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FUTURE AUTOMOTIVE POWERPLANTS AND AIR POLLUTION

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INTRODUCTION

An urgent need to greatly reduce undesirable exhaust emissions from vehicle powerplants now occupies our attention. The problems relating to air pollution are complex because there are many types of pollutants and several sources of pollutants from the various powerplants. The problem is further complicated by the fact that different areas of the country have different types and principal sources of air pollution.

Present automotive engines, gasoline and diesel, have a history of intensive development which extends back into the nineteenth century. There are now ninety-four million vehicles registered in the United States. Over ninety percent of all installed horsepower in the Unites States is in motor cars and trucks. The present almost exclusive use of piston engines for highway travel is based on important technical advantages, which will be pointed out very briefly.

To predict the future outlook for the several types of powerplants for vehicle propulsion is an imposing task, but it can at least be approached with greater confidence because of two recent papers. The first is the paper of Welsh,(1) representing the opinions of the Society of Automotive Engineers Powerplant Committee. The second is the report of Brubacher,(2) which is in part an industry concensus. My opinions in general are similar to those expressed in these reports.

The future outlook involves an examination of energy sources, power requirements and powerplant systems for converting a source of energy into mechanical power. Many systems are being suggested, including battery and fuel cell powered electric vehicles. Even the merits of the steam powered automobile are sometimes extolled, which, along with the battery-electric car, competed on a nearly equal basis with the gasoline engine car early in the twentieth century. The first portion of the paper will consider the more conventional powerplants and the possibilities of reducing their emissions. The last portion will consider more futuristic powerplants for vehicle use.

Size is a very important consideration in choosing a powerplant. Obviously, motorcycles and railway locomotives call for different powerplant solutions. My comments relate particularly to personal vehicle powerplants, and even these vary greatly in size.

ABSTRACT, OR SUMMARY AND CONCLUSIONS

1. The present types of piston engines will continue for many years to be the main source of power for highway transportation.

2. Major reductions of the undesirable exhaust emissions of present powerplant systems have been made during the last few years and will continue to be accomplished, under the the impetus of air pollution requirements and regulations.

3. There is a place for battery-powered vehicles in very small size and short-range applications, especially for areas with serious air pollution. It will, however, require batteries with much greater energy and power density, and greatly reduced cost before they will achieve significant use. The increased use of central station atomic energy in the future will give added advantages to battery-electric vehicles.

4. Our hope for reducing air pollution from vehicles during at least the next twenty years must result mainly from making improvements in the present types of cenventional engines.

5. The fuel cell may be more important than batteries for vehicle propulsion in the more distant future because 1, it is in an earlier stage of development and 2, it may be able to utilize a hydrocarbon fuel.

6. Any successful program for reduction of exhaust emissions from vehicles must include an effective engine inspection and maintenance program.

ENERGY SOURCES

The mobile or portable powerplant can use any energy source that can be suitably transmitted to the vehicle or stored on board. However, mobility places severe limitations on practical energy sources and powerplants.

The power of the wind served as a very direct and principal source of power for water transportation for centuries. Although sailing is an important sport, it is not competitive for transportation. Similarly, the conversion of solar energy for propulsion requires an area of on-board reflector surface which is wholly impractical, to say nothing about the problems of operation after sundown.

The fossil fuels, including coal, oil, and gas represent a vast supply of energy on earth, and are presently our principal energy source. Oil is presently of greatest importance to land transportation, because hydrocarbon fuels, such as gasoline, are highly concentrated sources of energy, and easily transported and stored. Our present rate of consumption of petroleum now exceeds 10.6 million barrels per day, and daily consumption now exceeds the rate of discovery.(3) Although the reserves of oil are large, there can be no doubt that they will eventually be exhausted. It is to be expected that its cost will increase as more difficult fields are tapped. There are also large deposits of shale rock in the Rocky Mountain Range, and also of tar sands in the U.S. and Canada. These sources can be used to produce motor fuels, but at increased cost. These are said to provide a reserve supply of hydrocarbon fuels for several centuries. The supply of gaseous fuel is believed to be much smaller and will probably be depleted much sooner. In view of the unknown supply and the ever mounting rate of consumption more attention should be directed to conserving the reserves of oil and gas.

The utilization of nuclear energy in the last generation is one of the great scientific achievements in history, and has made available a vast new source of energy for use. This source is best adapted to stationary use, since many difficult problems of shielding and safety attend its application. However, the nuclear submarine is an outstanding example of the application of nuclear power to transportation, and here it provides advantages not possible with any other energy source.

ENERGY CONVERSION SYSTEMS

There are almost countless ways to classify the many kinds of powerplants. For comparisons of very diverse types, which will include conventional engines and fuel cells, it is helpful to divide them all into two classes,[4] as follows:

1. Those whose method of operation requires that the energy of the fuel, or other energy source, be transferred as heat to a working fluid, which in turn goes through a cycle. This working fluid is commonly steam. For this type the machine both in theory and practice executes a cycle. Examples of this type are steam engines, nuclear powerplants, and hot air engines such as the Stirling engine.

2. Those whose method of operation does not require that the energy of the fuel or other source be transferred as heat to a working fluid. This type is concerned both in practice and in theory with processes, and not a cycle. Examples of this type are spark-ignited reciprocating engines, diesel engines, gas turbine engines, and fuel cells.

The thermal efficiency of the energy converters of type one are subject to the Carnot cycle limitation. This involves a principle of thermodynamics which in general states that the efficiency of these engines will be increased if the maximum temperature of the cycle is increased.

For the energy converters of item 2, maximum temperature is not essential to gain maximum efficiency. It is true that for many processes an increase in temperature increases the possibility of doing more work, but this correlation is fortuitous for this type and holds only over limited ranges and for only some of the converters. The efficiency of fuel cells is commonly reduced if their temperature is increased.

It is also a principle of thermodynamics that all practical energy conversion systems are limited in their efficiency, and cannot convert all of the energy of a fuel into power. The laws of thermodynamics establish the maximum efficiency possible, and this will be reduced by practical considerations. For example, it is estimated that the maximum overall efficiency to be expected from future practical reciprocating engines will not exceed 45%. The thermal efficiency of fuel cells is very much related to load, being most efficient at the lightest load. Present fuel cells are usually more efficient than conventional engines. Since they are in an early stage of development it is expected that their efficiency advantage will increase in the future.

PERSONAL TRANSPORTATION IN THE FUTURE

It is to be expected that with the completion of the Interstate Highway System vehicle speeds for intercity travel will increase. Since the power to propel a vehicle increases as the cube of the speed, this will increase the power required for future intercity vehicles.

Figure 1 shows the power required to propel automobiles of common weights and corresponding sizes at various speeds. As an example, at 70 miles per hour the power required to propel a 3000 pound

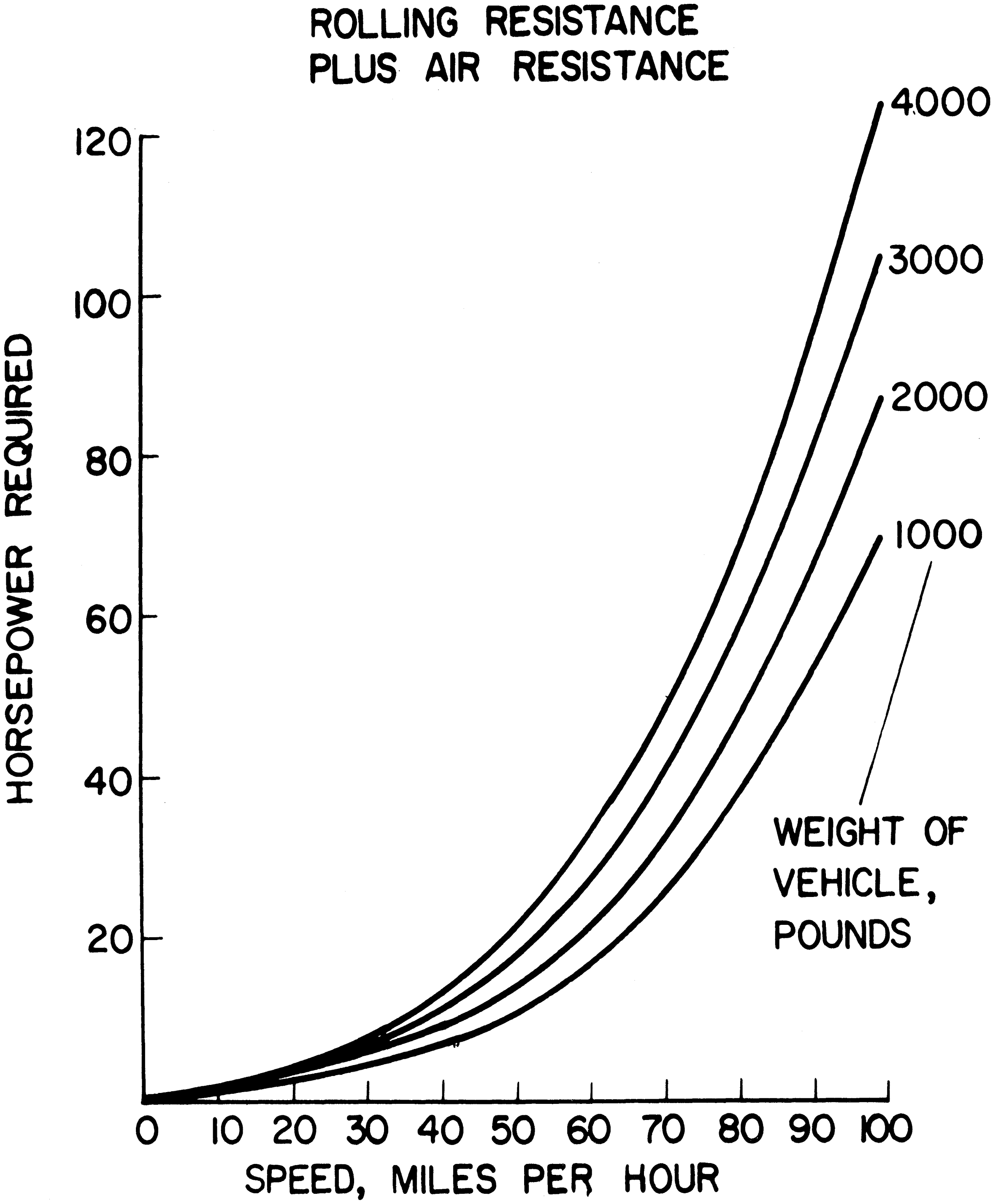

Figure 1. Power Required to Propel Vehicles.

vehicle is 40 horsepower. If the speed of this vehicle is increased to 80 miles/hour the power required will be:

$$40 \times \left(\frac{80}{70}\right)^3 = 59.\ \text{H.P.}$$

The future will bring further diversification of vehicle types for special uses, and an even greater range of vehicle sizes and installed horsepower. As congestion in the cities grows there will be increased need for and use of smaller vehicles for neighborhood errands and shopping. However, a vehicle to travel throughout the Los Angeles Valley will probably not become much smaller than the present range of vehicles.

REQUIREMENTS OF AN AUTOMOTIVE POWERPLANT

An automotive powerplant must meet many requirements to be acceptable. Among these are:

1. Absence of undesirable exhaust emissions. This relatively new criterion is listed first to emphasize it present and future importance. The emissions include: carbon monoxide, hydrocarbons, oxides of nitrogen, smoke, odor, atomic radiation, and others. This requirement will have an important effect on engine selection and design in the future.

2. Size and weight. These criteria are obviously important, and include the common criterion of maximum horsepower/unit of weight. Vehicle performance, including accelerating ability, will depend greatly on the use of an engine with high horsepower per unit of weight.

3. The powerplant must use a concentrated, low cost and easily handled energy source, or fuel.

4. Minimum fuel consumption. This is important from the cost standpoint, and affects the driving range of the vehicle between fueling stops. It is also important in the interest of conserving natural resources.

5. Flexibility. This includes the ability to operate at all necessary combinations of load and speed with simple power control means, with characteristics suitable for

vehicle propulsion (such as high engine torque at low speed).

6. Low initial cost, simplicity

7. Long life and Reliability. Reliability, low maintenance cost, and long life are increased with simplicity.

8. Ability to move quickly from a cold start.

9. Ability to provide passenger comfort in hot and cold weather. Summer cooling and winter heating can consume nearly as much energy as required for average vehicle propulsion in city driving.

10. Quietness. The ability to operate quietly will grow much more important in the future, as population density increases. The public is presently being subjected to an unreasonably high level of noise from many types of vehicles.

EMISSIONS FROM GASOLINE ENGINES

A brief discussion of the emissions from gasoline engines will point to some of the factors which influence the emissions and give insight into the general problem of emissions from engines.

Whenever hydrocarbon fuels are burned, at least trace amounts of unburned fuel and carbon monoxide will result. The quantity of these constituents are principally a function of the amount of fuel per unit amount of air, referred to as the air/fuel mixture ratio. The relation between the composition of the exhaust and the air/fuel ratio is shown on Figure 2. There is a theoretically correct mixture ratio of air and fuel which contains precisely the necessary amount of air to burn the fuel, with no air left over. This ratio is indicated on Figure 2 and is about 15 lbs. of air per lb. of fuel. With excess air (lean mixtures) there will be some oxygen in the exhaust, and a minimum amount of carbon monoxide and unburned fuel. When there is excess fuel (a rich mixture) there is insufficient oxygen and the quantities of unburned

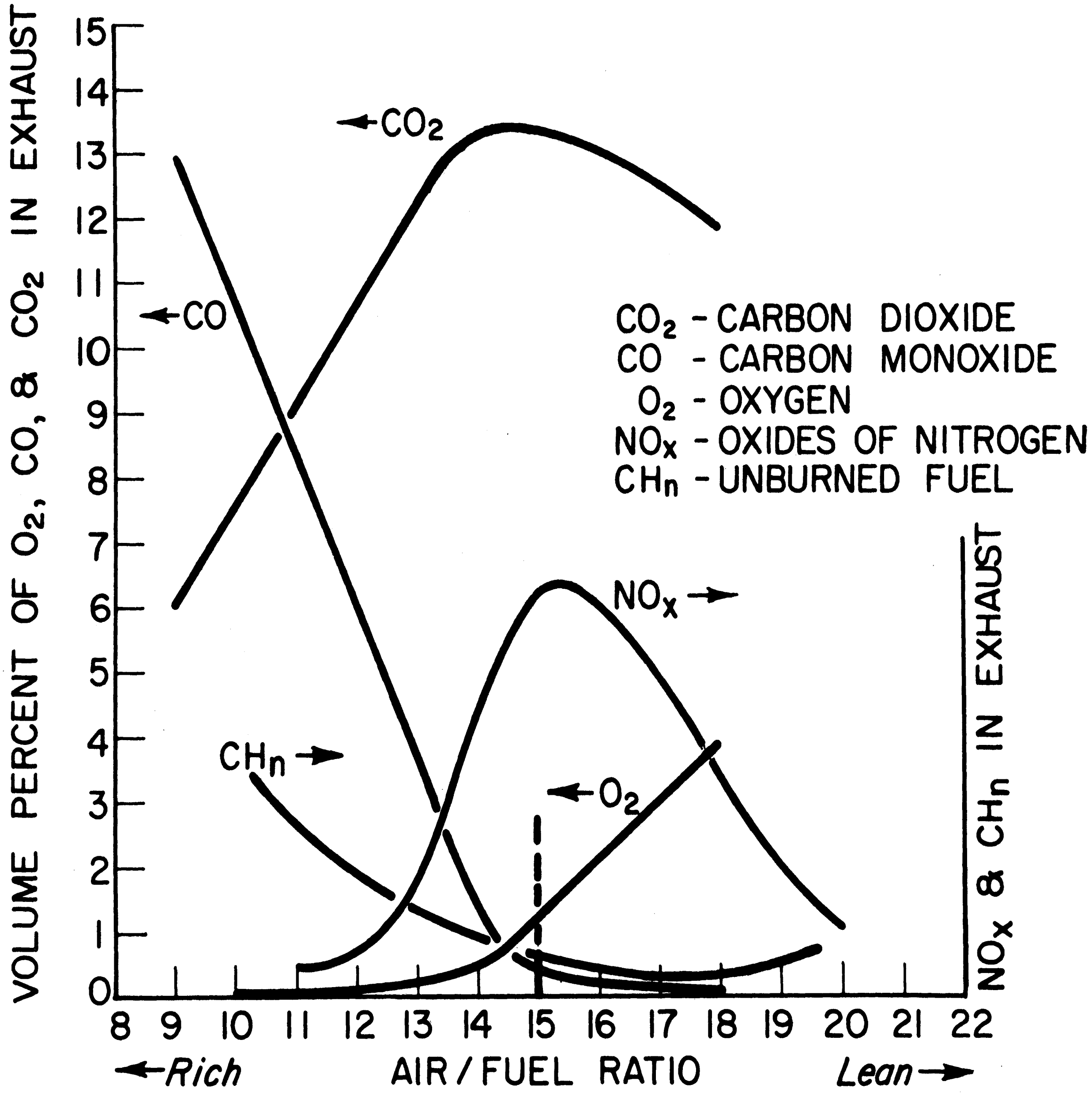

Figure 2. Composition of Automobile Engine Exhaust.

hydrocarbons (fuel) and carbon monoxide are greatly increased, as can also be noted on Figure 2. To reduce these constituents it is important to run the engine on a lean mixture (excess air).

Unfortunately, the lean mixture of about 16 pounds of air per pound of fuel, which gives minimum carbon monoxide and unburned fuel, together with best fuel economy, also causes the oxides of nitrogen to be near their maximum value. Oxides of nitrogen are formed whenever air is heated to high temperatures, as in the case of combustion. The problem of their control is very difficult, and a practical solution constitutes an important engineering challenge.

Unfortunately, gasoline engines have needed rich mixtures under many operating conditions to avoid hesitation and/or stalling, and to obtain the desired maximum power and engine performance. Typical mixture ratios used by an automobile engine at idle, part throttle (cruise), and at full throttle conditions are shown on Figure 3. By referring to Figure 2 for the given air/fuel ratios, the approximate exhaust composition can be determined for various engine conditions. For example, it can be noted that the rich mixture ratio of about 12/1 at idle produces 6% of carbon monoxide, and at this condition will be particularly lethal in a closed garage.

With the urgent need to reduce exhaust emissions, there is now much development activity in the automotive industry to take all possible steps to operate engines with the leanest practical air/fuel ratio at all operating conditions. The industry has never before had such an urgent incentive to improve its product, and I am confident that under this new stimulus much improvement will be made, and the improved products will also provide improved fuel economy.

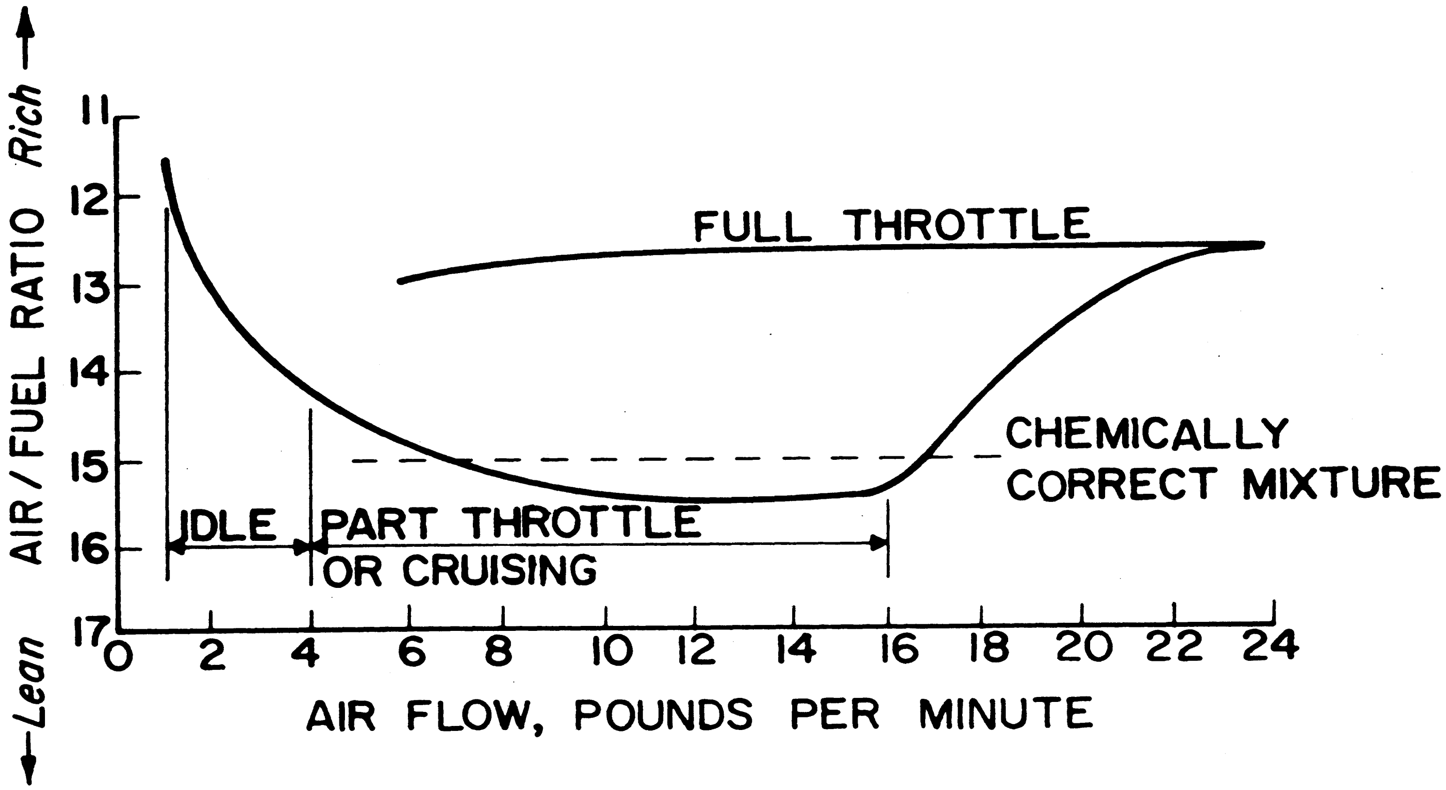

Figure 3. Typical Air/Fuel Mixture Ratios Used by Automotive Engines.

I am convinced that the present types of automotive piston engines will be our main automobile power source for many years. Therefore, possible means for reducing exhaust emissions within the engine is of major importance to this conference, and the possible means for accomplishing this will be discussed. This is the more important, since it is likely to be the most direct and economical approach to the problem.

REDUCTION OF EMISSIONS BY IMPROVED ENGINE DESIGN

The greatest potential for reduction in emissions in gasoline engines lies in improved fuel and air induction systems and in improved combustion chambers; this discussion will therefore be restricted to this portion of the engine.

The function of the carburetor is to provide the proper air to fuel mixture ratio for each engine condition, mix the air and fuel as intimately as possible, and provide means for regulating the engine power. The function of the engine intake manifold is to conduct the wet mixture of air and fuel to all the cylinders, in such a manner that all cylinders receive the same air/fuel ratio. This task is made very difficult because some of the fuel in the intake manifold will be vapor, some will exist as droplets in the air, and some will exist as a slow moving liquid film on the intake manifold wall. Figure 4 shows the general arrangement of these induction system components.

Brief comments follow concerning potential improvements:

Carburetors - There is need for carburetors that more nearly supply the optimum mixture ratio under all engine operating conditions, and under all atmospheric conditions. A few examples of needed improvements in carburetors will be given.

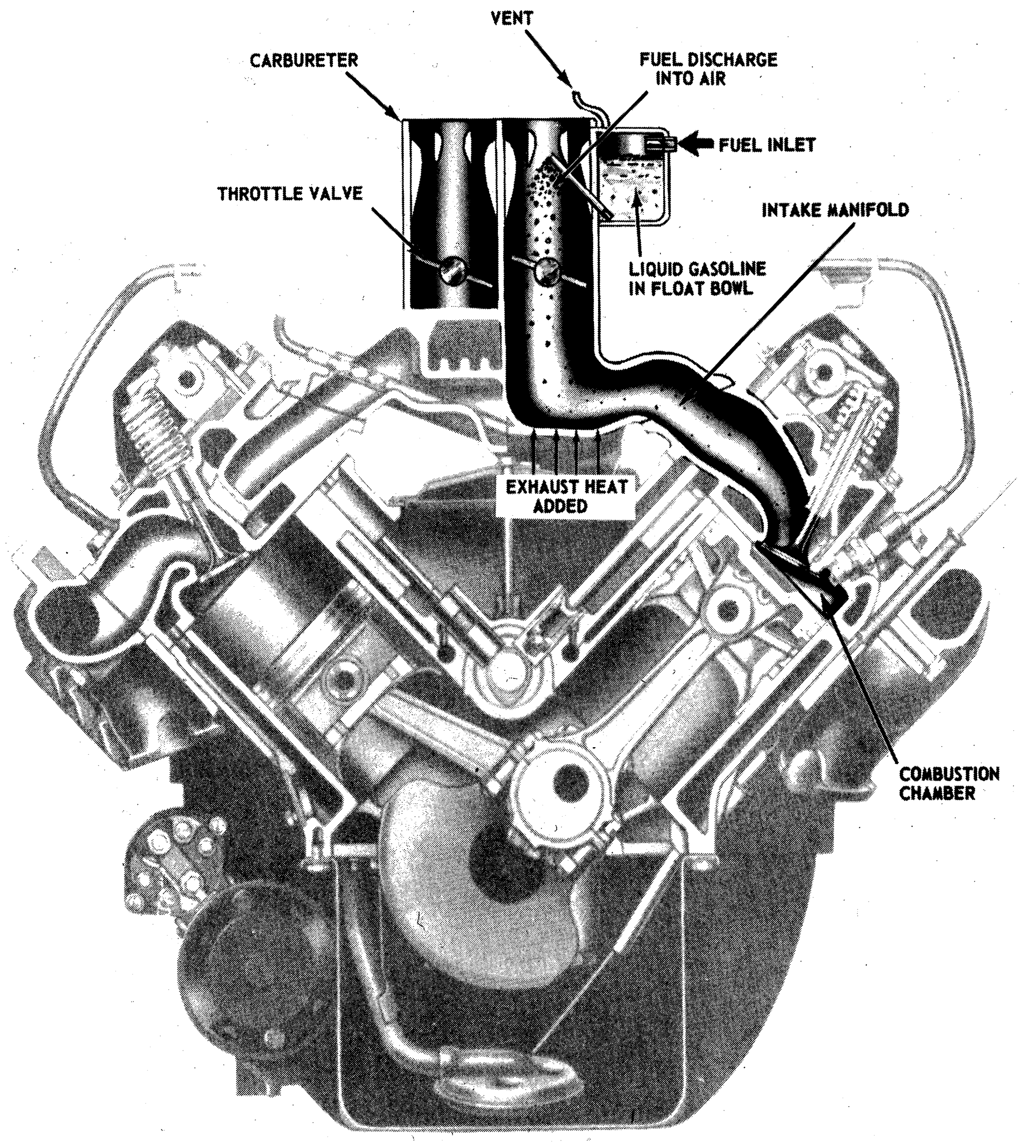

Figure 4. Induction System of a Typical V-8 Automobile Engine.

Present automotive carburetors run at least 6% richer in Denver than they do in Detroit, due to the average difference in atmospheric pressure.(5) The effect of this change of fuel/air ratio on exhaust emissions will vary according to the basic carburetor mixture ratio, but it can readily double the carbon monoxide in the exhaust.(6) Although means for accomplishing this altitude or pressure compensation are known and have been practised for many years on piston aircraft engines, the engineering challenge is to accomplish it with reasonable increase in complexity and cost, and with reliability.

Another defect of present carburetors is unsteady flow of fuel into the airstream, and imperfect mixing. This can result in a lack of constant mixture ratio to a given cylinder on successive engine cycles. This problem is especially prevalent at low cruising speeds. This condition is improved if the carburetor primary venturii are made small to provide high suction and good atomization. The development of improved multi-venturii carburetors to provide high suction and steady fuel flow under part-load conditions, and which meet all other metering requirements, are needed.

It was mentioned earlier and Figure 3 reveals that at full throttle carburetors are designed to provide about 20% more fuel than there is available air to burn. This added fuel at full throttle is provided by means of an enrichment valve in the carburetor, and permits the engine to deliver about 10% more horsepower than the best economy mixture. The use of this rich mixture (air/fuel ratio = 12/1) causes much additional carbon monoxide and unburned hydrocarbons, but also reduces the oxides of nitrogen. As efforts to control air pollution are intensified engines must be designed to operate satisfactorily without the enrichment at full throttle, and the public should develop driving habits which do not necessitate this high emission condition.

Still another source of unburned hydrocarbons is that due to evaporation from the carburetor float bowl and the fuel tank. Again, solutions are known but the real engineering problem is to accomplish this without undue cost, and with the necessary reliability.

With the new emphasis on reduction of exhaust emissions, these and other long-standing defects can and must be overcome.

Intake Manifolds - Throughout more than a half century of multicylinder automobile engine history the intake manifold has been designed largely on a trial-and-error basis, and has not yielded to analytical methods. The trouble arises from the wet mixture of air and fuel which must be distributed to each cylinder.

If some cylinders receive less fuel and therefore a leaner mixture than others, the overall mixture delivered by the carburetor must by enriched so that the leanest cylinder will not misfire. The potential for increasing the ability of the engine to run on leaner mixtures is quite large. In the work of Ref. 7, the high production six-cylinder engine tested with the standard carburetor showed variations of five air/fuel ratios. These variations were almost completely eliminated by a vaporizing system, and permitted the standard engine to run as much as four air/fuel ratios leaner. This ability to run with leaner mixtures should make possible carburetor settings with mixture ratios of 16/1 to 18/1 without engine misfiring and where most emissions are at a minimum.

Heating the inlet air, the use of smaller intake manifold pipes, and other factors reduce maximum power and performance.

Unfortunately, the criterion of maximum horsepower has been unduly emphasized in the past and other characteristics, including fuel economy and exhaust emissions, have been compromised. With the new emphasis on exhaust emission reduction much more attention is now being given to part-throttle conditions and economy, and which will also result in reduced emissions. I believe it will also be necessary for the public to accept some performance reduction in the interest of reduced exhaust emissions, and the public must be educated to accept this.

One approach to this intake manifold problem is the use of two intake manifold pipes from a multi-barrel carburetor to each cylinder intake port.[8] This permits the use of a small pipe with much heating of the inlet mixture for low power conditions, and the use of a large intake manifold pipe to each cylinder, with little heating, for the high power conditions. This system is also well adapted to the use of small primary venturii with high velocities for accurate metering and good fuel atomization for low power operation, and large secondary venturii air passages and unheated manifold pipes for maximum power.

Fuel Injection - This term applied to gasoline engines refers to one of several systems used to meter and distribute the fuel to the individual cylinders. In most automotive applications the fuel is supplied to the air in the intake port just ahead of the engine valve. The chief merit of a gasoline injection system is its elimination of the many difficulties resulting from the presence of gasoline in liquid form in the intake manifold of the carburetor engine, as discussed earlier.

Gasoline injection systems bring many metering difficulties and prove to be very expensive in comparison with a carburetor. In spite of much effort no gasoline injection system has been able to invade the high production automobile market. Looking ahead, gasoline injection is a sound approach to precise metering and potential exhaust emission reduction, and is worthy of research effort.

These are only a few examples of potential improvements in induction systems that can in the future accomplish reductions in the exhaust emissions.

In 1962, Ref. 10, I stated, "Mixture enrichment has been the necessary and all too easy way out of the defects of the complete induction system of the carburetted engine. Enrichment simply and effectively covers up many of the problems resulting from metering deficiencies, incomplete fuel vaporization, poor distribution, and transient conditions".

Unfortunately, the gasoline engine designer has until now never had the incentive to make such a detailed study of the fluid flow phenomena in the induction system and the flow patterns in the combustion chamber as his counterpart for the diesel engine has found necessary. The emissions problem has changed all this and, under the new incentives, I am sure much will be accomplished.

Combustion Chambers - The combustion chambers constitute spaces above the pistons where the fuel/air mixture is burned. The metal chamber walls are relatively cool in comparison with the burning charge. Therefore, when the flame approaches the wall, the flame is extinguished by cooling, leaving a paper-thin layer of unburned fuel next to the wall. This phenomenon is referred to as wall quenching. For an engine in good condition, wall quenching is the cause of an important amount of the unburned fuel in the exhaust under the crusing condition. Research work is under way to learn more about the details of the quenching phenomenon and to evaluate the factors which influence it. To minimize wall quenching the chamber should be compact, with as little wall surface as possible. Fewer large cylinders are better than a greater number of small cylinders from the standpoint of wall quenching because larger combustion chambers have less surface per unit of volume.

Cylinders and pistons must also be carefully designed to minimize the amount of charge in confined spaces, where the charge will be quenched and not burned. An example of this is the thin space above the top piston ring and between the piston and cylinder wall. This calls for very careful design and development. In the past the criteria of maximum engine output and minimum fuel octane requirements were most important. Today chambers are being carefully evaluated with the added criterion of minimum emissions and marked improvements are being made.

Combustion chamber deposits are also an important factor which influence the amount of fuel left unburned at the chamber walls. It is believed that this is mainly due to the fuel being forced into the porous deposits during the compression stroke, thus evading combustion, and then being ejected during the expansion stroke. The use of fuel and oil with additives which minimize the formation of deposits have therefore taken on new importance.

Tetraethyllead has been used in motor fuels for about 40 years as an economical means for improving the anti-knock quality or octane number of gasoline. This in turn has permitted the use of higher engine conpression ratios and greater fuel economy. In 1959, the maximum amount permitted was increased from 3 to 4 cubic centimeters per gallon.

In 1958 four hundred and fifty-five million pounds of tetraethyllead were used in motor gasolines.

Recently, its use as an octane improver has been questioned because of its possible toxic effects in the atmosphere. Much additional observation and research is necessary concerning the effects of lead in the atmosphere upon human life, as well as further studies of the effect of leaded fuels upon deposits and exhaust emissions. The gradual elimination of lead from motor gasoline would necessitate major changes in refining techniques and various estimates have been given concerning the increase in cost of gasoline, if the present octane numbers were maintained. These estimates vary from one to five cents per gallon.

Many other factors, including ignition timing and valve timing, have an important influence on exhaust emission and are being carefully studied. It is to be expected that with further study of all these factors, reductions in emissions will result. However, it is too early to predict what minimum values of emissions will be attained by means of design improvements within the engine.

REDUCTION OF EMISSIONS, EXHAUST SYSTEMS DEVICES

When all practical future steps have been taken to reduce the emissions from automotive engines, the next step may be the installation of a device on the exhaust system to further reduce these constituents. This might be an improved version of those already in use in California. Two types of devices appear to have merits, the direct flame afterburner(11,12) and the catalytic converter.(13) Both have as their objective the oxidation of CO and unburned fuel.

Unfortunately, these devices, like the engine improvements mentioned earlier, do not reduce the oxides of nitrogen. Removal of the oxides of nitrogen is a quite different task from that of oxidizing carbon monoxide and unburned fuel. Perhaps ultimately a device will be developed for use on the exhaust system which will be able to remove not only the small amount of remaining carbon monoxide and unburned fuel, but the oxides of nitrogen as well.

STRATIFIED CHARGE, SPARK-IGNITED ENGINE

There has been much discussion in the technical literature over many years concerning the possibilities of the stratified charge engine as a means for reducing the exhaust emissions of automotive engines.[14] The principal hopes for this system also include improved fuel economy at part load, due in part to the elimination of intake throttling, and to reduction of the maximum cycle temperature. Of particular interest here is the claim that the exhaust emissions are low because it burns with more excess air.

The concept involves the use of a near chemically correct mixture at the spark plug for easy ignition, and a very lean mixture in the portion of the combustion chamber most remote from the spark plug. Much development has been done to obtain the progressively leaner mixture across the chamber, including two-compartment chambers, and controlled air motion with fuel injection into the combustion chamber.

In general, any fuel and air mixture requires some minimum amount of fuel to support a flame front, or the flame will be extinguished. The difficulty with all of the stratified engine concepts lies in the fact that the flame front must progress from the spark plug location into a very lean mixture. If the most remote and lean parts of the charge, or isolated pockets of charge, do not burn, the unburned fuel in the exhaust can be much greater than for conventional engines using a homogeneous charge.

The first stratified and spark-ignited engine was demonstrated by Ricardo, who stated in 1922,[15] "The worst feature about it (the stratified charge engine) is that, if not just right, it may be very wrong; a very small change in form or dimension may upset the whole system...." All engineers who have tried to develop a stratified charge and spark-ignited engine can attest to the truth of Ricardo's statements made forty-five years ago. No production use has yet been made of the stratified and spark-ignited concept.

The engine has severe requirements for spark plugs and for the fuel injection equipment. Few data have been revealed to indicate that the exhaust emissions of the engine are superior to conventional engines. This engine type is not likely to achieve high production use for automobiles for at least a decade, and it may never do so.

THE DIESEL

The diesel, or compression-ignition, engine is now the main powerplant throughout the world for heavy truck and industrial use. Its predominance in this field is based on excellent fuel economy, reliability, and long life. Its present predominance in heavy trucks was also aided in the past by a tax differential between diesel fuel and gasoline.

The diesel however has bad manners, - it is noisy, it smokes, and it stinks. These problems are all related to its means of ignition and burning of the fuel. Following the beginning of injection of the fuel into the highly compressed hot air, a short time delay of a few thousandths of a second elapses before burning begins. During this time fuel continues to be injected into the air charge. At the end of the delay period, there is extremely rapid and uncontrolled combustion of the accumulated fuel, and a corresponding very rapid rate of pressure rise, which causes the sharp metallic combustion noise so characteristic of the diesel. For small engines which operate at higher crankshaft speeds the effects of this delay are more pronounced, since the crankshaft turns through more degrees during the ignition delay period, and more fuel is accummulated in the cylinder. Much progress has been made to overcome this problem of combustion noise in the diesel, involving different concepts of injection and means for fuel vaporization, but complete solution is not yet in sight.

Supercharging of Diesel Engines - The use of engine inlet air pressure greater than atmospheric is now standard practice in large stationary and marine engine diesel practice, and is common for trucks. It is clearly indicated that supercharging as a means to increase power outputs will become much more prevalent.

Although unsupercharged gasoline engines are capable of higher specific outputs than corresponding diesel engines, in the trend to higher outputs the diesel has a clear advantage over spark-ignited engines, because the problems of ignition and combustion control become less difficult at higher output. The gasoline engine, on the other hand, requires more expensive fuel of increased octane for increased output. There is every indication that the diesel will continue to be improved and will remain the main source of power for industrial and truck use for many years.

The exhaust from diesel engines is low in carbon monoxide because these engines use much excess air, especially at idle and light load. Until now it has been the opinion that the diesel is not a large contributor to photochemical smog. There is, however, growing evidence that the unburned hydrocarbons emitted by the diesel are more active in the formation of smog than those from the gasoline engine. Much more research is necessary on the problem of the relative reactivity of the different hydrocarbons, and there is great need for better instrumentation to permit measurement of the various molecular forms in the exhaust. A comparison of these emissions from different types of engines burning different fuels is now almost impossible.

There is presently much activity concerning the use of additives for diesel fuel to control smoke. These additives consist mainly of a metallic constituent, usually barium. The Public Health Service is concerned about the toxicity of the several forms of barium from the engine exhaust. The smoke reduction accomplished by these additives is quite dramatic, and is believed to be due to catalytic influence on the combustion of carbon. Such additives are presently in use in Europe and are being promoted for use in the U.S.

However, present technology is quite adequate to greatly reduce smoke without waiting for fuel additives or other new technology. Diesel smoke usually results from:

1. Use of a fuel with too high specific gravity, because these are less expensive and have higher energy content per gallon.

2. Injecting too much fuel into the engine cylinders in an effort to obtain more power.

3. Dirty fuel injectors or other poor maintenance.

It is presently economical to operate diesels with a smoking exhaust and this will continue until laws make it uneconomic. I believe only California is enforcing a smoke limit on diesel operators.

Regulation of this highway nuisance throughout the United States is long overdue. Improved instrumentation for measuring the smoke density of vehicle exhaust would greatly aid regulation.

GAS TURBINE ENGINES

The gas turbine engine is old in principle and, following World War II, became the dominant source of power for aircraft. Land-vehicle use involves much smaller engines, more operation at part load, and the need for a high gear reduction to the wheels. In this application it cannot yet compete in the market place with piston engines.

The development of turbine powered vehicles has been diligently pursued by the U.S. automobile industry for many years.[16] For automotive use, further reduction in fuel consumption must be accomplished, especially at part load. Marketing a gas turbine passenger automobile is difficult because a large commitment must be made to establish high production, which is essential to gain a near competitive price, and it is unknown how many potential customers are willing to pay a premium price for a turbine powered automobile.

In contrast with piston engines, the turbine suffers because metals must be continuously subjected to the maximum temperature of the cycle. This makes necessary the use of much excess air to limit the hot gas temperature. It is to be expected that important developments will occur to permit increased maximum cycle temperature, either through improved metallurgy or turbine blade cooling arrangements. Another deterrent to the use of gas turbines for automotive use is the need for and the very high cost of regenerators or heat exchanger equipment. If means are found to raise the maximum temperature of the cycle another few hundred degrees, and also reduce the engine cost, the turbine engine could become competitive for automotive use.

The gas turbine uses much excess air, and the exhaust emissions are low. Although direct comparisons are difficult to make, the tests of Turunen(17) indicate that the emission of unburned hydrocarbons and carbon monoxide from a turbine engine powered vehicle are about one-tenth that of a piston engine vehicle having a low California test, on the basis of emissions per pound of fuel burned. The comparison of oxides of nitrogen is more difficult, but it appears that the emission rates of oxides of nitrogen (pounds/hour) are equal to or slightly higher for the gas turbine engine.

It is likely that as a result of continuing development, important applications of the gas turbine engine will come first in the truck and industrial engine applications. The need for increased horsepower gives added advantage to the turbine over piston engines.

THE WANKEL OR ROTARY ENGINE

This much publicized engine is a positive displacement engine using the same cycle of events as conventional piston engines. Instead of the piston and cylinder used to provide a chamber of varying volume, the Wankel engine employs a triangular-shaped rotor which orbits within a housing. The three sides of the triangular rotor and the housing form three chambers of varying volume, which correspond to the combustion chambers of a conventional engine. The chambers of this engine are of necessity elongated, and have a large surface/volume ratio. The engine also has difficult sealing problems. The chief merit of the engine for vehicle use lies in the fact that for a given power it can probably be smaller, and offers new opportunities for installation in a vehicle. It may also prove advantageous in some applications where two-stroke cycle spark-ignited engines have been predominant, such as outboard marine engines.

Data concerning the exhaust emissions from this type of engine show the unburned hydrocarbons to be high. This is probably due to the large surface/volume ratio of the combustion chambers and to the fact that half of the charge leakage, or blowby, goes to the exhaust. Although the future place of this engine in the spectrum of powerplants is not yet established, it does not appear promising as a means to reduce the problems of air pollution from vehicles.

ELECTRIC VEHICLES

Electric vehicles can be powered by storage batteries, by fuel cells, or by direct transmission of electricity (as in a street car). This section will consider the problems and outlook for batteries as an energy storage system. Fuel cells are discussed in the next section.

The battery-electric vehicle must be considered as a system with its necessary stationary electric generating plant and its electric distribution equipment. Table 1 shows typical values, based on current practice, of the near maximum efficiency of these necessary steps in the chain of power supply to a battery-powered vehicle. Some of these efficiencies can vary widely. For example, the efficiency of the battery charge-discharge cycle is very dependent on the rate of charge and discharge. For shopping vehicle use it is to be expected that there will be much stop-and-go driving, with intermittent high rates of discharge.

TABLE I

ESTIMATED AVERAGE EFFICIENCY OF COMPONENTS
OF THE TOTAL BATTERY-ELECTRIC VEHICLE SYSTEMS

Component	Efficiency %
Central Powerplant	40
Electric Transmission and Transformers	85
Battery Charger - conversion of AC power to DC	80
Battery Charge - Discharge Effectiveness	70
Motor and Controls	75

The overall efficiency of this energy system is the product of all the component efficiencies, which is 14.%

The product of all these component efficiencies is 14.% which is the overall efficiency from the central powerplant fuel supply to the output shaft of the electric motor. This efficiency can be much less for off-design conditions. For a typical automobile, the overall thermal efficiency of its gasoline engine varies at steady speed in high gear from approximately 13% at 30 miles per hour to 22% at 70 miles per hour. It can be seen that the overall thermal efficiencies of the two power systems are of the same order of magnitude. However, these figures represent a comparison of a highly developed gasoline-powered automobile with a less-developed battery-powered system that probably has greater potential for future improvement in some of the efficiencies of Table I.

The low available energy per unit weight of batteries is the major technical block to the use of the battery-electric system for automotive propulsion. This is usually expressed as watt hours of energy available per pound, and is a measure of how far a battery-powered vehicle can travel before requiring a recharge of its batteries. Another nearly equally important criterion is the ability to deliver power at a high rate for short periods of time. This can conveniently be expressed as weight/power ratio. Values of these abilities are shown in Table II, taken from References 18 and 19, for conventional batteries and those that have been mentioned as having future potential advantages for vehicle propulsion. Warning is given, however, that these numbers can be very misleading since they depend on many factors and on whether a laboratory or commercial device is being considered.

TABLE II

COMPARISON OF BATTERY SYSTEMS

	Energy Density Watt-hrs. per lb. (Slow discharge 5 hrs.)	Weight/Power Ratio Lb. per kilowatt (Rapid discharge 1/4 hrs.)
Lead-Acid	10	20
Nickel-Cadmium	14	25
Silver-Cadmium	24	15
Silver-Zinc	50	4
Zinc-Air (General Dynamics	60	30
Sodium-Sulfur (Ford Motor Co.)	150	10
Lithium-Chlorine (General Motors Corp.)	150	3

It will be noted from Table II that the silver-zinc battery shows an energy density of five times that of our conventional lead-acid battery. Unfortunately, they are very expensive partly because of a high silver content. Also, their life as measured in terms of ability to be repeatedly charged and discharged is only about 10% of that of a lead-acid battery.

The zinc-air battery has energy density as good as the silver-zinc battery, and is very much less expensive. Unfortunately this unit is the poorest of those shown from the standpoint of weight per unit of power, and is unacceptable on this basis.

Many paths to possible higher output are being considered. The Ford sodium-sulfur unit, said to be in an early stage of development, is one example. This presents serious problems since sodium is very hazardous if it contacts water, and the unit must be operated at a temperature of 500°F or higher. The use of hazardous materials such as sodium at elevated temperatures poses serious problems of safety and starting for vehicle use. General Motors has concentrated some of its effort on the Lithium-Chlorine cell, which operates at a temperature slightly above the melting point of lithium, - about 1100°F. This molten material also presents problems of safety and start-up. No one knows when, or if ever, such batteries will be practical for propelling a personal vehicle.

The most advanced state of the art is illustrated by an experimental battery-powered car of General Motors,[19] shown on Figure 5. This is an experimental vehicle developed by General Motors to learn about and demonstrate the possibilities of an electric vehicle. The vehicle uses the basic structure and running gear of the Corvair automobile. It is fitted with a silver-zinc battery pack consisting of 286 cells with a total weight of 660 pounds. The car is equipped with a very compact alternating current 115 horsepower electric motor. A complex set of solid state devices for converting the direct current from the battery into AC with varying voltage and frequency are provided by the motor control. The car was designed to have performance comparable

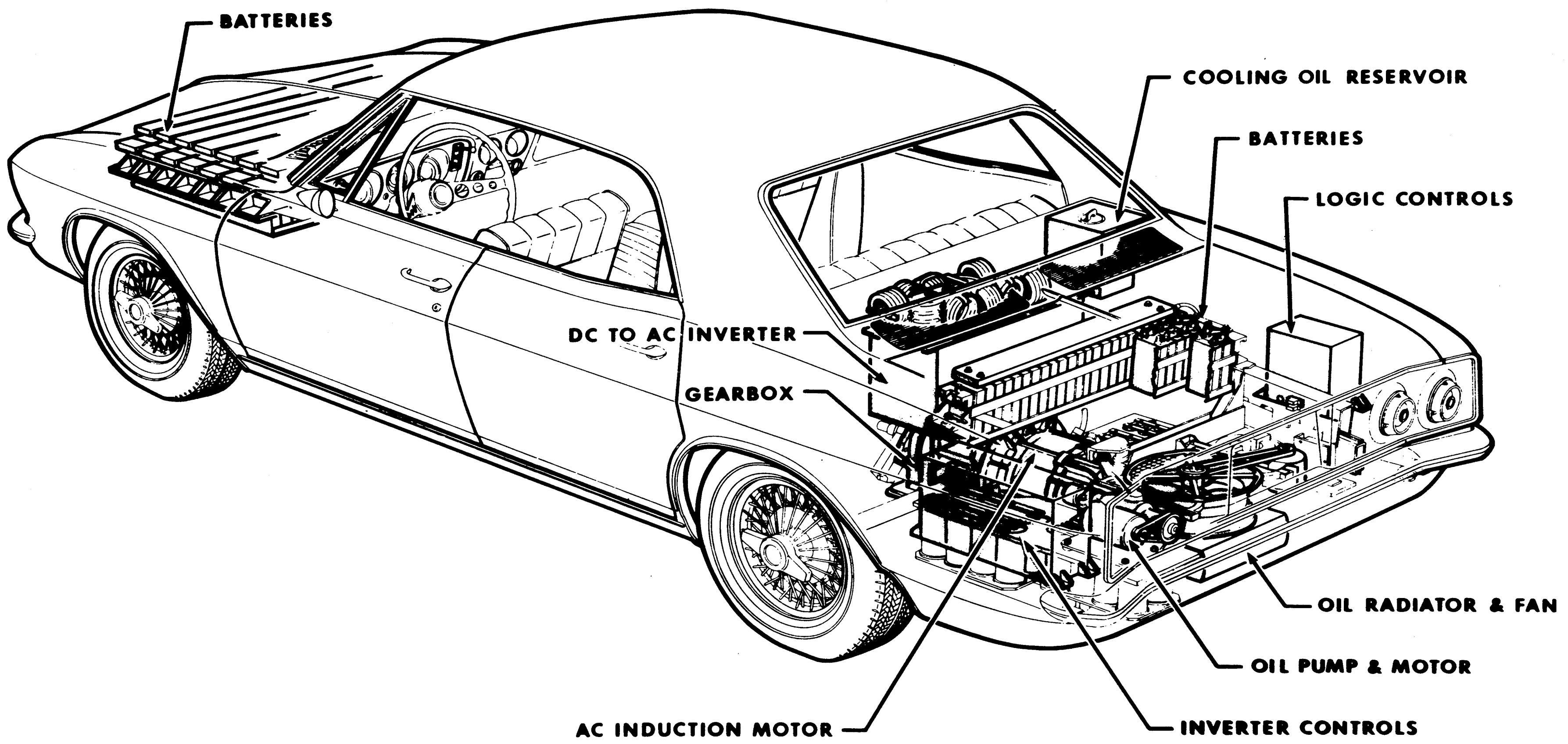

Figure 5. General Motors Battery - Powered Vehicle.

to a standard Corvair, but with a necessarily reduced operating range. The performance is indicated on Table III.

TABLE III

PERFORMANCE OF BATTERY-POWERED VEHICLE

	Battery-Powered Corvair	Corvair with Standard Powerplant
Weight	3400	2600 lbs.
Performance 0-60 mph	16 sec.	16 sec.
Top Speed	80 mph	86 mph
Range	40-80 miles	250-300 miles
Power Train Weight	1230 lbs.	610 lbs.

The limited range imposed by the batteries is apparent. On the basis of the estimated cost of these batteries when purchased for a production of 100,000 units, the computed cost to propel the car is approximately $3.00 per mile. This is more than 100 times the cost to propel a conventional automobile, and there is not enough silver for this use. To be successful, much less expensive battery combinations must be developed to a high standard of performance.

Another aspect of the battery-powered vehicle is the exhaust emissions of the total system in comparison with a gasoline engine. With the assumption that the central powerplant burned oil and the overall efficiency of the battery and gasoline engine powered systems are of near equal efficiency, and neglecting any battery emissions, the battery system would have only a small fraction of the unburned hydrocarbon and carbon monoxide of the gasoline automobile.[20] The oxides of nitrogen would be comparable, and the oxides of sulfur would be much larger, on the basis of present practices for both systems. The central station might also use gaseous fuel, with greatly reduced emissions.

The central station and battery electric vehicle system has the important advantage that the central station could be located outside an area subjected to unusually high pollution, such as Los Angeles. Also, there would be relatively few stations and therefore easier to control.

With the rapid development of central station atomic power, the emissions attendant to fossil fuel combustion would be eliminated, and a further advantage would accrue to the electric vehicle. It may now be projected that most large central station powerplants built after 1980 will be powered by atomic energy. However, it should also be kept in mind that the cost of generating electric power at the powerplant is only about 20% of its selling price. There is also a problem of disposal of radioactive waste from atomic powerplants.

If the present basic research relating to a sustained fusion reaction leads to the possibility of abundant power from sea water there would be a whole new outlook on power sources. At such a time our concern over world energy sources might also be ended. However, this represents a very much longer range projection.

There is a future place for battery-electric vehicles of small size and short range. Local shopping and short-range commuting are good examples. Applications where as much as half of the fuel is presently consumed while idling, such as some mail and delivery trucks, represent a potential field for electric vehicles. It does not seem likely however, that battery power will be used for decades for powering conventional size passenger automobiles in intercity service.

FUEL CELLS

A fuel cell is a device for converting chemical energy directly into electric energy. For a very interesting discussion of their principles and space applications, see Fortune magazine.[21]

Like most other powerplant systems, the fuel cell is not a recent conception. Sir William Grove of England, about 1840, demonstrated that hydrogen and oxygen could be combined with the aid of catalytic platimum electrodes to produce water and a small electric current. For generations only a modest and intermittent effort has been expended to produce electricity directly from fuels by these methods of electrochemistry. However, this has now been changed dramatically by the requirements of the space program, and intensive research by many groups is in progress. Some of the results of this effort are represented by the General Electric fuel cell powerplant system used in the Gemini 5 and 7 space flights. This system, consisting of many thin fuel cells, liquid hydrogen and oxygen storage tanks, coolant pumps, and preheaters to vaporize the hydrogen and oxygen, weighed four hundred pounds, and was capable of delivering one kilowatt. During the fourteen-day flight of the Gemini 7 this powerplant delivered about 200 kilowatt-hours of energy. For this application the fuel cell has many advantages, including the use of the same fuel and oxidant as the main propulsion engines, and its waste product, or exhaust, is drinking water.

An important aspect of this power system for space application has been the very large research effort that has been triggered. Most of the major companies involved in this effort, including General Electric, Pratt and Whitney, and Union Carbide, are all looking to commercial applications. Before there can be much commercial application of fuel cells their cost must be greatly reduced, - the platinum in the Gemini 1 kilowatt (1-1/3 H.P.) unit is estimated to cost $7,500.00.

Coming back to our earlier premise that an automotive portable power-plant must use a relatively cheap and easily handled fuel, it is almost essential that a fuel cell for land vehicle propulsion use a petroleum-base fuel and take its oxygen directly from the air.[22] Another approach is to reform the fuel before supplying it to the fuel cell, but such processes also add to the complexity and reduce the overall efficiency of such systems. Further, all fuel cell systems which burn conventional fuels and air are quite certain to have some products of incomplete combustion, and undesirable emissions.

General Motors has also developed an automotive vehicle to study the problems and possibilities of fuel cells as a means of vehicle propulsion, as outlined in the news release of Reference 19. This program was carried out with the cooperation of the Union Carbide Company, who supplied the fuel cells. Figure 6 shows a view of the vehicle, and indicates the principal components of the propulsion system. Some of the principal characteristics and performance of this vehicle, in comparison with the same vehicle with a conventional gasoline engine system, are shown on Table IV.

The electric control system and propulsion motor for the fuel-cell powered Electrovan were essentially the same types of equipment as used in the battery-powered vehicle. The liquid hydrogen and oxygen were kept in vented cryogenic insulated tanks at their very low boiling points of -423°F and -297°F, respectively, so some of the liquids are continuously lost by boiling away.

Figure 6 reveals that the fuel-cell vehicle was nearly filled with the necessary propulsion equipment and Table IV indicates that the range of operation was quite low, and that the power train weight was

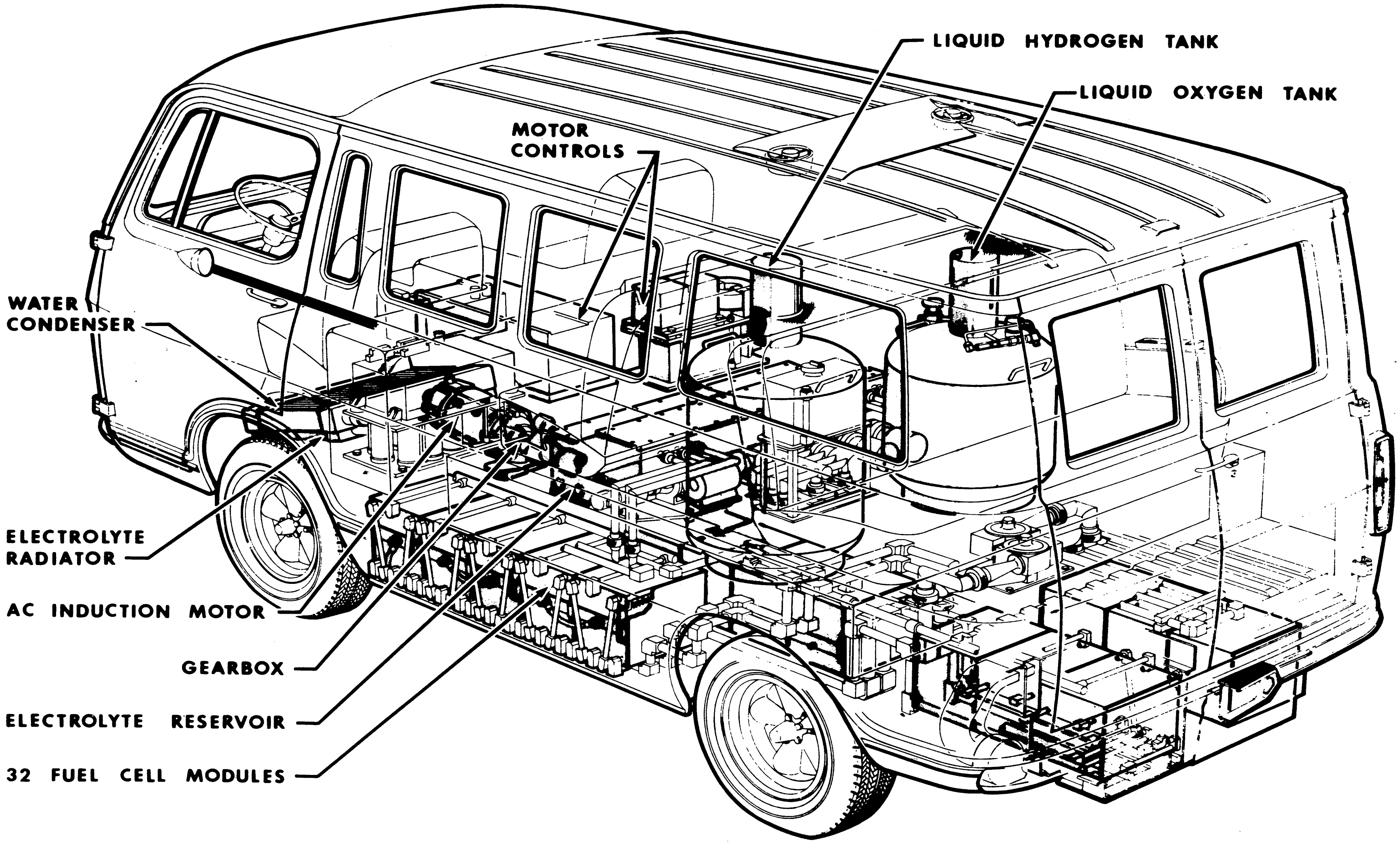

Figure 6. General Motors Fuel Cell-Powered Vehicle.

excessive. Obviously much remains to be done to make the fuel cell a practical vehicle propulsion system. Again, a highly developed engine-transmission system is being compared with a fuel cell system in an early stage of development.

TABLE IV

	Fuel Cell Powered Vehicle, The Electrovan	Conventional GMC Van
Weight	7100 lbs.	3259 lbs.
Performance 0-60 mph	30 sec.	23 sec.
Top Speed	70 mph.	71 mph.
Range	100-150 miles	200-250 miles
Power Train Weight	3650 lbs.	870 lbs.

The major problems of fuel cells involve processes of catalysis and catalytic materials. Catalytic processes are extremely complex and remain mysterious. In this fact lies hope that future development may lead to remarkable improvements in performance and reduction in cost. For this reason fuel cells may represent a much better long range hope than storage batteries as a means for vehicle propulsion. One should also not overlook the possibility of breakthroughs in technology in this field of relatively recent technology. The same is true for all fields of power development, but the chances for this are much less in well developed systems.

Perhaps the best opinion that can be expressed here is that of Dr. Arthur M. Bueche of the General Electric Company, which developed the Representatives Committee last summer, he stated,[23] "'When will we have fuel cell automobiles? I don't know. I don't know <u>when</u>, and I'm not really sure <u>if</u>. All I can say is: on the basis of what we know now, fuel cells might someday be very attractive for vehicles because they might not give off any appreciable noxious exhaust, and they might be developed to fit into more compact portable packages, and they might be made inexpensively enough for general use in vehicles.

That's a mighty long list of 'mights'. But fuel cell research has great momentum. The need for alleviating pollution from vehicles is very great. The accomplishments of man, when he puts his mind to it, are being dramatically demonstrated in today's world.'"

BIBLIOGRAPHY

1. Future Trends in Energy Conversion Systems, by Harvey W. Welsh, Society of Automotive Engineers paper No. 660603, Sept. 1966.

2. Potential New Motive Power for Automobiles, by Miles L. Brubacher, May 11, 1966. A report to the State of California Motor Vehicle Pollution Control Board.

3. An Appraisal of the Petroleum Industry of the United States, U.S. Dept. of the Interior, Jan. 1965.

4. An Engineering Evaluation of Energy Conversion Devices, Lauck, Uyehara, and Myers, SAE Transactions, Vol. 71, 1963, p. 41.

5. The Influence of Inlet Air Conditions on Carburetor Metering, by J. A. Bolt and M. Boerman, Society of Automotive Engineers paper No. 660119, Jan. 1966.

6. The Effects of Engine Operating and Design Variables on Exhaust Emissions, by D. F. Hagen and G. W. Holiday, SAE Tech. Progress Series, Vol. 6, 1964, p. 206.

7. The Influence of Improved Mixture Quality on Engine Exhaust Emissions and Performance, by J. A. Robison and W. M. Brehob, Western States Combustion Institute Meeting, Oct. 1965.

8. Potentialities of Emission Reduction by Design of Induction Systems, by Earl Bartholomew, Ethyl Corp., SAE paper No. 660119, Jan. 1966.

9. Vehicle Performance and Exhaust Emission, Carburetion vs. Timed Fuel Injection by J. H. Frieman and R. Stahman, SAE paper No. 650863, Nov. 1965.

10. Lean Fuel/Air Mixtures for High Compression Spark-Ignited Engines, by J.A. Bolt and D. H. Holkeboer, SAE Trans., Vol. 70, 1962, p. 195.

11. Development of Flame Type Afterburner, by J. W. Schnabel, Yingst, Henein et al., SAE paper No. 486 G, March 1962.

12. Design and Development of the General Motors Air Injection Reactor System, by Steinhagen, Niepoth and Mick, SAE paper No. 660116, Jan. 1966.

13. Development and Evaluation of Automobile Exhaust Catalytic Converter Systems, by Schaldenbrand and Struck, SAE paper No. 486 E, March 1962.

14. Engine Modifications and Exhaust Emission Control, A Survey and Appraisal, by Prof. W. E. Meyer, Penn. State Univ., published by Taft Sanitary Eng. Center, Tech. Report A62-8, U.S. Dept. of HEW, PHS.

15. Recent Research Work on the Internal Combustion Engine, Sir Harry R. Ricardo, Trans. of Soc. of Automotive Engineers, Part I, 1922.

16. Chrysler's Gas Turbine Car, by De Claire, G. and A. H. Bell, SAE paper No. 777D, Jan. 1964.

17. The General Motors Research GT-309 Gas Turbine Engine, by Turunen, W. A., and J. A. Collman, Gen. Motors Research, SAE paper No. 650714, Oct. 1965.

18. News release concerning battery research and electric vehicles by Ford Motor Co., Oct. 3, 1966.

19. News release concerning battery and fuel-cell powered vehicles, by General Motors Corp., Oct. 28, 1966. Presentations by E. N. Cole, L. R. Hafstad, H. Barr, and C. Marks.

20. A Compilation of Air Pollutant Emission Fractors for Combustion Processes, Gasoline Evaporation and Selected Industrial Processes, by Mayer, Martin, U.S. Dept. of Health, Education and Welfare, PHS, Division of Air Pollution, May 1965.

21. Bringing the Fuel Cell Down to Earth, by Lessing, L., Fortune, Sept. 1966, p. 129.

22. The Future of Fuel Technology, Institute of Fuels Conference on the Future of Fuel Technology, Amsterdam, 1963. Paper by Fantram, A.D.S.; Discussion of Fuel Requirements for Fuel Cells, p. 95, Book of the MacMillan Co., N.Y., 1964.

23. Testimony of Dr. Arthur M. Bueche, Vice-President, Research and Development Center, General Electric Co., before subcommittee on science, research and development, U.S. House of Representatives.