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THE ENVIRONMENTAL IMPACTS OF THE USE OF METHANOL AS A MOTOR VEHICLE FUEL

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Introduction

The Office of Mobile Sources within the Environmental Protection Agency has studied and evaluated alternative transportation fuels since its formation in 1970. EPA's responsibilities under the Clean Air Act also have necessitated a significant regulatory role dealing with transportation fuels. In particular, Section 211 of the Clean Air Act requires EPA to play a key role in the introduction of new fuels and fuel additives. Perhaps most visible was EPA's role in the introduction of unleaded gasoline to permit the use of catalytic converters on 1975 and later model year automobiles. More recently EPA has responded to a growing interest in the use of oxygenates (in particular methanol) for use in motor vehicles and for blending with gasoline.

From a technology assessment perspective, EPA has been motivated to investigate alternative transportation fuels because of concerns over diesel engine emissions. Diesel engines, which are becoming more numerous in both passenger cars and trucks due to their significantly higher efficiencies, produce relatively high levels of particulate matter and oxides of nitrogen. In a sense, fuel modification can be considered as an emission control technique.

EPA studies have suggested that neat or near-neat methanol is one alternative fuel which can provide the relatively low particulate and oxides of nitrogen emission levels characteristic of current technology gasoline-fueled vehicles while yielding improved energy efficiencies similar to those of diesel vehicles. In addition, only minor engine design modifications are necessary in order to produce vehicles which could successfully utilize pure methanol fuel. Studies by others in both the private and public sectors have shown that methanol can be produced from a wide variety of feedstocks which are distributed throughout the U.S., that the technologies to produce methanol from several feedstocks are available today, and that the overall economics of methanol production and usage appear favorable compared to other candidate alternative transportation fuels. EPA has recently published a report to Congress assessing the environmental and economic impacts of methanol and other coal liquids [1]. As a result of the increasing interest in methanol, EPA has recently completed several emission characterization test programs in order to better understand the emission impacts of methanol

utilization. EPA is currently in the process of projecting probable air quality impacts and health effects of methanol combustion.

Interest in the use of methanol in gasoline blends to extend petroleum supplies and raise octane ratings has accelerated during the last two years. Section 211 of the Clean Air Act requires EPA to approve methanol/unleaded gasoline blends and several companies have filed for fuel waivers. Many of the waiver applications have been approved and a few have been denied. EPA expects additional fuel waiver requests in the future.

This paper will examine the use of methanol as an automotive fuel both as a blending component and as a neat fuel. The focus of this paper will be on expected end-use environmental impacts of pure methanol combustion, and any resulting health effects, based on data from EPA test programs. It will also discuss possible environmental impacts associated with the transport and handling of methanol and safety concerns related to its use. It should be emphasized that any conclusions regarding the relative impacts of methanol usage must at this time be considered preliminary. Research is ongoing at EPA and other public and private organizations to better define the likely environmental impacts (and ways to ameliorate these impacts) of methanol usage.

Methanol as a Motor Vehicle Fuel Component

Methanol, usually along with cosolvents and sometimes certain inhibitors, is being seriously considered as a motor fuel component. Most of the current attention deals with methanol as a gasoline component, although EPA has performed some preliminary investigations into the use of methanol as a diesel fuel component [2]. Methanol concentrations in gasolines of up to about 10 percent are being considered. Clearly there are certain advantages of such blends, such as an economical means of extending petroleum reserves, higher octane ratings, and lower carbon monoxide emissions. However, there are several potential problems with methanol/gasoline blends including: 1) higher evaporative emissions, 2) poor vehicle driveability due to an enleanment effect, 3) material compatibility problems, 4) phase separation potential and 5) further stress on distillate availability.

Higher evaporative emissions may be a result of short-term or long-term effects. Higher short-term evaporative emissions would likely result from methanol blends due to the increased low-end volatility characteristics of methanol blends, unless appropriate volatility adjustments are made. Long-term evaporative emission concerns are associated with the possibility that methanol may reduce the effectiveness of the charcoal canister in the evaporative emission control system. Poor vehicle driveability may be experienced with some vehicles calibrated near to or lean of stoichiometric due to the additional enleanment effect of methanol/gasoline blends. While certain 1981 and later model year vehicles have closed-loop fuel control and may avoid lean driveability problems, concern remains for the other vehicles. The materials compatibility concern stems from methanol's deleterious effect on certain metals and elastomers. The materials compatibility problem can be either a short-term or a long-term concern. The tendency of phase separation in methanol/gasoline blends is well known, and can be initiated by small amounts of water. In addition to possible safety problems (i.e., vehicle stalling), phase separation would also worsen materials problems for those materials in contact with the methanol phase. Finally, using methanol in gasoline may exacerbate a potential future problem of distillate availability. Extending gasoline supplies alone would reduce the amount of oil refined and thus reduce distillate

production. There is a possibility, with the increased use of diesel engines in transportation and other demands on distillate fuels, that extending gasoline supplies through the use of methanol blends may be counterproductive.

EPA's involvement in considering these potential problems is limited to the provisions of Section 211(f)(1) of the Clean Air Act which prohibit the introduction of any new fuel or fuel additive for general use in 1975 and later model year automobiles, unless the EPA Administrator waives the restriction by determining that the new fuel or fuel additive will not cause or contribute to a failure of the vehicle emission standards. EPA's role in research pertaining to the issues involved with blends has necessarily been somewhat more limited than research associated with the impacts of utilizing pure methanol fuel. This is primarily due to the fact that there are an infinite number of possible methanol/gasoline blends, given varying concentrations of methanol, cosolvent alcohols, and other additives which might be used for other purposes such as inhibiting corrosion. Accordingly, it is not possible for EPA to design a test program to resolve all of the concerns associated with the entire range of possible blends. EPA's role is thus one of reacting to specific fuel waiver applications. Further, because of the number of waiver applications we have received in the past and expect to continue to receive in the future, EPA cannot carry out a comprehensive evaluation of each blend. Thus, we have generally relied on applicant data to resolve emissions, driveability, and materials compatibility concerns.

EPA has granted several methanol/gasoline waivers. Those waiver applications which have been denied have generally involved insufficient data being submitted by the applicant. EPA intends to continue to work with interested parties to help define the constraints on the appropriate use of methanol as a motor fuel component.

Pure Methanol as a Motor Vehicle Fuel

Methanol has long been recognized as a fine fuel for automotive engines. Many of its distinctive properties, such as its high octane number, high flame speed, and high heat of vaporization, make it an especially attractive fuel for Otto-cycle engines. Because of its low cetane number, methanol had traditionally been considered a poor diesel-cycle fuel. Recent developments have produced some promising concepts for methanol combustion in diesel engines, such as spark ignition and glow plug assisted ignition. EPA has reviewed the results of previous methanol research projects which indicated that methanol had the potential to produce improvements in emission levels and energy efficiency [3,4]. The next section of this paper will focus on EPA's own efforts to characterize the emissions from methanol-fueled vehicles.

Emission Characterization Programs

In order to assess the emissions and energy efficiency performance of pure methanol fuel combustion, EPA obtained three state-of-the-art methanol-fueled vehicles: Volkswagen Rabbit and Ford Escort passenger cars and a MAN heavy-duty engine designed for intracity bus operation. Gasoline-fueled versions of the Rabbit and Escort were tested at the same time for comparative purposes, as was a Volvo heavy-duty diesel engine (recently we have obtained some comparative data from a MAN heavy-duty diesel engine from the company). The primary differences between the methanol and gasoline-fueled passenger cars were the higher compression ratios used on the methanol versions. All of the Rabbits and Escorts utilized three-way catalytic converters. The MAN heavy-duty methanol engine is based on a diesel-cycle engine design with the addition of spark ignition to facilitate methanol combustion. The MAN methanol-fueled engine utilized an oxidation catalyst while the Volvo diesel engine did not (nor did the MAN diesel engine for which data have been obtained).

Each of these vehicles was subjected to a comprehensive emission characterization program at the Southwest Research Institute. Tables 1 and 2 summarize the test results from these characterization programs. EPA has reported the results in greater detail elsewhere (5,6,7). Although these are early prototypes and are basically straightforward conversions of their gasoline/diesel counterparts, they do provide EPA with

the opportunity to perform a preliminary assessment of the exhaust composition of methanol-fueled vehicles. Exhaust from each of the light-duty vehicles and heavy-duty engines tested in these programs was analyzed for each of the currently regulated pollutants: hydrocarbons, carbon monoxide, oxides of nitrogen, and particulate. Tests were performed for a range of other organic compounds such as methanol, formaldehyde, other aldehydes and ketones, and some individual hydrocarbons. In addition, several other unregulated pollutants (nitrosamines and total organic amines, ammonia, cyanide, and methyl nitrite) were measured during tests on one of the light-duty vehicles. Phenols, smoke, sulfate, and benzo(a)pyrene were also analyzed from the heavy-duty engines. The basic intent was to identify any possible emission surprises as early as possible with respect to methanol-fueled engines. The results of the test programs compare well with what was expected based on previous methanol research projects.

One of the most important classes of emissions from motor vehicles is composed of fuel-related emissions, which will be referred to as organic emissions in this paper. The great majority of fuel-related emissions from gasoline and diesel-fueled vehicles are hydrocarbon compounds, and the custom has been to use the term hydrocarbons to include all organic emissions measured by the EPA test procedure, which utilizes a flame ionization detector (FID). Since methanol is an oxygenated hydrocarbon itself, the emissions from methanol-fueled vehicles are predominantly oxygenated hydrocarbons such as unburned methanol and formaldehyde. Because of the inability of the FID to accurately measure oxygenated hydrocarbons, the organic compounds in methanol-fueled vehicle exhaust were determined by individual measurement procedures. Tables 1 and 2 give the total hydrocarbon, individual hydrocarbon, and oxygenated hydrocarbon emission results. It must be emphasized that the hydrocarbon values in Tables 1 and 2 include emissions also listed under the individual and oxygenated hydrocarbon values.

To make the data more understandable, Tables 3 and 4 show a more accurate breakdown of the total and individual organic emissions for the vehicles tested. The total organic emission is the sum of the individual organic components. For the gasoline and diesel-fueled vehicles, the hydrocarbon data are basically the FID-measured hydrocarbon results. For the methanol-fueled vehicles, the hydrocarbon data are the total individual hydrocarbon results. The oxygenated hydrocarbon values are listed separately.

Certain trends are apparent in Tables 3 and 4. Organic emissions from the gasoline and diesel-fueled vehicles are nearly all hydrocarbons with only trace levels of other classes of compounds. The methanol-fueled vehicle exhausts are dominated by unburned methanol emissions but contain small amounts of formaldehyde and hydrocarbons. The heavy-duty methanol engine contained very low levels of aldehydes and hydrocarbons, though it must be remembered that it was equipped with an oxidation catalyst. The environmental impacts of these different organic emissions will be discussed in a later section of this paper.

Both the CO and NOx results were mixed from the light-duty vehicle tests (Table 1), with methanol sometimes increasing and sometimes decreasing these emissions. However, all of the gasoline-fueled and methanol-fueled vehicles emitted very low emission levels, as they were all calibrated to meet the very stringent future California emission standards. Therefore, considering the level of control, the differences observed are quite small in absolute terms. One significant observation is that a trade-off seemed to be occuring between NOx emissions and energy efficiency. Although optimum methanol combustion would be expected to occur at very lean operation, both of the methanol light-duty vehicles utilized three-way catalytic converters and thus were forced to operate at very near stoichiometric conditions so that the NOx reduction catalyst would perform well. The methanol-fueled Escort showed no significant difference in energy efficiency at very low NOx levels, while the methanol-fueled Rabbit showed a significant increase in efficiency but at higher NOx levels. The methanol-fueled Escort was calibrated with more spark retard setting than the Rabbit thus resulting in low NOx and relative efficiency. Both CO and NOx emissions were lower with the methanol-fueled heavy-duty engine compared to the heavy-duty diesel engines. The low CO emissions were due to both low engine-out emissions and effective catalytic aftertreatment. The lower NOx emissions were expected, as NOx levels from heavy-duty diesels are typically relatively high and the lower flame temperature of methanol should provide lower NOx levels.

Emissions of particulate and unregulated compounds such as ammonia, cyanide, and organic amines are consistently lower from the methanol-fueled light-duty vehicles than from the gasoline-fueled vehicles. The very low level of particulate emission from the heavy-duty methanol engine is very impressive compared to the particulate levels of the two diesel engines. It can also be seen that smoke, sulfate, and benzo(a)pyrene levels were all lower from the methanol engine than from the Volvo diesel engine. No surprises appeared in these extensive

methanol characterization programs. However, the optimum emissions and efficiency configurations for methanol-fueled vehicles may very likely be different from the vehicles tested in this program.

In addition to the test programs which have been described, EPA has several contracted methanol engine optimization programs currently underway including projects with Ford Motor Company to optimize the Ford PROCO engine with methanol and with Ricardo Consulting Engineers to evaluate methanol performance with the Ricardo HRCC (high compression ratio, compact chamber) combustion system when fueled with methanol, as well as an in-house program at the Ann Arbor laboratory. While the in-house program is only a modest effort, preliminary results from the program are encouraging. The in-house program is first focusing on the determination of optimum engine efficiency and emission configurations, with the second phase involving final emission control system integration and vehicle testing. A parallel methanol exhaust aftertreatment project is also underway and preliminary results from this effort will be presented later. It is also important to point out that development/optimization activities for methanol engines are in a very early phase, as compared to gasoline and diesel engines. Therefore, it is reasonable to expect additional significant improvements in any methanol efficiency or emission results that are now available.

Figures 1 and 2 present thermal efficiency values at two different power settings from one of the engines being evaluated in the EPA in-house program (the Nissan NAPS-Z) compared to several advanced technology passenger car engines. (Other in-house engines show similar results with methanol, but the NAPS-Z engine has more versatility in parameter control and is receiving most of our experimental focus.) The NAPS-Z engine represents an advanced technology Otto-cycle engine, having both low friction and fast burn characteristics. The Volkswagen Rabbit turbocharged diesel engine is presented to represent state-of-the-art indirect injection passenger car engine technology. The turbocharged, direct injection Sofim diesel engine is representative of the best efficiency characteristics in research passenger car diesel engines. As can be seen, the methanol NAPS-Z is more efficient than any of the other advanced technology engines shown. The methanol results from the NAPS-Z engine, while very impressive, represent only simple compression ratio changes from the gasoline engine and parameter optimization for methanol fuel. Several alternative configurations are being evaluated for methanol which include water/methanol blends for reduced NOx emissions and possibly improved efficiency and specific power,

partial methanol dissociation for increased efficiency and reduced emissions, and turbocharger optimization. The methanol-fueled NAPS-Z engine also produces about 25 percent more power than its gasoline configuration.

Figures 3 and 4 present preliminary results from the EPA/Ricardo contract. These results come from a 1.5 liter HRCC engine Ricardo prepared for EPA. The engine has a 13:1 compression ratio, with methanol results being generated with the engine equipped with a very simple single barrel carburetor while the gasoline results are taken from the same engine fitted with an improved two barrel carburetor. The part-load conditions presented are within the range of operating conditions commonly encountered in a normal vehicle application. Although these results are from the same engine, methanol operation generally produced efficiency improvements of 4 to 6 percent over the gasoline fuel. These gains may be due to the effects of lower combustion temperatures when using methanol, the greater number of moles of combustion products per mole of fuel for methanol, and/or the faster combustion characteristics of methanol (higher flame speeds). The NOx emissions from methanol are significantly lower than with gasoline, and achieve very low levels at lean equivalence ratios where methanol combustion still appeared stable. In contrast, even with the HRCC engine, gasoline combustion appeared unstable at equivalence ratios lean enough to get significantly lowered NOx levels. A significant issue for methanol-fueled engines designed for very low NOx levels will be whether good vehicle driveability can be achieved when operating at an equivalence ratio near 0.7.

Another interesting result of the Ricardo study is the assessment of idle performance. Figure 5 presents idle fuel consumption and hydrocarbon emission results for several engines. The curves for each engine represent different spark timing and equivalence ratio settings. Of significance here is that the methanol-fueled HRCC engine idle fuel consumption is one-half that of the standard production gasoline engine, and within the range for production diesel engines.

If methanol-fueled engines can operate satisfactorily at lean equivalence ratios for optimum efficiency and very low NOx emissions, then oxidation catalysts (perhaps with some EGR) may be sufficient to meet stringent emission standards. There is also the possibility that the exhaust catalyst could be of the base metal variety, such as copper, chromium, or nickel, and not require noble metals, such as platinum and palladium. Unlike gasoline, methanol does not contain any sulfur or trace lead, which degrade base metal catalysts. This could

significantly reduce the cost of the catalytic converter system. This change could also improve the country's balance of payments, since all noble metals must currently be imported. While some base metals are also imported, their value would be significantly less and the result would still be a net decrease in imports. Of course, it may also be possible that a noble metal catalyst with significantly less noble metal loading could still be effective. In either case, a significant potential exists to use a lower cost catalyst with methanol-fueled vehicles. The in-house test program evaluating alternative catalysts is using the methanol-fueled Volkswagen Rabbit, characterized in its stock configuration in Table 1. Table 5 presents preliminary summary data on several alternative catalysts. Early results are encouraging.

Environmental Concerns of Pure Methanol Use

Several studies have been performed which assess the overall environmental effects of synfuel use [1,8,9]. However, while EPA is continuing to evaluate the environmental effects of the various alternative transportation fuels production processes, this discussion will focus on the concerns with the use of methanol as a motor vehicle fuel. The discussion will address specific exhaust emission concerns as well as general health and safety concerns associated with the handling and use of methanol.

Emission-Related Issues

Based on the results of the EPA test programs described above, as well as data from previous methanol research projects, it appears that pure methanol combustion would likely result in lower emissions of currently regulated pollutants. The hydrocarbon/organic emission comparison is difficult to make because of the different classes of compounds involved, and will be discussed in greater detail below. With respect to CO emissions the available data indicate that methanol-fueled vehicles will produce about the same levels as current vehicles. It is with respect to NOx and particulate emissions that methanol-fueled vehicles offer the greatest benefits. Although current unleaded gasoline-fueled vehicles emit very low levels of particulate and generally have fairly low NOx levels as well due to three-way catalytic converters, diesel vehicles emit relatively high levels of both pollutants. As petroleum prices have risen in the last five years, so has the popularity of diesel vehicles. Furthermore, it is expected that diesel fuel quality will continue to worsen in the future which would likely result in even higher diesel emissions. Methanol utilization may be one alternative for achieving the

energy efficiency of the diesel while maintaining very low NOx and particulate levels. Methanol would also produce lower levels of heavy organics and sulfur-bearing compounds.

There are three remaining emission-related issues of methanol use: the impact on photochemical oxidant levels, ambient methanol levels, and ambient formaldehyde levels.

As was shown in Tables 3 and 4 above, the methanol-fueled light-duty vehicles emitted somewhat more, and the methanol-fueled heavy-duty engine emitted somewhat less, total organics than did the gasoline and diesel-fueled baseline vehicles. But the primary justification for the regulation of organic emissions is not direct health impacts associated with the specific organic compounds themselves, but rather is their role as photochemical oxidant precursors in urban atmospheres. It is well known that different organic compounds have varying impacts on the photochemical oxidant process. Therefore, the relative masses of organic emissions in gasoline, diesel, and methanol exhausts are not as important as the relative photochemical reactivities of the species involved. Methanol-fueled vehicle exhaust is composed primarily of unburned methanol with the remainder almost entirely formaldehyde. While formaldehyde is known to be very photochemically reactive, unburned methanol itself is generally considered to be of low reactivity. Methanol exhaust contains almost no alkenes, aromatics, or nonmethane alkanes which are the major reactive components of gasoline and diesel exhausts.

It has been suggested that because of the dominance of unburned methanol, with its apparently low reactivity, in methanol-fueled vehicle exhaust that there is less potential for oxidant formation than with gasoline and diesel-fueled vehicles. There is little empirical evidence for this, however, and considerable atmospheric modeling and smog chamber work should be conducted to resolve this issue. EPA will be an active participant in this research.

Clearly the use of pure methanol fuel would result in a large increase in ambient methanol levels. The determination of the possible health impacts of likely ambient methanol levels is a primary objective of EPA research in this area. Because of our need to be able to determine the possible health impacts of motor vehicle pollutants in general, EPA, through a contract with Southwest Research Institute, has developed a methodology which identifies whether expected levels of pollutants are of possible public health concern or not [10]. The methodology uses mathematical models to predict ambient concentrations of mobile source pollutants for exposure situations such as

expressways, street canyons, roadway tunnels, and personal and parking garages based on emission factors for various vehicle categories. Two scenarios, representing "typical" conditions and "severe" conditions, are utilized in most of the exposure situations. EPA utilizes health effects literature searches to suggest a range of concern for the pollutant in question. The upper level of the range of concern is that value above which the studies show that the pollutant causes serious health effects. If the exposure situations are projected to result in ambient concentrations in excess of the upper level of the range of concern, then the pollutant is considered to be a "high risk" to human health. The lower level of the range of concern is the lowest level at which there is some suggestion of adverse physiological effects. If the projected ambient concentrations of all the exposure situations are below the lower level of the range of concern, then the pollutant is not considered to be a serious health risk. The region between the lower and upper levels of concern is the "range of concern" which indicates the bounds of uncertainty of adverse physiological effects based on the different health effects studies in the literature. If the exposure situations are projected to result in ambient concentrations within the range of concern for a particular pollutant, then the use of the particular technology/fuel should be subject to closer scrutiny.

EPA recently performed a preliminary study of the health effects of methanol based on a comprehensive literature search [11]. It considered the three primary methods of methanol intake: inhalation, ingestion, and skin absorption. Inhalation will be discussed in this portion of the paper, since it is related to the issue of methanol combustion emissions. Ingestion and skin absorption will be discussed later in the paper.

Inhalation studies reported in the literature have shown a wide range of effects. Headaches have been reportedly caused from inhaling methanol concentrations as low as 22 milligrams per cubic meter (mg/m^3). The odor threshold may be as low as 5 mg/m^3, although some studies indicate that the odor threshold is much higher. The OSHA work place standard for methanol is 200 mg/m^3 maximum. The threshold limit value (TLV) is 260 mg/m^3, with a 310 mg/m^3 short-term limit.

EPA will utilize the methodology described above to identify a range of concern for ambient methanol concentrations and to calculate projected ambient concentrations under various exposure situations. The contractor report on methanol health effects has suggested that a range of 1.0 to 3.0 mg/m^3 be considered for the lower limit of the range of concern for

ambient methanol concentrations [11]. EPA has performed some very preliminary air quality projections for various exposure scenarios assuming that the entire vehicle fleet were operating on methanol with 75 percent of the fleet involving successful catalytic converter operation and 25 percent of the fleet lacking effective aftertreatment (due either to no catalyst or an inoperative one). These early results indicate that under most of the worst-case exposure situations the ambient methanol concentrations would likely be below 3.0 mg/m^3, but that the most severe worst-case scenarios, such as the severe roadway tunnel and personal garage situations, might well be above that level. These are tentative results and EPA will be refining this analysis in the future.

The use of methanol fuel would also increase formaldehyde emissions. Table 6 lists formaldehyde emission levels for a variety of passenger cars that EPA has tested. It can be seen that formaldehyde emission levels from catalyst equipped methanol-fueled vehicles are similar to formaldehyde levels from non-catalyst equipped gasoline-fueled vehicles, but higher than the levels from catalyst-equipped gasoline-fueled vehicles. EPA is using the same methodology described above to define the possible health impacts of increased formaldehyde emissions. A preliminary formaldehyde health effects study has been performed based on a review of the literature [12]. Formaldehyde is a strong irritant of the human eye, nose, and throat and is capable of causing allergic sensitization. Acute human exposure to concentrations of 1.0 mg/m^3 have resulted in such irritation, as well as other effects such as changes in breathing rhythms and alpha-ryhthms. Slight irritation has been observed at levels as low as 0.2 mg/m^3. Odor thresholds range from 0.4 to roughly 0.01 mg/m^3 for sensitive subjects. The threshold limit value for formaldehyde is 3.0 mg/m^3.

Based on the formaldehyde health effects literature review, our contractor has suggested that the lower limit of the range of concern for ambient formaldehyde concentrations be either 0.06 or 0.2 mg/m^3. It recommended 0.2 mg/m^3 as the "most defensible choice" since formaldehyde levels as high as 0.1 mg/m^3 have been detected in the human breath of both smokers and non-smokers [12]. Again assuming that all motor vehicles were utilizing methanol fuel, with successful catalytic aftertreatment on 75 percent of those vehicles, our preliminary analysis indicates that most of the exposure situations would result in formaldehyde concentrations below 0.2 mg/m^3. Concentrations under the severe roadway tunnel and personal garage scenarios could exceed 0.2 mg/m^3. It must also be emphasized that this analysis is still in its infancy and much further work is necessary.

The methodology described above will focus only on the toxicological and non-carcinogenic effects of formaldehyde. In addition, formaldehyde has been shown to cause cancer in certain animal tests. The federal government is currently developing a general policy for use by federal agencies in regulating carcinogens. Thus, it is not now possible to predict the impact of any cancer-related regulation on methanol-fueled vehicles.

Because of the toxicological and carcinogenic concerns over formaldehyde, as well as its high photochemical reactivity, it is clear that formaldehyde emission control will be an important consideration for automotive manufacturers. Research testing of current technology catalytic converters has shown that they are able to remove up to and perhaps more than 90 percent of the formaldehyde from methanol-fueled vehicles. Nevertheless, reducing engine-out formaldehyde emissions and optimizing catalytic reductions will undoubtedly be high priorities if methanol-fueled vehicles are to come into general use.

Non-Emission-Related Issues

The previous section analyzed those environmental impacts which would be expected due to the emissions from methanol-fueled vehicles. This section will discuss other health and safety concerns associated with the handling, transport, and usage of methanol fuel. The following concerns have been identified: 1) ingestion and skin absorption of liquid methanol, 2) the near-invisible flame of methanol fires, 3) the fact that methanol vapors inside a fuel tank are likely to be ingitable, and 4) the impacts of a large methanol spill.

Methanol is highly toxic in heavy exposures, leading to blindness or death. Much of its notoriety in this area is due to people confusing it with ethanol and drinking it in large quantities. Hydrocarbon fuels, while also being toxic, do not suffer from this confusion and are not often taken internally. The absorption of methanol through the skin is also hazardous, more so than gasoline (though the presence of benzene in gasoline complicates this issue). Given the public's rather careless use of gasoline, widespread use of methanol would pose some concerns in this area. EPA's recent study on the health effects of methanol also considered ingestion and skin absorption of methanol [11], and results from that study will be summarized here.

Methanol was a frequent component of liniments, perfumes, and some patent medicines well into this century. It has seen widespread use as a solvent and as a high volume chemical.

While bioassay studies with methanol are limited, current results suggest that methanol is not mutagenic. Defining safe exposure and dose levels is extremely difficult because of the very large variability in individual response. In addition, the toxic effects are generally delayed (twelve to eighteen hours after dose) and may be as severe as blindness and even death. If death does occur, it is generally attributed to respiratory failure. To illustrate the wide variability and individual sensitivity to methanol ingestion, one death was reported in the literature from a dose of only 6 milliliters (ml) of methanol (about 1 teaspoon) while recovery has been reported for a 500 ml dose. Receiving a significant methanol dose through skin absorption is a real concern as the skin absorption rate is reported to be 0.2 milligrams per square centimeter per minute.

Based on the data available in the literature, a lower limit for the range of concern for methanol ingestion of between 0.1 and 1.0 ml has been suggested by our contractor [11]. Skin contact should also be avoided as 0.1 ml corresponds to approximately two drops of methanol. While some treatment is available for methanol ingestion, it seems prudent that every reasonable effort should be made to avoid methanol ingestion and skin contact. Several actions can be taken to address these concerns. A major public education campaign emphasizing the risk of methanol exposure would be fundamental. Use of the term methyl alcohol should probably not be permitted; perhaps a non-alcohol fuel name would be wise. Warning labels on dispensers and containers would need to be reviewed for effectiveness.

Another concern with methanol use is that the methanol flame is essentially invisible in daylight. Although methanol flames are cooler than gasoline flames and extinguish with water, methanol/water concentrations down to about 26 percent methanol are still flammable. On the other hand, methanol has a higher flashpoint and ignition temperature than gasoline, thus in open air it is considered less of a fire hazard than gasoline.

Due to methanol's volatility characteristics, the vapors in a methanol tank would be expected to be flammable. However, flame arresters in the tank filler neck or bladder tanks seem capable of mitigating this concern. Also, the electrical conductivity of methanol is higher than for gasoline which reduces the problem of static discharge causing ignition.

The possibility of using additives with methanol should be

investigated to help alleviate these concerns. Methanol additives should be sought which would: 1) cause vomiting if ingested, 2) make ingestion, inhalation and skin contact unattractive (e.g., unpleasant smell, or dye), and 3) provide a visible flame.

A final point which deserves mentioning is the difference between the impact of an oil spill and a methanol spill. The effects of oil spills are well known. The effects of a methanol spill are expected to be quite different, primarily because methanol is soluble in water. While high levels of methanol are toxic to fish and fauna, a methanol spill would probably quickly disperse to nontoxic concentrations and, particularly in water, leave little trace of its presence afterwards. Water life should be able to migrate back and plant life should begin to grow back fairly quickly, though complete renewal would take the time necessary for new plants to grow.

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Table 1

Average Light-Duty Vehicle
Emission And Energy Efficiency Results
Over the Federal Test Procedure

	Ford Escorts		VW Rabbits	
	Gas[a]	Meth[b]	Gas	Meth
Hydrocarbons (FID), g/mi	0.37	0.42[c]	0.11	0.39[c]
Carbon Monoxide, g/mi	4.49	6.03	1.08	0.88
Oxides of Nitrogen, g/mi	0.55	0.40	0.16	0.68
Particulate, mg/mi	9.2	6.3	11.8	4.7
Methanol, mg/mi	ND[d]	407	ND	440
Total Aldehydes and Ketones, mg/mi	0.2	33.6	ND	10.3
Formaldehyde, mg/mi	0.2	33.0	ND	10.3
Total Individual Hydrocarbons, mg/mi	155	50	40	5
Methane, mg/mi	96.1	48.3	14.0	4.8
Ethylene, mg/mi	8.7	0.3	4.8	0.2
Ethane, mg/mi	18.2	0.5	2.6	0.1
Acetylene, mg/mi	1.4	0.1	1.8	0.1
Propane, mg/mi	0.8	0.6	ND	ND
Propylene, mg/mi	6.1	ND	4.2	ND
Benzene, mg/mi	6.3	0.1	5.3	ND
Toluene, mg/mi	17.2	0.1	9.2	ND
Nitrosamines, mg/mi	ND	ND	ND	ND
Ammonia, mg/mi	[e]	10.0	[e]	[e]
Total Cyanide, mg/mi	[e]	ND	[e]	[e]
Total Organic Amines, mg/mi	[e]	0.1	[e]	[e]
Methyl Nitrite, ppm	[e]	0-0.5	ND	0-1.1
Energy Efficiency, mi/10^4 Btu	2.16	2.25	2.10	2.46

[a] Gasoline-fueled.
[b] Methanol-fueled.
[c] Hydrocarbons as measured by the FID (flame ionization detector) and expressed as methanol.
[d] None detected.
[e] Analysis not conducted.

Table 2

Average Heavy-Duty Engine Emission
And Energy Efficiency Results Over
The Transient Federal Test Procedure

	Volvo Diesel TC* No Cat	MAN Diesel TC, IC* No Cat	MAN Methanol NA* W/Cat
Hydrocarbons,[a] g/hp-hr	0.85	0.85	0.04
Carbon Monoxide, g/hp-hr	3.01	3.16	0.31
Oxides of Nitrogen,[b] g/hp-hr	8.34	8.54	6.61
Particulate, g/hp-hr	0.52	0.37	0.04
Methanol, mg/hp-hr	[c]	[c]	680
Total Aldehydes and Ketones, mg/hp-hr	10	[d]	1
Formaldehyde, mg/hp-hr	10	[d]	1
Total Phenols, mg/hp-hr	26	[d]	0
Total Individual Hydrocarbons, mg/hp-hr	97	[d]	1
Methane, mg/hp-hr	11	[d]	1
Ethylene, mg/hp-hr	78	[d]	1
Ethane, mg/hp-hr	1	[d]	1
Acetylene, mg/hp-hr	2	[d]	1
Propylene, mg/hp-hr	6	[d]	1
Benzene, mg/hp-hr	1	[d]	1
Sulfate, mg/hp-hr	28	[d]	[c]
Benzo(a)pyrene, ug/hp-hr	2.8	[d]	0.01
Fuel Consumption lb diesel equivalent/hp-hr	0.476	0.451	0.538
Smoke, peak percent opacity	33	[d]	0

* NA = Naturally Aspirated, TC = Turbocharged, IC = Intercooled; the brake specific fuel consumption is directly affected by the technology employed with improvements expected in going from NA to TC to IC. Therefore, direct efficiency comparisons are not possible.

[a] Hydrocarbons as measured by the HFID (heated flame ionization detector) and expressed as diesel-like species.

[b] No NOx correction factor used.

[c] Does not apply.

[d] No analysis performed.

Table 3

Average Light-Duty Vehicle
Organic Emission Results Over the Federal
Test Procedure (g/mi)

	Ford Escorts		VW Rabbits	
	Gas.	Meth.	Gas.	Meth.
Hydrocarbons [a]	0.37	0.05	0.11	0.005
Methanol	0	0.41	0	0.44
Formaldehyde	0.0002	0.033	0	0.010
Total Organics	0.37	0.49	0.11	0.46

[a] For the gasoline-fueled vehicles, this is the FID value. For the methanol-fueled vehicles, this is the sum of the individual hydrocarbon data from Table 1.

Table 4

Average Heavy-Duty Engine Organic Emission Results
Over the Transient Federal Test Procedure (g/bhp-hr)

	Volvo Diesel TC* No Cat	MAN Diesel TC,IC* No Cat	MAN Methanol NA* W/Cat
Hydrocarbons	0.82[a]	0.85	0.001[b]
Methanol	0	[c]	0.68
Aldehydes and Ketones	0.01	[c]	0.001
Phenols	0.03	[c]	0
Total Organics	0.86	0.85	0.68

* NA = Naturally Aspirated, TC = Turbocharged, IC = Intercooled.
[a] From Table 2, hydrocarbons less phenols.
[b] From Table 2, total individual hydrocarbons.
[c] No analysis performed.

Table 5

Methanol Catalyst Preliminary Summary

Catalyst	HC(FID) g/mi	CO g/mi	NOx g/mi	HCHO mg/mi
No Catalyst	0.90	7.70	2.17	330
VW Stock - 0% O_2	0.15	0.80	0.56	18
VW Stock - 3% O_2	0.19	0.73	1.80	23
A - 0% O_2	0.11	0.69	0.62	12
A - 3% O_2	0.12	0.39	2.01	16
B - 0% O_2	0.13	0.77	0.76	11
B - 3% O_2	0.13	0.40	2.05	14
C - 0% O_2	0.15	1.47	0.85	30
C - 3% O_2	0.16	0.35	2.07	73
D - 0% O_2	0.17	1.99	0.74	42
D - 3% O_2	0.14	0.38	1.98	68
E - 0% O_2	0.28	2.85	1.97	-*
E - 3% O_2	0.28	2.05	1.95	-

* Results not complete.

Table 6

Comparison of Average FTP Formaldehyde Emissions for Various Light-Duty Vehicles

	HCHO Emissions (mg/mile)
Gasoline-Fueled Vehicles	
1981 3-way-catalyst equipped cars	1
1978, 1979 3-way-catalyst equipped cars	2
1978 oxidation-catalyst equipped cars	3-11
1977 non-catalyst cars	16
1970 non-catalyst cars	51
Methanol-Fueled Vehicles	
1981 3-way-catalyst equipped, carbureted car (Escort)	33
1981 3-way-catalyst equipped, fuel injected car (Rabbit)	10

Figure 1

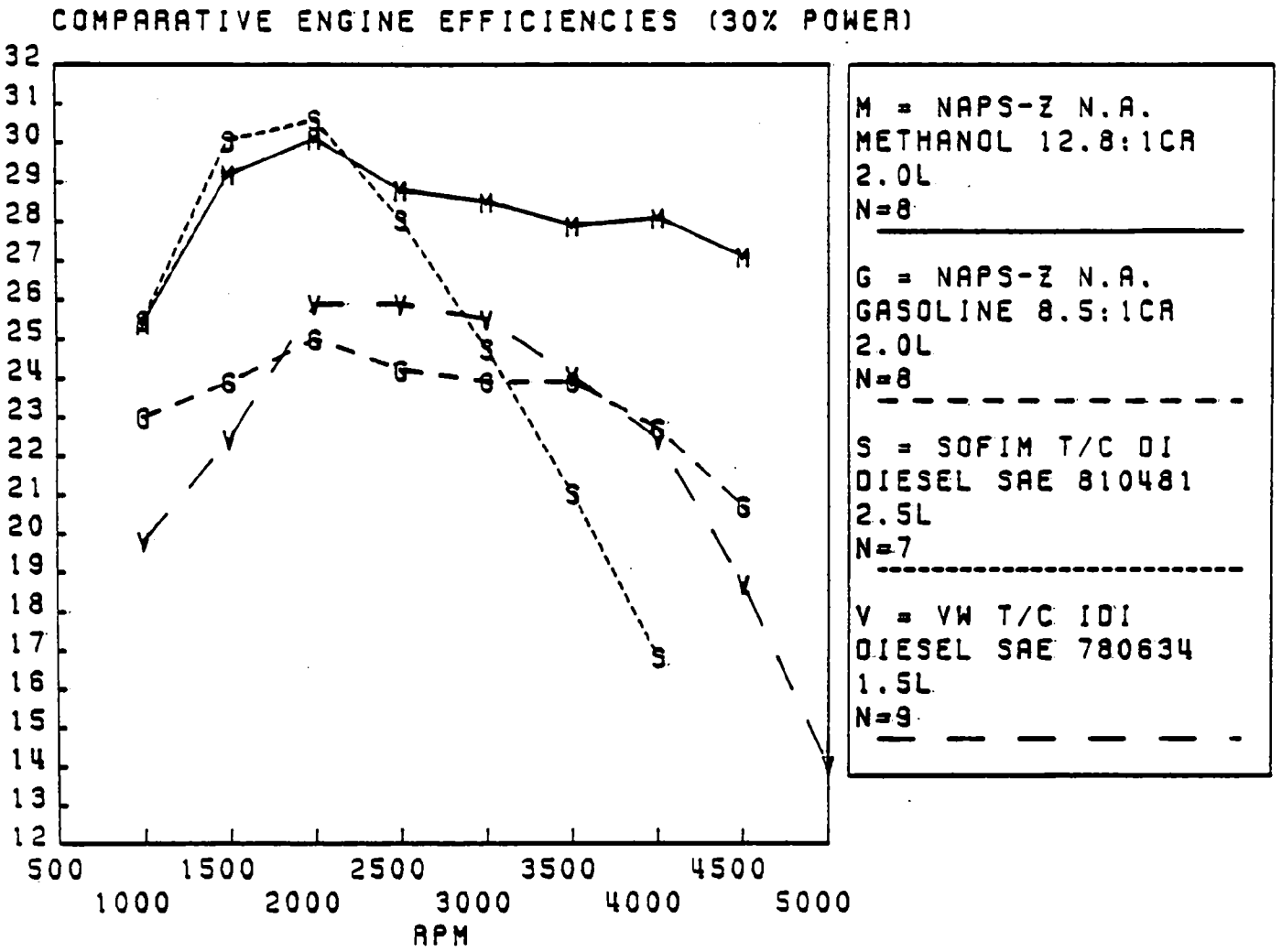

COMPARATIVE ENGINE EFFICIENCIES (30% POWER)
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
RPM
M = NAPS-Z N.A.
METHANOL 12.8:1CR
2.0L
N=8
G = NAPS-Z N.A.
GASOLINE 8.5:1CR
2.0L
N=8
S = SOFIM T/C DI
DIESEL SAE 810481
2.5L
N=7
V = VW T/C IDI
DIESEL SAE 780634
1.5L
N=9

Figure 2

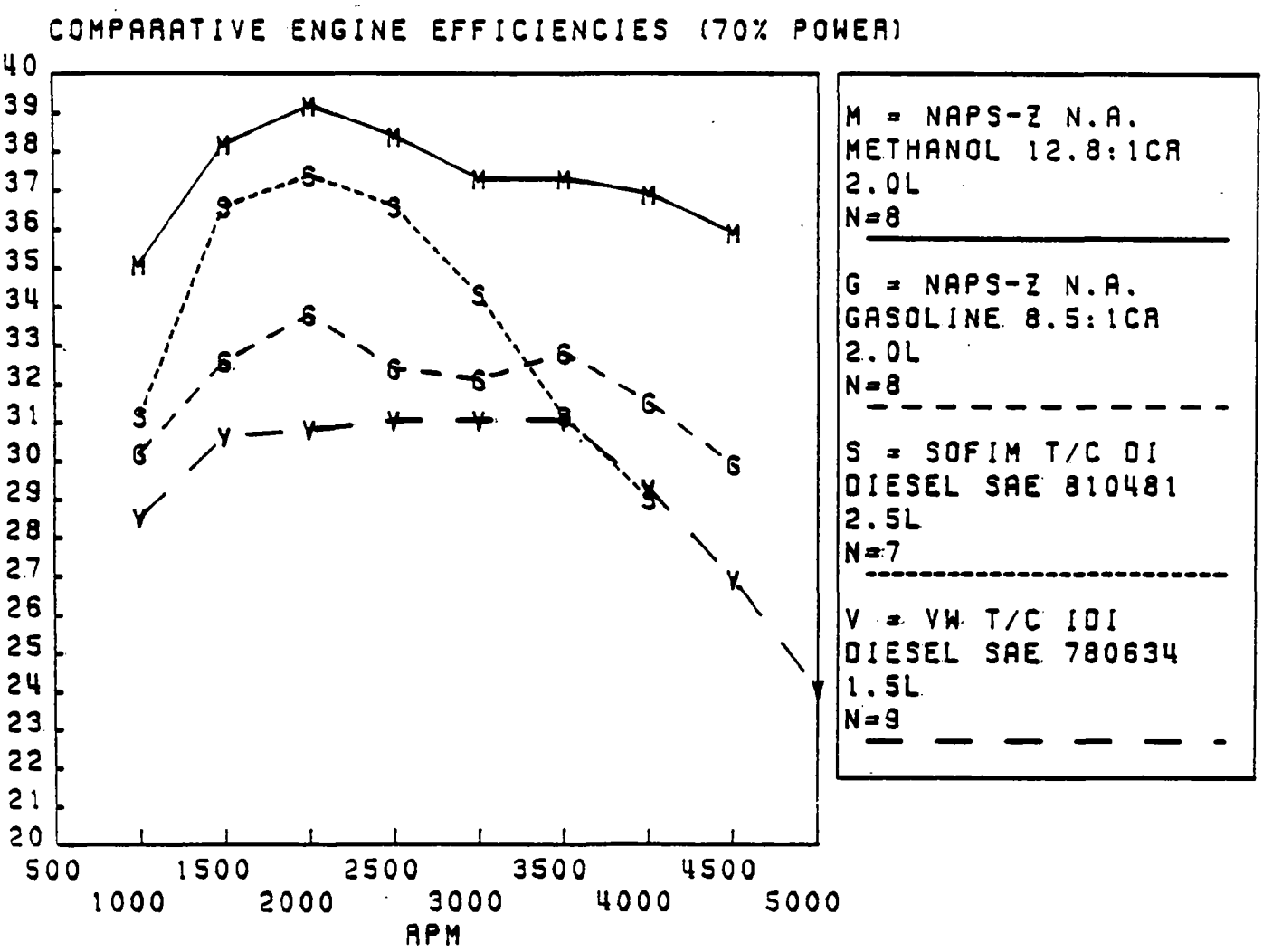

COMPARATIVE ENGINE EFFICIENCIES (70% POWER)
40
39
38
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
RPM
M = NAPS-Z N.A.
METHANOL 12.8:1CR
2.0L
N=8
G = NAPS-Z N.A.
GASOLINE 8.5:1CR
2.0L
N=8
S = SOFIM T/C DI
DIESEL SAE 810481
2.5L
N=7
V = VW T/C IDI
DIESEL SAE 780634
1.5L
N=9

Figure 3

HRCC ENGINE RESULTS
2OREV/S 1.5 BMEP BAR

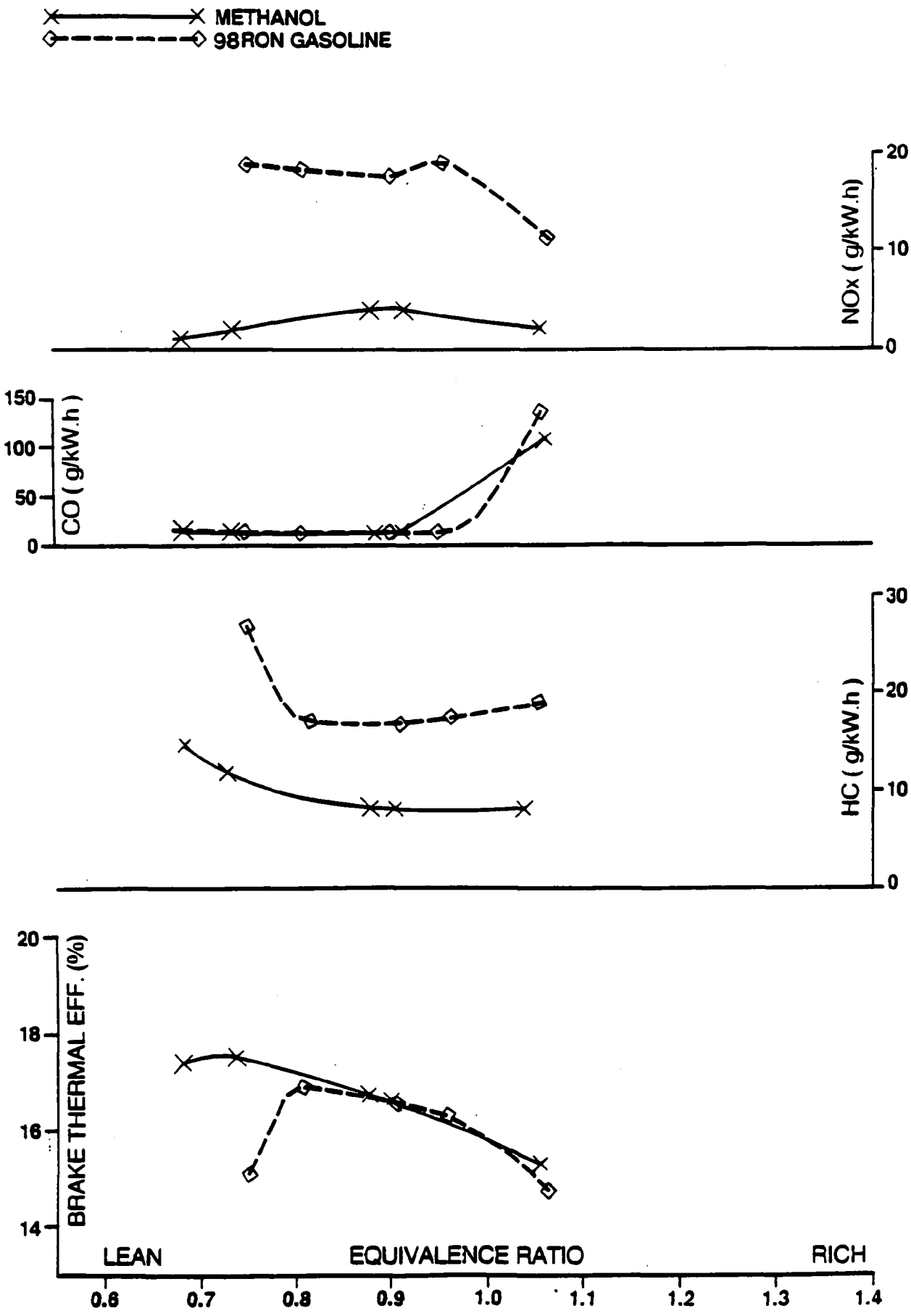
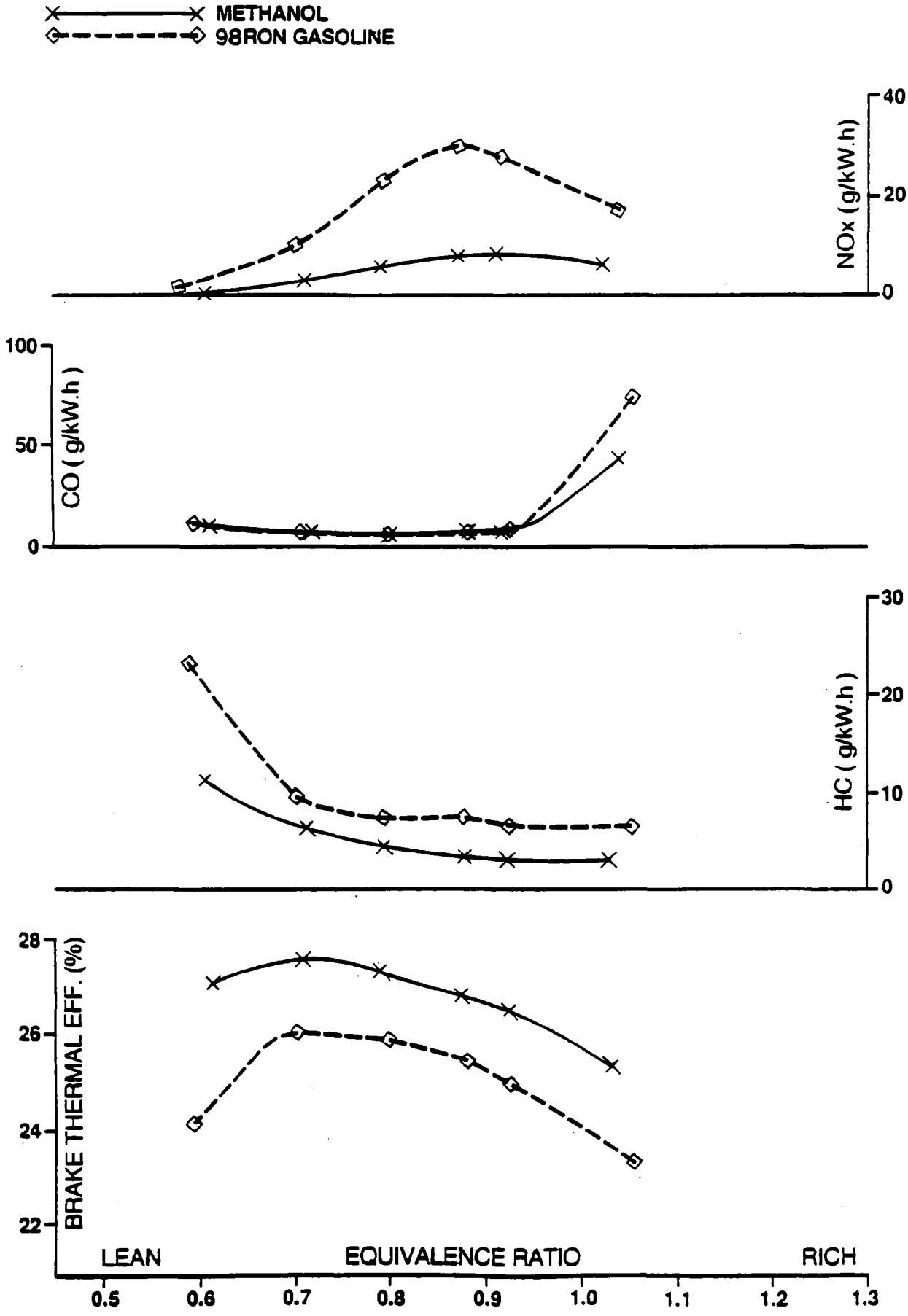


Figure 4

HRCC ENGINE RESULTS
60REV/S 4.0 BMEP BAR



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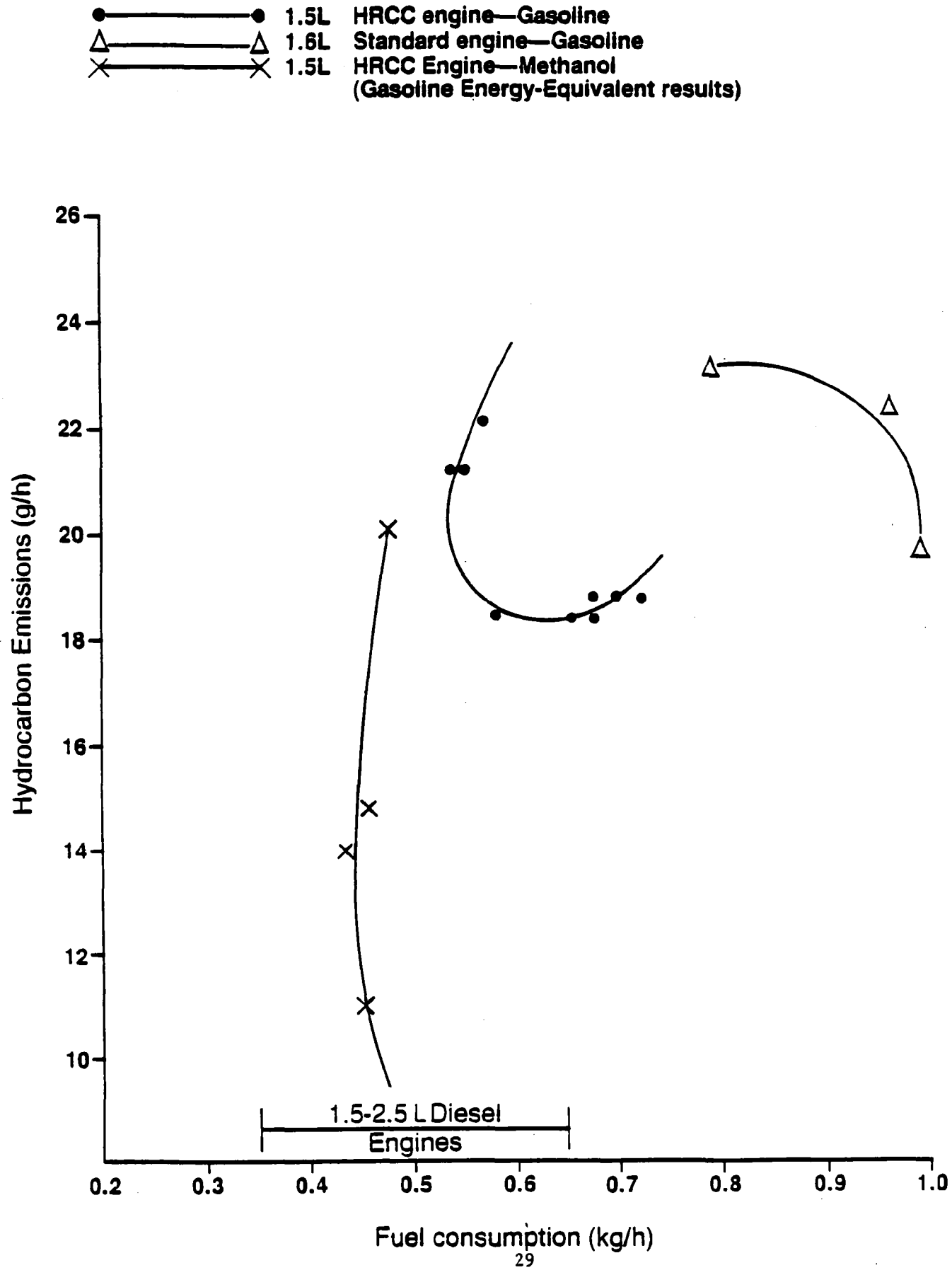
HRCC IDLE TESTS—900 RPM