EPA-AA-EOD-84/1

CATALYST ACTIVITY TEST SEQUENCE (CATS)

January 1984

by

Donald D. Danyko
William W. Watson

U.S. Environmental Protection Agency
Office of Air and Radiation
Office of Mobile Sources
Engineering Operations Division
Testing Services Group
2565 Plymouth Road
Ann Arbor, Michigan 48105

CATALYST ACTIVITY TEST SEQUENCE (CATS)

Abstract

The primary objective of this program was to establish vehicle operating modes during which a temperature rise across the catalytic converter could be measured and used for determining the catalyst activity. The results of twenty-five (25) vehicle tests are reported. Seventeen (17) vehicle tests were conducted using known good converters, six (6) using dead converters and two (2) using partially-active (lead-poisoned) converters. The test sequence consisted of a series of five engine operating modes. In general, with careful thermocouple attachment to the exhaust pipe surface at the inlet and output of the converter, active converters show a large enough temperature rise that they can be distinguished from dead converters.

Introduction

The primary objective of this program was to establish vehicle operating modes during which a temperature rise across the catalytic converter could be measured and used for determining the catalyst activity. In theory, unburned hydrocarbons, carbon monoxide and nitric oxides (three-way converters) from the engine will react in an active converter and produce heat. The procedure was intended to be quick, simple and cheap, and the equipment used, easy to install and durable. The potential application of the procedure would be as a secondary or referee test in cases where tampering or misfueling had been established by other means. This report details a procedure which has been developed emphasizing these objectives. Temperature data for seventeen (17) vehicles with good or active catalysts and eight (8) vehicles with inactive or partially-inactive catalysts is presented. The discussion also includes details on the general applicability of the hardware and instrumentation employed during the course of this effort.

Background

We were directed by Field Operations and Support Division, the sponsors of this project, to develop a non-idle procedure for assessing catalyst activity by measuring exhaust system skin temperatures. Procedure development was divided into two phases. Both phases included extensive collection of temperature data from vehicles being run on a chassis dynamometer. During the initial data collection period, the temperatures on the exhaust system skin near the inlet and outlet of the converter were measured during exhaust emissions

tests. The vehicles being tested represented a sample of in-use cars procured from the public. Attempts were made to gather temperature data from as many different vehicle types as possible (Table 1). No attempt was made to create a statistical or weighted sample of any kind. The exhaust emissions tests being performed included the FTP, HWFET and various other short cycle tests encompassing several different vehicle operating modes.

Following analysis of the temperature data from ten (10) vehicles, a procedure was designed to yield a temperature rise across the converter in as short a time as possible without operating the vehicle in an unusual manner. Temperature data was then gathered on vehicles using this test cycle. Throughout this second phase of testing, variations of the procedure were examined in order to resolve ambiguities in the temperature data.

Vehicle exhaust system configurations presented many challenges in attachment of the temperature measurement instrumentation. Hose clamps were used to fasten K-type thermocouples to the exhaust pipe as close as possible to the converter inlet and outlet. Special attention was paid to the location on the pipe (top, bottom or side) for each thermocouple. Visual estimates of the heat transfer properties of the pipe at the inlet and outlet to the converter were made in order to best yield comparable temperatures. A strip chart recorder was used to record the temperatures throughout the test cycle.

Discussion

The CATS procedure was designed to meet the following criteria:

1. incorporate vehicle operating modes which create high converter loading;

2. minimize time to identify an active converter;

3. minimize operating stress on the vehicle; and

4. make no alterations to vehicle hardware.

High converter loading results from rich fuel/air mixtures. Analysis of typical engine dynamics indicates rich mixtures are likely during start-up idle and high power modes. Consequently, the test segments of the cycle were designed so the vehicle would be operating at a rich fuel/air ratio.

Figure 1 (attached) shows the test cycle that was employed in the second phase of the data collection to achieve a temperature rise across the converter. All driving is done at FTP dyno settings for each vehicle. The cycle is initiated with a 30 mph steady state to warm up the engine, exhaust system and catalytic converter. As the temperature at the inlet to the converter reaches 400°F, the vehicle is ready to begin the actual testing segment of the procedure. The first two modes are "crowds", that is, accelerations under conditions of constant manifold vacuum. Crowds are a means of automatically adjusting engine loading for each engine/vehicle combination. The 7" crowd will give a temperature rise across the converter for most vehicles with active catalysts. The 4" crowds, in general, will supply a rich enough fuel/air mixture to assure catalyst activity in vehicles where the catalyst may be partially deactivated. The next mode, a 10-minute idle, is representative of another rich mixture mode of operation. Some vehicles which do not show catalyst activity during crowd conditions will demonstrate activity during this mode. Finally, a misfire condition is initiated at 2500 rpm by removal of a spark plug wire. This final test, by supplying an unburned charge to the converter, should yield good evidence of catalytic activity.

There are vast differences in the thousands of converter emission calibrations on the road today. A high percentage of good converters will likely show negative results in any one of the modes. Fewer will show negative results in two or more modes, and so on. Although the entire procedure requires twenty-five (25) minutes on the dyno, most vehicles with good converters will pass within the first three modes. Only the dead converter vehicles will have to run through the entire cycle. Although this procedure is not likely to identify 100% of the active converters correctly, the passing criteria for each mode can be adjusted to minimize errors of commission, omission or both.

Disadvantages of the procedure are:

1. Temperature measurements are highly influenced by thermocouple placement.

2. Many exhaust system configurations do not have 'equivalent' inlet and outlet thermocouple installation points.

3. Many exhaust system configurations make thermocouple installation difficult.

4. Each unique exhaust/converter system has its own heat capacity, heat transfer properties and catalyst loading design.

The first three disadvantages concern the thermocouple measurement technique and will be discussed later. The fourth addresses the high degree of variation observed between the individual temperature traces of the data fleet. This item identifies some factors responsible for the differences in temperature traces from vehicle to vehicle. These factors and the relatively different exhaust flow rates and temperatures of each mode have been used in the refinement of mode selections, their order and time length.

Data Analysis

Figure 2 (attached) is a typical trace of exhaust system skin temperature versus time. The outlet temperature of the active converters is shown higher than the inlet for each mode and the outlet of the inactive converters is shown lower. This representation reflects the results of the test fleet data summarized in Table 1. For example, on the average, the good converters on the seventeen (17) vehicles tested show about 60°F higher outlet temperature at the end of the 7" crowd mode. The range for the good converters is from -150°F to +320°F. Each mode has a similar high degree of variation.

Using the pass/fail criteria of Figure 1, all the good and both lead poisoned converters (about half-active) passed and the dead converters all failed. However, several of the vehicles were re-run due to non-equivalent thermocouple placement. Incorrect thermocouple installation caused the temperature rise measured across the converter to shift to the extent that the results were contrary to the actual converter condition (available FTP results). Results from the correctly-placed thermocouple trace were included in the table and the other results omitted.

Examining Table 1, we find the majority of the seventeen (17) good converter test vehicles demonstrating higher outlet temperatures during the crowd modes. This is the clearest demonstration of converter activity considering that both the inlet and outlet temperatures are rising (Figure 3). Figures 3 and 4 are temperature traces taken from the same vehicle. The difference is that the converter beads were removed (no activity) for the test trace of Figure 4. There is a 70°F crossover at the end of the 4" crowds for the good converter and no temperature crossover for the dead one.

Analysis of the idle portion of these traces is more complicated than the simple crowd analysis. Note that there is a temperature crossover for the dead converter (Figure 4) during the idle mode. During the crowd modes (high power output) the converter interior and shell are being heated by the high temperature exhaust. The engine exhaust temperature during the following idle is much cooler, so both the inlet and

outlet skin temperatures fall during this mode. The outlet skin temperature is partially maintained during this time by convective heat transfer from the converter interior to the cooler idle exhaust gas. Note also that in both figures neither temperature has reached an equilibrium (steady) condition after 10 minutes. This behavior is a result of (1) the heat capacity (retained heat from crowd modes), (2) the heat transfer (heat loss of the converter to its surroundings), and (3) the amount of heat being generated during the idle (HC, CO and NOx loading from the engine).

Early in the development of this procedure, equilibrium idle temperature comparisons were sought but cycle-time requirements limited this possibility. Reviewing the idle data in Table 1 indicates there are distinguishable temperature differences in the good and dead converter groups in spite of the complicated factors at work during this mode. Therefore a 100°F temperature difference at the five-minute idle point was chosen as a pass/fail criteria. It is important to recognize that the temperature condition of the converter at the beginning of the idle period shown in Figures 3 and 4 has an integral part in determining the five-minute point temperature difference. That is to say, each mode is a preconditioning for the following mode. The outlet pipe temperature is lower than the inlet for the dead converter (Figure 4) at the instant the idle mode begins, and higher for the good (Figure 3). At the end of the idle mode (beginning misfire) the outlet temperatures are very different in the two figures. The misfire portion of Figure 3 (good converter) may look very different if the vehicle were operated in a manner to bring the inlet and outlet temperatures together before the misfire begins.

It is possible to divide this procedure into discrete segments for special purposes, however the existing analysis criteria would no longer apply, and the diagnostic ability of any section will be less than the whole. Further development and analysis could also be directed into any given mode to determine its single maximum usefulness.

Hardware Applicability

Application of the temperature measurement hardware to the different exhaust system configurations created many complicated installations.

The equipment used for this measurement process was:

- K-Type Thermocouples, 1/16" Diameter (Calibrated)
- Vacuum Gauge (Calibrated)
- Worm-gear type hose Clamps
- Temperature Recorder, able to read from 0-2000°F. (Calibrated)

The primary problem areas were shields (attached to converter and exhaust pipes), converter location and exhaust system routing.

Shields protecting the exhaust pipes and converter created major complications. The imported vehicles appeared to have the most occurences of shields, whereas most domestic vehicles avoid the use of shields. For example, Subaru vehicles which posed the worst case, have shields welded on the entire exhaust system except for the converter. The converter has a bolted shield, where the removal of six bolts will expose the surface areas necessary for proper temperature measurement. In most cases however, the exhaust shields are bolted on, such as, Mazda GLC and Toyota Tercel. Once the nuts and the shields are removed, the inlet and outlet areas necessary for temperature measurement are adequately exposed. Problems that arose during installation on domestic vehicles were also with catalyst shields, and shields on mechanical components. Ford Escorts, for example, have a two piece shield welded around the catalyst. However, adequate space is allowed to properly attach the thermocouples if care is used during attachment. Chrysler Omni and Horizon models generally have a two catalyst system, with the first catalyst located six inches after the exhaust manifold along the fire wall. To properly expose the catalyst inlet pipe, removal of a shield above the right transaxle shaft is required.

Exhaust system routing and converter location created the second problem area. In most cases this problem was non-existent, but where it did exist, major obstacles were created. Some specific cases are Chrysler K cars and Omni-Horizon models, late model Hondas, all Subarus, Ford Escort-Lynx, Ford Mustang-Capri, and Ford Fairmont models.

The Chrysler K cars and Omni-Horizon models are equipped with a two-catalyst system. A splash shield blocks the access and one of the converters is located up and behind the engine against the fire wall, six inches below the exhaust manifold.

Late model Hondas, although none were tested, have the converter mounted to the outlet of the exhaust manifold. This will create a special problem, in that no inlet pipe mounting area exists.

All Subaru models have two seperate inlet pipes into the converter, with only one outlet pipe. And as mentioned earlier, welded shields encompass the inlet and outlet pipes, with a two piece shield bolted around the entire converter.

Finally, the aforementioned Ford models have catalysts with sharp angled inlets and outlets. The Fairmont models also have heavy steel flanges at the converter inlet and outlet areas.

During development of the procedure, differences as high as 70°F were measured simply by locating the thermocouples on different sides of the exhaust pipe. Therefore certain precautions must be observed when attaching the thermocouples. During tightening of the hose clamp, the tip of the thermocouple must be covered by the band. The axes of the thermocouple and the exhaust pipe must be parallel or the clamp will not apply adequate pressure. The worm gear on the clamp should be opposite the thermocouple. Otherwise, the metal in the worm gear creates a heat sink, giving an inaccurate temperature reading. The thermocouple wires must be kept away from moving parts and the hot exhaust system. All thermocouple mounting surfaces should be sanded to remove excessive corrosion, allowing for good contact and proper heat transfer. The hose clamps should be as tight as possible, holding the thermocouple firmly against the pipe. There should be no exhaust leaks near the thermocouples, or there will be an impact on measured temperatures. Thermocouples should be mounted as close as possible to the converter inlet and outlet, the farther away from the converter inlet and outlet the more heat that will be lost through radiation. If a bend exists in the inlet and outlet pipes, thermocouples should be mounted on the outside of the bend, allowing measurement at the hottest point on the pipe. Lastly, the thermocouples should be at least one to two inches away from overlapping pipe joints, inlet and outlet connection flanges, mounting brackets or hangers, and shields. All of these are heat sinks and can radiate heat away from the thermocouples. Note that in some cases one to two inches will not apply because of interfering brackets, etc. In these special cases, a brief analysis of the mounting problem and engineering judgement will allow for the proper thermocouple location.

Conclusion

Measurement of exhaust system skin temperatures, if done carefully, may indicate whether a catalytic converter is good or bad. Temperature measurement across the converter indicates thermal activity but it does not establish whether it is a result of hydrocarbon, carbon monoxide and nitric oxide conversion or of any combination of those three conversions. Assessment of temperature data taken from the exhaust system skin at the outlet and inlet of the converter is complicated by the variety of exhaust system configurations and the unique properties of each converter. The CATS procedure, by operating the vehicle in rich fuel/air mode, provides a test that was successful in identifying active and inactive catalysts. The procedure does require a large amount of equipment including a chassis dynamometer. Extensive engineering judgment was employed in interpretation of the data generated during this program, but with proper training the use of the procedure is clearly feasible.

Recommendations

The procedure should be performed as designed, since the differing exhaust system configurations and their corresponding heat transfer and heat capacity characteristics will alter the temperature data if a different sequence is used. The simplest and most effective means of thermocouple attachment is by hose clamp. Strip charts should be used to record the temperature data to allow analysis. A relatively small sample fleet of screened tampering/misfueled vehicles should be CATS tested and then FTP tested to determine real-world CATS accuracy prior to full scale implementation.

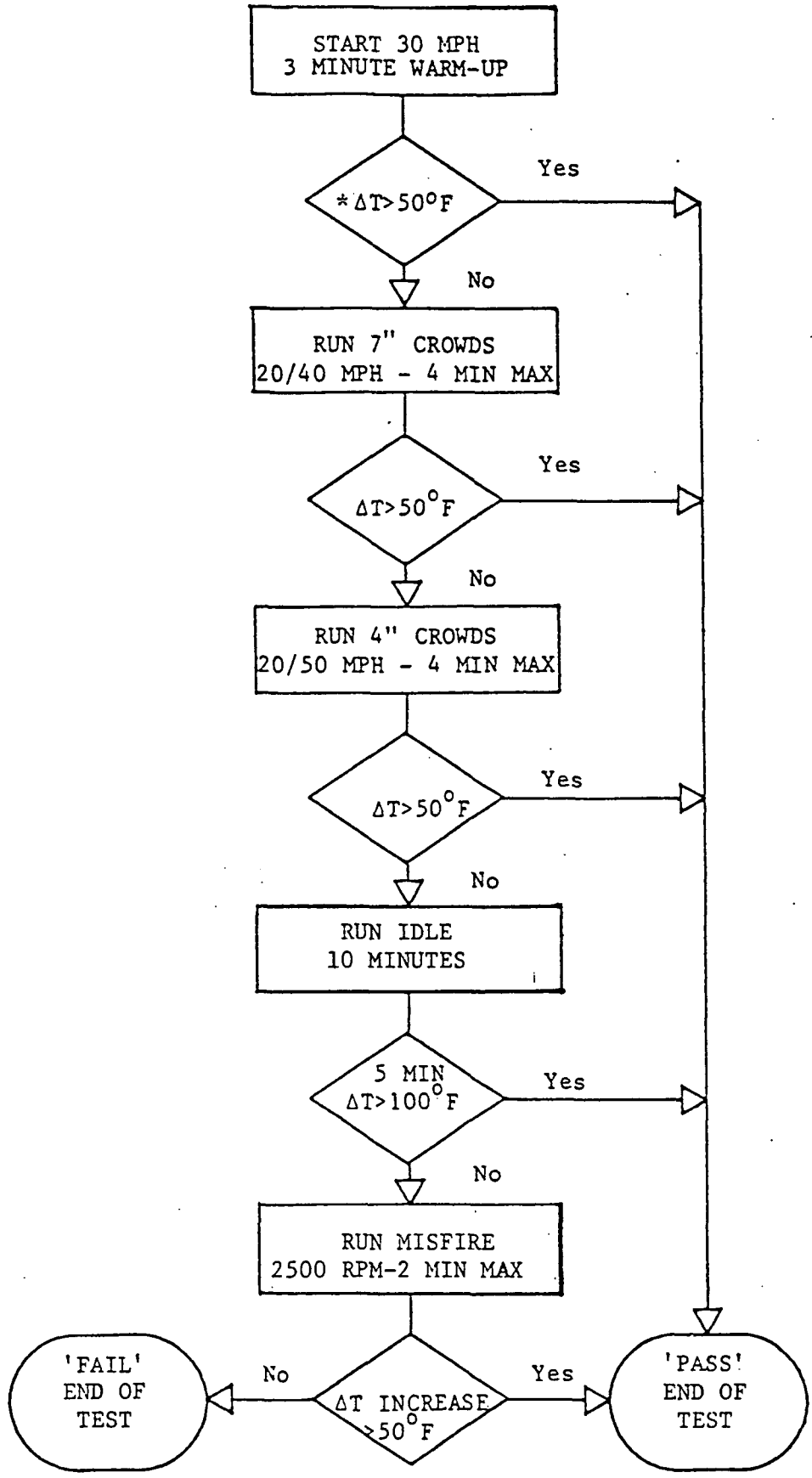
TABLE 1. Converter Activity Test Sequence Fleet Data

VEH #	MANUFACTURER/MODEL		ENGINE CLASS/TYPE		FTP (GM/MI) HC	CO	NOx	TEST MODE/TEMPERATURE RISE ACROSS CONVERTER °F CROWDS 7"	CROWDS 4"	IDLE START	IDLE 5 MIN	IDLE END	MISFIRE START	MISFIRE END
GOOD CONVERTERS														
10	GM	Camaro	-	V-8	0.2	3	0.9	10	-10	-10	185*	215	150	65
14	GM	Cutlass	A106	V-8	0.2	3	0.8	50	70*	70	170	155	145	175
4	GM	Regal	A110	V-6	0.8	8	2.9	80*	150	150	170	160	-	-
16	GM	Grand Prix	A110	V-6	0.4	7	0.6	-30	70*	70	200	230	200	130
5	GM	Skylark	A69	I-4	0.6	14	0.5	50*	130	130	85	0	-	-
6	GM	Citation	A69	I-4	0.3	3	1.1	-20	20	-20	80	0	115	330*
17	GM	Citation	-	I-4	0.2	4	0.4	-150	-110	-110	50	0	0	50*
1	Ford	Escort	A3	I-4	0.2	3	0.3	85*	260	130	210	80	40	190
2	Ford	Escort	A3	I-4	0.6	9	0.7	320*	275	320	85	20	-	-
9	Chrysler	Horizon	A86	I-4	0.5	8	1.0	80*	-220	-220	160	45	0	-20
		(Two Converters in Series)						-65	-110	-110	-160	-70	-60	-60
15	Chrysler	Champ	A109	I-4	0.6	6	1.0	80*	110	110	240	220	200	330
3	Nissan	Datsun 210	A73	I-4	0.4	8	1.2	100*	130	190	270	280	-	-
7	Toyota	Tergel	A125	I-4	0.3	5	0.5	120*	180	60	115	90	-	-
8	Honda	Accord	A83	I-4	0.5	7	0.4	60*	110	115	140	-	-	-
11	Toyota	Mazda	A111	I-4	0.8	10	0.6	170*	270	440	430	480	400	540
12	Isuzu	Subaru	A105	H-4	0.3	6	0.7	-20	-15	-15	60	-20	-15	85*
13	Isuzu	Subaru	A105	H-4	0.2	3	0.8	30	90*	90	170	140	70	150
DEAD CONVERTERS														
10	SAME VEHICLES AS ABOVE				2.5	24	3.4	-115	-145	-145	-30	-30	-60	-150
14					2.2	22	2.1	-100	-45	-45	15	-20	-20	-20
16					2.3	18	2.5	-80	-65	-65	60	35	20	-95
17					-	-	-	-190	-135	-135	-30	-65	-55	-70
1					2.5	31	0.9	-	-50	-150	-50	-40	-	-
9					2.9	42	1.0	-340	-300	-300	5	-90	-60	-230
					2.9	42	1.0	-100	-45	-45	55	45	0	-20
LEAD POISONED CONVERTERS														
16	SAME VEHICLES AS ABOVE				1.0	7	1.3	-30	-30	-30	140*	165	95	-10
17					-	-	-	-80	-80	-80	130*	50	55	70

* Refers to 'pass' point according to Figure 1 criteria.

Figure 1

Converter Activity Test Sequence (CATS) Flowchart



* ΔT is the temperature rise across the converter (outlet-inlet).

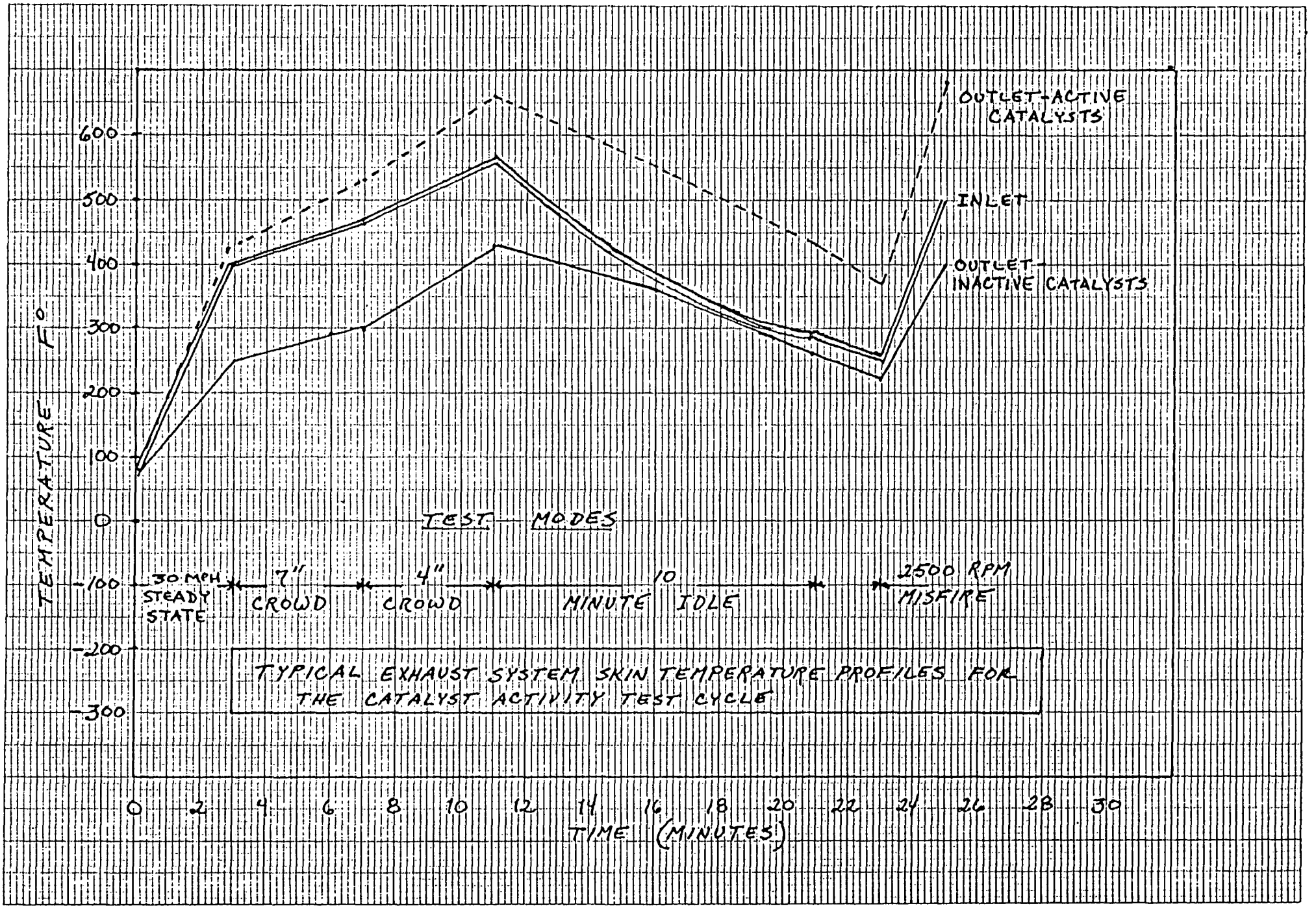

OUTLET-ACTIVE CATALYSTS
INLET
OUTLET-INACTIVE CATALYSTS
TEMPERATURE F°
600
500
400
300
200
100
0
-100
-200
-300
TEST MODES
30 MPH STEADY STATE
7" CROWD
4" CROWD
10 MINUTE IDLE
2500 RPM MISFIRE
TYPICAL EXHAUST SYSTEM SKIN TEMPERATURE PROFILES FOR THE CATALYST ACTIVITY TEST CYCLE
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30
TIME (MINUTES)

FIGURE 2

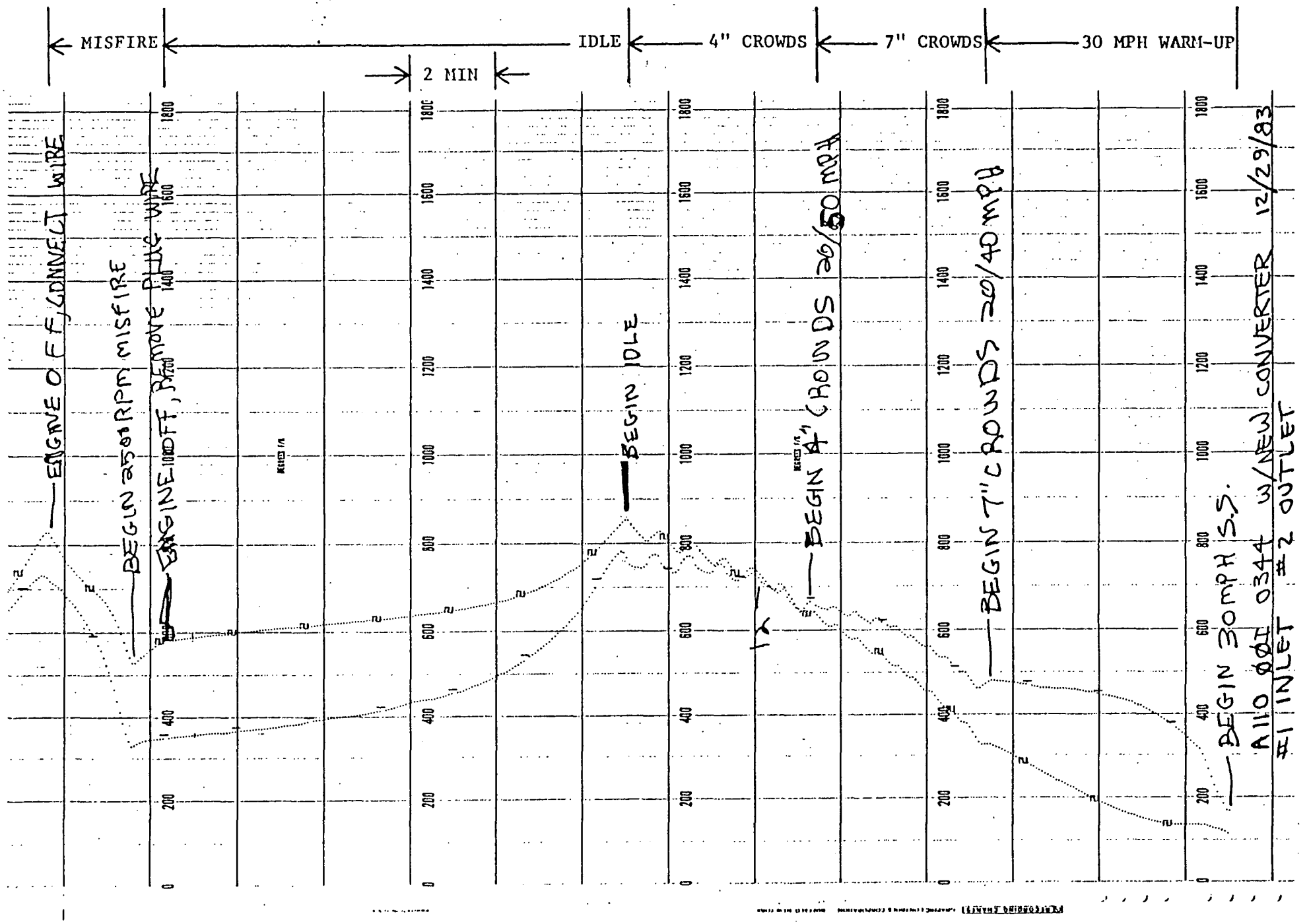


FIGURE 3. ACTUAL CONVERTER INLET AND OUTLET SKIN TEMPERATURE TRACE FOR A 1981 GM GRAND PRIX WITH A GOOD CONVERTER

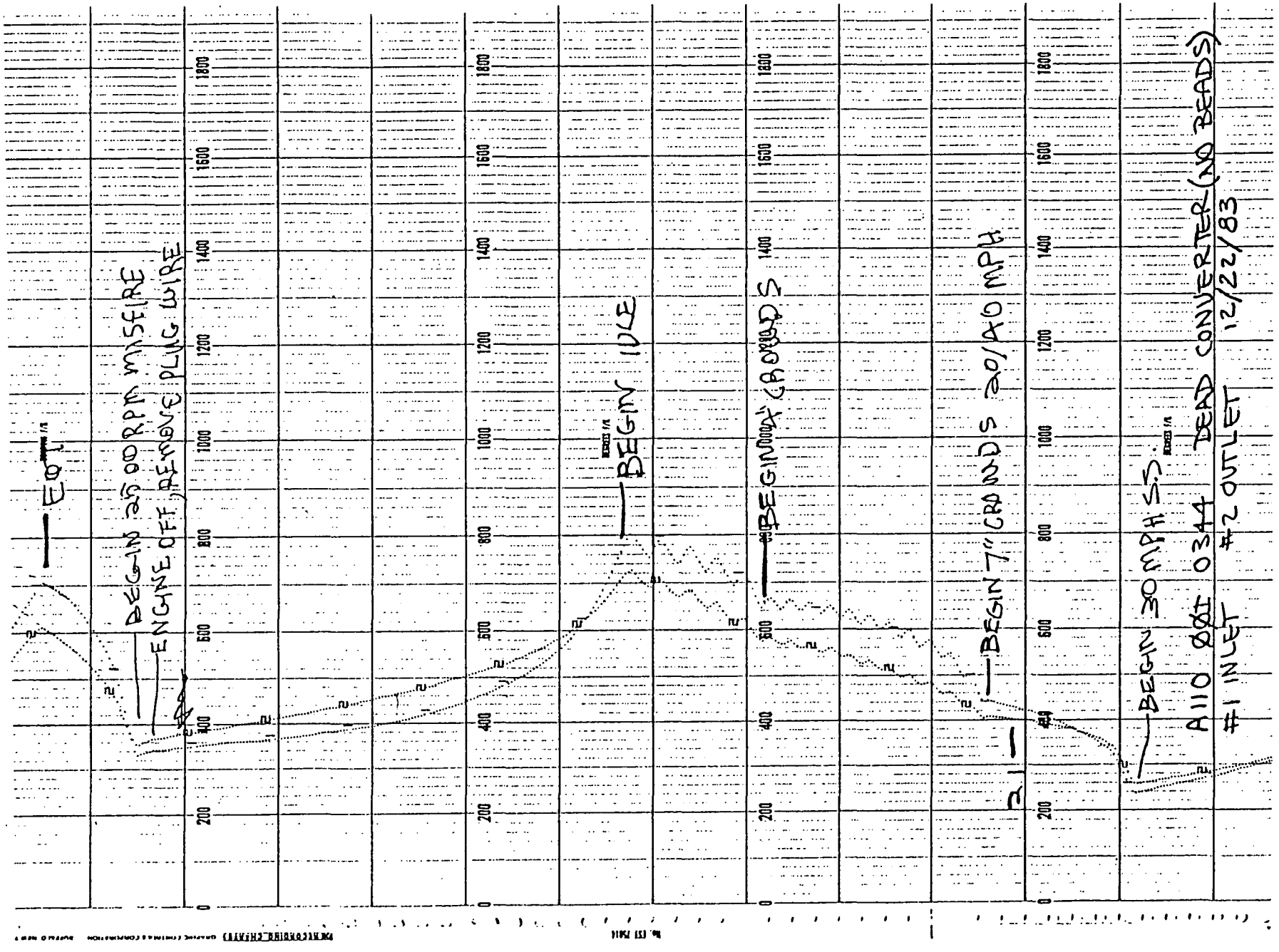


FIGURE 4. ACTUAL CONVERTER INLET AND OUTLET SKIN TEMPERATURE TRACE FOR A 1981 GM GRAND PRIX WITH A DEAD CONVERTER