

## CAN WE AFFORD A CLEANER VEHICLE FUEL?

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Although the automotive engine currently generates about 60 percent of the man-made air pollution in the United States, it does not necessarily follow that the substitution of a cleaner fuel for gasoline will alleviate the problem. A systems analysis, or a complete ecological balance, demands that pollution be evaluated on a global rather than a local basis. In addition, the availability and efficiency of utilization of prospective vehicle fuel substitutes must receive equivalent attention. When all of these factors are taken into consideration, gasoline still emerges as the most logical vehicle fuel for probably another half century.

By far, the leading source of air pollution from manmade, as opposed to natural, events is the combustion of fuels to produce energy. Much concern for air pollution is rightfully directed toward motor vehicles. Table 1 shows that transportation consumes 24 percent of our total energy expenditures while contributing 60 percent to our total air pollution.

A very tempting conclusion can be drawn from Table 1, *i.e.*, if automotive exhausts could be eliminated, the vehicle pollution problem would likewise disappear. From this shortsighted aspect, the electric car would appear to be the ideal solution for both air and noise pollution. Ignoring the multitude of technological problems that remain to be solved before this method of propulsion can be adapted for conventional uses, the electric car fails to compete favorably with the gasoline engine with respect to the three primary ecological factors: air pollution, efficiency of energy utilization, and availability of energy source.

1. *Air pollution.* To replace the gasoline internal combustion engine by electric-battery cars would require doubling our electrical generating capacity. In so doing, electric cars would simply shift the air pollution burden from one locality to another. In fact a recent study (3) has shown that the increased air pollution from these additions to our electric generating capacity could aggravate our present air pollution problem on an area-wide basis. It is now generally agreed that pollution must be assessed on a *global* rather than a *local* basis (2).
2. *Efficiency of energy utilization.* When power transmission and distribution losses are taken into account, electric energy represents by far the lowest efficiency of utilization of all forms of energy. Although new devices for direct conversion of heat to electricity, such as thermoelectric energy conversion, thermionic energy conversion, magnetohydrodynamic conversion, and fuel cells, offer promise for significant increases in efficiency, their widespread use for generating power at the levels demanded by the transportation industry is still many decades away.
3. *Availability of energy source.* Since the nation is already faced with an energy crisis, any shift of energy utilization to one of lower effi-

TABLE 1. Distribution of U.S. energy consumption and sources of air pollution.<sup>a</sup>

End Use	Input Energy Consumption <sup>b</sup> in 1970 (%)	Air Pollution Contribution <sup>c</sup> in 1965 (%)
Residential (2/3) and Commercial (1/3)	19	6
Industrial	26	17
Transportation	24	60
Electric Utilities	25	14
Other (including refuse disposal, petrochemical raw materials, etc.)	6	3
	100	100

<sup>a</sup> References 1 and 2.

<sup>b</sup> Electric utilities deliver almost one-half of their output to the combined residential-commercial market and most of the balance to industry.

<sup>c</sup> Carbon monoxide, sulfur oxides, nitrogen oxides, hydrocarbons and particulate matter.

ciency, such as would be brought about by the electric car, cannot be tolerated. Nevertheless, all projections on energy balances through the next century indicate that the share of electricity in the total energy market will continue to increase, based on nuclear energy. In fact, nuclear energy appears to be the ultimate answer to mankind's needs, projected utilization of geothermal, solar and tidal energy notwithstanding.

In the present discussion, problems of thermal pollution and disposal of radioactive wastes, which are equal to, if not more serious than, pollution from combustion of fossil fuels, will not be considered. However, generally not recognized is the fact that the U.S. proven and recoverable reserves of uranium oxide ( $U_3O_8$ ), measured in terms of thermal equivalents based on present nuclear technology, are *less than* our petroleum reserves and are about 60 percent of our natural gas reserves (4). The oft-reported argument that more uranium reserves would become available with increased exploration and development of improved recovery methods is reminiscent of the predicament with which the oil and gas companies have been faced for more than a decade. The uncertainty as to how much more can be delivered *economically* remains.

The future of nuclear power rests almost entirely, for the next century at least, on the rapid commercialization of the fast breeder reactor which catalytically burns uranium or thorium. The latter is in such plentiful supply in granite that it would constitute an almost inexhaustible supply of thermal energy. Deuterium in sea water is indeed inexhaustible provided that the fusion reaction can be controlled. To date, no responsible scientist has said that fusion is clearly feasible (5). Thus, the breeder reactor offers the most realistic promise for resolving our energy crisis during the next century. However, by the year 2000, it is doubtful that more than a few breeder reactors, having a total capacity to generate about 10 percent of the electric demand in this country, will be in commercial service. Subsequently, the growth rate in breeder reactors should increase rapidly. Because of the thermal pollution problem, most of the new breeder reactors will probably be located offshore. If these breeder reactor stations were required to supply the electricity to accommodate transportation, as well as our basic electric utility needs, it is conceivable that several hundred in-

dividual breeder reactor stations would be distributed over roughly 5500 miles of our coastline. The thought of these exposed facilities dotting our borders not only raises a question regarding aesthetics (visual pollution) but also raises concern in the event of a military attack.

Since the electric car creates more problems than it resolves, a combustion engine which emits no pollutants appears to be the ultimate choice for propulsion. Of all the fuels that have been considered, hydrogen is generally regarded as the "cleanest" since it can be burned with air in a controlled manner so as to emit only water vapor. What makes hydrogen so attractive is that a continuous supply is available from the electrolysis of water, which yields hydrogen and oxygen. Subsequently, when the hydrogen is burned as a fuel, it requires the same amount of oxygen as was released in the electrolysis step; essentially the combustion of hydrogen constitutes a closed cycle with the electrolysis of *pure* water without accumulation of any "foreign" substances. On the other hand, one cannot overlook the fact that electrical energy must be supplied from external sources to carry out the electrolysis. Whether this energy is supplied by either fossil fuels or nuclear reactors, the same arguments on global pollution and availability of the energy source, as presented above for the electric car, will apply. However, the electrolysis of water to produce hydrogen as the end-use fuel offers a distinct advantage over electricity as an end-use from the standpoint of efficiency of utilization. Recent studies (6) have demonstrated convincingly that if nuclear-generated electricity is used to electrolyze water, and if the resulting hydrogen is then transmitted by pipeline (in much the same way as natural gas presently is) it can be supplied directly for space heating and transportation combustion engines more economically than electricity can be converted for these two applications. The underlying reason is that hydrogen can be transmitted at about one-sixth of the cost that is required for transmitting the same thermal equivalent of electricity the same distance. (Pipelining hydrogen is estimated to cost about 60 percent more than natural gas.) Since it would not be economical to use hydrogen, produced by electrolysis of water, to generate electricity

at the destination, some electricity would still have to be generated at the nuclear plant and transmitted as such for those applications which require the direct use of electricity, e.g. lighting, appliances, and machinery.

A substantial transition from fossil fuels to electrolytic hydrogen by the year 2000 would require an incremental electrical energy output of 2 to 5 times the projected electrical energy demand based on the present fossil fuel technology (6). Since these plants would be located mostly off-shore, electrolytic hydrogen would have to be obtained from seawater, which would create an enormous problem in disposing of the by-products, chlorine and caustic soda, in addition to the radioactive wastes and thermal pollution emanating from the nuclear power plant.

In summary, for the long pull (50 years hence and beyond) a combination of nuclear power and electrolytic hydrogen offers the most attractive solution for man's insatiable demand for energy. In the interim, and conceivably for another century, man will have to continue to rely on fossil fuels as a primary source for energy and raw materials.

TABLE 2. Sources of energy in 1970 ( $68 \times 10^{15}$  Btu per year).<sup>a</sup>

	%
Petroleum (including imports and natural gas liquids) <sup>b</sup>	44.6
Natural gas	31.8
Coal	19.3
Hydroelectric	3.9
Nuclear (and wood)	0.4
	100.00

<sup>a</sup> References 1 and 7.

<sup>b</sup> Domestic crude = 31%, natural gas liquids = 2.6%, imports = 11%.

## FOSSIL FUEL RESOURCES

Next to hydrogen, natural gas is potentially the cleanest burning fuel for vehicles as demonstrated by numerous road tests involving more than 2500 vehicles over the past few years. However, its relative availability for vehicle use must be weighed against the competing demands for other uses.

The origin of our sources of energy in 1970 is given in Table 2. Note that petroleum and natural gas account for 76 percent of the total. The distribution of end uses for natural gas and petroleum are summarized in Table 3. Note that about 60 percent of the petroleum, as gasoline and kerosene, is primarily committed to propulsion of motor vehicles and aircraft.

From Tables 1, 2, and 3, it can be estimated that more than 50 percent of our annual natural gas consumption would have to be diverted to replace gasoline as a vehicle fuel. Presumably this demand could be met most readily by cutting off all of the natural gas presently supplied to industry on both a firm and interruptible basis. (Interruptible service primarily covers power plants or other large industrial users under contracts which permit interruption on short notice normally due to weather conditions so that service can be maintained for residential, commercial or firm industrial. Customers on interruptible service maintain facilities for switching to coal or oil as fuel during the period of interruption. For this inconvenience, the interrupted customer gets natural gas at a bargain price when it is available.) Should the supersonic jet transports—for which liquefied natural gas would be an ideal fuel—ever materialize in the U.S., their demand would be equivalent to about 10 percent of the present U.S. natural gas production.

TABLE 3. Distribution of end uses of natural gas and petroleum in 1968.<sup>a</sup>

	Vol. or Btu. (%)	
	Natural Gas	Petroleum
Residential	22	Gasoline (and special naphtha) 54 51
Commercial	8	Kerosene (and jet fuels) 8 8
Firm industrial	30	Distillate fuel oil 23 25
Interruptible	21	Residual fuel oil 7 8
Field use	12	Refinery fuel 8 8
Other	7	
	100	100 100

<sup>a</sup> References 8 and 9.

The world reserves of natural gas are the thermal equivalent of about half the crude oil reserves. Since roughly half of the crude is convertible to gasoline (Table 3), then the natural gas reserves are about the same as the gasoline reserves. As of 1970 the U.S. had about 18 percent of the world's natural gas reserves and only 6.5 percent of the world's crude oil. In the U.S. proved reserves of natural gas are about 40 percent greater than petroleum plus natural gas liquids (4, 10, 11).

The U.S. known or proved recoverable reserves of oil are probably adequate for another 10 years; our gas reserves may not see us through another 15 years. Our oil shale reserves, which are still awaiting commercial realization, are about equivalent to our combined oil and gas reserves. Therefore, from the standpoint of hydrocarbon reserves, we are theoretically self-sufficient for the rest of this century.

Coal, which currently supplies about one-fifth of the energy consumed in the U.S., should gradually regain its prestige as an energy producer before the end of this century because our proved recoverable coal reserves are on the order of seven times the combined reserves of natural gas, petroleum, shale oil and uranium oxide (4). Since conversion of coal to oil or gas is approaching economic feasibility, at recoveries of 50-70 percent of the coal-input, calorific values, our ability to meet demands for petroleum-related energy sources appears to be reasonably assured for possibly another century. Furthermore, the ultimate reserves of petroleum and natural gas yet to be discovered in the United States are probably 100 times their present annual consumption (12). (Some speculations of the ultimate reserves of all fossil fuels yet to be discovered in the United States reach 500 times our present annual consumption.)

About 20 percent of the coal produced in the United States is carbonized in coke ovens. Since the exhaust gases from these ovens contain about one-third methane, this potential source for methane is not trivial. Conceivably, about 500 million cubic feet of natural gas could be recovered each day, an amount equivalent to about 5 million gallons of gasoline (2 percent of the present total gasoline production).

The fact that the United States has 18

percent of the indigenous gas reserves and only 6.5 percent of the crude oil reserves would indicate that we should place greater emphasis on importation of crude oil than on natural gas, particularly since the world reserves of natural gas are one-half of the crude oil reserves. Crude oil has been moving abundantly in international trade since World War II, whereas natural gas consumption has been virtually confined to the producing country until the recent advent of liquefied natural gas. One can now anticipate a much greater growth rate for natural gas consumption worldwide, relative to crude oil. Consequently, from the standpoint of competing demands, the world's crude reserves will likely continue to be more available to the U.S. than the world's natural gas reserves. Thus, the gasoline-powered vehicle presents a more favorable future because of the greater import potential for crude oil as compared to natural gas.

On the other hand the U.S. is in an enviable position with regard to coal and can lay claim to one-third of the world's coal reserves (13). Based on processes under current development, coal can be gasified to a natural gas with a 70 percent recovery in calorific value, whereas it can be converted to satisfactory gasoline with a recovery of little more than one-half of the calorific value. In this case the pendulum would swing in favor of the natural-gas powered car from the standpoint of more efficient utilization of our coal resources.

Another potential source of energy is solid waste which is accumulating in the U.S. at a per capita rate faster than our escalating demands for energy (14, 15). Presently, 84.6 percent of our solid wastes go into dumps, 5.4 percent into landfill, 8 percent into incineration, and 2 percent into composting, sewers, recycling and salvage (2, 16). In the final analysis we may be driven to incinerating all non-reclaimable refuse, since open dumping and land-fill disposal are rapidly becoming more restricted and costly. Excluding such solid wastes as glass, metal, plastics, ashes, sand, and dirt, but including paper, wood, rags, and garbage, it is estimated that half of the total energy requirements of Table I could be supplied by burning such refuse. As of 1969, only three solid waste incinerators for generating power, having a total capacity of 600,000 pounds of steam per hour,

had been reported in the U.S. The technology is more advanced in Europe where properly designed incinerators for power generation emit negligible quantities of pollutants (2, 17). In addition to generating power, incineration of organic residues has the salubrious effect of accomplishing quickly that which takes mother nature several years. More importantly it could relieve half of the demand on our conventional energy resources while alleviating the solid waste problem.

Along these same lines, the Bureau of Mines reported in 1969 a process for converting garbage to oil. In 1971, a report described a process for combining carbon monoxide and manure or any cellulosic waste under moderate pressure and temperature to produce a low sulfur, paraffinic oil of constant quality from a wide variety of cellulosic materials (18). It is estimated that if all of the domestic animal wastes were collected and converted to a fuel oil, it would be at least equivalent in quantity to the distillate fuel oil now being consumed (see Table 3).

Thus, the practice of ecology in its broadest sense is potentially capable of extending the life expectancy of our fossil fuel reserves quite dramatically.

## VEHICLE FUELS AND ECOLOGY

Of the 142 million tons of major pollutants dumped into our air each year, automobiles contribute about 60 percent, or 85.2 million tons, composed of (2):

Carbon monoxide	77 percent
Hydrocarbons	14 "
Nitrogen oxides	7 "
Sulfur oxides	1 "
Particles	1 "

The carbon monoxide and hydrocarbon emissions, which together amount to 91 percent of the pollutants, are primarily indicative of a poorly designed fuel delivery system and combustion chamber; they represent a 13 percent waste in energy. Although the amount of hydrocarbons emitted from vehicles is an order of magnitude lower than that continuously produced by natural events, they can participate in forming photochemical smog and are suspected of contributing to cancer (19). On the other hand, although carbon monoxide can be lethal, its presence in the atmosphere as a result of vehicle emissions is still orders

of magnitude less than the level to which many people voluntarily expose themselves when smoking. Furthermore, carbon monoxide does not appear to accumulate in either the atmosphere or the human body although the mechanisms for its relatively rapid removal are not understood (19). Thus, on the ecological balance sheet, carbon monoxide from vehicle emissions represents a greater liability under energy degradation than under pollution.

The third major pollutant, collectively nitrogen oxides, is also due to the combination of high temperatures and air-fuel mixture ratios required to deliver the desired engine performance. Compared to other man-caused discharges of sulfur oxides and particulate matter into our atmosphere, the contributions of these two items from vehicle emissions are quite insignificant.

Practically all of the pollutants (carbon monoxide, hydrocarbons and nitrogen oxides) now resulting from burning gasoline in internal combustion engines can be virtually eliminated by burning gasoline in a complete combustion engine at moderate temperatures. Such an engine is available, for example, the Williams engine (20), in the form of a "steam engine" which was perfected a century before the gasoline-powered, internal combustion engine was even conceived.

Most of the current effort to reduce vehicle pollutant emissions in order to meet Federal air quality standards is concentrating on the development of auxiliary devices such as catalytic converters, afterburners, crankcase blow-by controls, and fuel injectors. Present indications are that these devices may not be perfected to the level of operating reliability required to meet Federal standards by 1975. General Motors has embarked on a crash program to develop the Wankel rotary engine since it is more compatible with emission control devices, such as catalytic converters, than the present Otto reciprocating engine. As vehicle registrations continue to increase, so will the total quantity of vehicle pollutants emitted. Consequently, Federal standards will continue to become more restrictive until eventually they will probably insist on virtually complete combustion.

Another approach to the vehicle pollution problem has been directed to finding

a "clean-fuel" replacement for gasoline. As mentioned before, natural gas offers attractive possibilities from the standpoint of both burning qualities and availability. Propane has comparable burning qualities, but its availability is less than 5 percent of what would be required to satisfy the vehicle fuel market. King and co-workers in Canada and Schoepel at Oklahoma State University (the latter working under a grant from the National Air Pollution Administration) have reported promising results with modified internal combustion engines burning hydrogen (6). Methyl alcohol also looks promising, particularly since it would involve the least troublesome switchover in refinery strategy and the minimum changes in present vehicle engines and fuel delivery systems.

An assessment of the ecological merit of a particular vehicle fuel which is based solely on the vehicle exhaust emissions can be grossly misleading. One has to consider the total environmental or global effects attributable to the use of a specific vehicle fuel. As the world's population and industrialization continues to expand, the concept of localized environments becomes

TABLE 4. Comparison of air pollution resulting from worldwide natural and man-caused events.<sup>a</sup>

Air pollutant	Additions to the atmosphere in tons per year	
	Natural events <sup>b</sup>	Man-caused <sup>c</sup>
Particulate matter	10 <sup>8</sup>	10 <sup>8</sup>
Carbon dioxide	2 x 10 <sup>11</sup>	2 x 10 <sup>10</sup>
Carbon monoxide	0.2 x 10 <sup>8</sup>	2 x 10 <sup>8</sup>
Nitrogen oxides	2 x 10 <sup>8</sup>	5 x 10 <sup>7</sup>
Sulfur dioxide	negligible	1 x 10 <sup>8</sup>
Hydrocarbons <sup>d</sup>	3 x 10 <sup>8</sup>	9 x 10 <sup>7</sup>

<sup>a</sup> Reference 19.

<sup>b</sup> Meteoric and natural dust, fogs, volcanoes, decay of organic matter, respiration, marsh gas, coal mines, seed germination, lightning storms, injured vegetation, forest fires, biological reactions and bacterial decomposition.

<sup>c</sup> Space heating, industry, transportation, power plants, solid waste disposal, evaporation and transfer.

<sup>d</sup> Methane evolved from bacterial decomposition is the hydrocarbon produced in largest amount by natural events. The amount is equivalent to about 65 percent of the present annual consumption of natural gas in the United States.

more unrealistic. Table 4 provides perspective in this regard by comparing the remarkably constant contributions to air pollution by natural events with the accelerating contributions by man-caused events.

It is readily apparent from this tabulation that man has approached, and in some cases even exceeded, nature's quota.

We no longer can ignore the facts that vehicle engines in the United States alone consume close to a billion tons of oxygen and produce a comparable amount of carbon dioxide plus about half this amount of water. These quantities are in addition to the 85.2 million tons of other pollutants mentioned previously. They acquire additional significance when correlated with the cycle times for biosphere exchanges which are: for carbon dioxide 300 years; oxygen, 2000 years; water 2 million years (21). The fact that carbon dioxide is now accumulating in the atmosphere at the rate of about 8 million tons per year indicates that the natural process of photosynthesis is beginning to fall behind on its function of exchanging equal volumes of oxygen and carbon dioxide with the atmosphere (19, 20, 21). As the population of the world continues to expand, atmospheric carbon dioxide is continuously increasing at the expense of oxygen, both as a result of respiration and greater demands for energy (22, 23).

As amplified previously, we shall have to continue to rely on vehicle fuels derived from fossil fuels. For the sake of illustration, with no pretense for completeness, the over-all "cleanness" of the four principal contenders, gasoline, natural gas, hydrogen and methanol, will be compared on the basis of oxygen consumption, carbon dioxide production, and energy consumed in manufacturing the vehicle fuel from the fossil fuel, which is expressed by an energy utilization factor or index. The oxygen consumption and carbon dioxide production include not only the amounts resulting from combustion (assumed to be complete) in the vehicle but also the amounts involved in producing the fuel. These quantities were obtained by performing routine thermochemical calculations for the chemical reactions which transpire in both the fuel manufacturing and vehicle combustion steps. For example, even though hydrogen burning in the vehicle produces no carbon dioxide, in manufacturing it by reforming a heavy oil the amount of carbon dioxide generated is greater than that produced in burning a thermally equivalent amount of gasoline.

Table 5 summarizes these comparisons; it is based on the calorific equivalent of gasoline as supplied to the vehicle engine. Because the values in this table are only intended to reflect relative trends, the oxygen and carbon dioxide factors are reported as fractions or multiples of the gasoline values. The energy utilization factor represents the calorific fraction of the raw material that is retained in the finished fuel product; therefore it is an index of the degree to which our natural resources are being conserved. The gas demand and petroleum demand represent the fractions of the total annual consumption for all uses which would have to be diverted to supply the vehicle fuel demand. The "Cost, FOB plant" is something less than a desirable comparison factor since, for example, the hydrogen would have to be supplied in high pressure gas bottles for vehicle use, and consequently its cost as a vehicle fuel would be several times greater than that shown by the value in the table.

From Table 5, it is quite evident that hydrogen derived from natural gas or oil scores very poorly in this simplified evaluation. In particular, in producing hydrogen from reforming petroleum stocks one-third more carbon dioxide is emitted and one-third more oxygen is consumed than in burning an equivalent amount of gasoline in a vehicle. It also results in a 30 (100 minus 70) percent degradation in our petroleum resources. An alternative source for hydrogen, as well as for methane and synthetic gasoline, is coal. Had these processes been included in the evaluations, the oxygen, carbon dioxide and energy

index factors would have been about the same as for hydrogen from gas or oil. However, because the U.S. coal reserves are so vast as compared to our gas or oil reserves, the low energy utilization factor would be more tolerable.

Methanol also appears to be out of the question as a vehicle fuel since it results in the maximum degradation of our natural resources, either gas or petroleum, and would virtually deplete them for other uses just to satisfy the vehicle fuel market. Another possible, and substantially adequate, source for alcohols would be the fermentation of organic wastes, wood and residue grains. In this case the oxygen consumption index as listed in the table would remain about the same, but the carbon dioxide index would double. It should be noted that similar amounts of oxygen, carbon dioxide and heat losses would be involved if the organic wastes were left to decay naturally. (In the early 1940's both France and Spain utilized alcohol derived from fermentation of grapes as an engine fuel, but probably the most ingenious was the baker in Sweden who condensed and extracted alcohol from the steam of baking bread and provided enough fuel for his fleet of thirty trucks.)

Although this table is not comprehensive by any ecological standards, it does serve to illustrate that what may at first appear to be a clean fuel might not be a bargain after all. Natural gas scores high, but its availability, compared to other demands for its use, for widespread use as a vehicle fuel is doubtful. From an overall viewpoint, the much maligned gasoline certainly com-

TABLE 5. Comparison of vehicle fuels relative to the thermal equivalent of gasoline.

Factor	Fuel		Hydrogen from		Methanol from	
	Gasoline	Natural gas	Natural gas	Oil	Natural gas	Oil
Oxygen <sup>a</sup>	1	0.58	1.52	1.38	0.90	0.92
Carbon dioxide <sup>a</sup>	1	0.90	0.66	1.32	0.93	0.95
Energy index <sup>b</sup>	0.92	0.88	0.60	0.70	0.60	0.53
Gas demand <sup>c</sup>	—	0.53	0.87	—	0.87	—
Petroleum demand <sup>c</sup>	0.58	—	—	0.71	—	0.94
Cost, FOB plant	1.0	0.7	1.0	1.2	1.4	1.5

<sup>a</sup> Oxygen consumed or carbon dioxide liberated in manufacturing the fuel and in subsequently burning it in the vehicle, expressed as a fraction or multiple of the corresponding values for the thermal equivalent of gasoline.

<sup>b</sup> The fraction of the energy initially available in the raw material which remains in the derived fuel. The difference between these values and unity represents energy consumed in manufacturing the fuel. For example,  $(1 - 0.92) 100 = 8$  percent of the thermal energy in crude petroleum is used up in manufacturing gasoline.

<sup>c</sup> The fraction of the present annual production of natural gas or petroleum, as the case may be, which would have to be diverted to supply the U.S. demand for vehicle fuel.

pare favorably with natural gas. It also beats anything that the so-called "clean fuels," such as hydrogen and methanol as derived from fossil fuels, have to offer.

## CONCLUSIONS

One indisputable consequence of our complex, changing biosphere is that we are continually growing longer on human resources and shorter on material resources. From the standpoint of maximum utilization of both, a calamitous "solution" to our transportation problem might lie in human powered bicycles or chariots. The lethargic human race is already generating about 5 percent as much carbon dioxide as the total amount produced by all combustion operations. During heavy muscular endeavors, man could be expected to increase his carbon dioxide production rate by a factor of five; thus, aside from limiting population growth, those activities which cause the human race to breathe faster may ultimately have to be discouraged.

The automobile pollution problem is sufficiently acute to demand resolution within the next decade. Therefore, any solutions to the problem that rely on an adequate supply of nuclear-generated electricity, either for the electric-battery car or for electrolytic hydrogen, as a vehicle are not realistic since they cannot exert a significant impact for at least another 30 to 50 years, or even longer. In ordering our priorities, ecology should not be compromised by past technological shortcomings; rather, it should be exploited to define the requirements that advancing technology must satisfy. (We should not toss the baby out with the bath water!)

To conclude:

1. The vehicle engine, whether it be a reciprocating piston, rotary piston, gas turbine or a "steam engine," must exhaust virtually completely burned gases at a sufficiently low temperature to minimize nitrogen oxide emissions. With the exception of the steam engine, all other engines will probably have to utilize auxiliary, emission-control devices.
2. Fossil fuels will continue to be our primary source of vehicle fuels for many decades to come.
3. Only natural gas and gasoline (and possibly the light fuel distillates) as derived from fossil fuels demonstrate sufficient merit from a total ecological balance.
4. Depending on how wisely we manage our fossil fuel resources and solid waste disposal, gasoline could continue to supply our transportation needs for, conceivably, another century.
5. Hydrogen and methanol, as derived from fossil fuels, have unacceptably low ecological merit for vehicle fuels.

The primary objective of this paper was to demonstrate a conceptual approach to a systems analyses or ecological evaluation of the vehicle pollution problem. However, it does not purport to address itself to all of the factors involved in a complete ecological balance, which is quite delicate and agonizingly complex.

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