EXHAUST EMISSION ANALYSIS OF THE WILLIAMS RESEARCH GAS TURBINE AMC HORNET

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Background

The New York City Air Resources Board was awarded an EPA Grant for the purpose of evaluating field experience with a turbine powered passenger car. The Test and Evaluation Branch was given the task of testing this prototype vehicle and developing simplified test procedures which could be used by New York City personnel. Initial testing of the vehicle was performed in December 1971 using the 1970 Federal Test Procedure to satisfy the NYC-Williams contractual obligations. The vehicle was then delivered to the New York City Air Resources Board on January 30, 1972, for acceptance and some public demonstrations. The vehicle was returned to the EPA laboratory for more extensive testing to obtain complete emission data and to develop a test procedure to be utilized by New York ARB while the vehicle is on location in New York City. The turbine car arrived at the EPA facility February 25, 1972. Testing was conducted through the month of March and returned to Williams Corporation for a 60-hour teardown and inspection as previously agreed with New York City ARB. The vehicle was returned to EPA after the engine had been torn down for inspection and after modifications were made to the shut-down fuel drain system, combustor louver design and gear-box breather system. It should be kept in mind that this vehicle incorporates a "state of the art" engine and does not represent the emission levels that can potentially be achieved with gas turbine power plants.

Vehicle Tested

The Williams Gas Turbine, WR-26, regenerative turbine automotive engine was mounted in a 1971 American Motors Corporation Hornet test vehicle. The engine utilizes a single power turbine to develop 80 horsepower. The engine regenerator incorporates two large discs of a ceramic-glass material for inlet air preheating. The standard AMC automatic transmission is coupled to the engine through a drop shaft gear system. Indolene Clear gasoline was the test fuel used throughout the test program.

Test Program

Testing was accomplished using the 1970, 1972, and 1975 Federal Test Procedures. In addition, steady state

and proportional sampler tests were conducted. As a means of cross checks, continuous raw exhaust was sampled during some of the aforementioned test procedures.

A 1200 CFM constant volume sampler (CVS) system was used for the majority of the testing. Because of high back pressure in the system a minor modification had to be made to the CVS. The dilution air filters at the CVS were blocked-off and air from the test cell was drawn into a plenum collecting the vehicle exhaust. Mixing occurred at the exit of the vehicle exhaust.

The cold start tests were made on a chassis dynamometer after the vehicle had been parked in a 68-86° ambient condition for at least 12 hours. Hot start data was taken after the vehicle had been brought up to operating temperature. It was then shut down and restarted according to the FTP being performed.

The concentrations of pollutants were measured using both hot and cold flame ionization detectors (FID), for unburned hydrocarbon (HC). Non-dispersive infrared (NDIR) analyzers were used for carbon monoxide (CO) and carbon dioxide (CO_2). A chemiluminescent analyzer was used to determine both nitric oxide (NO) and nitrogen dioxide (NO_2). The sum of NO and NO_2 is reported as NO_x. Concentrations obtained were then used to calculate the mass of emission per mile of operation and reported as grams per mile (gpm).

To measure fuel consumption, a weigh scale system was used and a carbon balance technique was additionally applied to provide a cross check. A significant difference was noted throughout the test program between the actual fuel weight data and a carbon balance calculation performed using the emission data collected. As of this report an explanation for this difference has not been found and further investigation is continuing. (See table 6)

Running the vehicle with the turbine bypass in the closed position was found to reduce the hydrocarbon (HC) between 50 - 70%. This is due to the more even combustion during deceleration requiring fewer relights. The bypass system for this particular vehicle has been set to operate in the open position. However, it can easily be operated in the closed position by merely flipping a switch. Operating in the open mode provides some engine braking and

cooler starting, which is not true in the closed position. Steps are being taken to eliminate the bypass system from future engines. Another method to achieve engine braking and cooler starting will be employed.

The purpose in performing numerous techniques and test procedures was to try to establish an acceptable test procedure for gas turbine testing for the New York City Air Resources Board.

When sampling from low emission high flow vehicles the hydrocarbons in the dilution air can contribute a major portion of the total hydrocarbons and the correction factor as called for in the Federal Register does not represent a true picture. For the 1972 FTP tests, the following calculation procedure was used:

$$Ce = \left(Ct - Cb \frac{Vt - Ve}{Vt}\right) \frac{Vt}{Ve} \quad (1)$$

Where:

Ce = concentration of undiluted exhaust

Ct = concentration of sample bag

Cb = concentration of background dilution air

Vt = volume flow rate of sample, or total CVS flow

Ve - volume flow rate of engine exhaust

Then the mass (gpm) of each pollutant emitted is calculated from:

$$W = K\ Ce\ Vei \quad (2)$$

Where:

K = density of each pollutant

Vei = average volume of engine exhaust per mile

(1) See emissions results, page 2, report 71-30, "Exhaust Emission Analysis of the Williams Research Gas Turbine Volkswagen", Leonard D. Verrelli, EPA.

In all, eighteen (18) tests were performed according to the 1972 FTP. Of the eighteen tests, six were cold starts with the bypass open, six were hot starts with the bypass open and three cold starts, three hot starts with the bypass closed.

It was suggested by the manufacturer towards the end of the test program, to try some emission tests with the bypass closed. A few were accomplished. (See Table I). Table III reflects the same testing after engine modifications were made.

Additionally there were twelve tests run using the 1975 FTP. These tests used a different method to calculate mass emissions.

First a dilution factor is calculated according to this equation:

$$DF = Vt/Ve$$

Where:

DF = dilution factor

Vt = CVS volume flow rate

Ve = engine volume flow rate

Then:

$$C_c = Ct - Cb \left(1 - \frac{1}{DF}\right)$$

Where:

C_c = corrected concentration of dilute exhaust

Ct = concentration of sample bag

Cb = concentration of background dilution air

Then the mass emissions in grams per mile are calculated from:

$$Mass = K\ C_c \cdot Vte$$

Where:

K = density of pollutant
Vte = volume pumped through CVS during test

Of these eighteen 1975 tests, six were cold starts with the bypass open, six were hot with the bypass open, four cold with bypass closed and two hot with bypass closed. This data is summarized in Table II. Additionally Table IV reflects 1975 FTP after engine modification.

The proportional sampler data taken using the 7-mode driving cycle was calculated using the following procedure:

$$\frac{CFM}{mile} \times \text{concentration} \times K = \text{pollutant in GPM}$$

Where:

CFM = airflow of the engine in cubic feet/min.

Miles = distance traveled over the cycle in a min.

Concentration = pollutant measured in PPM

K = density factor of % for HC = 16.33×10^{-6}

CO = 32.97×10^{-6}

CO_2 = .5186

NO_x = 54.16×10^{-6}

The proportional sampler sampling method was explored for two reasons, one, to develop a procedure that could be adapted to the equipment the New York City ARB had available, secondly, to compare previous emission data obtained while testing the Chrysler turbine as reported in SAE report #680402, "Emissions From A Gas Turbine Automobile" dated May 20-24, 1968. This data is summarized in Table V.

Conclusions

By positioning of the power turbine bypass in the closed position it was demonstrated that low hydrocarbon (HC) emissions are possible with this engine; however, carbon monoxide (CO) and nitric oxides (NO_x) were not reduced sufficiently to be able to meet 1975 or 1976 emission standards.

As a result of our extensive emission testing, an in depth driveability investigation with the vehicle was not possible. Limited testing revealed slower than normal accelerations, limited engine retardation and a maximum speed of from about 78 mph.

The various methods of testing used provided a good data base for evaluating test methods and procedures. The proportional sampler method of collecting emissions proved to be the most practical for work to be performed at the New York City ARB.

TABLE I

FY72 Federal Test Procedure
Before Engine Modification

	[1]BPO cold 5 tests	BPO hot 3 tests	[2]BPC cold 1 test	BPC hot
HC GPM	1.48	1.52	1.26	---
CO GPM	10.52	9.42	9.83	---
CO_2 GPM	1726	1676	1769	---
NO_x GPM	3.16	3.25	3.29	---

[1]Bypass open

[2]Bypass closed

TABLE II

1975 Federal Test Procedure
Before Engine Modification

	[1]BPO cold 5 tests	BPO hot 4 tests	[2]BPC cold 2 tests	BPC hot 1 test
HC GPM	2.84	3.33	1.23	1.64
CO GPM	9.12	8.56	9.67	9.10
CO_2 GPM	1659	1636	1634	1675
NO_x GPM	2.97	2.79	2.86	3.00

[1]Bypass open

[2]Bypass closed

TABLE III

After Engine Modification
1972 Federal Test Procedure
Power Turbine Bypass Open

	Cold Start	Hot Start		
Test #	12-2236	12-2237	12-2238	12-2243
HC*	.97	.57	.71	.93
CO*	10.1	9.14	8.58	7.34
CO_2*	1864.0	1874.0	1704.0	1462.0
NOx*	3.68	3.5	3.3	2.4

Power Turbine Bypass Closed

	Cold Start		Hot Start		
Test #	12-2239	12-2240	12-2241	12-2242	12-2245
HC*	.23	.27	.31	.31	.26
CO*	7.9	6.84	7.02	7.50	7.8
CO_2*	1599.0	1547.0	1559.0	1538.0	1454.0
NOx*	2.64	2.59	2.77	2.55	2.8

*GPM

TABLE IV

After Engine Modification
1975 Federal Test Procedure

Power Turbine Bypass Open

	Cold Start	Hot Start	
Test #	12-2244	12-2246	12-2250
HC*	.62	.74	.72
CO*	7.43	7.77	6.92
CO_2*	1443.0	1435.0	1371.0
NOx*	2.8	2.0	2.5

Power Turbine Bypass Closed

	Cold Start		Hot Start
Test #	12-2247	12-2248	12-2249
HC*	.32	.23	.23
CO*	6.34	7.41	6.33
CO_2*	1385.0	1454.0	1382.0
NOx*	2.7	3.07	2.7

*GPM

TABLE V

Proportional Sampler Evaluation
Using 7-mode Cycle (Hot)
Bypass Open
Before Engine Modification

Test #	HC gpm	CO gpm	CO_2 gpm	NOx gpm
12-2188	.84	6.34	1323.0	2.77

Before Engine Modification

Test #	HC gpm	CO gpm	CO_2 gpm	NOx gpm
12-2251	.37	6.71	1567.0	2.64

Chrysler Turbine Data *

HC gpm	CO gpm	CO_2 gpm	NOx gpm
.91	7.04	940.0	1.86

*Test data shown was calculated from the results reported in the SAE report, "Emissions From A Gas Turbine Automobile", #68042, May 1968.

TABLE VI

Fuel Consumption Data
(miles per gallon)

Before Engine Modifications

Test Procedure	BP*	Test No.	Actual Weighed Data	Carbon Balance
1972 FTP (cold start)	0	12-2208	6.15	4.91
1972 FTP (hot start)	0	12-2209	6.28	3.65

Fuel Consumption Data
After Engine Modifications

1972 FTP (cold start)	0	12-2236	5.8	4.6
1972 FTP (cold start)	C	12-2239	6.7	5.4
1972 FTP (hot start)	0	12-2237	6.2	4.6
1972 FTP (hot start)	0	12-2238	7.0	5.1
1972 FTP (hot start)	0	12-2243	7.0	5.9
1972 FTP (hot start)	C	12-2240	7.1	5.6
1972 FTP (hot start)	C	12-2241	8.1	5.5
1972 FTP (hot start)	C	12-2242	7.2	5.6
1972 FTP (hot start)	0	12-2245	6.9	5.9
1975 FTP (cold start)	0	12-2244	7.1	6.1
1975 FTP (hot start)	0	12-2246	5.1	6.3
1975 FTP (hot start)	C	12-2247	5.1	6.5

*BP - Bypass 0 - Open C- Closed