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Technical Report

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

by

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I. Summary

Methanol may be catalytically decomposed to hydrogen and carbon monoxide (H_2/CO) gas. This gaseous mixture may be an ideal cold start assist for an M100-fueled engine as well as serving to increase the thermal efficiency of the engine during transient operation.

The work described in this interim report concerns the conversion of a 16-valve, 4-cylinder light-duty engine to operation on a mixture of H_2/CO gaseous fuel. This engine will be evaluated on emission level and lean limit operation criteria for two fuels: H_2/CO gas and M100 neat methanol.

Modifications to the engine to accommodate the gaseous fuel are discussed and a description of the specially constructed fueling system is provided. The emissions measurement system constructed for the test cell is also discussed.

II. Introduction

Light-duty M100 neat methanol-fueled engines are 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.

Methanol may be catalytically decomposed to H_2 and CO gases. 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 increase engine thermal efficiency and reduce emissions measured as hydrocarbons (HC) below levels from similarly sized methanol-fueled engines.

The goal of this project is to modify a 16-valve, 4-cylinder light-duty engine to accept a mixture of H_2/CO bottled gas, and to evaluate this engine using two fuels:

1. H_2/CO bottled gas; and
2. M100 (neat methanol).

The criteria for evaluation is the engine's ability to run without driveability problems at the lean limit of operation over several steady-state speed and load conditions.

III. Discussion

The 16-valve, 4-cylinder engine used in this project was supplied by the Nissan Motor Co., Ltd. This engine was modified for use on M100 neat methanol prior to its consignment to the U.S. Environmental Protection Agency (EPA); engine specifications are provided in detail in Appendix A.

Several modifications to the engine were necessary in order to operate on H_2/CO fuel; these modifications are discussed below. Included also are discussions of the bottled gas fueling system and emission measurement system.

A. Engine Modifications

Methanol can be dissociated to H_2 and CO via the reaction:

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

A bottled gas mixture from Linde Gases with a composition of 66 volume percent H_2 and 34 volume percent CO was obtained in order to simulate the products of this reaction; this fuel is to be introduced via one of the intake valve ports (Figure 1). The other intake valve supplies the air needed for the combustion process in each cylinder.

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 explosion if fuel exclusively, and not an explosive 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 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 gasoline-fueled engine. This assembly controls the air flow so that it is through one intake runner when needed and through both intake runners when 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.

Figure 1

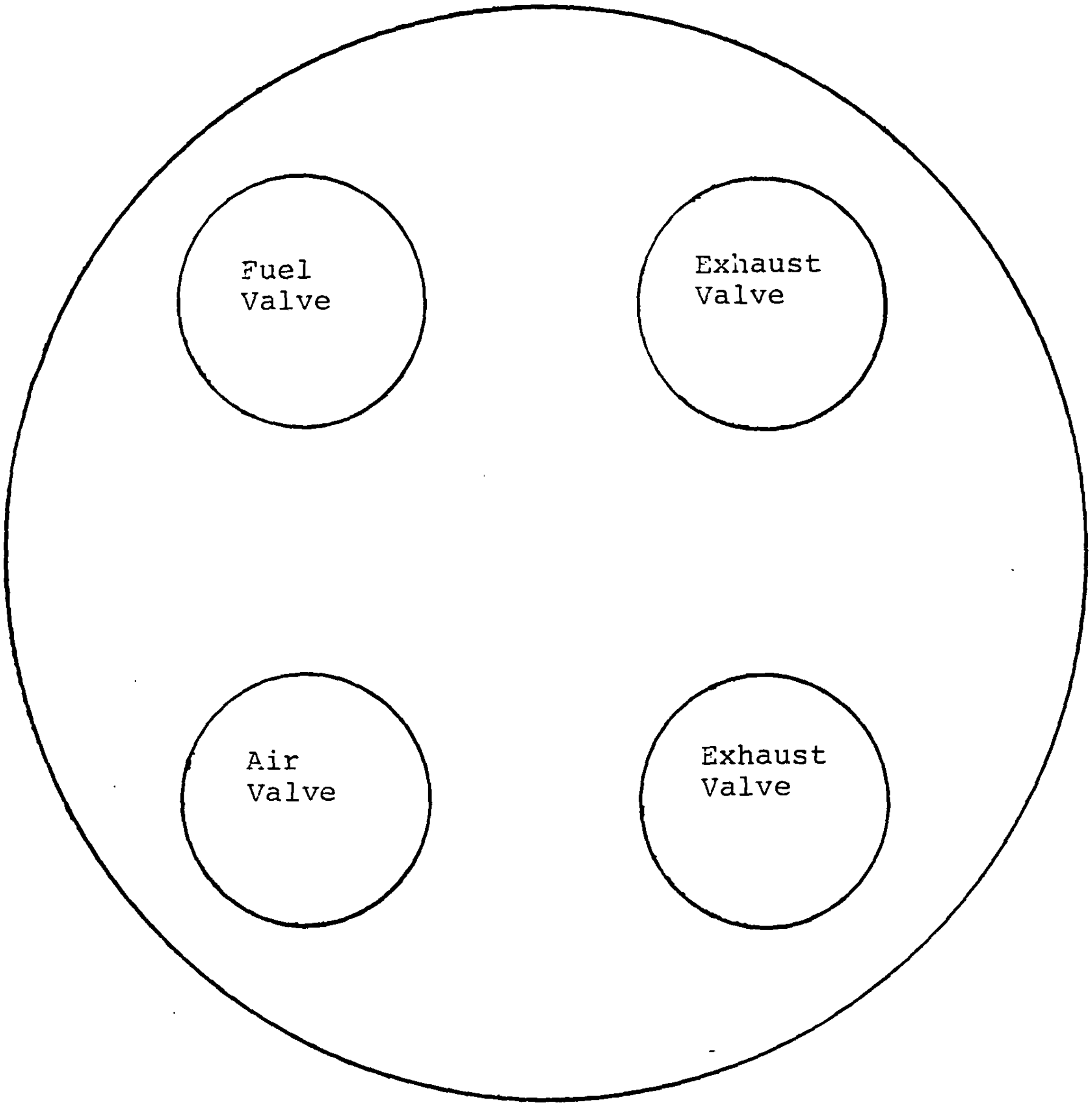

Diagram of Valve Arrangement For Individual Cylinder -

H_2/CO Fueling System

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	Not to Scale	

The hole in the assembly left by the power valve slide was sealed to prevent leakage of fuel and air. 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 test engine referred to in this paper. 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 proposed air/fuel lobe scheme for the intake camshaft.

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.

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 reported that the engine head was milled to increase the compression ratio on the modified engine; this modification may also account for some of the timing difference.

The redesign of the intake camshaft to accommodate H_2/CO fueling has been outsourced to General Kinetics Co., Inc., Detroit, Michigan. A summary of the proposed camshaft specifications for the redesigned shaft is given in Table 3. Timing and design for the air as well as the fuel cams will be altered. Air valve opening will commence at 15 crankshaft degrees before top dead center (BTDC), and will close at 30 crankshaft degrees after bottom dead center (ABDC). Shortening the period during which the air intake valve will be open may necessitate decreasing air valve lift; this dimension has not yet been finalized. Opening of the fuel valve will commence at 15 degrees ABDC, and will close at approximately 65° BTDC, for an open time of 100 crankshaft degrees. The height of the fuel valve lift will be less than or equal to .200 inch. Valve head diameter for both air and fuel valves will be similar to stock intake valve, 1.340 inch.

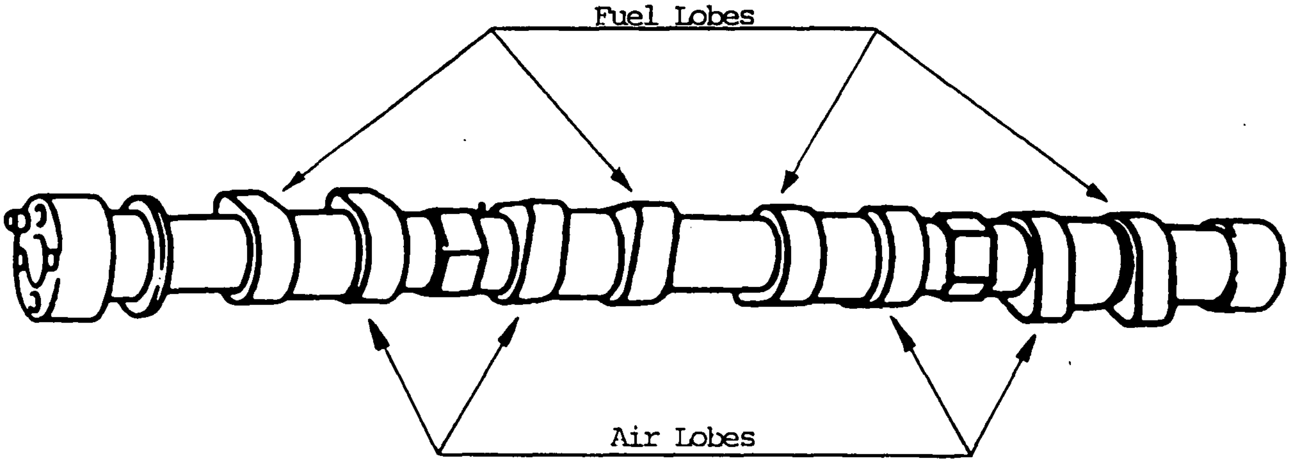

Figure 2

CA18DE Engine Intake Camshaft -

Fuel/Air Cam Lobes Indicated

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Table 1

Current 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

Table 2

Current Intake Camshaft Specifications

Specification	Standard CA18DE Engine	Measured By EPA On Test 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

Proposed Intake Camshaft Specifications

Specification	Air Valve	Fuel Valve
Cam height	Less than 1.59 inches	To be determined
Valve lift	.335 inches	.200 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 inches.

A buildup of the gas could occur in the engine during operation due to leakage past the valve stem seals and from blowby. This buildup might reach explosive proportions if the crankcase ventilation system is unable to remove the H_2 gas quickly enough. To prevent the accumulation of an unsafe concentration of explosive gases and air, the engine was modified to provide a blanket of inert gas where this buildup might occur. A valve cover was modified to accept a connection from a bottle of N_2 gas. A port on the valve cover over the exhaust side camshaft was connected to the room air system scrubber. N_2 gas at 2-4 SCFH will be admitted to the engine during H_2/CO gas operation. This carrier gas will mix with and dilute blowby, also providing an inert atmosphere which will not promote an explosion. This blowby/carrier gas mixture will be exhausted to the scrubber; the line which vents the crankcase to the combustion chambers will be plugged, ensuring flow to the scrubber only.

Several other minor modifications will be made to ensure better control of the air/fuel mixture from the control room, engine start from the control room, etc. Further major engine modifications may be made after testing on H_2/CO fuel begins.

B. Fuel System

It was necessary to construct a special fuel system to accommodate the fueling of the test engine with the gaseous blend. A diagram of the system is provided in Figure 3.

The H_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 1800-1850 psi. A fuel supply cylinder will be 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, will be 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 acctuator 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.

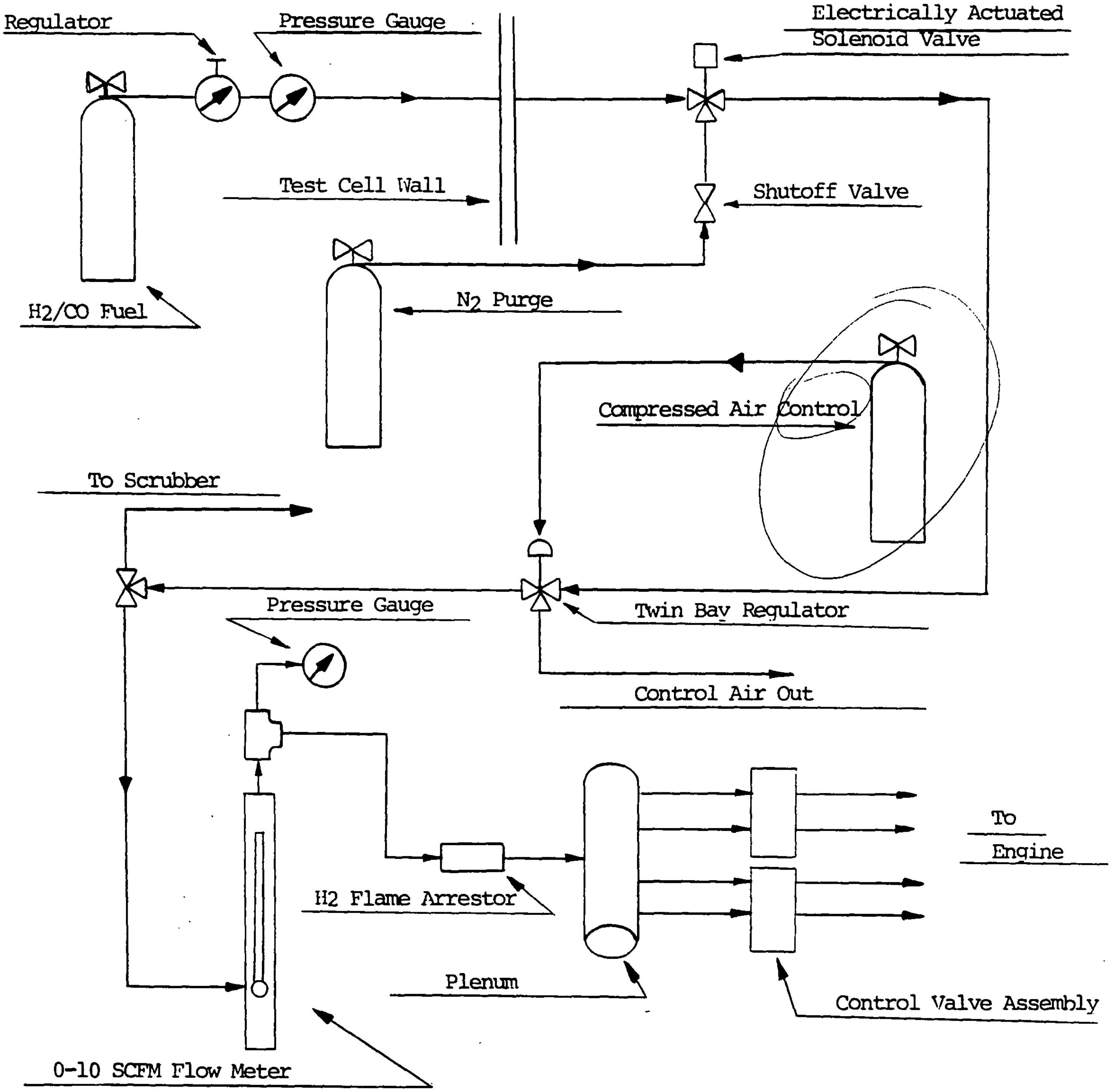

Figure 3

Fuel System for H_2/CO Operation

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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 will flow 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 hydrogen flame arrestor. The flame arrestor is located immediately upstream from a cylindrical plenum, this plenum serving as a header to four flexible fuel lines. The fuel lines are connected to threaded fittings which are screwed into the fuel injection ports in the valve control assembly. H_2/CO fuel is then directly supplied to the combustion chambers by the opening of the fuel valves.

C. Emissions Measurement

An emissions measurement system was fabricated for the test cell; a flowchart of the system is given in Figure 4.

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 AIA23 infrared analyzer.

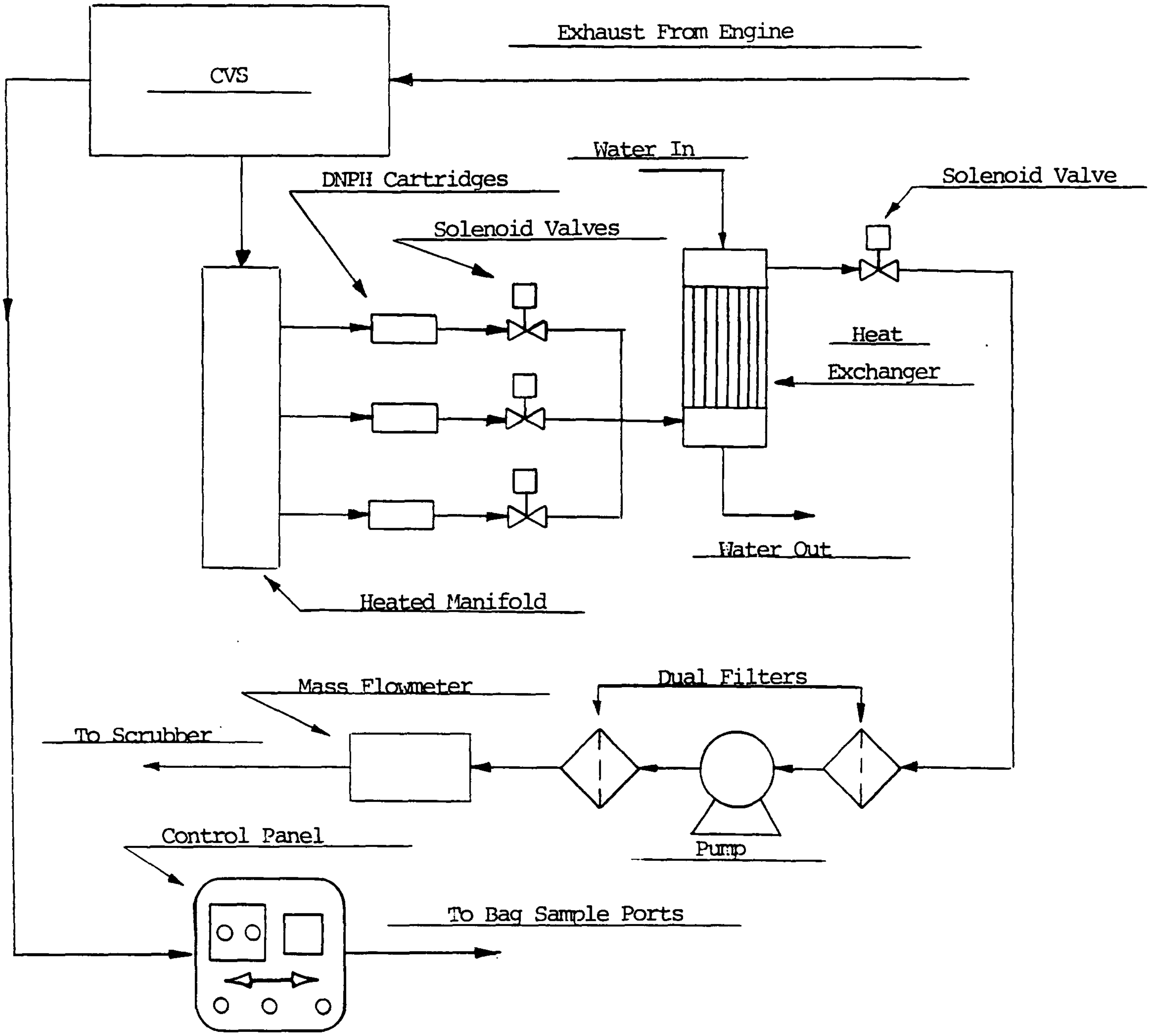

Figure 4

Emissions Measurement System

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A second sample line extends from the CVS to a heated manifold. This manifold contains ports for three dinitrophenylhydrazine-coated (DNPH) formaldehyde 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.

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

Nissan has requested that the engine not be operated at wide open throttle conditions due to poor intake mixing. We therefore decided to measure emission over four speed and load conditions that do not excessively burden the engine: idle (no load), 1600 rpm/30.8 ft-lb, 2400 rpm/40.5 ft-lb and 3200 rpm/48.5 ft-lb respectively.

Air/fuel ratio and injection timing may be varied through the use of a rheostatically equipped control panel that Nissan provided with the engine. Our first attempts at testing the engine with M100 fuel utilized the same control settings that the engine was equipped with upon arrival at EPA. The air/fuel ratio settings provided by the manufacturer were fairly rich. The engine was warmed to steady-state conditions and tested over four modes: idle, 1600 rpm/30.8 ft-lb, 2400 ppm/40.5 ft-lb and 3200 rpm/43.4 ft-lb. A/F ratio was measured with an NTK Micro Oxivision MO-1000 air/fuel ratio meter. A/F ratio varied from a low of 4.67 at 1600 rpm to 5.60 at 3200 rpm. Ignition timing was 23° BTDC for all modes tested.

Fuel consumption during this testing was excessively high; we were unable to determine HC and CO emissions levels because they were offscale on the most concentrated analyzer ranges. NOx emissions were so low as to be unmeasurable during this testing, however. A problem with the solenoid valve system prevented the acquisition of good formaldehyde data. The overhead pipe carrying exhaust from the engine to the CVS also developed several leaks at critical joints during this testing; a considerable amount of fluid leaked from the exhaust system. Testing was finally halted during the 3200 rpm mode because a severe backfire problem developed in the exhaust system.

This testing was repeated using the Micro Oxivision meter as a guide to leaning out engine A/F ratio over the modes upon which we evaluated the engine. The results of this testing are given in Table 4.

A/F ratio was controlled to near stoichiometric conditions for this testing. HC emissions were very low; at 2400 rpm/40.5 ft-lb torque no HC were detected. The bag sampling system appeared to function normally during testing, however. NOx emissions varied considerably from the 1600 rpm/30.8 ft-lb mode to the others tested. Both NOx and formaldehyde emissions were considerably higher at the 1600 rpm/30.8 ft-lb torque point compared to the higher speed/load points. Again, engine backfire problems curtailed testing at idle conditions.

This testing was again repeated; results are provided in Table 5. A/F ratios for this testing were held to ratios similar to those given in Table 4. Engine speed/load conditions here given also approximated those given in Table 4.

The very high HC emission level at the 1600 rpm mode in Table 5 contrasts sharply with the .002 g/bhphr figure from the earlier testing. CO levels between the two data sets are also difficult to compare. No CO was detected in the bag samples at idle and 1600 rpm conditions; this contrasts with the .46 g/bhphr at 1600 rpm recorded earlier. CO levels at 2400 and 3200 rpm conditions from the later testing increased more than three hundred percent from earlier levels.

NOx levels indicate differences between emission levels determined during these two test periods. Results from the later testing show much lower NOx levels at 1600, 2400 and 3200 rpm than those from the tests conducted earlier. HCHO levels remained approximately the same at 1600 rpm between the data sets; again no HCHO was detected at 2400 and 3200 rpm conditions.

No engine operability problems were encountered during this later testing, and an idle test was conducted to measure emission levels at no-load conditions. Emissions are expressed as g/hr or mg/hr. No earlier idle tests were completed, so figures for comparison are not available.

Emission levels by pollutant vary considerably between the data sets presented in Tables 4 and 5. While these levels may be of interest as a first approximation, the variability is too great to allow for a reliable characterization of emission levels from M100 operation. Additional testing is being conducted in order to make this characterization possible.

Table 4

Emission Testing, Nissan CA18DE Engine M100 Fuel, First Data Set

Engine Speed (rpm)	Torque (ft-lb)	Air Fuel (Ratio)	Brake Horsepower (bhp)	Brake Specific Emissions				
				BSHC (g/BHPhr)	BSCO (g/BHPhr)	BSCO$_2$ (g/BHPhr)	BSNOx (g/BHPhr)	HCHO (mg/BHPhr)
1600	30.8	6.60	9.62	.002	.46	781	8.89	1.48
2400	40.5	6.34	18.97	--	.35	472	0.20	--
3200	48.4	6.35	30.22	.004	.14	686	0.79	--

-- Denotes none detected.

Table 5

Emission Testing, Nissan CA18DE Engine M100 Fuel, Second Data Set

Engine Speed (rpm)	Torque (ft-lb)	Air Fuel (Ratio)	Brake Horsepower (BHP)	Brake Specific Emissions				
				BSHC (g/BHPhr)	BSCO (g/BHPhr)	BSCO$_2$ (g/BHPhr)	BSNOx (g/BHPhr)	HCHO (mg/BHPhr)
750	Idle	6.88	0.0	0.38*	--	1826*	.05*	11.9**
1600	30.4	7.00	9.39	11.81	--	762	.86	1.16
2400	40.8	6.38	18.90	0.07	1.45	634	.01	--
3200	42.5	6.35	26.25	0.04	2.63	457	.01	--

-- Denotes none detected.
* g/hr
** mg/hr

IV. Future Effort

This document is an interim report only; a substantial amount of work remains to be accomplished on this project. An outline of some of these tasks in given below, together with short comments concerning progress being made toward completion of the work.

A. New Emissions Tests: M100 Fuel

The emission test results provided in Tables 4 and 5 are inconclusive. We are currently retesting the engine with M100 fuel to obtain a reference emissions profile. This testing will be redone utilizing two separate (bag sampling and continuous sample) banks of HC and NOx analyzers in order to improve the accuracy of these measurements.

B. Rebuild Continuous Emissions Measurement System

An emissions measurement system capable of continuously measuring HC and NOx emissions is present in the test cell. This system has not been operational because of analyzer pump problems. New pumps were ordered and received; this analyzer system is now being made operational. We plan to use these analyzers as a check on the bag analysis system for gaseous pollutants.

C. Finish Camshaft Modification: Test Engine

The camshaft redesign to accommodate the fueling scheme in Figure 1 is currently underway. After this new shaft is designed and built, it will be installed on the test engine and evaluated. The need for any redesign change should be made apparent during this evaluation; any succeeding shaft will incorporate these changes.

D. Develop Leanness Indicator

The testing referred to in C, above, has as its goal the determination of 1) the lean limit, at certain speed and load points, of the test engine when operated on H_2/CO gaseous fuel and 2) any improvement in the emissions profile resulting from the use of H_2/CO as a fuel. In order to quantify the maximum lean limit information a correlation of engine performance with increasingly lean operation is necessary. This correlation could be done mechanically or through the use of electronic data acquisition hardware.

Our current plan is to gather a magnetic signal, convert it to a voltage and process the voltage as a time interval with reference to an algorithm that relates crankshaft rotation time to engine roughness. Engine roughness increases as the lean misfire limit is approached, hence a quantifiable correlation should be possible. If it is not possible to determine the lean misfire limit electronically due to equipment availability problems, etc. a mechanical means of making this determination will be developed and used.

APPENDIX A

Test Engine Specifications

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 system
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 2.0 to 0.5 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