Cornell for the following year as an assistant professor of aeronautical engineering. After a four-year tenure on the University of Maryland faculty, he returned to Cornell as professor of aerospace engineering, engineering physics, and electrical engineering.

In addition to being a fellow of the AIAA, he is a member of the American Institute of Physics, the American Physical Society, the International Scientific Radio Union, and Sigma Xi. He is also a corresponding member of the International Academy of Astronautics.

THE GAS TURBINE AS A VEHICLE ENGINE

by Frederick C. Gouldin

The versatile gas turbine, already well established as an aircraft engine, is emerging as a viable power source for trains, ships, electric-power plants, and a growing number of other applications. Because of attractions such as smooth operation, low maintenance cost, multifuel capability, high performance, and a history of steady and rapid improvement, the gas turbine has also been considered for a long time as a possible competitor to the piston engine for both trucks and cars. In fact, its application to automotive vehicle propulsion has been just around the corner for some twenty years.

Rover of England built the first gas turbine vehicle in 1945 and has continued development to the present time. Chrysler has been a leader among American manufacturers in automotive gas turbine development; its program was initiated in 1954, a fifty-car evaluation program using a fourth-generation engine design was begun in 1963, and a seventh-generation system is now under development. Ford and General Motors have also maintained development programs since the early 1950s. Why, then, is the vehicular gas turbine still just around the corner?

KEEN COMPETITION AND ENGINEERING PROBLEMS

There are two basic reasons for the automotive gas turbine's state of apparent limbo. First, its competitor is no slouch. Modern spark ignition and diesel engines, after seventy-five years of continuous development, are highly refined and sophisticated power systems finely tuned to particular markets. Most car buyers' demands—for low capital cost, high specific power, low maintenance requirements, and, if they can get it, low fuel consumption—are well satisfied by these engines. Furthermore, America has committed much of her manpower and economic resources to the manufacture and maintenance of piston engines, and the conversion of these resources to any alternate power system would be difficult, time-consuming, and possibly disruptive.

The second reason for the turbine's difficulty is strictly an engineering one. Automotive applications require relatively low-power engines which can operate over a wide load range with reasonable fuel economy. Gas turbines, however, have generally been used at higher powers than those required for vehicles, and turbines rated below 1,000 h.p. are generally low-performance, low-efficiency systems. As turbine power is scaled down, fixed parasitic and blade-tip losses become important and reduce compressor and power turbine efficiencies. Tip losses can be reduced, but only at a price. Partial load operation increases fuel consumption unless the effect is offset by means of complex and expensive control systems and equally expensive regenerative cycle modifications. Low acceleration has also been a problem in turbine vehicles; and although this problem too can be solved by cycle modification and special transmissions, the solution is not cheap. Finally, conventional turbine design involves exotic materials and close tolerances, requirements that entail high capital cost. These various problems can be summarized in a sentence: Present technology is capable of producing a turbine that would be equal in performance to conventional high-power spark and

" . . . the gas turbine has great potential and will be superior to the spark ignition engine."

diesel engines, if not superior to them, but at a price no one is interested in paying. This was, in fact, the conclusion reached by Chrysler.

THE CHANGING OUTLOOK FOR USE IN VEHICLES

More engineering development is required to produce a fully competitive gas turbine that would perform well but cost less. Yet there has been little incentive for the research, for the spark engine is established and performs its function well. Research on a vehicular gas turbine engine has proceeded at an almost tortoise-like pace when compared with the rapid development of gas turbines for other applications; what little progress has been made has come as spin-off from more auspicious applications. In view of this picture, a continued slow, steady development of vehicular gas turbines has been predicted. Applications are expected first in large trucks rather than in passenger cars, since the higher-priced diesel engine is more vulnerable to competition from a durable, low-maintenance alternative. This would be followed, in ten to fifteen years, by the appearance of turbines in large, high-powered automobiles.

Events of the past few years have radically changed this picture, however. Because of recent environmental concerns and rapidly constricting fuel supplies, the conventional spark engine has lost much of its competitive edge. Radical changes appear necessary if the spark engine is to be as clean, low-cost, and conserving of fuel as is now required. In fact, these goals appear to be mutually exclusive for the spark engine unless new approaches to emission control are taken. With its competitor weakened, perhaps mortally wounded, the turbine's position has improved considerably, and interest in it is growing rapidly. To many people it seems possible that a cleaner, more efficient, and cheaper gas turbine for large vehicles can be in production in five to ten years, provided that the necessary resources are committed to its development.

LEGAL CONTROLS ON EMISSIONS FROM VEHICLES

Current federal legislation calls for strict limitations on the amount of pollutants that can be emitted by light-duty vehicles. (The ultimate allowable levels according to presently established standards are listed in Table I, page 3.)

All of the carbon monoxide and nitrogen oxide (NO_x) emissions and approximately 65% of the hydrocarbon emissions from the internal combustion engine of a conventional automobile come from the tailpipe. The remaining 35% of the hydrocarbons —evaporative emissions from the fuel tank and carburetor and blow-by from the crankcase—are easily controlled. The NO_x emissions, chiefly nitric oxide, result from the fixation of molecular nitrogen, a highly temperature-dependent reaction that occurs at negligible rates except at peak combustion temperatures. The cause of hydrocarbon emissions is quenching of the fuel pyrolysis reactions in the thin thermal boundary layers covering the cylinder walls and piston faces. CO occurs primarily when there is insufficient oxygen for complete oxidation to CO_2, either in the bulk gases when the overall fuel-air mixture is rich, or, when the mixture is lean, in small fuel-

TABLE I. VEHICULAR GAS TURBINE EMISSIONS*

	Steady-State Values (g/kg of fuel)†		Values for Simulated Federal Driving Cycle (g/vehicle mile)	
	NO_x	CO	NO_x	CO
Ultimate Federal Standards	1.39	11.8	0.4	3.4
AiResearch	—	—	3.1	0.578
Northern Research	2.5	7.1	—	—
Solar	2.0	12.0	—	—
United Aircraft	7.9	20.3	—	—
Williams Research	—	—	2.12	4.5
Conventional Burner	—	—	3.1	11.2

* Data from a paper by J. J. Brogan and G. M. Thur, "Advanced Automotive Power Systems Development Program," presented in September 1972 at the 7th Intersociety Energy Conversion Engineering Conference in San Diego, California.

† Based on a gas mileage of 10 mpg.

rich pockets of gas which result from incomplete mixing of fuel and air in the carburetor and intake manifold.

It may be noted that NO_x is formed in a high-temperature oxidation process, while hydrocarbons and CO occur because oxidation is frustrated. Thus the control of all three pollutants would appear to be inherently difficult, since oxidation and reduction cannot easily be accomplished at the same time. It is possible, however, to oxidize CO and hydrocarbons at temperatures that are too low for NO_x formation; this difference in temperature dependence means that control of all three pollutants is feasible, though it is far from easy. Indeed, acknowledgment of the difficulty is reflected in the recent decision by the Environmental Protection Agency administrator to grant automobile manufacturers additional time to meet emission standards. (Because of the energy crisis, further delays have been voted by the House of Representatives and the Senate, with final resolution still pending as of this writing.)

EMISSION LEVELS FOR GAS TURBINE ENGINES

With a gas turbine engine, the situation is significantly different. In the gas turbine (see Figure 1), there is a continuous combustion process which is almost completely independent of the working cycle. This independence means that few constraints are placed on the combustion process by cycle operation, and one is free to fine-tune combustion for low emissions. Another important distinctive feature of the gas turbine is the low allowable power turbine inlet temperature. Because of material limitations, maximum turbine inlet temperatures are restricted to between 1,100°K and 1,500°K, with the higher temperatures found only in advanced aircraft systems. These low temperatures are achieved by running very lean mixtures, containing between 300% and 600% excess air, depending on the unit design and load setting. Because of these features of low maximum temperature, high excess air, and continuous combustion, one expects and generally observes very low emissions from gas turbines. This inherent cleanliness gives the turbine a considerable competitive advantage.

Gas turbines in automobiles have not yet attained their full potential for low emissions, however. On a concentration basis, the emissions are far below those from an equivalent spark engine, but, since the mass flow rate is much higher through a turbine than through a spark engine, a comparison on the basis of grams per mile or grams per kilogram of fuel consumed is not so favorable. Table I shows emission levels for CO and NO_x

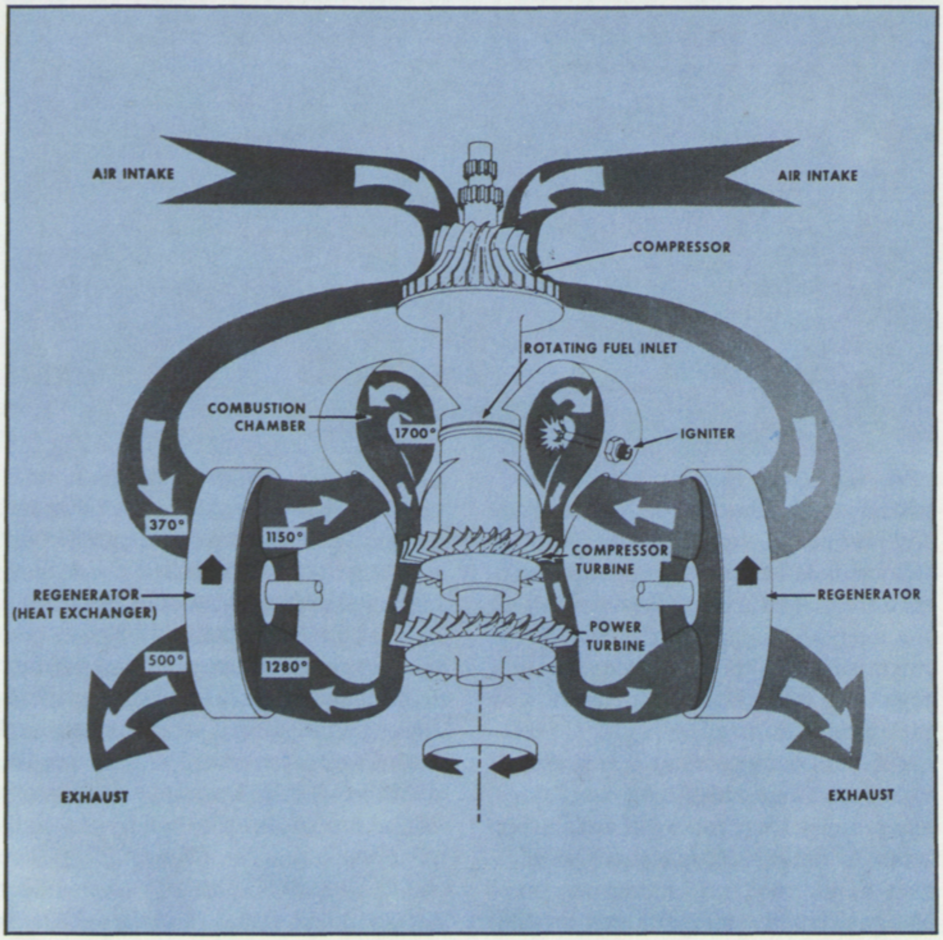
from a number of experimental vehicular gas turbines. (Hydrocarbon levels are not included in the table, since they meet standards without difficulty. Soot emissions, which have been a problem in aircraft turbines, have never been a problem in automotive turbines because of their combustor design.)

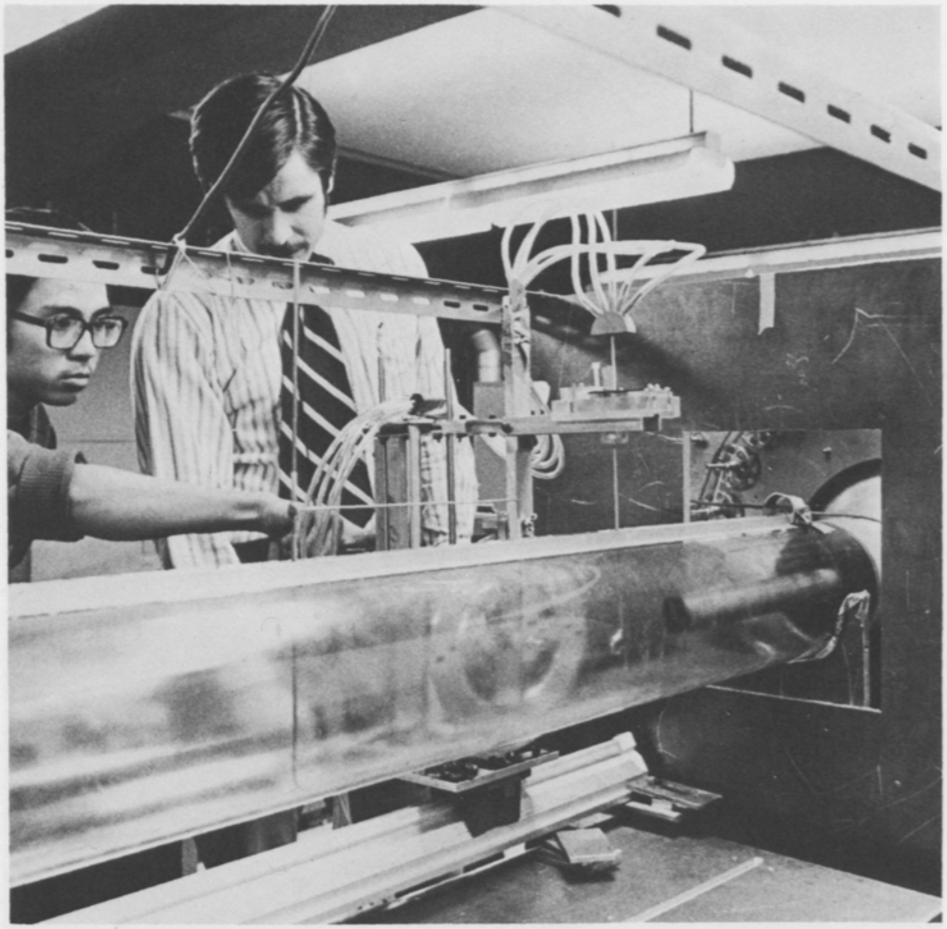
Although the measured emissions are low, they do not meet our expectations and certainly do not meet standards. The reasons for the unexpectedly high emissions are easily understood if one looks at the combustor in some detail. A turbine combustor is located between the compressor and power turbine (see Figure 1), and has the job of introducing fuel, mixing it with the high-pressure air coming from the compressor, and burning the resulting mixture. All of this must be done efficiently, cleanly, at low pressure loss, and over the full range of operating conditions.

COMBUSTOR DESIGN FOR LOW EMISSIONS

The design of the combustor must take into account the fact that a mixture as lean as that used in a gas turbine—with 300% to 600% the amount of air theoretically required—is outside the flammability limits for all fuels of interest, and that therefore the air must be mixed with the fuel in stages. Reaction is initiated and almost completed in a primary combustion zone (see Figure 2) where the fuel mixture is comparatively rich; the remaining air is added in a dilution zone. The design must also allow for the fact that in the turbine the flow velocities are very high for combustion processes (about 100 feet per second); conditions in the

Figure 1. Schematic diagram of a small, lightweight gas turbine engine designed by the Williams Research Corporation. The illustration shows air flow and temperatures at full power. Fresh air enters through two intakes and is drawn into the compressor where it is compressed to four times atmospheric pressure. The air is preheated as it passes through the front half of the regenerator cores (rotating heat exchangers). It passes into the combustion chamber into which fuel is sprayed and burned, raising the temperature to 1,700°F. The hot gases pass through the compressor turbine and then through the power turbine, delivering power to the rear wheels. Then the gases pass through the rear half of the regenerators, which recover heat from the exhausts to preheat the air entering the combustion chamber, thus enhancing fuel economy and reducing exhaust temperatures. (Courtesy the Williams Research Corporation.)





Graduate student Bach Vu works with Professor Gouldin on an experiment designed to study recirculating flows that are characteristic of gas turbine combustor flows.

primary zone should be the best possible for combustion, which means that there should be a nearly stoichiometric mixture of fuel and air. As a result of the near-stoichiometric richness of the mixture in the primary zone, it is a region of very high temperature and NO_x production.

CO emissions arise in a very different way. Under high-load conditions, the primary zone burns hot and carbon tends to oxidize completely. The addition of air in the dilution zone cools the gas, but the temperatures are still high enough to oxidize any CO and there is plenty of oxygen present for complete oxidation. At low load, however, and especially at idle, the overall air-fuel ratio is extremely high and the mixture is lean even in the primary zone; the results are lower temperature, less vigorous combustion, and high CO production. Then, during the addition of secondary air, some pockets of gas are cooled too rapidly for complete oxidation of CO to CO_2. The result is that CO emission levels under low-load conditions are very high as compared to the levels at high load, and since idle and low-load operation is very significant in the urban driving cycle, overall CO emission is high.

The key to turbine emission reduction is control of conditions in the primary zone. It is there that liquid fuel is injected, vaporized, mixed with air, heated to ignition, and burned almost completely, and it is there that NO_x production must be reduced and combustion strengthened under idle conditions. To make effective design modifications, it is necessary to study all the basic processes: fuel injection, droplet vaporization and combustion, convection and turbulent mixing, and gas-phase chemical kinetics.

The complexity of such a study is readily apparent. Fuel vaporization, for example, is dependent primarily on droplet size, injector spray pattern, and ambient temperature; in most combustors the larger fuel droplets are not completely vaporized before combustion, and in some combustors a significant amount of the fuel burns in diffusion flames surrounding the individual droplets. The mixing and heating of vaporized fuel depend on

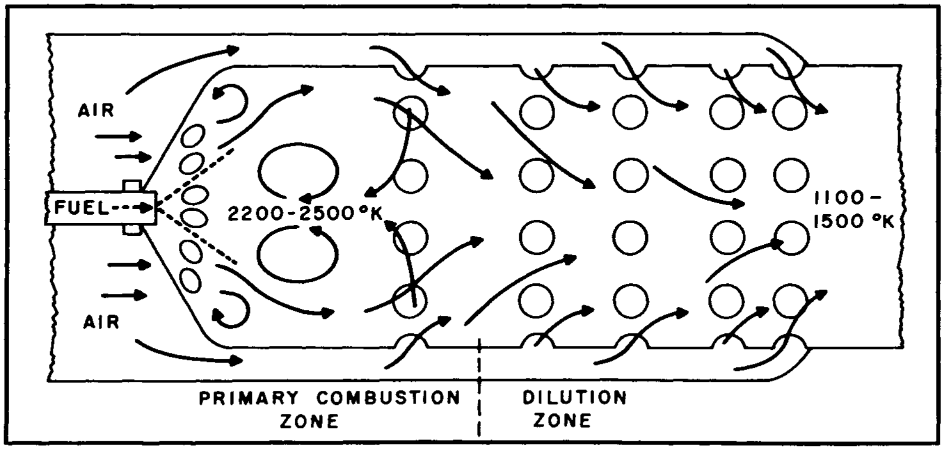


Figure 2. Schematic of a combustor for a vehicular gas turbine engine. In order to provide a very lean fuel mixture at the exit of the combustor and still retain flammability, two combustion zones are provided. The fuel mixture is comparatively rich in the primary combustion zone, where most of the fuel is burned. Air is then added in the dilution zone to lean the mixture and cool the gases.

turbulent mixing and the complex convective flow patterns in the primary zone. The chemical processes which consume fuel and produce and destroy NO_x and CO are complex and involve many different chemical reactions. It is possible to analyze these reactions only with the aid of computers and only under conditions in which mixing and heat transfer are absent or can be modeled by very simple expressions. Even then the results may be off by several hundred percent because of the lack of good data on rate constants.

Nevertheless, the prospects for developing low-emission combustors in gas turbine engines are very good. Studies of an idealized combustor, in which it is assumed that droplet vaporization is complete, mixing is perfect, and the processes are controlled by gas-phase chemical kinetics, show that such a combustor could be run virtually pollution-free. CO and hydrocarbon emissions could be reduced almost to zero and NO_x emissions to levels well below the federal standards. Thus there is no chemical kinetic limitation to clean combustion. In a real combustor, the prospects for altering configurations, fuel injection, and flow patterns to give low emission without influencing performance are very good, primarily because the turbine is a continuous combustion device and few constraints are placed on the combustion process by cycle design.

Activity in the field of gas turbine emission control is quite intense and still on the rise as a result of automotive standards, impending aircraft emission standards, and stationary source standards that would apply to industrial gas turbines. Much of the work, especially industrial work, is of a semi-empirical nature, characteristic of combustor design. The phenomena governing spray dynamics, turbulence, and flow patterns are as complex and difficult to model as the chemistry, and this complexity has frustrated attempts to develop more sophisticated design techniques. Support for this kind of work comes from industry and government, primarily the Environmental Protection Agency (EPA) and the National Aeronautics and Space Administration (NASA).

There is also a growing amount of modeling work in university, industrial, and governmental laboratories. A large fraction of this work has been directed to the formulation of semi-empirical expressions of pollutant emissions from more or less conventional combustors. Such modeling can help a designer in refining existing combustors, but it does not supply the fundamental understanding needed to support radical design innovation.

The development of fundamental understanding has appeared feasible only in recent years and relatively little work of this type has been done. This situation is rapidly changing, however, for research in this area has been undertaken at a number of institutions, including Cornell, with support from agencies such as the National Science Foundation and NASA.

THE MECHANISMS WHICH MUST BE STUDIED

The vaporization and combustion of droplets and combustor aerodynamics are the controlling mechanisms which most need to be studied.

The distinguishing feature of droplet vaporization and burning is that they are controlled by turbulent and

Several gas turbine engines for passenger vehicles have been developed and built.

Right above: This Chrysler Corporation turbine car was one of fifty distributed to 203 motorists for a consumer test program between 1963 and 1966. These motorists drove the cars a total of more than one million miles. The car, styled by Chrysler and crafted by Ghia of Italy, has a 110-inch wheelbase and an overall length of 201.6 inches. Chrysler claims that the fourth-generation, 130-horsepower engine is equivalent in overall performance to a V-8 piston engine of more than 200 horsepower. (Courtesy the Chrysler Corporation.)

Right below: A Williams Research Corporation engine was installed in a standard production passenger car (a Hornet) for New York City's low-emissions vehicle demonstration program. The compact 800-horsepower engine is 24 inches long, 26 inches wide, and 16 inches high, and weighs 250 pounds without accessories. (Courtesy the Williams Research Corporation.)

molecular transport processes near the droplet and by cooperative effects between droplets, and not by chemical reactions. The designer can direct his efforts at pollution control to such areas as injector design, control of spray patterns and droplet size, and conditions that influence droplet vaporization and combustion under forced convection. However, because of the nature of diffusion-controlled combustion, these changes will not have great influence on CO and NO_x emissions.

Combustor aerodynamics is a much more interesting area of research because of the greater potential for control. In the past, aerodynamic studies were severely hampered because turbulence was poorly understood, the equations for reactions governing pollutant formation and reduction were difficult, if not impossible, to solve, and experiments to determine flow properties were extremely difficult to execute with accuracy. This picture has changed in the past five to ten years, however. Models are now available for determining turbulent mixing rates; advances in numerical techniques and the availability of large computers allow researchers to solve the complicated governing equations; and experimental equipment for measuring flow —hot wire anemometers and laser doppler velocimeters, for example— and for determining chemical composition have been developed. Our work at Cornell is an example of how these new tools can be used. We are developing computer codes for calculating flow patterns in, and emissions from, turbine combustors, and we are testing the results in the laboratory. The fundamental understanding so obtained will prove invaluable in future design efforts.

A COMMERCIAL GAS TURBINE VEHICLE

We have seen that emission control in the gas turbine engine depends on the ability to alter flow patterns, mixing, and fuel injection to give cooler, cleaner combustion. Since the details of combustor design have little influence on overall engine performance, the designer has a free hand in attempts to provide for low emission levels—a freedom that is not possible in work with a spark engine where combustion is strongly coupled to performance. Indeed, the development of low-emission gas turbines is really only a matter of time. First will come combustors that are modifications of present designs; these will be relatively clean and capable of meeting the proposed standards. Later designs, based on current fundamental research, will be quite different, and emissions will begin to approach the very low levels inherently possible with a gas turbine. The significance of further pollutant reduction, beyond that called for by the currently legislated standards, must not be overlooked, for as total yearly vehicle mileage increases, vehicle emissions must be continually reduced if the status quo is to be maintained.

The impact of emission standards on the spark engine will be severe. Cost will increase, maybe by as much as $300 per engine; required maintenance will increase, along with an expected 20% rise in fuel consumption; and driveability of the vehicle will decrease. Such changes will certainly make the turbine more attractive, since it can be cleaned without penalties, especially those of cost and fuel consumption.

But that is not the end of the story. Because of the short lead times involved, the automotive industry is committed to the spark engine for meeting the current standards; there simply is not enough time to introduce a new system on a large scale. In 1977 there will be on the market a spark engine which meets standards. This feat will have required a large investment of manpower and materials which will not be abandoned lightly for a gas turbine or any other engine; moreover, vehicular gas turbine development is bound to suffer during this time of development because of its lower priority. Unless something happens to change the picture, the gas turbine will still be number two in 1977.

What is needed is the commitment of resources outside Detroit to develop a clean gas turbine to compete with the "clean" spark engine. It must be clearly superior, however, for only then will it seem reasonable to attempt the large-scale conversion that would be required.

The Environmental Protection Agency has an extensive program on alternate engines and considers the gas turbine one of the most viable. This program is intended to develop a prototype low-emission, advanced vehicular gas turbine by 1975-76. Performance, acceleration, efficiency, cost, and emissions are the major concerns. Most of the work is being performed by outside contractors, including NASA (Lewis), Chrysler, United Aircraft, Williams Research, and the Solar division of International Harvester.

Projects to develop other gas turbine applications may also have an effect on design for automobiles. The Advanced Research Projects Agency of the Department of Defense is involved with turbine development for tanks and heavy-duty vehicles; of particular interest is a large contract with Ford and Westinghouse for the development of high-temperature ceramic components, including combustors and power turbines. Also, some spin-off from aircraft and industrial gas turbine development can be expected. Aircraft development is the one to watch: emission standards

" . . . the decision to convert . . . to gas turbine power is not really a technical matter; it is an economic and political one."

are now being promulgated and are scheduled to go into effect in 1979, and many of the solutions that must be found will be applicable to automobiles. The emission of CO and hydrocarbons under idle conditions, for example, is a problem for the aircraft turbine as well as for the automotive turbine. The control of NO_x emission is also important in both applications. Because of possible impact on the stratosphere, NO_x emission was a significant factor in the decision to cease development of the American supersonic transport.

Whether or not these efforts will be sufficient to develop a clearly superior gas turbine in the 1970s remains to be seen. Much will depend on the success of the large programs to develop clean spark engines. I think it is clear that the gas turbine has great potential and will be superior to the spark ignition engine. However, the decision to convert any significant fraction of our ground-transportation industry to gas turbine power is really not a technical matter; it is an economic and political one. The imposition of vehicular emission standards and heightened awareness of the need for energy conservation has changed the balance, but because of our commitment to a clean spark engine, the balance may not have been shifted decisively to the gas turbine.

Frederick C. Gouldin, assistant professor of mechanical and aerospace engineering, has been conducting research on the aerodynamic design of a nonpolluting gas turbine combustor for about three years. In another research effort, part of the Cornell Energy Project, he is working on an assessment of fossil fuel technology, including study of pollution control techniques used by the electric utility industry and new technology such as coal gasification and the use of MHD topping units.

Gouldin came to Cornell in 1970 as a member of the thermal engineering faculty. He received his university education at Princeton, which awarded him the B.S.E. degree, with high honors, in aerospace and mechanical science in 1965, and the Ph.D. in the same field in 1970. While an undergraduate he worked summers as a computer programmer for the Naval Research Laboratory and in the combustion laboratory of the Atlantic Research Corporation. During his graduate years, he held a NASA Trainee Fellowship and a Guggenheim Fellowship, and in 1970 he was named a Teeter Award Winner by the Society of Automotive Engineers.

He is a member of the American Institute of Aeronautics and Astronautics, the Combustion Institute, the Society of Automotive Engineers, the American Association for the Advancement of Science, and the honorary society Sigma Xi.

HYDROGEN: FUEL OF THE FUTURE FOR TRANSPORTATION ENGINES

by P. C. T. de Boer and William McLean

Energy, the handmaiden of man's progress through the centuries, is in the deepest trouble. Demand in the United States for all sources of energy is rising at a steady five per cent and demand for electricity alone is skyrocketing at nine per cent per year—it is doubling every decade. Continuation of this trend is clearly impossible, given the current means of obtaining energy. In a few decades there will be no oil for conversion to electricity or for transportation, nor will there be any natural gas, the cleanest-burning fossil fuel . . . Thus the energy crisis, one that has little to do with summertime difficulties of power companies or the political considerations of importing Mideast oil. It requires recognition of the fact that our energy resources are dwindling, the bitter realization that at some not-so-distant hour the party will be over.

This statement, written two years ago by environmentalist Wilson Clark, seems prophetic in view of the serious fuel shortages being experienced this winter. The real prophecy, however, goes beyond the problems of current shortages, which are caused by slowdowns in the recovery-to-refinery-to-user petroleum distribution system; rather, it is concerned with the ultimate energy crisis when fossil-fuel supplies are exhausted some time in the next century.

What energy sources will be available to a society that consumes power at an ever-increasing rate? How will the nature of these supplies affect the design and operation of future transportation engines? What are some of the fuel options for future transportation systems? We would like to consider these questions in this article. In particular, we will discuss the potential use of hydrogen as a synthetic automotive fuel, a subject we are investigating in a current research project sponsored by the U.S. Department of Transportation.

THE ENERGY PICTURE IN THE U.S. AND THE WORLD

A recent projection of total demand by the United States for energy resources is shown in Figure 1. An enormous increase in energy consumption is forecast for the next fifty years, an increase to be met primarily by increased coal production and rapidly expanded nuclear-energy capacity. The future role of other energy sources, such as solar and geothermal, is largely uncertain at the present time and is not included in the projection.

Petroleum supplies are of special concern to the transportation sector, because vehicles are currently fueled almost exclusively with petroleum derivatives. Figure 2 shows a projection, to the year 1985, of petroleum use for various purposes in the United States. Transportation currently accounts for about half of all petroleum consumption, and this share is expected to remain about the same. Total petroleum demand already exceeds domestic supplies, and unless the overall trends are altered, the dependence on foreign imports will increase markedly during the next several years. Transportation demand alone is predicted to exceed domestic supplies by 1980. The world petroleum supply, of course, is far greater than the United States supply; nevertheless, peak worldwide production of petroleum is expected early in the next century (Figure 3), with a subsequent rapid decrease as supplies are exhausted.

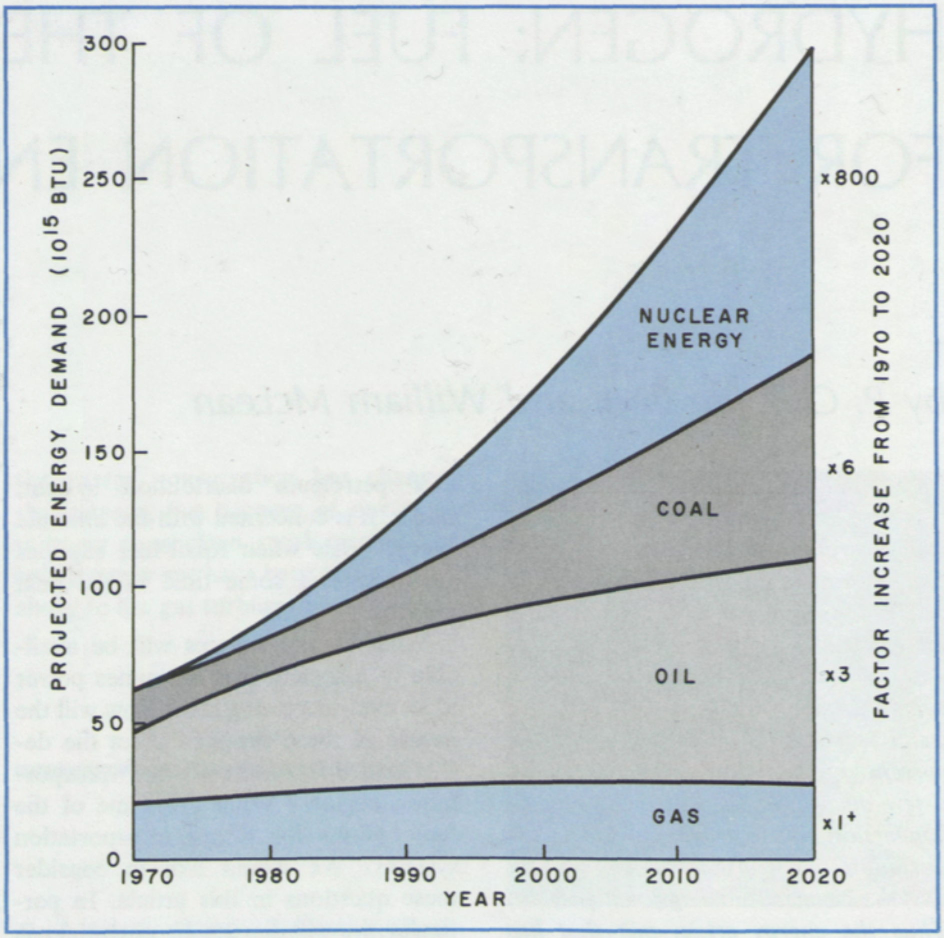


Figure 1. Projected increases in demand by the United States for energy resources. The rapidly increasing demand is expected to be met by increased use of nuclear and coal resources. (From figures supplied in April, 1972, by Associated Universities, Inc., in a report to the White House Office of Science and Technology.)

THE IMPENDING NEED FOR SYNTHETIC FUELS

In view of the inevitable exhaustion of petroleum and natural gas supplies, the rapidly rising energy demands will most likely be met in increasing proportions by coal and nuclear fuels. In the short term, from now to about 1985, rapidly increasing use of coal is expected, and the production of nuclear energy should increase rapidly after that.

Today both coal and nuclear energy are used primarily to generate electricity, since usage of either of these energy sources is technically or economically feasible only at large central generating stations. How, then, can the future need for gaseous and liquid fuels be satisfied when natural gas and petroleum reserves are depleted? Clearly there will be a need for synthetic liquid or gaseous fuels which can be generated from coal or nuclear energy and which can be stored and transported. While it is difficult to predict when the transition to synthetic fuels will take place, the eventual occurrence of this transition appears inevitable.

Figure 3 includes a recent estimate of the expected rate of production of synthetic fuels, which are classified for convenience according to their source as either fossil (from coal) or nonfossil (manufactured with use of nuclear energy). It is possible to produce methane, gasoline, methanol, hydrogen, and other energetic compounds from coal, while nuclear energy in the form of electricity or heat may be used to produce hydrogen from water.

At the present time a few pilot plants are in operation for production of synthetic natural gas (methane) from coal, and other plants are planned for the near future. Although the manufacture of hydrogen from coal has not been demonstrated on a commercial scale, the technology is quite similar to that used for producing methane from coal, and therefore the feasibility of the process seems assured.

As nuclear energy usage begins to become significant, synthetic fuels from nonfossil sources will be required. Hydrogen from water is the obvious choice here. Two methods of production are possible. The first, electrolysis, is the

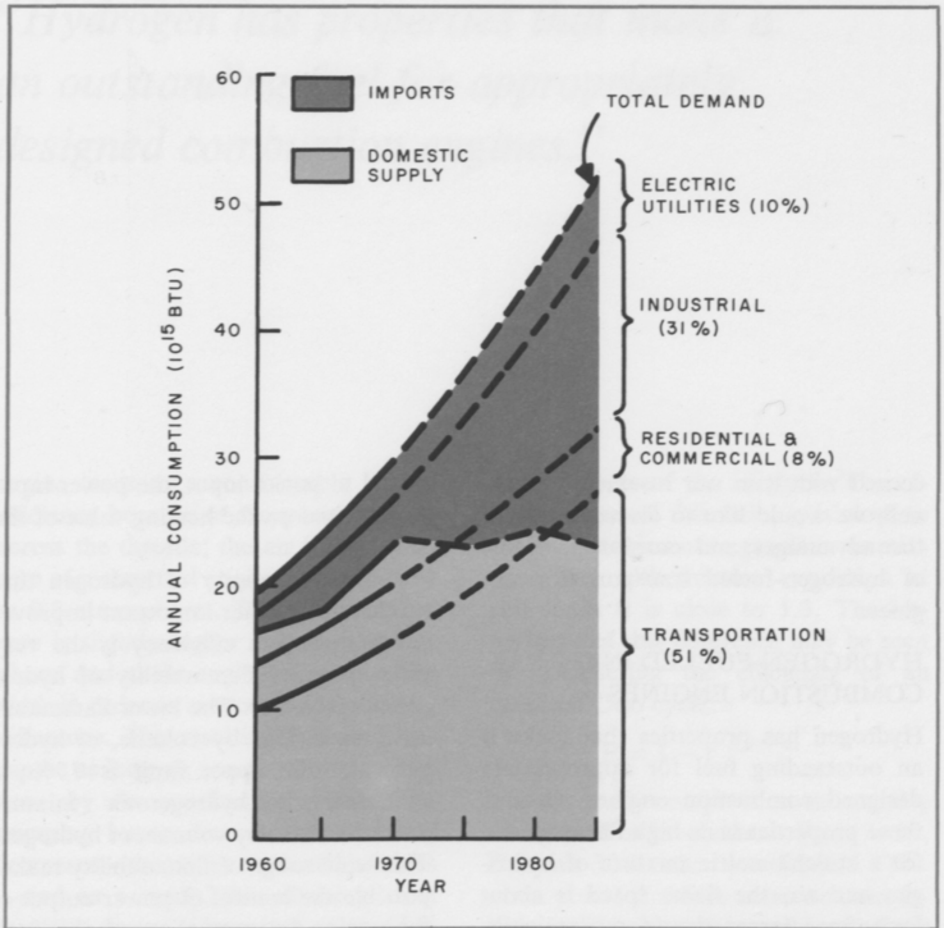


Figure 2. Projections of United States petroleum demand and supply. A substantial increase in imports is assumed. It may be noted that transportation uses account for about half of all oil consumption. (From National Petroleum Council data.)

familiar electrical separation of water into hydrogen and oxygen that is usually demonstrated in high school chemistry classes. In this procedure, the nuclear heat would be converted to electrical energy in a standard nuclear electric plant, and then this electricity would be used to produce hydrogen from water. A second production method, the direct use of nuclear heat to dissociate water by catalytic processes, is currently under development in Italy and in the United States.

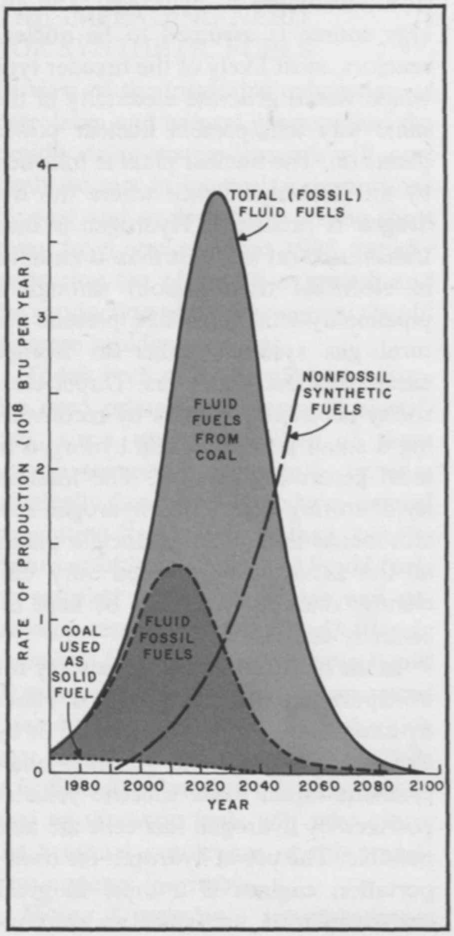
Given the ready availability of hydrogen from coal and from water by means of nuclear energy, and its potential for satisfying the synthetic liquid and gaseous fuel requirements of the future, it is no wonder that energy systems based on a *hydrogen economy* have been mentioned so prominently in recent months.

THE HYDROGEN ECONOMY AND ITS PROMISE

Figure 4 shows one concept of a future energy system which makes use of the storability, portability, and transmission advantages of hydrogen. The energy source is assumed to be nuclear reactors, most likely of the breeder type which would generate electricity in the same way that present nuclear power plants do. The nuclear plant is followed by an electrolyzer unit where the hydrogen is produced. Hydrogen is then transmitted (at less cost than is entailed in electrical transmission) through a pipeline system much like present natural gas systems, either to storage areas or directly to users. Direct electricity needs are satisfied by reconverting a small portion of the hydrogen in local generating stations. The feasibility of storing energy in a hydrogen system means that the large nuclear plants of the future can be used very efficiently, since the load can be kept essentially constant.

In the hydrogen economy, energy for transportation can be provided either by direct combustion of hydrogen or by the use of hydrogen to generate other synthetic liquid fuels. Electric vehicles powered by hydrogen fuel cells are also possible. The use of hydrogen for transportation engines is a topic of great current interest, and since we are con-

Figure 3. Estimated production rates of fluid fuels from various sources. As oil and gas reserves are depleted, fluid fuels, including hydrogen, will be obtained from coal conversion and by production from nonfossil sources. (Adapted from Hydrogen and Other Synthetic Fuels, *report TID-26136 of the Federal Council on Science and Technology.)*



cerned with it in our research at Cornell, we would like to discuss some of the advantages and current problems of hydrogen-fueled transportation engines.

HYDROGEN-FUELED INTERNAL COMBUSTION ENGINES

Hydrogen has properties that make it an outstanding fuel for appropriately designed combustion engines. One of these properties is its high flame speed: for a stoichiometric mixture of hydrogen and air, the flame speed is about four times larger than for a stoichiometric mixture of gasoline and air. This causes the combustion process to be completed rapidly, and means that in an internal combustion engine, most of the hydrogen can be reacted near the beginning of the expansion stroke of the piston. In contrast, the combustion process for gasoline typically continues during about half of the expansion process. Rapid combustion tends to increase engine efficiency, and engines running on hydrogen have generally proved to be more efficient than those running on gasoline. Efficiency in this sense is defined as the ratio of power output to power input, the power input being based on the heating value of the fuel.

Another property of hydrogen that can lead to further important improvements in engine efficiency is the very wide range of flammability of hydrogen-air mixtures. The lower flammability limit is 4%, by volume, of hydrogen, and the upper limit is 75%; a stoichiometric hydrogen-air mixture contains 30%, by volume, of hydrogen. This wide range of flammability makes possible the control of power output of the engine by regulation of the fuel-supply rate. Full load is achieved with a near-stoichiometric mixture, while part loads are achieved with lean mixtures. At a given speed, the engine should be capable of providing any part load down to one-fifth of the full load; and with hydrogen as the fuel, the fuel-air ratio at one-fifth load is still well above the lower flammability limit.

A fuel-regulation scheme, which is called *quality governing* or *mixture regulation,* offers various large advantages. An important one is that the air intake does not need to be throttled. Obtaining part loads by throttling the

"Hydrogen has properties that make it an outstanding fuel for appropriately designed combustion engines."

engine leads to a considerable loss in efficiency because of the pressure drop across the throttle; the air intake pressure of a throttled engine can be as low as 0.3 atmospheres. The exhaust pressure is slightly higher than one atmosphere, and so the engine must do pump work in order to overcome the pressure difference. The resulting pumping loss can be as large as one-third of the work done by the combustion gases. The pumping losses decrease as throttling decreases—that is, as the load increases—and as a result, the efficiency of a throttled engine is largest at or near full load. When an automobile travels at high speed, the increased engine efficiency due to low throttling partly compensates for losses arising from air resistance and tire friction. However, since automotive engines are operated most of the time at only a fraction of their full-load capacity, important increases in average fuel consumption can be realized by unthrottled operation.

Besides eliminating pumping losses, mixture regulation at part loads increases engine efficiency by facilitating high effective values of the ratio of specific heats of the mixture. The effective value of this ratio, γ, is close to 1.2 for stoichiometric gasoline-air mixtures, but with mixture regulation at part loads it is close to 1.3. The importance of this difference may be seen by considering the efficiency of an idealized Otto cycle:

$$E = 1 - r^{-(\gamma - 1)}$$

where r is the compression ratio and γ is assumed to be constant. For $r = 10$, E equals 50% when $\gamma = 1.3$ and 37% when $\gamma = 1.2$. More accurate calculations indicate that the combined effects of increased specific heat ratio and elimination of pumping losses can make unthrottled operation at light loads as much as 55% more efficient than throttled operation. The efficiency can be increased further by increasing the compression ratio, a possibility we will discuss later.

Mixture regulation appears to be quite feasible for engines running on hydrogen. This is not the case for engines running on gasoline, however. In gasoline engines, mixture regulation is difficult to achieve because the lean mixtures required cannot be ignited. At the lower flammability limit, a gasoline-air mixture contains about 5% by weight gasoline, only a little less than the stoichiometric percentage of 6.8%. The only way in which mixture regulation can be made to work for engines running on gasoline is through the use of a *stratified charge*. In this case, the fuel-air mixture is not uniform throughout the cylinder, but instead is rich near the spark plug, in order to facilitate ignition, and lean in the rest of the cylinder. Even then, a great deal of effort is required to make the engine run as desired; as a result, mixture regulation so far has proved to be impractical for gasoline engines.

INJECTION OF HYDROGEN VERSUS CARBURETION

One of the principal requirements of an engine is that it should be capable of providing a high specific power output—that is, a high power output in relation to the weight of the engine. An important parameter in this connection is the chemical energy content of the gases in the cylinder before combustion. This energy content is higher for gasoline than for most other fuels. Hy-

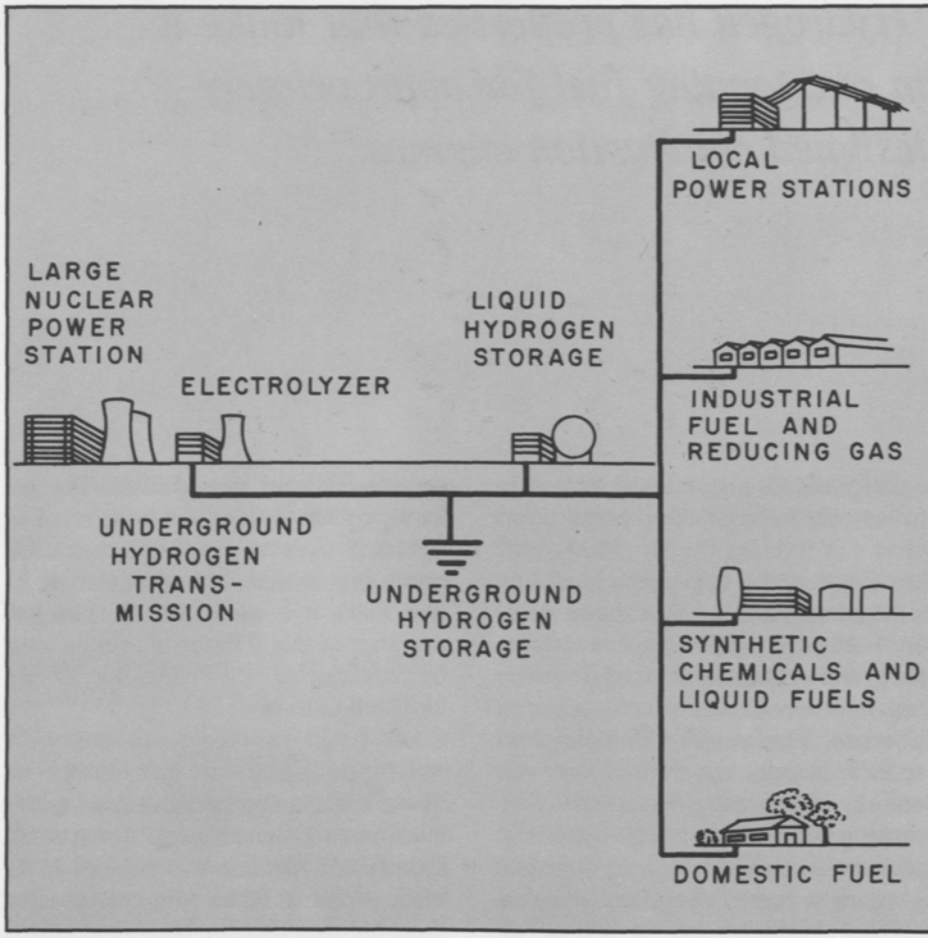


Figure 4. A concept of a total hydrogen energy system, showing production, storage, transportation, and delivery. (Adapted from Hydrogen and Other Synthetic Fuels, *report TID-26136 of the Federal Council on Science and Technology.)*

drogen can be even better than gasoline in this respect, provided that the hydrogen is injected after the cylinder is first filled with air. Effectively, this is a form of supercharging. The improvement in specific power which can be obtained by using hydrogen instead of gasoline as the fuel is about 20%. Without the supercharging effect, though, about 30% of the available cylinder volume is needed for hydrogen, and in that case the maximum power delivered is some 10% less for hydrogen than for gasoline.

There are additional ways in which cylinder injection of hydrogen is superior to carburetion. Two severe problems are encountered when a conventional carbureted engine is run on hydrogen: flashback and knock. Flashback is propagation of the flame into the carburetor; it is accompanied by a loud noise, and is very undesirable and unsettling. Knock is a loud noise originating in the cylinder. In an engine fueled by hydrogen, flashback is promoted by the high flame speed. Knock is caused mainly by uncontrolled ignition by hot carbon deposits or hot suspended carbon particles, a condition that is facilitated by the low ignition energy of hydrogen-air mixtures. However, when the hydrogen is injected into the cylinder rather than carbureted, flashback is no longer possible, while knock can be eliminated by injecting the hydrogen near the end of the compression stroke of the piston and by burning the hydrogen immediately upon injection.

When a carburetor rather than an injection system is used, other methods must be found to solve the flashback and knock problems. Many of the methods that have been proposed are based on the reduction of flame speed. This can be achieved by using either a very lean or a very rich mixture, or by recycling at least 20% of the exhaust gas through the cylinder. It is also helpful to use a low compression ratio. Unfortunately, all of these methods compromise specific power, and most of them also decrease efficiency. On the other hand, the injection scheme has the disadvantage that the equipment needed is much more complicated than a carburetor. At the present time, it is not clear which of the two fuel-induction systems will prove to be most attractive for practical applications.

NO_x EMISSIONS FROM HYDROGEN-FUELED ENGINES

Another factor involved in the choice of a fuel-induction system is compression ratio. Not only engine efficiency, but maximum power output as well, increases when the compression ratio increases. The compression ratio of a carbureted engine is limited by knock, but there is no such limitation for an injected engine: the only serious limitation on increasing compression ratio is the adverse effect it has on exhaust emissions. One of the reasons for the current interest in hydrogen as a fuel is that its main combustion product is water: since hydrogen contains no carbon molecules, combustion with air cannot result in the formation of carbon monoxide or hydrocarbons. On the other hand, any combustion process involving air can result in the formation of nitric oxide (NO) and other oxides of nitrogen, denoted as NO_x. Unfortunately, increases in the compression ratio result in higher combustion temperatures and therefore higher NO_x emissions. At the present time there are conflicting reports in the literature about the seriousness of the NO_x problem in hydrogen-fueled engines, but it clearly will be a factor in determining the future of the hydrogen-fueled internal combustion engine.

At Cornell we are working on a project to establish the magnitude of NO_x emissions as a function of a variety of engine parameters, such as compression ratio, air-fuel ratio, ignition timing, engine speed, and percentage of exhaust gas recirculation. For the experimental work we are using a so-called Cooperative Fuel Research (CFR) engine, which is a standardized engine designated by the American Society for Testing and Materials (ASTM) for the determination of the octane number of fuels. At the same time, we are using computer models to calculate the amount of NO_x formed under various conditions. In this modeling it is crucial to follow the temperature history of each part of the mixture within the cylinder, since temperature gradients within the cylinder can markedly affect average NO_x concentrations. The results of this research should establish the degree to which hydrogen-fueled engines can comply with exhaust pollution standards.

PROBLEMS OF SAFETY, COST, AND STORAGE

There are various other problems involved in the use of hydrogen in transportation engines, which our work does not touch on directly. These are problems of safety, cost, and storage. All three have received a great deal of attention in recent studies of the hydrogen energy economy.

The general conclusion about the safety problem is that working with hydrogen presents hazards no more severe than those incurred in working with gasoline. In at least one respect, they are less severe: in case of spillage into the atmosphere, hydrogen will quickly rise, whereas gasoline will tend to spread along the ground, remaining there for a considerable time before it evaporates. It is believed that the hydrogen safety problem can be reduced to the level of an acceptable risk.

The present cost of hydrogen is considerably higher than that of gasoline. However, if the various processes mentioned in this paper prove to be feasible on a large scale, the price differential will probably disappear. This is especially likely in view of the rapidly rising cost of gasoline.

The storage problem looms as the most important to be solved before hydrogen can be used in transportation engines. The basic problem is that a large volume of stored gas yields a comparatively small amount of energy. A standard cylinder 9 inches in diameter and 55 inches long, containing hydrogen at 2,400 psi, has a heat content equivalent to only 0.7 gallon of gasoline. Two ways of solving this storage problem are currently being investigated: cryogenic storage, and storage in the form of metal hydrides. Cryogenic storage requires rather large and expensive dewar flasks, plus equipment to evaporate the liquid hydrogen at the rate required. Storage as a metal hydride carries a weight penalty, and it requires a high heat-supply rate—more than is generally attainable with use of exhaust gas as the heat source—in or-

Professors de Boer (left) and McLean adjust the fuel injector pump of the CFR engine modified to run on hydrogen.

der to liberate the hydrogen. Those who are investigating these possibilities are quite optimistic about the prospects for their schemes, however. The information now available indicates that cryogenic storage is the more attractive of the two possibilities.

HYDROGEN: FUEL FOR THE CAR OF THE FUTURE?

Several functional automobiles equipped with hydrogen-fueled internal combustion engines—most of them built by student groups at various universities in the United States— are already in existence; and since interest in the use of hydrogen is rapidly increasing, it seems safe to predict that within a few years there will be many more hydrogen-fueled automobiles in operation. As time progresses and research efforts expand, these engines will become more sophisticated and more practical. And in view of the great long-term advantages offered by hydrogen as a fuel, these prototype cars may well be the predecessors of the automobile of the future.

P. C. T. de Boer and William J. McLean have been working together for several years on the research project on hydrogen as a fuel that they discuss in their Quarterly *article. Both are members of the faculty of the Sibley School of Mechanical and Aerospace Engineering.*

An associate professor, de Boer has a broad background and a wide-ranging interest in applied and theoretical aspects of physics and mechanical and aerospace engineering. His research at Cornell has centered on high-temperature gases and automotive pollution control.

A native of The Netherlands, de Boer received his first university degree, in mechanical engineering, from the Technological University in Delft in 1955, and subsequently was a research associate there. After serving in the Dutch army for two years, he began graduate study at the University of Maryland and was awarded the Ph.D. degree in physics in 1962. He remained at Maryland as an assistant professor until his appointment to the Cornell faculty in 1964.

In 1968 he was a visiting professor at the von Kármán Institute for Fluid Dynamics in Brussels, Belgium. During this period he held a NATO Senior Fellowship in Science. In 1971-72 he spent a sabbatical leave at the Ford Motor Company, conducting a research program on precision fuel metering and fuel atomization.

In addition to his academic work at Cornell, de Boer's activities include serving as an industrial consultant in the fields of fuel injection systems and combustion. He is a member of the American Institute of Aeronautics and Astronautics, the American Physical Society, the American Association of University Professors, the Royal Netherlands Institute of Engineers (KIVI), Sigma Xi, and Sigma Pi Sigma.

McLean, a specialist in combustion and air pollution problems, has been an assistant professor at Cornell since 1972. In addition to his work on the hydrogen fuel project, he is involved with chemical kinetic studies pertaining to the production of undesirable emissions from combustion systems.

McLean holds three degrees in mechanical engineering from the University of California at Berkeley: the B.S., awarded in 1963; the M.S., 1965; and the Ph.D., 1971. As a graduate student, he held an Air Pollution Special Fellowship, awarded by the Environmental Protection Agency.

McLean has had several years' experience as a development engineer with the Aerojet General Corporation and as a research scientist at the Lockheed Research Laboratory, investigating environmental effects of supersonic transport aircraft.

He is a member of the Combustion Institute and Sigma Xi.

CORNELL'S ELECTRIC CAR

The Development of an Urban Vehicle With No Emissions

by Joseph L. Rosson

Public recognition of the national need to reduce air pollution caused by internal combustion engines has been growing since its beginnings in the mid-1960s. By 1970, according to a survey conducted by Opinion Research Corporation, some fifty million Americans felt they would be interested in purchasing an electric automobile as a second car. And although the zero-pollution feature of the electric car is what has made it attractive to a large segment of the population, the current shortage and ultimate lack of crude oil have given additional impetus to the search for alternatives to petroleum as a fuel source. The apparent movement of the United States and other industrial nations toward an electricity-based energy economy should speed the development of the electric car.

Since 1969, the School of Electrical Engineering at Cornell has had an active program for the design and development of an electric vehicle for urban use. The impetus for the program came from Wally Rippel, a graduate student (M.S. '70) who was concerned about air pollution in cities (see the article about his project in Vol. 5 No. 2 of the *Quarterly*). Since those beginnings, almost seventy graduate and undergraduate students have participated in Cornell's Electric Car Project. Three electric vehicles have been designed, built, and tested by teams of students.

One of these cars, the 1971–72 model, was entered by its student design team in the 1972 North American Urban Vehicle Design Competition and won the Emissions Award. Participating in the final tests, held at the General Motors Proving Grounds in Milford, Michigan, were sixty-six prototype urban vehicles powered by such diverse kinds of energy as gaseous fuel, liquid fuel, electricity, and hybrid combinations of liquid or gaseous fuel and electricity. The Cornell team was led by the principal designers, all of whom now hold advanced degrees in electrical engineering: Geoffrey Hanshaw (M. Eng. '73), Foster Hinshaw (M.Eng. '72), and Henry Coyne (M.S. '72). This vehicle is still in operation and has logged over 3,500 miles while undergoing tests in urban traffic.

An examination of the specifications and performance characteristics of Cornell electric car models (Table I) provides a view of the advantages and limitations of vehicles powered by electricity, and a basis for speculation on the prospects for their use in the future.

CHARACTERISTICS OF THE CORNELL ELECTRIC CAR

In the 1972 Urban Vehicle Design Competition, the Cornell vehicle was found to be not only pollution-free, but the most efficient of all the entries. The final report for the competition states that ". . . . the Cornell machine was able to convert electric energy to mechanical energy more efficiently than all other vehicles converted their liquid or gaseous fuels to mechanical energy." The measured energy efficiency of 381 miles per million BTU of stored energy can be equated to approximately 42.8 miles per gallon of gasoline for a typical automobile with an internal combustion engine. This high efficiency is partly responsible for the low cost of electricity for urban driving, which is calculated as approximately 0.7 cents per mile. This very low figure is deceptive, however, because there are no state and federal taxes on the use of electricity, as there are on liquid fuel;

TABLE I. THE CORNELL ELECTRIC CAR: SPECIFICATIONS AND PERFORMANCE CHARACTERISTICS

	THE 1971-72 MODEL	THE 1973-74 MODEL*
Fuel	Electricity from 96-volt lead-acid batteries with a total weight of 1,600 lbs., a usable energy of approximately 19 kilowatt-hours, and recharge capability of 300 to 400 cycles from deep discharge	Electricity from 72-volt lead-acid batteries with usable energy of approximately 15 kilowatt-hours and recharge capability of 300 to 400 cycles from deep discharge
Power Drive	Direct current (d.c.) motor with a continuous rating of 18 horsepower, 96 volts, 140 amperes; separately excited connection	Direct current (d.c.) motor with a one-hour rating of 30 horsepower, 96 volts, 233 amperes; separately excited connection
Charger in Vehicle	Input: 115 volts, 60 hertz, single-phase; output: 96 volts with automatic current control	Input: 115 volts, 60 hertz, single-phase; output: 72 volts with automatic current control
Transmission	Three-speed automatic Volkswagon rear drive	Three-speed automatic Volkswagon rear drive
Curb Weight	3,500 lbs. (front 40%, rear 60%)	2,600 lbs. (front 40%, rear 60%)
Passenger Capacity	Five persons (no luggage or carrying space)	Two persons (10 cu. ft. of storage space)
Estimated Cost	$3,800	$2,800
Range	60 miles (approximate) in urban traffic	50 miles (approximate) in urban traffic
Normal Cruising Speed	25 mph	25 mph
Top Speed	60 mph	60 mph
Acceleration	2.17 feet per $(\text{second})^2$ going from 0 to 30 mph	2.86 ft./$(\text{second})^2$, going from 0 to 30 mph
Energy Efficiency	381 miles per million BTU stored (equivalent to 42.8 mpg)	381 miles per million BTU stored (equivalent to 42.8 mpg)
Charging Time	Approximately 10 hours (from deep discharge to full charge)	Approximately 10 hours (from deep discharge to full charge)
Noise Level	64 decibels at 30 mph (maximum value, measured 25 ft. from center line of vehicle)	64 decibels at 30 mph (maximum value, measured 25 ft. from center line of vehicle)
Emissions	None	None

*Predicted performance characteristics

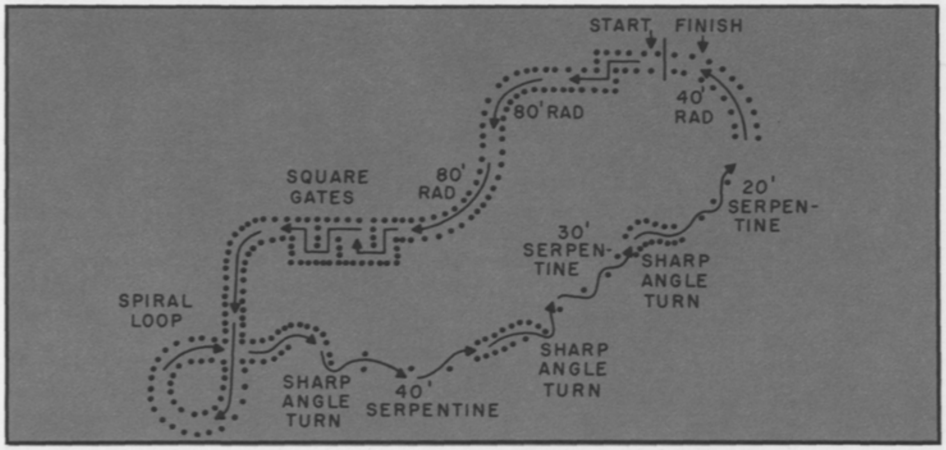


Figure 1. The slalom course, designed to test handling characteristics, that was used in the 1972 North American Urban Vehicle Design Competition. The black dots signify pilons; a two-second penalty was imposed for each pilon knocked over. The Cornell electric car traversed this course in 61.5 seconds, as compared with the average for thirty-five entries of 63.4 seconds.

furthermore, the depreciation costs of the comparatively expensive lead-acid batteries have not been included in the calculation.

The Cornell vehicle did not prove to be outstanding in the acceleration test of the competition. In accelerating from 0 to 30 mph, the average rate for thirty-five competing vehicles was 4.88 ft. per (second)^2; the corresponding figure for the Cornell car was 2.17. This relatively poor performance can be attributed to the weight of the main batteries (1,600 lbs.) and the torque–speed characteristics of the electric motor (18 hp.). The Cornell group does not expect that in the foreseeable future the electric car will approach the speed–acceleration characteristics of present-day internal-combustion-engine automobiles; there are still too many technological and materials problems involved in the development of batteries and electric motors capable of producing such performance characteristics. The student designers do feel, however, that speed and acceleration have been oversold to the consumer. Their experience has been that they quickly adjust, with a minimum of discontent, to the more limited performance of their electric cars, and they believe that when electric cars are generally available, consumers will adjust just as easily.

The good handling characteristics of the Cornell vehicles were demonstrated by results of the slalom course test in the 1972 competition. All vehicles were required to traverse a course (Figure 1) which was designed to test: (1) maneuverability through tight gates, to simulate urban driving in congested areas; (2 cornering capability; and (3) ability to maintain proper tire camber in turning, a measure of the effectiveness of the vehicle's suspension system. The average time required for thirty-five internal-combustion-engine vehicles to traverse the slalom course was 63.4 seconds; the best time was 54.6 seconds for a six-cylinder, 1,010 cu. cm. vehicle; and the poorest time was 90.2 seconds for a 1970 compact vehicle. The Cornell electric car had a timed run of 61.5 seconds. The good handling characteristics of the Cornell vehicle are owing, in part, to advantageous placement of batteries, a matter of fortuitous circumstance rather than conscious design. The distribution and placement of batteries produces a very low center of gravity, and causes the vehicle to understeer.

The level of noise emitted by the Cornell electric car was 64 decibels, as measured at a distance of 25 feet from the vehicle while it was traveling at 30 mph. Thirty-five vehicles with internal combustion engines produced an average noise level of 76.3 decibels under similar conditions. The relative quietness of the Cornell car was expected.

The design group is presently working on a third car in an attempt to develop a lower-cost vehicle that will move smartly in urban traffic. The new car, which is in operation and is undergoing first tests, has the specifications and predicted characteristics listed in Table I.

EMPHASIS ON DESIGN OF PROPULSION CONTROLS

Since it would be prohibitively expensive and beyond the competence of student teams to develop unique automobile bodies and all working parts, the principal design efforts in the Cornell electric car program have been

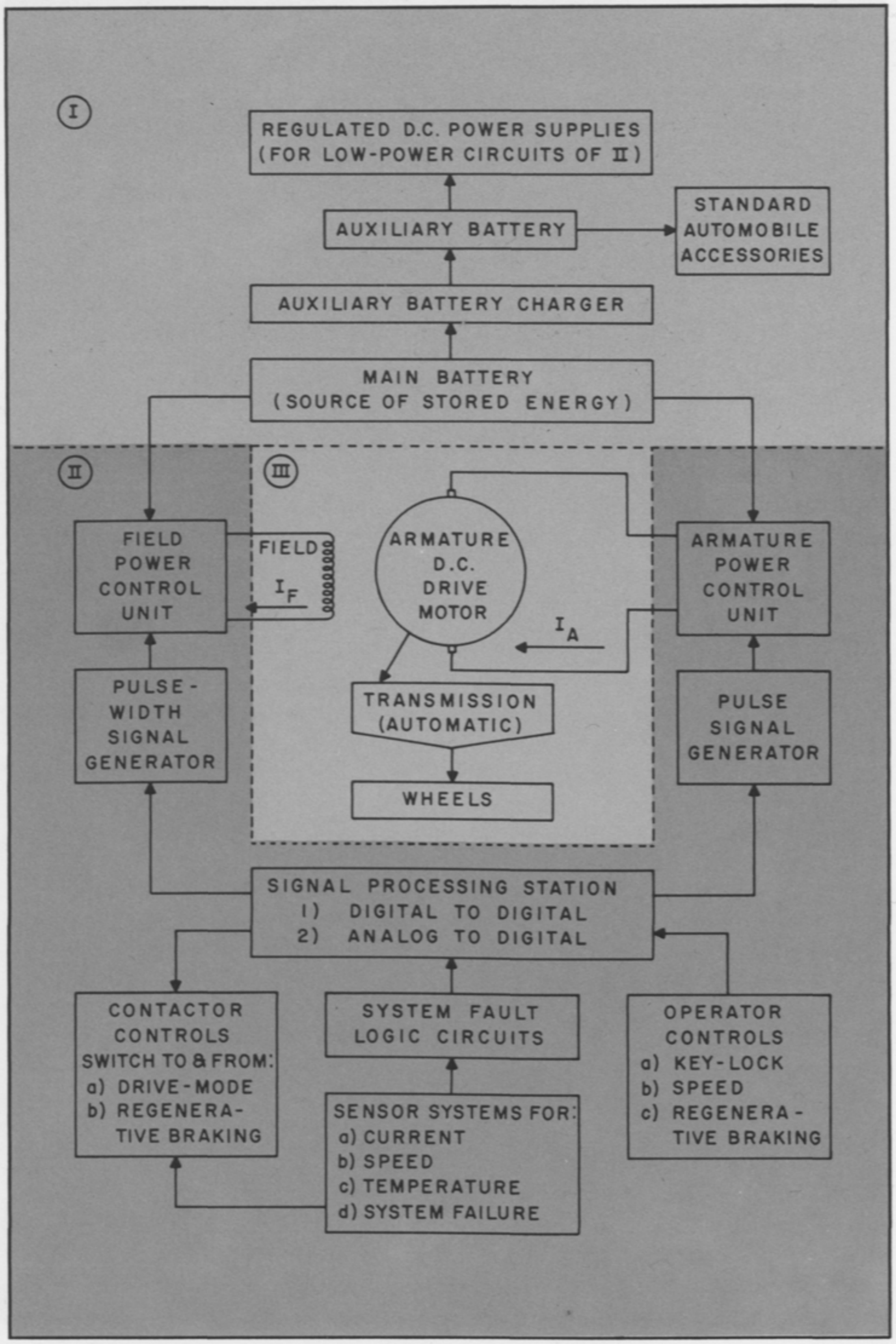


Figure 2. The propulsion system of an electricity-powered vehicle. The three principal units are: I. The energy source. II. The power-control system. III. The energy-conversion system. In the Cornell project, work has been concentrated on system II. The arrows indicate the directions of power or signal flow.

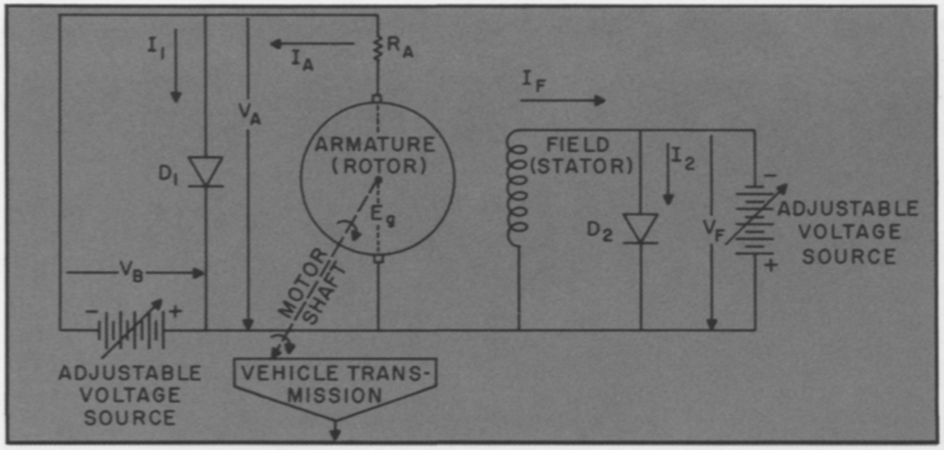


Figure 3. A simplified diagram of the separately excited d.c. motor used in the Cornell electric car. Vehicle speed is regulated by operator control of two adjustable voltage sources which supply V_A, the armature voltage, and V_F, the field voltage which develops the magnetic field of the stator. E_g is the generated voltage. The circuit elements D_1 and D_2 are diodes which allow for the dissipation of energy stored in the motor's magnetic circuits.

concentrated on the development of systems to control propulsion. It is in this area that a group of electrical engineers can be expected to make the most meaningful technological contributions.

The propulsion system of an electric care can be divided into three principal units (see Figure 2): an energy source (the main battery), a power-control system, and an energy-conversion system (the motor and transmission). A brief review of each of these units may give some insight into their importance in the overall system.

THE MAIN BATTERY: THE CHIEF DRAWBACK

Little genuine advancement in the technology of batteries suitable for electric vehicle energy sources has been made over the past sixty to seventy years. At the present time, as was true in the early 1900s, the lead-acid battery is the most practical energy storage unit that is fully developed and commercially available for the electric vehicle.

The lead-acid battery has an energy density of about 12 watt-hours per pound at the consumption rates of electric vehicles. By contrast, an equivalent weight of gasoline has an energy density in the vicinity of perhaps 1,200 watt-hours when converted to usable mechanical energy. New battery systems, such as lithium-sulfur, sodium-sulfur, and zinc-air have energy densities of 100 to 150 watt-hours per pound, and show promise for development, but it seems probable that another seven to ten years will elapse before a battery with an energy density of this magnitude becomes commercially available. Until this development is effected, the internal combustion engine will no doubt continue its overwhelming lead in vehicle propulsion. Even with this pessimistic appraisal, however, the Cornell group believes that a small market does exist for a limited-range electric vehicle such as its 1973–74 model.

SOLID-STATE DEVICES FOR CONTROL SYSTEMS

The Cornell designers have concentrated their efforts on the development of power-control systems, diagrammed in area II of Figure 2, which they believe will be compatible with future battery systems. A power-control system processes the driver's commands to control the flow of energy to and from the batteries and the drive motor for speed control and regenerative braking. The opportunities for significant developments in these systems have been made possible by rapid advances in the technology of solid-state devices such as silicon-controlled rectifiers, power transistors, and integrated switching circuits. Without such advances, developments in electric cars would be little better than could have been achieved sixty years ago when the Baker Electric was being built.

The three systems that have been developed at Cornell are efficient and reliable in their operation. The system efficiency of each of the three is about 98%, and each has been trouble-free after completion of the initial field testing.

THE SEPARATELY EXCITED D.C. MOTOR

Historically, the series direct current (d.c.) motor has been the preferred choice for vehicle propulsion. This motor has the characteristic of increasing

The 1973-74 model of the Cornell electric car is now being developed by a team of electrical engineering students. Shown with Professor Rosson are Goeffrey Hanshaw (at left) and Lawrence Rossi, who is this year's student project leader. Work is proceeding in the electric car laboratory, a separate building near the engineering campus. For this model, the students hope to expand their efforts beyond the engine design which usually constitutes the project. They are designing and hope to build a fiber-glass body in a dune-buggy style with two bucket seats.

This car is designed to cruise at 25 mph in urban traffic, go about fifty miles between charges, and cost about $2,800.

shaft speed with decreases in armature current and developed shaft torque, and so meets typical vehicle traction requirements. Instead of this common choice, the Cornell group selected a separately excited d.c. motor as its propulsion unit (see Figures 2 and 3). This type of motor allows the driver to have better control of speed and of the regenerative braking system. Such a motor selection would not have been likely eight years ago, but the availability of inexpensive and reliable high-power solid-state devices makes possible the development of reliable and simple speed-control systems for separately excited d.c. motors.

The operation of a d.c. motor, in simplified terms, depends on the generation of a voltage which is produced by the rotation, in a magnetic field, of conductors on the armature. In the Cornell scheme, there are two separate controls—one to vary the armature voltage, V_A, and one to vary the voltage, V_F, which regulates the amount of field current, I_F. At low speeds, control is exerted by varying the magnitude of V_A; V_F and hence I_F, the field current, are maintained at constant values equal to their respective ratings. As vehicle speed increases, a maximum value of V_A, equal to the battery voltage, is attained, and further increases in speed are obtained by reduction of V_F. Speed control of the vehicle, therefore, is obtained through control of the average values of both V_A and V_F, the armature and field voltages.

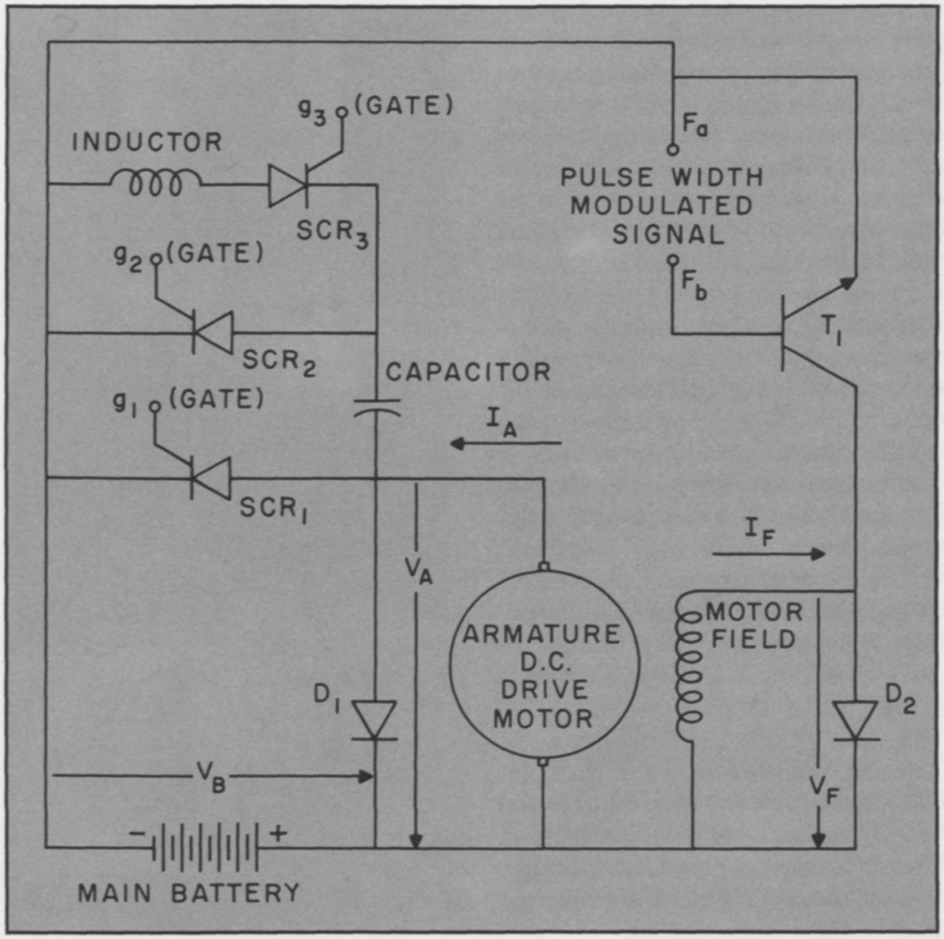
Acceleration depends on the torque that is developed; for maximum acceleration, the armature and field currents must be at their maximum permissible values. In the operation of an electric vehicle, it is permissible for armature currents to reach 300% of their rated values for short periods of time (20 to 30 seconds) without damaging the drive motor. This fact allows for optimum vehicle acceleration characteristics at starting and for passing.

Figure 4 illustrates, in simplified form, the power circuits used for speed control of the 1971–72 Cornell electric car. The magnitude of V_A is controlled by the relative timing of current pulses supplied to silicon controlled rectifiers. The magnitude of V_F is controlled by the "on" time of a power transistor, and this "on" time, in turn, is controlled by the time width of synchronous pulses of voltage applied as indicated in the figure.

THE EDUCATIONAL VALUE OF THE PROJECT

The electric car project has been an excellent program to introduce seniors and graduate students in the Master of Engineering (Electrical) degree program to realistic and complex design problems. The project has stimulated interest in design among these students;

Figure 4. A highly simplified diagram showing how vehicle speed is controlled by the use of high-power semiconductor devices. This shows the essence of the scheme used in the 1971–72 Cornell electric car. The magnitude of the armature voltage, V_A, is controlled by the relative timing of current pulses injected into gates, g_1, g_2, and g_3, of the silicon controlled rectifiers SCR_1, SCR_2, and SCR_3. The magnitude of the stator voltage, V_F, is controlled by the "on" time of the power transistor, T_1. The "on" time of T_1 is controlled by the time width of the synchronous pulses of voltage applied between points F_a and F_b.



" . . . the Cornell group believes that a small market does exist for a limited-range electric vehicle such as its 1973-74 model."

in a few cases, their motivation has been so great that it has been necessary to limit their working time so as to keep their academic programs in balance. The faculty recognizes that few students, if any, will subsequently participate in industrial programs for the development of electric vehicles, but feels that through the experience of working on the project, most of the student designers acquire an appreciation of the problems associated with a cooperative design effort. Without exception, the participating students have gained confidence in their abilities to participate in the design of circuits and systems that use the most modern electronic devices and energy converters.

Limited but necessary support for this design and development project has been provided through the generosity of Electric Fuel Propulsion, Inc., the Firestone Tire and Rubber Company, the General Electric Company, the Long Island Power and Light Company, the New York State Electric and Gas Company, and the Philadelphia Electric Company. The electrical engineering faculty is grateful for the support of these organizations.

Joseph L. Rosson, professor of electrical engineering and assistant director of the School of Electrical Engineering, has pursued an active teaching, administrative, and research career at Cornell since he joined the faculty in 1951.

Rosson received the B.S. degree from the University of Tennessee in 1942, and after four years of active duty in the U.S. Navy during World War II, he taught for a year at the University of Tennessee Junior College. Subsequently he came to Cornell to undertake graduate studies in electrical engineering and was awarded the M.E.E. degree in 1951.

In addition to teaching, he has been on numerous University and College of Engineering committees and has served as acting director of the School of Electrical Engineering. His research projects at Cornell include a cable project at the University's High Voltage Laboratory, a study of atmospheric refraction of radio waves, and the development of feedback engine controls.

Rosson has served as a consultant to the Westinghouse Electric Company, the Edison Illuminating Companies, the General Electric Company, and the former Cornell Aeronautical Laboratory. He is a member of the Institute of Electrical and Electronics Engineers, and the honorary societies Tau Beta Pi, Eta Kappa Nu, Sigma Xi, and Phi Eta Sigma.

AUTOMOTIVE POWER PLANTS

The Long-Term Outlook

by Wallace E. Wilson

Whatever the effects may be of shifting priorities for energy and the environment, changes in transportation are sure to be among them. Nothing in the twentieth century, an era of change, has evolved so quickly. Over the past seventy-five years, two major forms of transportation—the motor vehicle and the airplane—have been introduced and undergone rapid development.

Economically and socially, the motor vehicle has become the dominant form of transportation. To a great extent, the automobile determines how we live, where we live, and where we work; the truck is the prime mover of manufacturers' freight. In direct competition with other forms of transportation, the car has provided a new level of comfort and convenience for people, and the truck a new level of efficiency for moving freight.

FACTORS IN THE SUCCESS OF AUTOMOTIVE ENGINES

Part of the reason for the success of today's cars and trucks has been, until recently, the availability of low-cost fuel. Petroleum fuels provide relative safety, convenient on-board storage, and high-energy density in terms of both weight and volume. At General Motors, we continue to evaluate all types of fuel, including synthetic fuels, but we have not found any that are even close rivals—yet. This situation may change as the supply of petroleum becomes shorter and the cost of gasoline higher.

The spark ignition and diesel engines evolved as the best for the car and truck against stiff competition. Although the internal combustion engine was a poor third to steam and electric cars in 1900, the inherent technical and economic advantages of the gasoline engine moved it into first place within a few years.

Some of the disadvantages that caused steam and electric power plants to lose out in early competition remain as obstacles to their broad automotive application today, but in recent years new considerations have emerged. It is now recognized that energy consumption and emission control must be considered along with performance, cost, and durability. This calls for reconsideration of the old and an open mind to the new; all forms of energy and all concepts of power plants must be considered.

General Motors monitors many power plants on a continuing basis, since new technology, new materials, new criteria, and new operating requirements can change the evaluation of a power plant. Since 1963 we have made careful technical reviews of more than three hundred proposals for alternate power plants. We have examined some concepts analytically on paper, simply to determine whether they violated any of the fundamental laws of physics, chemistry, or thermodynamics. And over the years, General Motors has used the more promising concepts in building one-of-a-kind working automobiles. On various occasions we found that concepts which appeared very promising on paper encountered major technical problems during construction and trials.

THE IMPORTANCE OF THERMAL EFFICIENCY

A primary consideration in any engine is thermal efficiency. At maximum power and without emission controls, a steam engine for a car would have a

Left: General Motors' experimental steam-powered Pontiac Grand Prix is the world's first steam car with complete power accessories, including air conditioning.

Right: These are among General Motors' experimental electric car models. Top to bottom: a vehicle for special-purpose urban uses; a model with dual-battery system to improve range and power; the Electrovair II, with expensive silver-zinc batteries weighing 680 pounds and permitting a range of 40 to 80 miles.

thermal efficiency of around 15-20%, and the diesel and Stirling engines would reach 35-40%. In between would be the spark ignition internal combustion engine at 27-30% and the stratified charge engine at 30-35%. A calculation of the thermal efficiency of an electric drive for a car would have to include the efficiency of the generating plant and losses incurred in transmission and conversion; on this basis the electric power plant in a car would be comparable to the spark-ignition gasoline engine.

Of course, peak thermal efficiency is not the only criterion; in vehicle applications, part-load efficiency is equally important. That is one of the reasons the internal combustion engine and the diesel have been so successfully adapted to motor vehicles, and why the gas turbine engine presents a problem for passenger car use at this point in development.

Each power plant has its own unique emission problems. In addition, there are trade-offs such as weight, manufacturing cost, and performance during the highly variable driving cycle.

GM'S EVALUATION OF VARIOUS CAR ENGINES

In the estimation of General Motors, the *steam or Rankine cycle engine* appears to be one of the least promising of proposed automotive power plants. One problem is fuel economy. Other problems include weight and size (particularly of the heat exchangers for vaporizing and condensing), complexity in the mechanism and controls, cost, water consumption, water freezing, lubrication, and NO_x emissions. Use of working fluids other than steam is often proposed, but these introduce new problems. Our evaluation of automobiles powered by steam engines is based on close observation and study since 1926 and on experience since 1968 in building and testing experimental models.

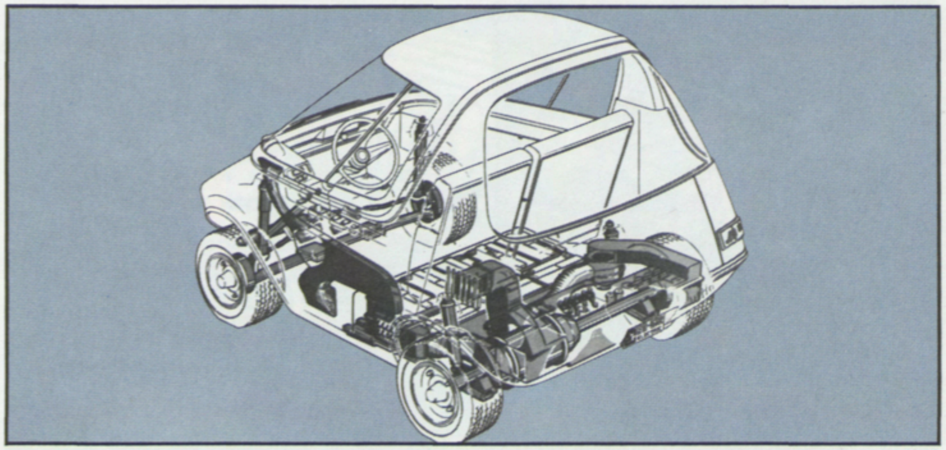
The *Stirling engine* is based on a concept patented more than a century and a half ago by a Scottish minister. At General Motors an active research program on the Stirling engine, involving the analysis, design, construction, and testing of a number of engines, ran from 1959 to 1970.

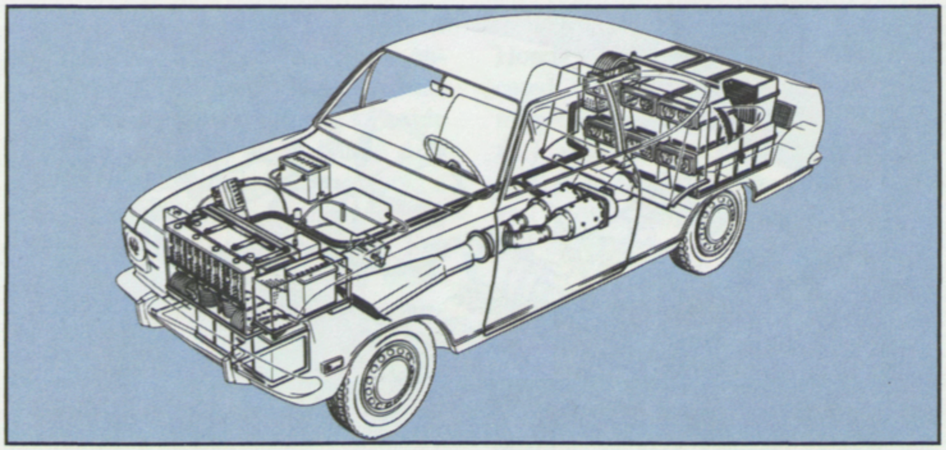
The Stirling tends to have a very high efficiency. It is quiet, its major components are durable, and its hydrocarbon and carbon monoxide emissions are extremely low. On the other hand, there are some major disadvantages. It requires a large radiator for cooling, the engine is heavy and bulky, and the hydrogen or helium working fluid is difficult to seal for life. Also, the engine is complicated and expensive, and it may be slow to respond to operating conditions which suddenly change the power demand.

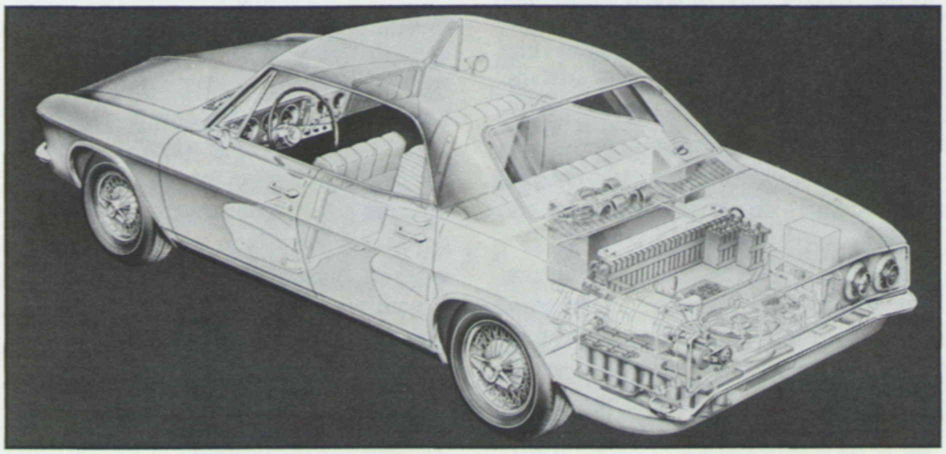
BATTERIES OR FUEL CELLS AS POWER PLANTS

Battery electric power plants seem to some to offer a total solution to the air-pollution problem, but they do not. They simply transfer the problem from the tailpipe of the automobile to the smokestack of the central electric-power station, where sulfur dioxide and particulates presently create a more severe problem.

In building a number of battery electric vehicles for experimental purposes, General Motors has come to the con-



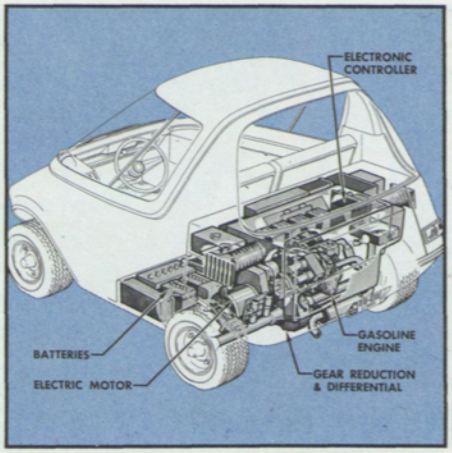




" . . . all forms of energy and all concepts of power plants must be considered."

clusion that in order to overcome the high cost of a battery electric car and the operating limitations, breakthroughs in battery technology are needed. Since about 1959, we have been carrying on a substantial research program in high-power-density and high-energy-density battery systems. We see the lithium-chloride battery as probably the best to date, but not yet the breakthrough we are looking for. With such a breakthrough, the electric car might participate in a mix of power plants to be used in transportation systems of the future.

A *fuel cell* might be the best alternative in the long run. Emissions are very low and the efficiency is very good. Range is less limited than with storage batteries, since fuel is carried aboard. There are, however, major disadvantages at the present time: extremely low power output per unit of weight and volume, high cost, and a limited range of possible fuels. General Motors has been doing fundamental research on fuel cells since 1960, and in 1966 built a fuel-cell-powered vehicle for test purposes.

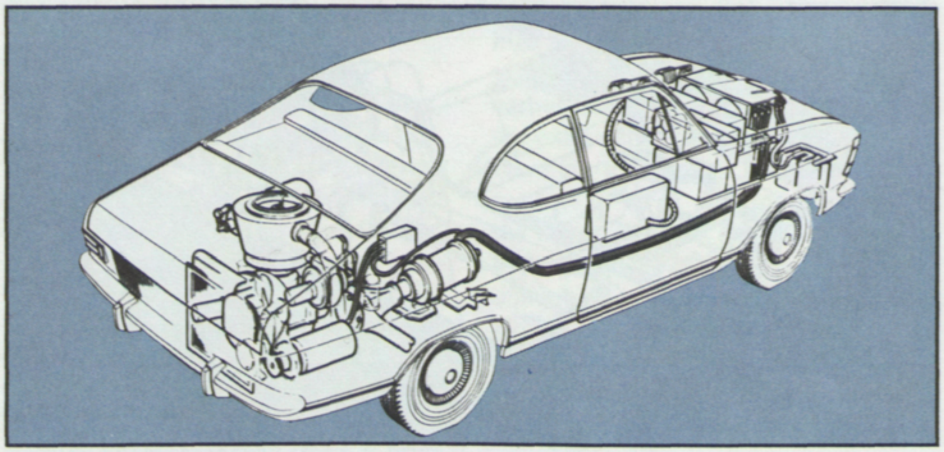


These three cars are among General Motors' experimental models.

Left: This hybrid model with a gasoline-electric power plant is designed for urban use.

Below: The Stirlec II combines a Stirling engine and an electric power source.

Right: The experimental Electrovan is powered by a hydrogen-oxygen fuel cell.

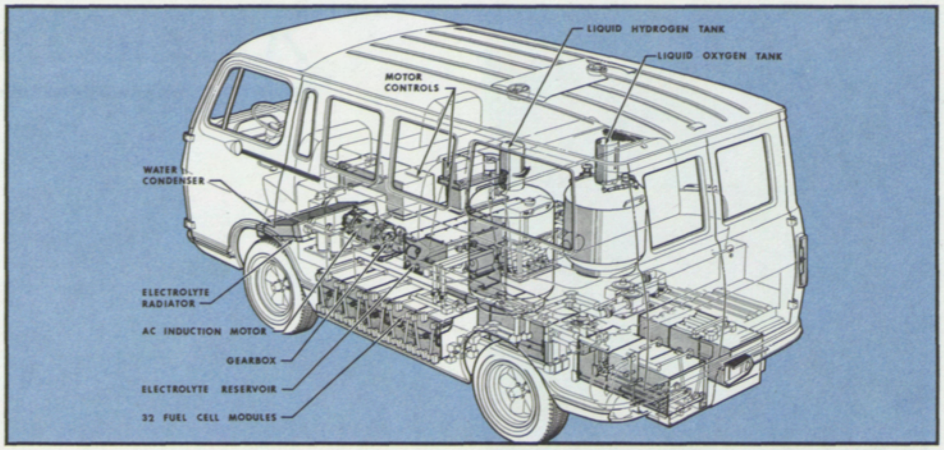


PROSPECTS FOR GAS TURBINES AND DIESELS

The *gas turbine* has been under development at General Motors for more than twenty-five years; in the 1950s experimental passenger cars as well as turbine-powered buses and trucks were built. At the present time, the gas turbine is approaching commercial feasibility and application for trucks, buses, and other heavy-duty vehicles, but it is a different story for automobiles. Present gas turbine configurations are heavier than the piston engine, and because of costly metals and machining, the engine is expensive. Moreover, in stop-and-go city traffic, fuel economy and acceleration characteristics are still unsatisfactory. General Motors does have a major gas turbine passenger car program underway, however, and we feel that considerable progress can be made in the problem areas.

The *diesel engine* is obviously feasible for automotive use. Mercedes-Benz, Peugeot, and General Motors' German subsidiary, Opel, all market diesel passenger cars in Europe. However, this type of vehicle has not been generally accepted for a number of reasons: low power-to-weight ratio, noise, smoke, odor, cold starting difficulties, and high initial cost. Diesel passenger car sales in Europe, where fuel economy was a strong incentive before it became a major concern here, have accounted for less than two percent of the market. Nevertheless, General Motors is continuing its study of the diesel engine for passenger car use.

In past years, a variety of *stratified charge engines* have been known to have good fuel economy, less restrictive



fuel requirements than those of the conventional internal combustion engine, low carbon monoxide emissions, and sometimes low nitrogen oxide emissions. On the other hand, they usually have had poor driveability, a lack of flexibility in normal driving, complicated fuel control systems, low power output, and difficulty in maintaining tuning. High hydrocarbon emissions, noticeable as smoke, have also been experienced.

EFFECT OF STRATIFIED CHARGE ON EMISSIONS

Last year Honda announced that it had a new type of engine which allowed its small car to meet the original 1975 emission requirements with minimal penalties. It was a "jet-ignition" stratified charge engine. Our evaluation is that in compact and subcompact cars, this engine may be adequate for meeting the current 1976 emission standards; whether the technology is adequate for larger cars in production volumes is less certain. Our testing indicates that this engine will not meet the current 1977 emission requirements, however, even in lightweight cars. The Honda CVCC engine is more complicated than current piston engines, it may be more expensive, and it probably will need a thermal reactor or catalyst to clean up hydrocarbons. General Motors is continuing to work on this development.

A ROTARY-ENGINE AUTOMOBILE IN 1975

Of all the alternate power plants, the *rotary engine* is closest to volume production. In fact, General Motors has announced plans to start production of a rotary-powered small Chevrolet in the 1975 model year.

The rotary engine has four basic and major advantages. The engine is as much as 50% smaller than a comparable piston engine, a feature that gives it a high power-to-bulk ratio. In addition, it is about 30% lighter than a comparable piston engine, and so has a high power-to-weight ratio. It also has about 40% fewer major components and is extremely smooth and quiet. Finally, because of its small size and weight for its power output, it gives the car designer new appearance and packaging opportunities.

There have been certain problems with the rotary engine, as there usually are in any major engine development, but progress has been made in seals, in emissions, and in fuel economy. The true costs of manufacturing the rotary engine cannot be established until it has been in production and the machine-tool industry has had the opportunity to develop processes and techniques specifically for this engine.

THE PISTON ENGINE: STILL GOING STRONG

Major technical advances are still needed to solve development problems of alternate power plants. Although one or more of these alternatives, or possibly a hybrid combination of two of them, may become feasible in the future, for the near term and well into the 1980s, the majority of cars on the road will be powered by the internal combustion piston engine. It has advantages in cost, performance, and durability, and its emission problems are in the process of being solved.

Control hardware has reduced automotive emissions substantially. Measured against the original baselines for reductions, the emissions of 1974 cars are 80% lower in hydrocarbons, 69% lower in carbon monoxide, and 38% lower in oxides of nitrogen than those of the uncontrolled cars of the early 1960s.

These reductions are being achieved at what General Motors believes is a reasonable cost-benefit relationship. For the 1975 models, we expect the internal combustion engine equipped with a catalytic converter to meet the interim federal standards of 90% less hydrocarbon and 83% less carbon monoxide emission. Based on our tests with converter-equipped cars, there will also be a substantial improvement in fuel economy—amounting to a sales-weighted average of about 13% over 1974—and better driveability.

DECISIONS ON STANDARDS AND HOW TO MEET THEM

What will be required after 1975 is not yet clear. (At the time of this writing, the Senate had voted to extend the 1975 standards through 1976, and the House had voted for a two-year extension. A House-Senate conference was to resolve the differences.) The requirements of manufacturing lead time and the increased concern over energy make it essential that Congress make an early determination of the timetable and the ultimate standards. Involved are serious questions about what air quality is necessary to protect public health; General Motors has contended all along that the very strict standards now on the books for 1976-1977 are not necessary from a health standpoint and are an unnecessary cost penalty for the consumer.

There are differences of opinion on how to control emissions of internal combustion engines and of alternate power plants. But among automotive engineers, there is general agreement that no alternate system has any definite possibility of meeting the 1976-1977 standards. Any alternative to the internal combustion engine is farther down the road.

Wallace E. Wilson is a General Motors Corporation group vice president with jurisdiction over the Automotive Components and Non-Automotive and Defense Group. He has ties with Cornell as a member of the Engineering College Council, an advisory group to the dean.

A graduate of the University of Michigan, Wilson began his General Motors career in 1936 as a draftsman at the Oldsmobile Division in Lansing, his home town. After serving in various engineering capacities with Oldsmobile, he was transferred in 1942 to General Motors' wartime Eastern Aircraft Division in Trenton, New Jersey, for assignments on a torpedo bomber program.

At the end of World War II, Wilson returned to Oldsmobile, and then in 1948 was named assistant to the resident manager of the AC Spark Plug Division plant in Milwaukee. In 1951 he was transferred to the Buick-Oldsmobile-Pontiac Assembly Division plant in Kansas City, Kansas, where he was placed in charge of the engineering connected with the manufacture of the F-84F Thunderstreak fighter-bomber. Then, after serving as general manager of the Products Division at Rochester, New York for several years, he was elected a vice president of General Motors in 1963 and placed in charge of the Manufacturing Staff. He became group executive in charge of Automotive Components in 1967 and was serving in that position when he received his present assignment in 1970.

Wilson has been active in community projects wherever he has been assigned. His activities in Rochester included service on the Industrial Management Council and the Bureau of Municipal Research, and he retains his membership on the Board of Trustees of the Rochester Institute of Technology. Long active in Boy Scout councils, he is a member of the National Executive Board, Scouts of America and president of the East Central Region, Scouts of America. He is active also in youth programs of Future Farmers of America.

REGISTER

Neil M. Brice

Howard N. McManus

Within a one-week period this winter, the College of Engineering experienced the loss of two of its faculty members.

Neil M. Brice, 39, professor of electrical engineering, was killed January 31 in an airplane crash in Pago Pago, Samoa. Howard N. McManus, 52, professor of mechanical and aerospace engineering, died February 6 following a brief illness and subsequent surgery. Brice leaves a widow and three children; McManus, a widow and five children.

At the time of his death, Brice was on sabbatic leave at the University of Sydney, participating in a Cornell-Sydney exchange program in ionospheric research. He had also lectured, consulted, and attended conferences in England, India, Japan, Hong Kong, and New Zealand, and was on his way to Hawaii when his plane crashed.

Among his recent honors was the award of a doctorate by the University of Queensland in his native Australia, where he studied for his A.B. and M.S. degrees in physics. Also, he had just been elected a Fellow of the Institute of Electrical and Electronics Engineers (IEEE). An earlier honor, in recognition of his participation in scientific expeditions to Antarctica, was the designation of a mountain there as Mt. Brice.

Brice came to Cornell in 1966 after receiving the Ph.D. in electrical engineering from Stanford University and teaching for two years at Carleton University in Ottawa, Canada.

A specialist in atmospheric science, his research was concerned with atmospheric phenomena of the earth and other planets, and included studies of the earth's radiation belts, their effect on communications, and possible means of control. During a leave in 1970-71, he served as director of the solar-terrestrial physics program of the National Science Foundation.

He was a member of the American Geophysical Union, the American Association for the Advancement of Science, and IEEE.

McManus, a member of the College faculty since 1957, had served as chairman of the Department of Mechanical Systems and Design and was responsible for much of the development of Cornell's program in this area. He had also served as chairman of the Graduate Professional Program Committee.

McManus held two degrees in mechanical engineering from the State University of Iowa and the Ph.D. from the University of Minnesota. Before coming to Cornell, he taught at Minnesota and at Northwestern University.

In addition to teaching, McManus was active in industrial and government-sponsored research. Over the years, he supervised numerous projects in thermal and mechanical engineering research, served as consultant to several firms, and spent many summers working in governmental and industrial laboratories. In 1971 he spent a sabbatic leave at the University of Nottingham in England.

He was a member of the American Society of Mechanical Engineers, the American Society for Engineering Education, and the American Association of University Professors.

The deaths of Professors Brice and McManus are a great loss to the engineering and scientific communities in which they were so active and respected, and especially to their friends and associates at Cornell.

FACULTY PUBLICATIONS

The following publications and conference papers by faculty members and graduate students of the Cornell College of Engineering were published or presented during the period May through July 1973. Earlier publications inadvertently omitted from previous listings are included here with the date in parentheses. The names of Cornell personnel are in italics.

Listings from several departments have been held for publication in the next issue, in order to permit late coverage of the deaths of two College of Engineering professors.

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Options for Engines

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Like many engineering problems, the question of what to do about automobiles has no single, obvious solution, as the collection of articles in this issue illustrates. The dual problems of air pollution and gas shortages present conflicting demands and involve matters well beyond the immediate ones of engineering design. Indeed, these complex problems have ramifications into practically all aspects of our national life.

The mandate to engineers to come up with a nonpolluting engine, for example, is complicated by a wide range of contingencies. Radical changes in engine parts would involve radical changes in existing manufacturing plants and expertise—a significant factor in an economy heavily dependent on the automobile industry. The impending shortage of petroleum—which has been obvious for a long time—is an immensely important factor, but again the economics and politics of conversion to alternate power sources extends the simple consideration of how one might run a car on something other than gasoline well beyond the drawing board, the shop, and the prototype model. The question of the place the automobile can or should have in an evolving transportation system carries implications for the whole economic, political, and social structure of the nation. American life has come to be organized around the automobile, and for the average citizen, living and working where he does and often without a viable alternative for transportation, a car is a necessity. Other broad questions are coming to the forefront of public awareness: for example, where should the responsibility lie for providing badly needed direction to technological development?

In the context of such pressures, how can and do engineers respond? Often they are limited by the circumstances of their employment, but what about those in universities, who have more opportunity to take independent views? What leadership can they offer? The articles in this *Quarterly* issue provide an example. Our Cornell professors are working to solve immediate problems with skill and imagination. They are developing alternative solutions, not necessarily tailored to fit present industrial priorities, although these are taken into consideration. They are looking ahead and trying to prepare for anticipated problems. They are attempting to take into account the complex implications of technological development and change.

The "engineering approach" is necessarily many-sided. Responses to the problem of what to do about automobiles, for example, may range from improvements in a spark plug to a blueprint for a whole new energy economy. Engineering leadership today requires both immediate pragmatism and the long view.

THE EDITOR