EPA/AA/CTAB-88-04

Technical Report

Effects of Cranking Speed and Finely Atomized Fuel Delivery On Minimum Cold Starting Temperature of a Methanol-Fueled (M100) Vehicle

by

David M. Blair

May 1988

NOTICE

U. S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Emission Control Technology Division
Control Technology and Applications Branch
2565 Plymouth Road
Ann Arbor, Michigan 48105

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
ANN ARBOR, MICHIGAN 48105

OFFICE OF
AIR AND RADIATION

June 20, 1988

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, "Effects of Cranking Speed and Finely Atomized Fuel Delivery On Minimum Cold Starting Temperature of a Methanol-Fueled (M100) Vehicle," (EPA/AA/CTAB/88-04) describes cold start testing conducted at the Motor Vehicle Emissions Laboratory on a M100-fueled Volkswagen Rabbit.

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 Jr. Date: 6-16-88
Charles L. Gray, Jr., Dir., ECTD

Nonconcurrence: ______________________ Date: __________
Charles L. Gray, Jr., Dir., ECTD

Attachment

cc: E. Burger, ECTD

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I. Introduction

A serious problem concerning the development of a production model neat methanol-fueled (M100) vehicle is the inability to start such vehicles reliably at cold temperatures. Individuals familiar with the United Parcel Service (UPS) 292 flexible-fuel engine, which has been reported to start at -29°C with methanol fuel, suggest that increased cranking speed may improve the cold startability of a neat methanol-fueled vehicle.[1]

Another method of improving M100 cold startability was suggested by the output of a methanol engine computer simulation developed by Richard K. Pefley at the University of Santa Clara. Professor Pefley's simulation suggested that reducing the median droplet size of the methanol delivered to the engine would improve cold weather starting due to the enhanced heat transfer coefficient of the smaller droplets.[2] Most written papers agree that reducing fuel droplet size will increase the heat transfer coefficient of the droplets [3,4,5,6], but only one [3] believes that there would be enough heat (energy) available in a methanol-fueled engine cylinder for this improved heat transfer coefficient to have any major effect on the minimum cold start temperature of a methanol-fueled vehicle.

However, since a vaporized fuel/air charge may not be required for flame propagation [7] in an engine cylinder, the finely atomized fuel should be burnable even if there is insufficient energy from the heat of compression in the combustion chamber for total fuel vaporization. The problem then becomes one of supplying the proper spark to ignite a fuel droplet which would then start a flame propagating through the remaining droplets in the combustion chamber. It may be possible to supply the required spark to initiate flame propagation through the use of a high energy ignition system, a fast breakdown ignition system (on the order of nanoseconds), a long duration spark ignition system or a multiple restrike ignition system.

A 1981 Volkswagen Rabbit, modified to operate on M100 fuel, was cold start tested at the U.S. EPA's Motor Vehicle Emissions Laboratory from March 13, 1987 to April 21, 1988. A starting system, which provided faster cranking speeds, was tested alone and in combination with a manifold-mounted fuel delivery system capable of generating methanol fuel droplets at or below 5 microns in diameter. Start attempts were also made using several modified ignition systems, which provided higher energy spark, in combination with the faster cranking speed and atomized fuel delivery systems.

II. Summary

Test results showed that increasing (doubling) cranking speed and delivering finely atomized fuel to the intake

manifold did not significantly lower the minimum cold starting temperature of an M100-fueled vehicle. However, there still exists the possibility that a different type of atomizing nozzle and/or a different ignition system could lower the minimum cold starting temperature.

III. Discussion

A. Equipment Description

A Duvac power system was installed in the Volkswagen to provide a faster engine cranking speed. This system supplied 24 volts to the standard engine starter motor while maintaining a 12-volt accessory voltage and allowing the two 12-volt batteries to be charged simultaneously from the standard Volkswagen alternator. Since we were supplying 24 volts to a starter motor designed for 12-volt operation, some of the power produced by this additional voltage went into thermal heating of the starter motor. Most went into the production of the motor electric field since the crank speed of the 24-volt operated starting system was nearly double that of the 12-volt system. Concern over excess heating of the starter motor and subsequent failure required that the maximum cranking time be limited to 15 seconds on the first attempt and 10 seconds on subsequent attempts.

The system used to produce the finely atomized fuel was a Hartmann whistle atomizing nozzle supplied by Sonic Development Corporation. This nozzle was chosen since it is made of methanol-compatible materials, is readily available, and is capable of delivering fuel droplets with a median diameter of less than 5 microns at low flow rates. This nozzle has the disadvantage of having a large outlet velocity since compressed air at 50-80 psig is required to produce the fine atomization. This large velocity makes droplet entrapment in the manifold runner flow very difficult. A schematic of the system used to supply fuel and air to this nozzle is presented in Appendix G.

Ignition system descriptions are located at the beginning of Appendix D (high energy ignition), Appendix E (continuous ignition system), and Appendix F (high energy, fast breakdown ignition system).

B. Starting Procedure

The vehicle was cranked to start in increments of 10 seconds, an exception to this being a 15-second crank on the first attempt at each temperature. Cranking ended with the elapse of 10 seconds (15 seconds for the first crank segment) or vehicle start. If the vehicle did not start, a pause of 15 seconds was done to allow starter cooling. This cycle of crank and pause was repeated until 55 seconds of cranking time (5 start attempts) had elapsed. Failure to start was concluded if the vehicle had not started after this time.

The vehicle was to remain at idle for 1 minute after starting. If the engine stalled after starting, the above crank-pause sequence was repeated. If the vehicle stalled and then was successfully restarted, the 1-minute idle period was begun at the time of this restart.

1. Fast Crank System Only

With the fast cranking starter system installed on the Volkswagen, start attempts were made at 75°F, 50°F, 45°F and 40°F. The temperatures measured for this portion of the testing were the ambient air temperature and the oil temperature measured in the oil pan of the vehicle at the tip of the oil dipstick. The data presented in Table 1 show that the minimum starting temperature of the vehicle was 50°F. This is the same minimum starting temperature of the vehicle without the addition of the fast crank system. Another point to note from the data is that although the vehicle may start, there is no guarantee that the vehicle will idle acceptably. Work is needed in the area of optimum fuel delivery and spark strategy after the cranking segment of starting is completed. No work was done to optimize fuel delivery or spark strategy with only the fast cranking starter system. As shown in Table 2, the engine parameter and systems were not altered from standard methanol-fueled Volkswagen engine specifications during testing with the fast cranking speed starter motor.

2. Fast Cranking System With Finely Atomized Fuel Delivery

The Volkswagen's intake manifold was modified to accept the Sonic Development Corporation atomizing nozzle in a location previously occupied by the standard upper cold start injector. This placed the nozzle at a 45° angle from the horizontal which directed the center-line of the spray at the divider of the number 4 and number 3 intake runners. The number 4 and number 3 runners are the closest to the throttle body.

The data in Appendix C was used to set the air and fuel pressures used for testing. A delivered equivalence ratio of 2.0 was chosen for the starting work so an ignitable mixture could be present in the cylinders even when manifold wall wetting occurred. A larger equivalence ratio was avoided due to concerns over the effects of evaporative cooling.[2] The 035 nozzle was chosen for the test work since the other two nozzles were designed to supply larger charge volumes as shown in Table C-2. The 052 and 086 nozzles were also found to be difficult to control when operating under the vacuum conditions present in the manifold. The starting procedure consisted of cranking the engine and then opening the fuel and air supply valves to the Sonicore nozzle. If a start was achieved, fuel from the main port fuel injectors was turned on after approximately 5 seconds of running solely on atomized fuel. Fuel and air to the atomization nozzle were then slowly reduced to keep the vehicle from stalling. Starting with this system was

Table 1

Results of Testing With Fast Cranking Speed

M100-Fueled Volkswagen Rabbit

Temperature(°F) Air	Oil	Start (yes/no)	Stall (yes/no)	Comments
75	75	Yes	Yes	480 rpm crank speed 55-60 second idle
50	51	Yes	Yes	480 rpm crank speed, 22-second idle'
45	45	No	--	360-480 rpm crank speed
40	40	No	--	300 rpm crank speed

Table 2

Engine Specifications Used With Fast Cranking Starter System and Finely Atomized Fuel Delivery System

M100-Fueled Volkwagen Rabbit

Ignition timing	0° ATDC
Spark plugs	W4CC Bosch gapped @ .7mm
Distributor and coil	Standard hall-effect unit with standard Bosch coil
Cold start injectors	Two standard Bosch manifold injectors; these were disconnected when tests with finely atomized fuel were conducted
Mixture control unit	Standard unit with idle CO output set according to Alcohol Energy Systems report
Entire fuel delivery system	Standard; this system was disabled during tests with the finely atomized fuel delivery system.

NOTE: "Standard" refers to systems or specifications on the M100-fueled vehicle, which were installed or specified by Volkswagen of America.

Table 3

Testing With Fast Cranking Speed and Finely Atomized Fuel Delivery (Temperature °F)

Air	Oil	Coolant	Fuel Bladder	Zero Air	Start* (yes/no)	Comments
75	75	75	75	75	Yes	420 rpm crank speed
65	65	65	65	65	Yes	420 rpm crank speed
60	60	60	60	60	Yes	420 rpm crank speed
50	50	50	50	50	Yes	400 rpm crank speed
54	47	55	45	52	Yes	420 rpm crank speed
47	45	45	45	45	No	300 rpm crank speed
54	32	49	45	47	No	400 rpm crank speed
55	30	40	43	45	No	450 rpm crank speed
40	40	40	40	40	No	300 rpm crank speed

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* After vehicle no-starts the plugs were removed. Plugs 2, 3, and 4 were observed to be shorted liquid methanol fuel.

successful at 60°F and 50°F, as shown in Table 3, but was unsuccessful at the lower temperatures of 45°F or 40°F. After no-starts at these temperatures, the spark plugs were removed and three of four spark plugs (numbers 2, 3, 4 cylinders) were found to be shorted with liquid methanol fuel. Engine compression was checked after the no-start conditions to determine if methanol fuel had washed away the lubricating oil from the piston rings. Compression, however, was found to be within specifications.

Testing, at this point, was attempted with a higher energy ignition system. These results are presented in Appendix D and show no improvement in minimum starting temperature. Plug wetting was still a problem.

Testing conducted with a continuous ignition system, as outlined in Appendix E, indicated that the fuel supplied by the atomizing nozzle could be ignited at 70°F, 60°F and weakly at 50°F but could not be ignited at 45°F or 40°F. A possible problem with fuel delivery at lower temperatures was now uncovered. The possibility also existed that the heat of compression was just not enough to vaporize the methanol fuel at the lower temperatures, and the ignition systems could not provide the spark to start a flame propagation in the cylinder, especially since the fuel delivered by the atomizing nozzle was at a temperature 40°F-50°F less than the ambient temperatures due to the cooling effect associated with expanding a compressed gas through an orifice.

3. Manifold Modifications

Bench testing of the manifold with no internal vacuum was performed upon removing it from the vehicle. A true bench analysis could not be performed since flow bench hardware was not available for use. Testing revealed that with the nozzle in its current 45° position the number 1 runner was starving for fuel while liquid fuel poured out of runners 3 and 4. The manifold was modified to incorporate a nozzle in two different positions: 1) 90° to horizontal in the center of the manifold, which directed the centerline of the spray at the divider between runners 2 and 3; and 2) in the end of the manifold through the present cold start injector opening which placed the centerline of the spray at the divider between the two throttle body butterfly valves.

Both of these nozzle positions produced an even fuel distribution between runners, but approximately 90 percent of the fuel was running out the runners in liquid form at the lower ambient temperatures of 40-50°F. The liquid was collected and then measured using graduated cylinders. The outlet velocity of this nozzle is very high which causes the atomized fuel to impinge on the rough cast aluminum walls of the manifold. A layer of liquid fuel forms in the manifold which will then flow out the runners.

A search for a low outlet velocity, methanol-tolerant, piezoelectric atomizing nozzle with the required flow rate has not been successful to date. Modification of the existing nozzle was attempted to lower the outlet velocity. The final configuration consisted of shrouding the Sonicore nozzle with a 2-inch length of nominal 3/4-inch pipe and feeding the flow from the nozzle into the pipe and then into the end position of the manifold. This configuration produced an even flow of atomized fuel out of all four runnners, but approximately 40 percent of the fuel supplied to the Sonicore nozzle was still being lost down the number 1 runner in liquid form. This is an improvement, but is far from the optimum configuration which would yield no liquid flow from the runners. Recall, however, that this manifold bench testing was conducted at atmospheric conditions. The actual fuel distribution and wall wetting will be different under manifold vacuum and flow conditions.

4. Testing with Modified Manifold

The test results obtained while using the modified manifold are presented in Table 4. The higher energy ignition system was retained for this testing. An attempt was also made to improve startability by changing the delivered equivalence ratio, manifold vacuum, ignition timing, spark plug type and spark plug gap. These results show that the modified intake system did not improve the Volkswagen minimum starting temperature of 50°F.

IV. Conclusions and Future Effort

One problem with attempting cold starts using a manifold-mounted fuel system is delivering fuel evenly to all of the cylinders while minimizing wall wetting of the manifold and runners. An additional problem of charge cooling was also observed with atomized fuel delivery system. Since the fine droplet sizes were achieved by supplying pressurized fuel and air to an ultrasonic nozzle, a cooling effect is present when the mixture expands through the nozzle orifice. At idle conditions, the fuel/air mixture at the nozzle outlet was 40°F to 50°F lower than the fuel and air temperatures delivered to the nozzle. This cooling is caused by the expanding mixture, rather than traditional vaporization as in gasoline-fueled engines.

It is interesting to note that backfire through the intake was present at the lower temperatures during the first crank attempt. This occurrence may be due to the slightly higher cranking speed during the first start attempt due to the freshly charged, warmer batteries being used, or possibly during the first attempt manifold wall wetting with fuel had not yet occurred and thus liquid fuel had yet entered the combustion chambers. Liquid fuel in the cylinder could cause a loss of compression due to oil film loss and/or it may wet a plug causing it not to fire. The backfire, however, may be due to the higher temperature charge (relative to the charge temperature which would be delivered later in time) which was present at the beginning of the first cranking segment. The cooling effect due to the expansion of the air through the nozzle orifice would not be stabilized at the beginning of the

Table 4

Testing After Manifold Modification With Fast Cranking Speed and Finely Atomized Fuel Delivery (Temperature °F)

M100-Fueled Volkswagen Rabbit With High Voltage Ignition

Air	Oil	Coolant	Fuel Bladder	Zero Air	Start (yes/no)	Comments
70	70	70	70	70	Yes[1]	Started on first attempt
60	60	60	60	60	Yes[1]	420 rpm crank speed
52	49	50	51	50	Yes[1]	400 rpm crank speed
48	43	47	47	46	No[1]	390 rpm crank speed
48	42	48	47	47	No[2]	380 rpm crank speed
47	43	46	46	45	No[3]	380 rpm crank speed
48	45	46	47	48	No[4]	380 rpm crank speed first 15 seconds, 200 rpm on last 10 seconds; Backfire in intake during first 5 seconds of cranking
43	42	42	43	42	No[4]	390 rpm crank speed first 15 seconds, 200 rpm on last 10 seconds; Backfire in intake during first 5 seconds of cranking
47	44	46	45	46	No[5]	380 rpm crank speed
48	45	47	47	47	No[6]	370 rpm crank speed
48	46	48	47	48	No[7]	380 rpm crank speed
46	42	44	45	45	No[8]	370 rpm crank speed

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[1] Ignition timing set at 0° BTDC Bosch W4CC plugs @ .7mm.

[2] Ignition timing set at 10° BTDC Bosch W4CC plugs @ .7mm.

[3] Ignition timing set at 10° BTDC Autolite 4054 plugs @ .7mm.

[4] Ignition timing set at 10° BTDC Autolite 4054 plugs @ .7mm, no air through idle-air bypass.

[5] Ignition timing set at 0° BTDC Autolite 4054 plugs @ .7mm, no air through idle-air bypass.

[6] Ignition timing set at 10° BTDC Autolite 53 plugs @ .7mm, no air through idle-air bypass.

[7] Ignition timing set at 10° BTDC Autolite 53 plugs @ .3mm, no air through idle-air bypass.

[8] Ignition timing set at 10° BTDC Autolite 4054 plugs @ .3mm, no air through idle-air bypass.

first crank segment. Air at ambient temperature will be present in the intake manifold at the beginning of cranking and the nozzle itself will not yet be significantly cooled by the expanding air/fuel mixture, thus, the maximum fuel/air temperature delivered to the cylinder will occur at the beginning of the first crank attempt. An incoming fuel/air charge with a higher temperature will require less energy to vaporize into an ignitable mixture, thus the higher temperature incoming charge will start a vehicle easier at low temperatures if the heat of compression is relied upon for fuel vaporization prior to spark ignition. We may have been operating near the low fuel/air temperature limit which could be vaporized by the heat of compression when the engine backfired at the 43°F and 48°F ambient temperatures. The delivered fuel/air temperature was probably below 40°F when the backfire occurred, but this could not be confirmed with the available measurement equipment.

We can presume that since there was no decrease in minimum starting temperature, the heat of compression was relied upon to vaporize the methanol fuel droplets into a mixture which would be ignitable during the tests when the vehicle did start. At lower temperatures, there was insufficient energy (heat) available to vaporize the methanol droplets into an ignitable mixture. Since it seems that the tested ignition systems could not supply the proper spark to initiate flame propagation without a vapor present, starting was not achievable at lower temperatures.

The relatively cold methanol fuel droplets delivered from the nozzle would obviously require more energy to vaporize than fuel droplets delivered at ambient temperature. The amount of energy increase for a methanol droplet/air charge delivered at 10°F is 10-20 percent higher than the same equivalence ratio charge delivered at 50°F. Knowing that the charge volume will be the same at any temperature, the charge at 10°F will have more pounds of air than the charge at 50°F due to the increased density of air at the reduced temperature. Additional fuel must also be added at 10°F to operate at the same equivalence ratio which would be delivered at a fuel/air temperature of 50°F. Additional energy at a fuel/air temperature of 10°F is not only required to raise the temperature of the more massive fuel/air charge, but extra energy will also be required for the heat of vaporization of the additional fuel supplied.

Thus, there exists the possibility that this M100-fueled vehicle could be successfully started at lower ambient temperatures using only the heat of compression to form an ignitable mixture if the atomized fuel were to be delivered at the ambient temperature. This was somewhat confirmed by a test conducted with the engine oil and coolant at 47°F and the fuel bladder and zero air temperature at 73°F. The vehicle started instantly but stalled after 3-4 seconds. A fine wire thermocouple installed at the nozzle exit indicated that the temperature of the delivered fuel air mixture did not exceed the ambient temperature, and that the vehicle stalled when the fuel/air temperature reached 32°F. The response time of the thermocouple was not sufficiently fast enough to give total assurance that the first fuel/air mixture delivered was indeed below the ambient temperature.

A piezoelectric type atomizing nozzle operating at frequencies above 120 KHz should produce ambient temperature methanol droplets below 15 microns in diameter. An added advantage of the piozoelectric nozzle would be its low outlet velocity which should minimize manifold and intake runner wall wetting. However, a piezoelectric atomizing nozzle which can produce droplets below 5 microns in diameter was found not to be commercially available, since approximately 1000 Khz would be required to achieve this fine atomization.

The temperature of the incoming air/fuel charge should have little effect on minimum starting temperature if energy can be transferred successfully from the spark plug to the methanol fuel droplets. This is due to the spark energy being over 100 times greater than the energy required to vaporize and ignite a single fuel droplet. Theoretically, only a single droplet needs to be ignited before a flame front can be formed which will then propagate through the combustion chamber.[7,8]

Information in a recent Society of Automotive Engineers Paper [8] suggests that the energy required to vaporize and then initiate a flame propagation through methanol fuel droplets can be supplied by a high voltage, alternating current-type ignition system such as the EPIC system manufactured by Echlin.[9]

EPA, in the near future, will be testing the M100-fueled Volkswagen with an increased cranking speed system, finely atomized fuel delivery system, and an EPIC ignition system. A long duration spark system and a General Motors HEI system will also be tested. A combined system has the possibility of being a cost-effective approach to M100 cold starting.

V. Acknowledgments

The author appreciates the efforts of Lenny Kocher of the Facility Support Branch, Engineering Operations Division, who modified the Volkswagen manifold used in this test program. The efforts of Bob Moss and Ray Ouillette of the Test and Evaluation Branch, Emission Control Technology Division (ECTD) are also appreciated. Ray and Bob did the vehicle modification and installed the required hardware.

In addition, the author appreciates the efforts of Jennifer Criss and Marilyn Alff of the Control Technology and Applications Branch, ECTD, who typed this manuscript.

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APPENDIX A

Methanol-Powered Volkswagen Test Vehicle
Specifications and Changes To Accommodate Methanol Fuel

Vehicle Item	Specification/Change
Engine:	
Displacement	1.61 liter
Bore	8.00 cm
Stroke	8.00 cm
Compression Ratio	12.5:1
Valvetrain	Overhead camshaft
Basic Engine	GTI basic engine - European high performance engine to withstand higher loads - U.S. cylinder head
Main Fuel System:	
General	Bosch K-jetronic CIS fuel injection with Lambda feedback control, calibrated for methanol operation
Pump Life	1 year due to corrosiveness of methanol. Improved insulation on wiring exposed to fuel
Accumulator-Maximum Holding Pressure	3.0 Bar
Fuel Filter	One-way check valve deleted because of fuel incompatibility
Fuel Distributor	5.0-5.3 bar system pressure, calibration optimized for methanol, material changes for fuel compatibility.
Air Sensor	Modified air flow characteristics
Fuel Injectors	Material changes for fuel compatibility, plastic screen replaced by metal screen
Cold Start Injectors	2 injectors, valves pulse for 8 seconds beyond start mode below zero degrees centigrade
Fuel Injection Wiring	Modified for cold start pulse function and to accommodate relays and thermo switch
Idle Setting	Specific to methanol calibration

APPENDIX A (cont'd)

Methanol-Powered Volkswagen Test Vehicle
Specifications and Changes To Accommodate Methanol Fuel

Vehicle Item	Specification/Change
PCV:	PCV valve with calibrated plunger-no orifice
Ignition:	
Distributor	Slightly reduced maximum centrifugal advance and slightly modified vacuum advance/retard characteristics
Standard Spark Plugs	Bosch W4CC
Transmission:	
General	1981 production automatic 3-speed
Torque Converter Ratio	2.44
Stall Speed	2000-2200 rpm
Gear Ratios:	
1	2.55
2	1.45
3	1.00
Axle	3.57
Fuel Tank:	
Material	Steel
Coating	Phosphated steel
Seams and Fittings	Brazed
Cap	European neck and locking cap
Fuel	Neat methanol (M100)

APPENDIX B

Modifications to the Methanol-Fueled Volkswagen to Incorporate Fast Crank and Atomization Hardware

Vehicle Item	Specification/Change
Engine compartment wiring	Made compatible with 12-volt run/24-volt crank system
Cold start injectors	Disconnected for atomized fuel testing
Fuel pump relay	Bypass switch, installed to control standard fuel injectors electronically
Manifold	Drilled, welded and tapped to incorporate a blow-off valve and the atomization nozzle
Idle air bypass	Relocated position at inlet to the manifold
Oil dipstick	Modified for thermocouple installation
Upper radiator hose	Modified for thermocouple installation

APPENDIX C

Air/Fuel Ratio Calibration of Sonic Development Corporation H-Series Atomizing Nozzles

The calibration chart which accompanied the Sonic Development Corporation atomizing nozzles was based on 70°F water as the operating fluid. This chart gave fuel flow and air flow rates versus air and fuel pressures along with the median droplet diameter that each combination would produce. Sonic Development Corporation engineers could not answer these questions:

Should pressure or mass flow be held constant (in relation to the supplied calibration chart) when atomizing a different fluid?

Would droplet size stay constant (in relation to the supplied calibration chart) if water were being atomized at reduced temperatures?

Since the above questions could not be answered without the aid of expensive equipment (droplet size analyzer, accurate fuel and air flow meter accurate to ±.01 gal/hr, pressure gauges ±.1 psi), it was decided to assume the water calibration chart supplied by Sonic Development Corporation also would be applicable to methanol at 40°F to 70°F. This decision was based on bench test data which concluded that for any given air pressure, a single air flow rate would result regardless of the fuel pressure/fuel flow through the nozzle over the air pressure range which produced 5-micron droplets. The bench test data correlated with the Sonic Development Corporation data for air pressure versus air flow as did results from fuel pressure versus fuel flow testing. The deviation of the bench test results from the supplied calibration chart was within the accuracy range of the test equipment of ±3 psi on pressures and ±.2 gal per hour fuel flow.

Air fuel and equivalence ratios were calculated, and are given in Table C-1, for all of the combinations which Sonic Development Corporation presented as producing 5-micron drops. Notice that all of the combinations produced air/fuel ratios richer than stoichiometric, and all but one produced an equivalence ratio greater than the selected value of 2.0.

Table C-1

Nozzle Characteristics at Room Temperature (70°F) to Produce 5-Micron Drops

	Fuel Flow		Pressure	Air flow		Pressure		Equiv.
	(gal/hr)	(lb/min)	Psig	SCFM	(lb/min)	(psig)	A/F	Ratio
035 Nozzle:								
	1.0	(.1096)	7	1.2	(.0916)	50	.835	7.725
	1.5	(.1644)	20	1.5	(.1145)	62	.696	9.267
052 Nozzle:								
	1.0	(.1096)	14	3.4	(.2594)	80	2.367	2.725
	1.5	(.1644)	16	3.4	(.2594)	80	1.578	4.088
	2.5	(.2740)	22	3.6	(.2747)	80	1.002	6.434
	3.5	(.3837)	31	3.9	(.2976)	85	.775	8.317
086 Nozzle:								
	1.0	(.1096)	0	6.3	(.4807)	45	4.385	1.471
	1.5	(.1644)	1	6.7	(.5112)	47	3.110	2.074
	2.5	(.2740)	5	9.0	(.6867)	63	2.506	2.574
	3.5	(.3837)	10	11.0	(.8393)	78	2.187	2.948

NOTES:

Stoichiometric air/fuel ratio = 6.45
lb air/min = .0763 * SCFM Air
lb fuel/min = .1096183 x gal fuel/hr
Density methanol = 49.2 lb/ft^3

Table C-2

Required Air at Optimum Equivalence Ratio of 2.0 (A/F = 3.225)

	Fuel (lb/min)	Sonic Air (lb/min)	Additional Air (lb/min)	Total Air (lb/min)	Total Charge Volume CFM*
035 Nozzle:					
	.1096	.0916	.26186	.35346	4.63
	.1644	.1145	.41569	.53019	6.95
052 Nozzle:					
	.1096	.2594	.09406	.35346	4.63
	.1644	.2594	.27079	.53019	6.95
	.2740	.2747	.60895	.88365	11.58
	.3837	.2976	.93983	1.23743	16.22
086 Nozzle:					
	.1096	.4807	-.12724	.35346	4.63
	.1644	.5112	.01899	.53019	6.95
	.2740	.6867	.19695	.88365	11.58
	.3837	.8389	.39813	1.23743	16.22

NOTES:

Additional air = 3.225 * fuel - sonicore air
Total air = additional air + sonicore air

* Assume standard conditions in manifold.
Charge volume = air volume since fuel volume is negligible.

APPENDIX D

Testing With A High-Energy Ignition System

The high energy ignition system consisted of a high-voltage inverter and a special coil. As recommended by the manufacturer, the plug gap of the standard Bosch W4CC plugs was increased from .7mm to 1.0mm. Both the fast cranking starter system and finely atomized fuel delivery system were retained on the vehicle during the testing with the high energy ignition system. The results of testing this system, which reportedly delivers 40,000 volts, are presented in Table E-1. The results show that no improvement in minimum cold starting temperature was realized when this system was installed on the M100-fueled Volkswagen.

Table D-1

Testing With Fast Cranking Speed, Finely Atomized Fuel And Higher Voltage Ignition System (Temperature °F)

M100-Fueled Volkswagen Rabbit

Air	Oil	Coolant	Fuel Bladder	Zero Air	Start* (yes/no)	Comments
60	60	60	60	60	Yes	400 rpm crank speed; spark backfire through intake on first attempt
45	45	45	45	45	No	400 rpm crank speed; spark backfire through intake on first attempt**
40	40	40	40	40	No	320 rpm crank
53	26	50	38	43	No	320 rpm crank
34	34	36	40	39	No	320 rpm crank
40	50	40	49	40	No	320 rpm crank
45	45	45	50	45	No	320 rpm crank
35	22	43	48	31	No	350 rpm crank long-plugs (Bosch W7D) gapped @ .012 inches

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* After vehicle no-starts the plugs were removed. Plugs 2, 3 and 4 were observed to be shorted by liquid methanol fuel.

** This was the only test which produced a backfire without the vehicle starting.

APPENDIX E

Testing with Continuous 10,000 Volt Ignition System

The continuous ignition system, which consisted of four oil furnace transformers rated for continuous duty at 10,000 volts A.C. 23 milliamps, was connected to Champion N3C plugs gapped at 3.2mm. Standard plug gap is .7 mm. This system took the place of the standard ignition system. Power from the vehicle's batteries was disconnected from all components and accessories, except for the starter motor, during the continuous ignition system testing to avoid possible electronic damage from the high voltage alternating current.

Testing of the continuous ignition system on the Volkswagen indicated that igniting the Sonicore supplied fuel at 70°F was not a problem. Testing of this system at 30°F and 40°F, however, indicated that the Sonicore supplied fuel could not be ignited at these temperatures. Ignition of the Sonicore supplied fuel at 50°F was accomplished, but the start of ignition was delayed compared to the almost instantaneous ignition of the fuel at 70°F.

The procedure when testing the continuous ignition was: 1) crank the engine; 2) turn on power to the transformers; and 3) open the valves which supply the pressurized fuel and air to the Sonicore nozzle. Using this procedure, ignition occurred within 1-3 seconds after the fuel and air valves were opened at 70°F. A 5-10 second delay was present between opening of the fuel and air valves and start of ignition at 50°F and no ignition occurred at 40°F and 30°F, with 20 seconds of cranking time. Inspection of the plugs after the no-starts revealed wet spark plug insulators and wet metal surfaces inside the plug base, but the electrodes did not appear to be shorted with liquid of methanol fuel.

A bench trial was conducted at 40°F to observe whether the liquid methanol on the spark plug would inhibit the spark at the plug gap. This testing concluded that with the 3.2mm plug gap the thin layer of methanol on the inside metal surfaces of the plug caused the spark to jump to the side of plug base. This was now the narrowest gap thickness due to the high conductivity of the methanol. After 3-4 seconds the methanol would evaporate and the spark would return to the center electrode.

Regapping of the plugs to 2.3mm alleviated the problem of the spark jumping to the side of base during bench testing. These regapped plugs were then installed in the engine and retested at 45°F. Fuel ignition still did not occur with the regapped plugs.

In an attempt to limit the occurrence of the erratic spark, while retaining the maximum possible gap, the air gap area between the center electrode and the side of the spark plug shell of four Bosch W4CC spark plugs was filled to the tip of the center electrode and over the sides of the spark plug base with Sauereisen electrotemp (ceramic) cement. Bench testing with these modified plugs indicated that this cement is electrically conductive when 10,000 volts are applied. The maximum plug gap obtainable which would fire properly was only .3mm. When a larger gap was attempted, the ceramic cement glowed in a radial line indicating the transformer-supplied current was flowing through the cement to ground on the threaded shell of the plug.

The cement on one of the plugs was filed down even with the end of the spark plug base. This exposed about .063 inches of spark plug tip length and substantially reduced the amount of ceramic cement in actual contact with the copper center electrode. This allowed the ceramic-filled maximum plug gap to be increased to 1.6mm. This is the same maximum value which can be obtained with a standard Bosch W4CC plug.

The modified and standard plugs were then bench tested after coating the electrode area with methanol at 30°F and 70°F to determine the effect of adding the ceramic on the erratic spark condition. The standard plug outperformed the ceramic-filled plug at both temperatures. At 30°F the methanol film burned off the ceramic filled plug, which ended the erratic spark within 6 to 10 seconds. The standard plug, however, burned off the methanol film within 3-5 seconds. It is interesting to note that the methanol film actually burned off; a flame was present on the spark plug base while the plug was firing erratically.

Discussion of connecting one of the oil furnace transformers to a distributor led to some calculations. If the engine is cranking at 350 rpms and we know the alternating current (A.C.) transformer is operating at 60 HZ, then in 20° of crank angle duration, which is typical of a long duration spark system, the plug will only see .571 sparks. Thus, no restrike is possible. One may be tempted to say that the plug will see 10,000 volts x 23 milliamps = 230 watts during this 20° period, but since we are dealing with A.C., the 10,000 volt and 23 milliamp values are root mean square (RMS) values of a sinusoidal wave. In actuality, the plug can see wattages ranging from 0 to about 300 watts during the 20° of crank duration. Since the voltage is sinusoidal and voltage potential across the plug determines whether the plug will fire or not, there is no guarantee that the plug will be firing over the entire 20° of crank duration. At higher engine speeds there is no guarantee of the plug firing at all, since the 20° of spark duration will become compressed on a time axis and it may fall in an area for which the instantaneous voltage will never reach the value required to jump a spark across the plug gap.

APPENDIX E (cont'd)

A high voltage, higher frequency ignition system would guarantee a spark in the plug gap at the instant the fuel would become ignitable (vaporized) in the cylinder if one is relying on the heat of compression to vaporize the fuel before ignition occurs. A high voltage, high frequency ignition system also could supply the energy required to start a flame propagation through fuel droplets in the combustion chamber.

It would be reasonable, at first glance, to say that the lack of ignition at the colder ambients could be explained by the low frequency of the alternating current. But since the fuel repeatably ignited at 70°F with the same cranking speed at which fuel would not ignite at 45°F, another explanation of nonignition must be examined.

Table E-1

Testing With Fast Cranking Speed, Finely Atomized Fuel Delivery and 10,000 Volt Continuous A.C. Ignition Source

M100-Fueled Volkswagen Rabbit

Temp(F°)	Comments
70*	Heavy backfire through intake 1-2 seconds into test
50*	Light backfire through intake 7-8 seconds into test
45*	No sign of ignition or backfire
40*	No sign of ignition or backfire
30*	No sign of ignition or backfire
40-45**	No sign of ignition or backfire
40-45***	No sign of ignition or backfire

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* Gapped plugs @ .125 inches.

** Gapped plugs @ .090 inches.

*** Gapped plugs @ .012 inches.

APPENDIX F

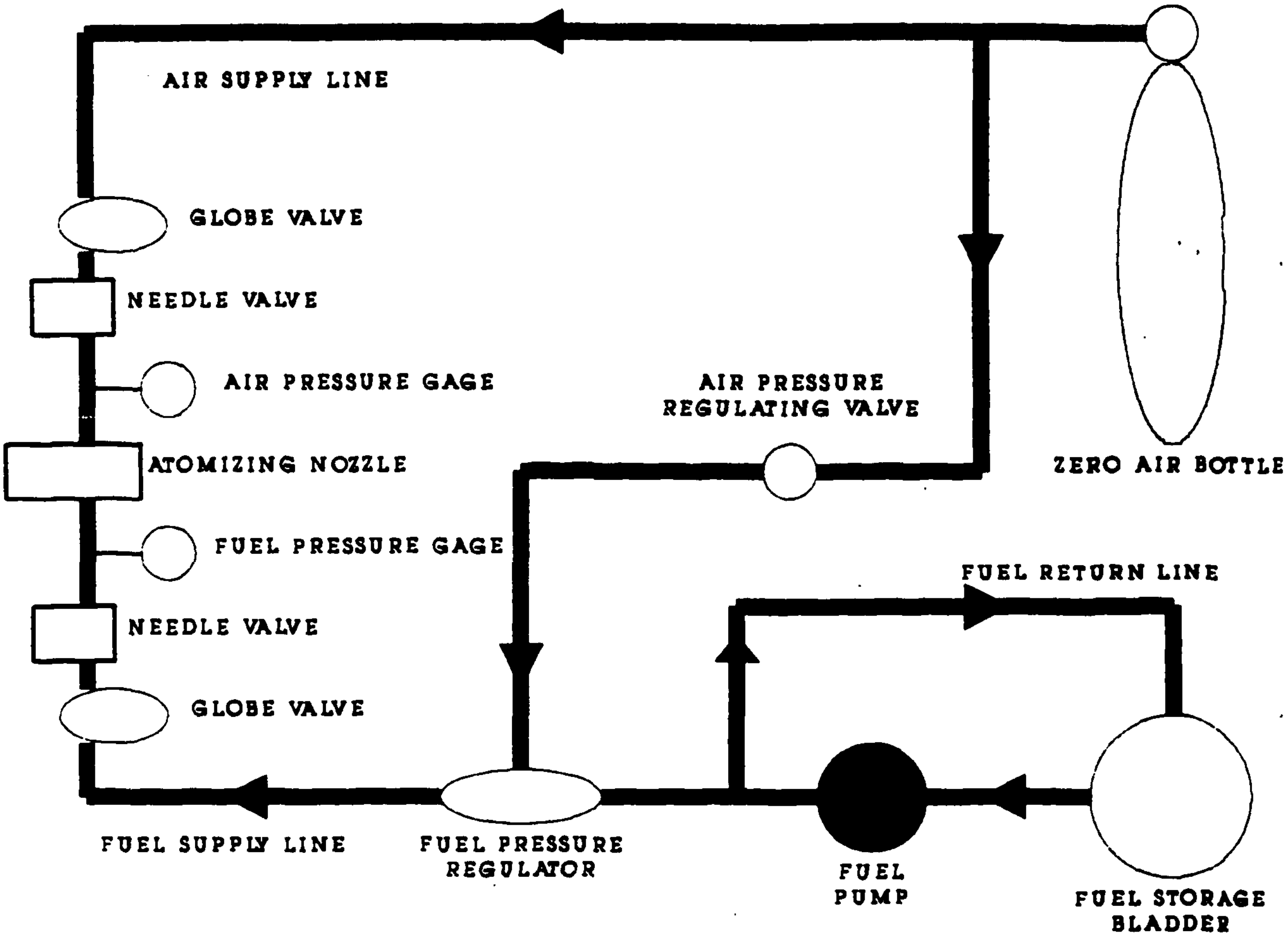
Testing With a High Energy Fast Breakdown Ignition System

The high energy, fast breakdown ignition system replaced the entire standard Volkswagen ignition system. A special distributor with a hall effect pickup was used as a crank angle sensor, not as a switch for the high voltage current. The signal from the hall effect unit was entered into a "black box" along with battery voltage. The output was passed through four special high voltage leads to the specially made, oil-filled, spark plug boots. The plugs were a modified surface gap-type developed especially for this prototype ignition system by Champion Spark Plug. A plug gap of 2mm (.080 inch) was used which produced an output voltage of 30 to 40 Kv. This system delivered a single spark at approximately 200 milli-Joules in about 30 nanoseconds.

Testing of this ignition system was successful at 65°F and 70°F, but preliminary results show that this system will not substantially lower the minimum cold starting temperature of the M100-fueled Volkswagen. Testing conducted with this system at 20°F and 30°F proved unsuccessful.

APPENDIX G

SCHEMATIC DIAGRAM OF THE SYSTEM USED TO SUPPLY THE FINELY ATOMIZED FUEL



NOTE: ALL LINES AND FITTINGS ARE
TEFLON OR 316 STAINLESS STEEL