EPA/AA/CTAB-89-02

Technical Report

Conversion of Methanol-Fueled 16-Valve, 4-Cylinder Engine to Operation On Gaseous $2H_2/CO$ Fuel - Interim Report II

by

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March 1989

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Technical Reports do not necessarily represent final EPA decisions or positions. They are intended to present technical analysis of issues using data which are currently available. The purpose in the release of such reports is to facilitate the exchange of technical information and to inform the public of technical developments which may form the basis for a final EPA decision, position or regulatory action.

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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OFFICE OF
AIR AND RADIATION

APR 24 1989

MEMORANDUM

SUBJECT: Exemption From Peer and Administrative Review

FROM: Karl H. Hellman, Chief
Control Technology and Applications Branch

TO: Charles L. Gray, Jr., Director
Emission Control Technology Division

The attached report entitled, "Conversion of Methanol-Fueled 16-Valve, 4-Cylinder Engine to Operation On Gaseous $2H_2/CO$ Fuel - Interim Report II," (EPA/AA/CTAB/89-02) describes progress to date on a project to convert a Nissan CA18DE engine previously modified for operation on M100 neat methanol to operation on dissociated methanol ($2H_2/CO$) gaseous fuel. This engine has been operated on both M100 and simulated dissociated methanol (hydrogen and carbon monoxide) gaseous fuels. This report describes the modifications made to the engine and summarizes the results of testing to date. Further work on this project will be described in a future technical report.

Since this report is concerned only with the presentation of data and its analysis and does not involve matters of policy or regulations, your concurrence is requested to waive administrative review according to the policy outlined in your directive of April 22, 1982.

Concurrence: Charles Gray Date: 4-19-89
Charles L. Gray, Jr., Dir., ECTD

Nonconcurrence: ______________ Date: ________
Charles L. Gray, Jr., Dir., ECTD

cc: E. Burger, ECTD

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I. Summary

The work described in this report concerns the conversion of a 16-valve, 4-cylinder light-duty automotive engine to operation on a mixture of hydrogen (H_2) and carbon monoxide (CO) gaseous fuel. This engine will be evaluated to determine the difference in emission levels and lean limit operation between two different fuels: M100 neat methanol and simulated dissociated methanol gaseous fuel ($2H_2/CO$). The engine will eventually be used as a test bed for a practical, onboard methanol dissociation fuel system.

Modifications made to the test engine to enhance the characteristics of $2H_2/CO$ fuel are discussed in this report. A description of the CA18DE test engine modified for use on M100 neat methanol by Nissan Motor Co., LTD, is also included.

The engine ran very smoothly at idle and under load conditions with the simulated dissociated methanol $2H_2/CO$ fuel. Visible engine vibration from gaseous fuel operation was noticeably reduced from levels experienced with the engine operating on liquid methanol fuel.

The test engine was able to operate very lean with the $2H_2$ + CO fuel. The air/fuel (A/F) ratio was computed to be 14.8:1 at no load, 625 rpm and 26.5:1 at no load, 1500 rpm. When 10.3 BHP was being produced (27.1 ft-lb torque, 2000 rpm), the A/F ratio dropped to 11.9:1. All of these A/F values are lean when operation on $2H_2$ + CO is concerned, since the stoichiometric A/F ratio is the same as it is for methanol, 6.4:1. The leanest A/F ratio 26.5:1, is much closer to the stoichiometric A/F ratio for H_2 (34:1) than it is to that of CO (2.5:1) so the operation seems to be enhanced by the H_2 in the gaseous fuel.

A direct comparison of emissions test results from the engine when it was alternately fueled with M100 and $2H_2/CO$ fuels is not possible at this time. The testing with M100 fuel utilized a catalytic converter in the exhaust stream while $2H_2/CO$ fuel results are engine-out emissions. The $2H_2/CO$ fuel emissions test results may vary substantially between tests because the limited amount of $2H_2/CO$ fuel in the "T" cylinder storage bottles did not permit starting and warming to steady-state conditions prior to testing.

Additional emissions testing at various engine speed/load operating conditions will be conducted to better characterize the emissions profile of this engine when operated on both M100 and dissociated methanol. A/F ratio under these test conditions will also be determined.

II. Introduction

Section 211 of the Clean Air Act [1] requires the U.S. Environmental Protection Agency (EPA) to play a key role in the introduction of new motor vehicle fuels. EPA studies [2] have suggested that methanol stands out from other alternative transportation fuels from an environmental perspective. The use of alcohol fuels can also play a significant role in the reduction of the foreign trade deficit and aid the security interests of the United States by reducing U.S. dependence on imported petroleum.[3]

Methanol may be catalytically decomposed to H_2 and CO gases according to the reaction:

$$CH_3OH_{(l)} \text{ ---- } 2H_{2(g)} + CO_{(g)}$$

The decomposition of methanol to this gaseous fuel mixture has been postulated as a more efficient method of using methanol as a light-duty motor vehicle fuel. The major attraction of methanol decomposition is that the resulting gases have a higher heating value per pound than the original liquid methanol. Bechtold [4] states that the lower heating values for the decomposed gas are 11520 and 10850 BTU per pound, for methanol decomposed by decomposition and steam reforming, respectively. This compares favorably with 9600 BTU per pound for liquid methanol.

Light-duty M100 neat methanol-fueled engines are also difficult to start and run in cold weather because of the high boiling point of methanol, methanol's high heat of vaporization (5.5 percent of the heat of combustion compared to less than 1 percent for gasoline), and the increased fuel flow needed for methanol (about double that of gasoline). Gasoline-fueled engines start with less difficulty under the same conditions partly because of the easily ignitable light ends of this fuel such as butanes, which are vaporized at relatively low temperatures. Hydrogen's higher flame speed and lower boiling point may make it an ideal cold start fuel. The nature of the decomposed methanol fuel may also reduce emissions measured as HC below levels from similarly sized methanol-fueled engines.[5]

Numerous research studies have been conducted to determine the practicality of dissociated methanol as an alternative light-duty automotive fuel.[6,7,8,9,10] Ricardo Consulting Engineers, U.K., has contracted to build, optimize and demonstrate for the U.S. EPA an engine fueling system using dissociated methanol product gas.[11] Methanol would be dissociated onboard the vehicle using a catalyzed dissociator; heat from the engine exhaust system would be used to provide energy for the endothermic dissociation reaction.

In order to assist this program at Ricardo, a project was begun to convert a methanol-fueled engine to operation on $2H_2/CO$ gaseous fuel. The goal of this project was to modify a 16-valve, 4-cylinder light-duty automotive engine for use with $2H_2/CO$ gaseous fuel and to evaluate this engine using two fuels:

1. $2H_2/CO$ bottled gas (in the same molar proportions as dissociated methanol, $2H_2/CO$); and

2. M100 neat methanol (liquid fuel).

The criteria for evaluation was the engine's ability to run without driveability problems at the lean limit of operation and emission levels over several steady-state speed and load conditions. Once the conversion and initial testing were completed, the engine was to be used as a test engine for the onboard dissociator under development at Ricardo. This report contains a summary of the work to date performed to facilitate conversion to the gaseous fuel, as well as results from initial testing of the engine on both liquid and gaseous fuels.

III. Description of Test Engine

The test engine used for this project was a Nissan CA18DE engine. This engine is an in-line, 4-cylinder, 1.8-liter capacity powerplant. The valve arrangement is a 4-valve per cylinder configuration, consisting of two intake and two exhaust valves per cylinder. The valves are operated by two overhead camshafts, one each for the intake and exhaust side. The stock gasoline-fueled version of this engine has a compression ratio of 10.0 and a standard compression pressure of 14.0 kg/cm^2 at 350 rpm.

A CA18DE engine was modified by Nissan Motor Company, LTD to better utilize the qualities of M100 neat methanol, rather than unleaded gasoline. Metal from the bottom of the head was shaved in order to increase the compression ratio to 11.0. Standard compression pressure was raised to 16.5 kg/cm^2 at 350 rpm by this modification. A detailed description of engine specifications from this engine after the modifications made for methanol compatability is given in Appendix A.

Two external control devices were also added by Nissan as modifications to the stock engine. The first, an air/fuel mixture control device, varied air/fuel ratio by controlling fuel injection quantity. Excess air ratio (lambda) may be varied from 0.5 to 2.0 through the use of this control. The second device varied ignition timing between 0° before top dead center (BTDC) and 54° BTDC.

Following the conversion from gasoline to M100 fuel operation, Nissan Motor Company, LTD lent this engine to the U.S. EPA for use with methanol fuel research efforts.

IV. Modifications For $2H_2/CO$ Fuel Operation

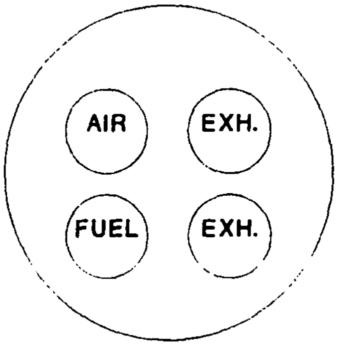
Several modifications to the engine were necessary in order to operate on $2H_2/CO$ fuel; these modifications are discussed below. Included also is a discussion of the bottled gas fueling system.

A. Engine Modifications

Dissociated methanol product gas is a mixture of H_2 and CO gases in the molar ratio $2H_2/CO$. We did not possess a methanol dissociation system capable of generating the necessary quantities of gaseous $2H_2/CO$ fuel at the time work on this project was begun. The engine was therefore tested on a bottled gas mixture of $2H_2/CO$; several bottles of 66 volume percent H_2 and 34 volume percent CO were obtained from Linde Gases, Inc. to simulate the products of the dissociation reaction.

The Nissan CA18DE engine utilizes a 4-valve per cylinder valvetrain configuration; both the stock gasoline and M100 methanol modified versions utilize two intake and two exhaust valves per cylinder. This arrangement was modified to allow for admission of air to the cylinder through one intake valve only; the second intake valve supplied the gaseous fuel. The exhaust-side valve scheme was not modified (Figure 1).

FIGURE 1



VALVE SCHEME

2H2/CO FUEL CONVERSION

NISSAN CA18DE ENGINE

The advantages of structuring the intake process this way are threefold. First, air flow into the engine may be less restricted if the fuel, already in the gaseous state, is introduced into only one of the intake runners. Second, there may be less chance of flashback and a resulting manifold ignition if fuel exclusively, and not a combustible fuel/air mixture, is introduced at an intake valve. Finally, fuel may enter the combustion chamber at the designer's discretion, rather than at the same time the air needed for combustion is admitted.

It was necessary to alter the fuel and air intake system in order to allow for the admission of gaseous fuel only through one of the intake valves. An intake air control assembly encloses the swirl control valves and is situated between the intake manifold and the combustion chambers on the liquid-fueled engine. This assembly controls the air flow so that it is through one intake runner and/or through both intake runners as necessary. This is to control in-cylinder charge motion on the liquid-fueled engine. The control valve slide and actuator were disassembled and the swirl control valves removed. The runners through the valve assembly that contained wells for fuel injectors were welded shut approximately 1/2-inch upstream from the well holes. These seals prevent the admission of air to the ports through which the gaseous fuel passes.

The hole in the assembly left by the power valve slide was sealed to prevent leakage of fuel and air between runners. A metal impregnation technique was used to seal the holes. The sealed holes were then coated with a layer of epoxy.

Fuel injectors are not used to feed the gaseous state fuel. The rail and the individual injectors were removed and 3/8-inch inside diameter stainless steel pipe fittings were used in their place. The stainless steel fittings were threaded and the insides of the aluminum injector wells were then threaded to accept the fittings.

Stock dual-overhead camshafts were used by Nissan to equip the CA18DE engine modified for use on M100 methanol. A drawing of the stock intake-side camshaft is presented in Figure 2. It was necessary to redesign the intake side lobes in order to accommodate the air/fuel induction strategy depicted in Figure 1 for the gaseous fuel. Figure 2 also presents the air/fuel lobe scheme for the intake camshaft when operated on gaseous fuel.

Nissan reported that the valve timing events for the M100-modified engine were similar to those of the stock gasoline-fueled version. Valve timing was measured independently, however, as these measurements were necessary as a point of reference for the redesign of the intake side camshaft. These measurements are given in Table 1. Table 2 is a summary of the intake valve events in a stock (gasoline-fueled) engine as well as the measured events from the modified engine.

FIGURE 2
CA18DE ENGINE INTAKE CAMSHAFT -
FUEL/AIR CAM LOBES INDICATED

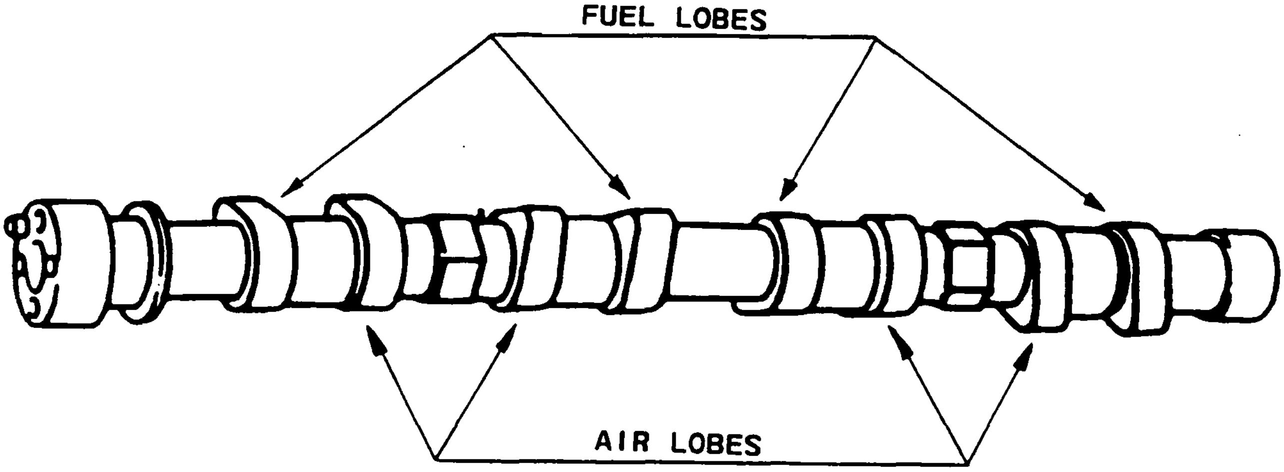


Table 1

Stock Intake Valve Event Timing Measured By EPA

Crankshaft Position	Valve Lift
7-1/2 degrees ATDC	.005 inches
15 degrees ATDC	.020 inches
24 degrees ATDC	.050 inches
35 degrees ATDC	.100 inches
59 degrees ATDC	.200 inches
129 degrees ATDC	.332 inches (maximum lift)
17 degrees ABDC	.200 inches
42 degrees ABDC	.100 inches
53-1/2 degrees ABDC	.050 inches
65 degrees ABDC	.020 inches
91-1/2 degrees ABDC	.005 inches

It should be noted that a valve lift of .005 inch was used to denote valve-open and valve-closed events. The criteria Nissan used to define opening and closing was not available. There is a substantial difference, evident in Table 2, between the valve timing information provided by Nissan and the timing measured by EPA. The definition of what constitutes valve opening may explain some of this difference. Also, Nissan milled the engine head to increase the compression ratio on the M100-modified engine; this modification may also account for much of the timing difference.

The production of the intake camshaft to accommodate $2H_2/CO$ fueling was outsourced to General Kinetics Co. Inc., Detroit, MI. A summary of the camshaft specifications for the redesigned shaft is given in Table 3. Timing and design for the air as well as the fuel cams was altered. Air valve opening commences at 15 crankshaft degrees before top dead center (BTDC), and closes at 30 crankshaft degrees after bottom dead center (ABDC). Opening of the fuel valve commences at 15 degrees ABDC: it closes at approximately 65° BTDC, for an open time of 100 crankshaft degrees. The height of the fuel valve lift is .0787 inch. Valve head diameter for both air and fuel valves are similar to stock intake valve, 1.340 inch.

The intake cam lobes on the stock camshaft opened the valves through a hydraulic lifter mechanism. To accommodate the acceleration change caused by shortening the cam event to 100° from 248° while maximizing valve lift, it was necessary to increase the diameter of the base circle of the fuel cam. Lengthening the base circle diameter of the fuel cam, while maintaining the same lift, mitigates wear caused by the contact of the sharply accelerating cam on the lifter, hence increasing lifter durability.

The stock hydraulic lifter system, however, was clearly unacceptable for the increased base circle diameter of the fuel lobes. Had the stock lifter been used, contact with the lengthened cam base circle would have kept the fuel valves open continuously. It was necessary, then, to replace the hydraulic lifters with mechanical lifters that could be tailored to the new base circle height. A lash of .003 inch was also added to the new mechanical lifters to improve wear. The design and construction of the mechanical lifters was done by Batten Engineering of Romulus, MI.

A 4-cylinder light-duty automotive engine with a stock valve configuration similar to the test engine has been modified for H_2 fuel operation and is described in the literature.[12] Though our gaseous fuel was of a different composition than the pure H_2 fuel in reference 12, this paper was useful because it described a modified fuel system that could potentially be adapted for our application. The valve timing information was of particular interest to us; the fuel valve timing specifications were used as a general guide during the design of the gaseous fuel intake system for our engine.

Table 2

Stock/M100-Modified Intake Camshaft Specifications

Specification	Standard CA18DE Engine	Measured By EPA On M100-Modified Engine
Cam height	1.5939--1.5951 inches	--
Valve Lift	.335 inches	.332 inches
Valves open* (crankshaft degrees)	15° BTDC	7.5° ATDC
Valves close*	53° ABDC	91.5° ABDC

-- Indicates not measured by EPA.

* Lift = 0.005 inches measured by EPA; criteria not available for standard engine.

Table 3

Intake Camshaft Specifications - $2H_2/CO$ Fuel Modification

Specification	Air Valve	Fuel Valve
Valve lift	.3220 inches	.0787 inches
Valve head diameter	1.340 inches	1.340 inches
Valve opens* (crankshaft degrees)	15° BTDC	15° ABDC
Valve closed* (crankshaft degrees)	30° ABDC	65° BTDC
Total value event	225°	100°

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* Valve lift = 0.005 inch.

B. Fuel System Modifications

The $2H_2/CO$ fuel is a gaseous blend with a composition of 66 and 34 volume percent H_2 and CO respectively. This fuel is stored in compressed gas cylinders ("T" size) at 1600-1800 psi. A fuel supply cylinder is anchored to a concrete safety stop outside of the test cell, approximately 10 feet from the cell wall during testing. The bottle, fitted with a regulator and pressure gauge, is opened by a hand valve prior to testing. The fuel line from the bottle is 1/4-inch stainless steel tubing, 22 feet in length from bottle to cell wall.

The stainless steel fuel line enters the cell through a hole drilled through the concrete block wall. A Gould electrically controlled solenoid valve is located in the line immediately after the wall. An electrical signal from an accutator in the control room controls the opening of the valve to accept flow from either of two lines. The first line is connected to the fuel supply while the second extends from an N_2 gas source outside the cell. This N_2 gas is used to purge the fuel lines in the cell prior to and immediately after testing. A shut-off valve in the purge line, when closed, keeps N_2 gas out of the cell fuel lines following the purge operation.

The fuel line from the cell wall to a fuel flow regulator measures approximately 54-1/2 feet. This regulator is a Twin Bay Model TB-100. Gas flow through this regulator is controlled by a flexible diaphragm. The diaphragm is opened proportionally to the pressure exerted by a stream of air provided by a tank of compressed air; the pressure exerted by this airstream is controlled by a valve located in the cell control room.

H_2/CO fuel flows from the Twin Bay regulator to a switching valve. This valve has two positions: the first supplies fuel to the engine, while the second diverts the gas stream to the scrubber during purging of the test cell fuel lines. During testing, the fuel flows from the valve to a rotameter calibrated to measure 0-10 SCFM. The fuel passes through this gauge and then through a tee; a pressure gauge in the control room is operated by flow through this tee.

The final stage of the fuel system supplies the gaseous fuel to the combustion chamber ports. From the tee mentioned above, the fuel passes to a a cylindrical plenum, this plenum serving as a header to four flexible fuel lines. Inserted in each of the four fuel lines approximately 17 inches from each cylinder is a 2-stage H_2 flame arrestor. The fuel lines are connected to threaded fittings which are screwed into the fuel injection ports in the valve control assembly. The $2H_2/CO$ fuel is supplied to the combustion chambers by the opening of the fuel valves.

V. Exhaust Analysis

Engine exhaust passes from the exhaust pipe to a 2-1/2 inch diameter flexible metal tube. This tube passes the exhaust overhead to a 6-inch rigid tube hung from ceiling supports. The rigid tube delivers the exhaust to a Philco Ford 350 cfm constant volume sampler (CVS). Total length of the flexible and rigid tube sections is 40 feet.

A gaseous sample line and electronic ties have been extended through the cell ceiling and connect the mechanical CVS with an electronic display panel in the cell control room. A fitting in the sample line at the control room enables bag sampling at this point. Analysis of bag samples is accomplished at a bank of analyzers located in another test cell. Emissions measured as hydrocarbons (HC) are measured on Beckman model 400 flame ionization detector (FID). NOx level determination is conducted on a Beckman model 951 chemiluminescent NO/NOx analyzer. CO is measured by infrared technique using a Horiba model A1A23 infrared analyzer.

Exhaust formaldehyde was measured using a dinitrophenyl hydrazine (DNPH) technique.[13] Exhaust carbonyls including formaldehyde are reacted with DNPH solution forming hydrazine derivatives; these derivatives are separated from the DNPH solution by means of high performance liquid chromatography (HPLC), and quantization is accomplished by spectrophotometric analysis of the LC effluent stream.

A second sample line extends from the CVS to a heated manifold. This manifold contains ports for three DNPH sampling cartridges. Flow to individual cartridges is controlled by three solenoid valves located downstream from the DNPH cartridges. The hot sample gas flows through a cartridge and then to a heat exchanger where the gas is cooled to 21°C.

Flow for the formaldehyde sampling system is measured with a Porter Mass Flow Controller calibrated to 5 standard liters per minute. Gaseous sample from the heat exchanger flows past a solenoid valve and is pumped through a dual filtration system to remove any water present in the sample. The pump is a Gast model 746A with a maximum rated pressure of 100 psig. The exhaust sample is then passed through the mass flowmeter where sample flowrate is determined; an electronic gauge in the control room is wired to the flowmeter and displays both flowrate and total accumulated volumetric flow through a selected DNPH cartridge.

VI. Results From Testing

Several attempts were made to characterize the emissions profile of the test engine when it was operated on M100 fuel. These test results are compared below to emission levels measured when the engine is fueled with $2H_2/CO$ to quantify any change in emission levels due to the different fuels.

Nissan requested that the engine not be operated at wide open throttle conditions due to poor intake mixing. We therefore measured emissions over speed and load conditions that do not excessively burden the engine: idle (no load), 1600 rpm/30.8 ft-lb and 2400 rpm/40.5 ft-lb.

Air/fuel ratio (A/F) and injection timing may be varied through the use of a rheostatically equipped control panel that Nissan provided with the engine. A/F ratio was measured with an NTK Micro Oxivision MO-1000 A/F ratio meter. This meter was used as a guide to control engine A/F ratio; A/F ratio was controlled to near stoichiometric conditions for testing with liquid fuel.

Following the conversion of the intake system for operation with gaseous fuel the engine was again emission tested over several modes with $2H_2/CO$ bottled gas fuel. The results from this preliminary testing on both liquid and gaseous fuels are presented in tabular form below.

Though test results from operation on both fuels by mode are presented in the same table for comparison, significant differences in test conditions occurred. These differences unfortunately make only general comparison of test results from these fuels possible.

We initially set up the engine in the liquid fuel mode with a catalytic converter in the exhaust stream. Emission results from M100 testing were of course affected by the placement of this converter in the exhaust stream. Emissions from testing on the gaseous fuel were not influenced by a catalytic converter; these are engine-out emissions. Future efforts will include additional testing which will enable a better comparison of engine-out emissions with both fuels. It is also possible to run the test engine for only a short time on the bottled gas fuel. Safety factors prohibit filling a gas T-cylinder with the $2H_2/CO$ mixture to more than 1800 psig. This is enough fuel to allow for a brief warmup and 5 minute emission test at 2000 rpm/27 ft x lbs of torque, for example. Consequently, warmed steady-state conditions were not reached prior to emissions testing on the bottled gas fuel. Adequate fuel storage for emissions testing is therefore another problem to be addressed in our future efforts.

Table 4 presents the results from emission testing with both fuels at no load idle conditions. It was not possible to warm the engine to steady-state conditions prior to testing with the gaseous $2H_2/CO$ fuel, however. Gaseous fuel testing consisted of a cold start, adjusting engine speed by varying the A/F mix until the desired speed was attained and then sampling exhaust emissions over a 5-minute period. Exhaust emissions sampling with M100 fuel was conducted over a 5-minute period with the test engine warmed to steady-state conditions (coolant and oil temperature monitored).

The engine idled at 750 rpm with M100 fuel under control of the electronic control unit; the engine was idled at various speeds with gaseous $2H_2/CO$ fuel. The engine appeared to run much smoother on the gaseous fuel; it did not appear to labor perceptibly at 575 rpm.

A/F ratio with M100 fuel operation was measured with an NTK MO-1000 meter. The warm engine was controlled to near stoichiometric conditions using the A/F control box. The A/F ratio meter proved unsuitable for the gaseous fuel mixture, however. A maximum value for lambda (A/F actual over A/F stoichiometric) of 2.29 can be displayed by the meter. This equates to an A/F ratio of 14.7 (6.4 is approximately a stoichiometric condition for M100).[14] The sensor to the meter was calibrated as if methanol fuel was being used, as the carbon/hydrogen and oxygen/carbon ratios are similar for M100 and the $2H_2/CO$ mixture. The meter indicated a lambda value of 2.29 at 625 rpm; adjustments to the fuel and air to raise the engine speed cause the meter to tilt, indicating an out-of-bounds (excessively lean for the meter) condition had been reached.

Air and fuel were measured directly into the engine in order to calculate A/F ratio for the gaseous fuel at idle. Air was measured with a hot wire anemometer through a calibrated orifice, while gaseous fuel was measured with a rotameter. An example of the calculation of A/F from this data is included in Appendix B.

A/F ratio with the gaseous fuel was very lean when compared to liquid fuel operation. A/F ratio with gaseous fuel was calculated at 14.8 for 625 rpm and no load idle conditions. The mixture became leaner as engine speed increased. Between 1200 and 1500 an A/F ratio of approximately 26.0 was measured. An A/F ratio of 26 equates to an equivalence ratio of approximately 0.25; Hama, et al. [12] obtained A/F ratios as low as 0.20 when operating on pure H_2 fuel. A graph of A/F ratio versus engine speed at no-load idle conditions for $2H_2/CO$ fuel is given in Figure 3.

Table 4

Emission Testing, Nissan CA18DE Engine M-100, $2H_2/CO$ Fuels, Cold Idle Mode

Fuel	Engine Speed (rpm)	Air/ Fuel (ratio)	HC (g/hr)	CO (g/hr)	CO2 (g/hr)	NOx (g/hr)	HCHO (mg/hr)
M100*	750	6.88	0.38	--	1826	0.05	11.9
$2H_2/CO$	575	N/A	0.01	61.96	928	--	21.5
$2H_2/CO$	625	N/A	--	98.24	1541	--	21.1
$2H_2/CO$	625	14.8	--	47.03	1475	--	28.3
$2H_2/CO$	900	N/A	0.02	66.36	1696	--	18.2
$2H_2/CO$	1000	20.2	0.28	166.01	2062	0.55	27.6
$2H_2/CO$	1000	24.3	--	247.38	1945	0.06	35.1
$2H_2/CO$	1200	26.0	--	346.15	2326	0.12	15.1
$2H_2/CO$	1250	26.5	--	261.64	2545	0.11	18.4
$2H_2/CO$	1500	26.0	0.14	439.32	3016	0.12	22.9
$2H_2/CO$	1500	26.0	--	309.06	3127	0.11	18.8

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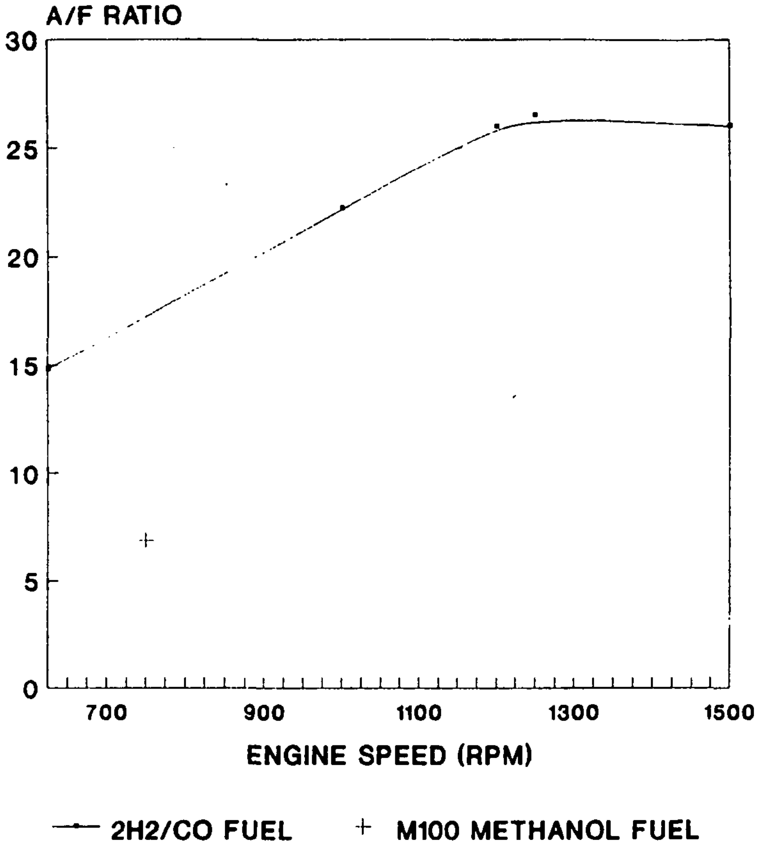
* Engine warmed to steady-state conditions; catalytic converter in place in the exhaust stream.

N/A Not available.

-- None detected.

FIGURE 3
A/F VERSUS ENGINE SPEED
NO LOAD IDLE CONDITIONS



Emissions measured as hydrocarbons (HC) with a propane calibrated FID were 0.38 grams per hour with the engine fueled with M100. Engine-out HC emissions were essentially negligible with gaseous $2H_2/CO$; two tests indicated more than insignificant amounts of HC, however. The gaseous fuel results are engine-out emissions, however, while the M100 data was influenced by the presence of a catalytic converter in the exhaust system. Additional testing will have to be conducted to confirm or deny these levels.

CO emissions are also presented in units of grams per hour. The catalyst-equipped M100-fueled engine produced no measureable amounts of CO; this was the result of a single test, however. Additional testing under engine-out conditions will have to be conducted in order to provide sufficient data for comparison. CO emissions from gaseous fuel operation increased as engine speed increased. It is interesting to note, however, that in the case of the gaseous fuel, this CO might be better described as "unburned fuel" rather than viewed as a product of partial combustion.

It was more difficult to identify a relationship between engine speed and emissions levels of NOx and HCHO at no load idle conditions with gaseous fuel. NOx emissions are identified with higher temperature engine operation; as engine oil and coolant temperature were not stabilized prior to emissions testing, combustion chamber temperatures may have varied during each emissions test. One test at 1000 rpm engine speed gave a value of 0.55 grams per hour for NOx, much higher than previous or successive tests. HCHO emissions do not appear to correlate well with engine speed and hence fuel consumption. One control test of a DNPH cartridge, however, indicated contamination or a chromatograph inconsistency that would have allowed an error of 10 milligrams per hour to be added to HCHO actually measured. Several more tests will have to be conducted to determine the magnitude of this error.

Table 5 presents the results of several emission tests conducted with the engine operating under load. The tests with M100 fuel were conducted with the engine operating at warmed, steady-state conditions and with a catalyst in the exhaust stream. The gaseous fuel tests measured engine-out emissions. The engine was not run at speeds higher than 2000 rpm on gaseous fuel.

The first tests with M100 fuel were conducted at an engine speed of 1600 rpm and a brake torque of 30-31 ft x lbs (9.4 -9.6 brake horsepower). Emissions results were inconclusive as they varied considerably. Brake specific HC varied from 0.002 to 11.81 grams per brake horsepower hour (g/BHP-hr); brake specific NOx varied from 8.89 to 0.86 g/BHP-hr. These tests will be repeated after the engine is reconfigured to run on liquid fuel again; catalyst light-off and the problem with air/fuel mixing with liquid fuel that Nissan made us aware of may have contributed to this variability. Testing at 2400 rpm was also inconclusive, due greatly to the limited number of tests conducted. CO_2 emissions varied from 472 to 634 g/BHP-hr over these two tests, a very substantial difference.

Testing with gaseous fuel was conducted at 2 different engine speeds: 1500 and 2000 rpm. At 1500 rpm the throttle was opened to 4.5 in. HG manifold vacuum. Fuel was adjusted to bring A/F ratio to 16.07 and 11.9 at 1500 and 2000 rpm respectively. A load of 24.1 ft x lbs was placed on the engine at 1500 rpm; 26.6 ft x lbs was placed on the engine at 2000 rpm. Manifold vacuum at 2000 rpm was 7.0 in. HG.

The engine ran very smoothly under load with the gaseous fuel. The lower manifold vacuum figures, however, suggest that the throttle was substantially open, indicating that further increases in power may be difficult to obtain at these engine speeds with the engine as presently configured.

Table 5

Emission Testing, Nissan CA18DE Engine M100, $2H_2/CO$ Fuels, Load Testing

Fuel	Engine Speed (rpm)	Torque (ft lb)	Air/ Fuel (ratio)	Brake HP (BHP)	Brake Specific Emissions BSHC (g/BHPhr)	BSCO (g/BHPhr)	$BSCO_2$ (g/BHPhr)	BSNOx (g/BHPhr)	BSHCHO (mg/BHPhr)
M100*	1600	30.8	6.60	9.62	.002	0.46	781.	8.89	1.5
M100*	1600	30.4	7.00	9.39	11.81	--	762.	0.86	1.2
$2H_2/CO$	1500	24.1	16.07	7.01	0.20	1.91	717.	2.84	4.7
M100*	2400	40.5	6.34	18.97	--	0.35	472.	0.20	--
M100*	2400	40.8	6.38	18.90	0.07	1.45	634.	0.01	--
$2H_2/CO$	2000	26.6	11.9	10.32	0.13	2.27	426.	8.57	2.0

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* Engine warmed to steady-state conditions; catalytic converter in place in the exhaust stream.

-- None detected.

The emissions results from gaseous fuel testing are inconclusive due to the limited number of tests performed at the time of this report. NOx, however, was measured at 8.57 g/BHP-hr at 2000 rpm engine speed, a higher level than had been recorded during liquid fuel testing at greater speed and load conditions. Again, liquid fuel emission results were influenced by the presence of a catalytic converter. CO, at 2.27 g/BHP-hr, 2000 rpm conditions might be considered somewhat low when compared with the warmed, catalytic converter equipped liquid fuel emission results. More carefully controlled emission tests will be performed in order to properly characterize the emissions profile from the engine when operated on both the liquid and gaseous fuels.

VII. Project Highlights To Date

1. The engine ran very smoothly at idle and under load conditions with the simulated dissociated methanol $2H_2/CO$ fuel. Visible engine vibration during gaseous fuel operation was noticeably reduced from the level experienced with the engine operating on liquid methanol fuel.

2. The engine was able to operate over a very wide range of A/F ratio setpoints with the $2H_2/CO$ gaseous fuel. A/F ratio was calculated between 14.8 and 26.5 at no-load idle conditions between 625 and 1500 rpm. At conditions of 2000 rpm engine speed, 10.32 BHP, A/F ratio dropped to 11.9.

3. A direct comparison of emissions test results from the engine when it is alternately fueled with M100 and $2H_2/CO$ is not available at this time. The testing with M100 fuel utilized a catalytic converter in the exhaust stream while $2H_2/CO$ fuel results are engine-out emissions. The $2H_2/CO$ fuel emissions test results may vary substantially between tests because the limited amount of $2H_2/CO$ fuel in the "T" cylinder storage bottles did not permit starting and warming to steady-state conditions prior to testing.

VIII. Future Effort

This engine conversion project was begun to develop an engine that could be used as a suitable test bed for a practical, onboard methanol dissociation system. Further development of this engine concept will be structured to accommodate this goal. Immediate plans concern development of two measures of engine performance:

1. Emissions/fuel economy; and

2. Engine performance at lean operating conditions.

Further emissions testing at various engine speed/load operating conditions will be conducted to characterize the emissions profile of this engine when operated on both M100 and dissociated methanol. A/F ratio at these various test points will also be determined.

Previous testing with M100 liquid methanol was conducted with a catalytic converter in the exhaust stream. This catalytic converter will be removed in order to provide engine-out emissions data for comparison.

The effect of changes in spark timing on engine performance and emissions in the testing reported on here was not measured. Spark timing will be adjusted in future testing in order to obtain mean for best torque (MBT) conditions for a range of engine speeds.

One way to determine the proximity to the lean misfire limit at various engine-operating conditions is to obtain a quantifiable measure of increasing engine roughness as the air/fuel mixture is leaned out. A measure of proximity to lean misfire limit may be obtained directly, through measurement of changes in cylinder pressure during the combustion effort. An indirect method might involve the measurement of the variability in successive crank rotation times as leanness increases. The test engine is not equipped with a knock sensor; it should therefore be possible to obtain a quantifiable measure of engine performance as the lean misfire limit is approached when the engine is fueled with the gaseous $2H_2/CO$ blend.

Kistler Instrument Corporation has modified a spark plug from this engine to accept a pressure transducer adaptor. This adapter, when fitted with a Kistler Model 601B1 pressure transducer will allow measurement of cylinder pressure in the otherwise unmodified engine. Future work will include measuring cylinder pressure changes and relating them to changes in A/F ratio as the lean limit is approached.

IX. Acknowledgments

The CA18DE test engine described in this report was modified for use with M100 neat methanol and loaned to EPA by the Nissan Motor Corporation as part of an ongoing joint cooperative effort to investigate the potential of neat methanol as an alternative motor vehicle fuel. The authors also appreciate the efforts of Jennifer Criss and Marilyn Alff of the Control Technology and Applications Branch, ECTD, for typing, formating, and editing this report.

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APPENDIX A

TEST ENGINE SPECIFICATIONS - M100 FUEL OPERATION

Manufacturer	Nissan Motor Co., LTD.
Basic engine designator	CA18DE
Displacement	1809 cc
Cylinder arrangement	4-cylinder, in-line
Valvetrain	Dual-overhead camshaft
Combustion chamber	Pentroof design
Bore x stroke	83 mm x 83.6 mm
Compression ratio	11.0
Compression pressure	16.5 kg/square cm (350 rpm, 80°C)
Fuel control system	Electronically controlled fuel injection
EGR	EGR not used
Valve clearance	0 mm (automatically adjusting)
Idle speed	750 rpm
Engine oil	Special formulation supplied by Nissan for methanol engine operation
Fuel	M100 neat methanol
Air/fuel control	Excess air ratio may be varied from 0.5 to 2.0 by means of an external control
Spark advance control	Ignition timing can be varied from 0° BTDC to 54° BTDC by means of an external control

APPENDIX B

AIR/FUEL RATIO CALCULATION WITH $2H_2/CO$ Fuel

Air/fuel ratio is defined [15] as:

$$\frac{\text{Mass flowrate of air}}{\text{Mass flowrate of fuel}}\text{, dimensionless} \qquad (1)$$

Molecular weight of air, 28.89, approximately.

Calculate molecular weight of fuel, $2H_2/CO$:

$$\begin{aligned} 2/3\ (\text{molecular weight of H2, 2}) &= 1.333 \\ 1/3\ (\text{molecular weight of CO, 28}) &= \underline{9.333} \end{aligned}$$

Molecular weight of fuel, approximately 10.666

At standard conditions, for gases,

$$PV = nRT \qquad (2)$$

Where:

P, pressure, atmosphere
V, volume, cubic feet
n, lb. moles
R, constant, .7302 atm ft^3/lbmol °R [16]
T, temperature, °R

At standard conditions,

$T = 492$ °R

$P = 1$ atm

Mass flowrate may be defined as:

$$\frac{PV_T}{RT}\text{(molecular weight)} = n_T\text{(molecular weight)} \qquad (3)$$

Where:

V_T, Volume/time, ft^3/minute

n_T, lb moles/minute

Given,

Air flowrate, 6.0 standard cubic feet/minute (SCFM)

APPENDIX B (CONT'D)

AIR/FUEL RATIO CALCULATION WITH $2H_2/CO$ Fuel

Fuel flowrate, 1.1 SCFM

Calculate A/F ratio:

Mass flowrate of air, from (3)

$$\frac{(\text{latm})(6.0\ \text{SCFM})(28.89\ \text{lb./lbmol})}{(.7302)\ (492^\circ\text{R})} = .4825\ \text{lb./minute, air}$$

Mass flowrate of fuel,

$$\frac{(\text{latm})(1.1\ \text{SCFM})(10.666\ \text{lb./lbmol})}{(.7302)(492^\circ\text{R})} = .0327\ \text{lb./minute, fuel}$$

From (1),

$$\text{A/F} = \frac{.4825\ \text{lb/minute}}{.0327\ \text{lb/minute}} = 14.8\text{, answer}$$